BREEDER REACTOR ECONOMICS

DISCLAIMER

Prepared For:
Breeder Reactor Corporation
July 1, 1975

DOE|SF|00893 - -T24

NASAP TECH. DATA
CENTER Room F-435
Document No. 6E-003

Breeder Reactor Economics

T. R. Stauffer Harvard University
R. S. Palmer General Electric Company AM03-76SF00893
H. L. Wyckoff Commonwealth Edison Company

DOE/SF/00893--T24

DE85 018251

INTRODUCTION AND SUMMARY

This paper focuses on the comparative economics of fast breeder reactors versus light water reactors and develops an internally consistent set of financial techniques whereby a utility may determine and compare the costs of generating power with either system. The general methodology is used here to estimate the break-even capital costs for the breeder as a function of future uranium prices but is equally applicable to other reactor types. It is shown that by the time the breeder reactor (breeder) is commercially available, it is likely a utility would select a breeder even though its capital cost might be twice that of a light water reactor (LWR).

The fast breeder reactor is one of the promising energy conversion systems under development to meet the world's energy needs. While the level of development effort on other energy options such as solar, geothermal, and fusion will hopefully be increased, these technologies are in their infancy and their ultimate capability to contribute to mankind's energy needs in a significant way is yet uncertain.

At least through the first several decades of the next century, the world must be prepared to supply its energy needs using fuels that have proved themselves. These are coal and uranium. In particular, fission via the breeder should be capable of providing for the world's energy needs in an environmentally acceptable manner, for as long as is required to bring other prospective energy conversion methods to commercial status — even centuries if this should be necessary.

If the breeder is important to the nation, then breeder economics are also important. The electric utilities, and the various governmental agencies that regulate the electric utility industry will need to understand how the breeder's economics will compare with those of a light water reactor.

The economic benefits of the breeder relative to the LWR can be divided into two categories:

1. **Direct Benefit**
   This equals the savings in lifetime fuel cycle costs that accrue because of the breeder's more efficient use of uranium (i.e., greatly reduced mining requirements) and the lack of need for fissile enrichment, less the effects of higher breeder capital costs. This is the direct financial savings realized by a utility which purchases an LMFBR rather than an LWR or fossil plant. It is this determination of the direct power costs of the breeder relative to the LWR, as perceived by the utility, that will serve as a basis for the comparative cost data that is presented here.

There is a second benefit that while not included in the data provided here, should at least be mentioned.

2. **Indirect Benefit**
   This is the reduced fuel costs that accrue to all LWR's because the introduction of breeder reactors slows — or eliminates — the steady increases in uranium costs due to the depletion of resources. Simulation studies reveal that the indirect benefits can be as large as the "direct benefits."*

Both benefits ultimately will be realized by the nation's consumers as lower rates for electricity, but the individual utility, in deciding between an LMFBR or a competing reactor system, will perceive only the direct benefit.

Here, we shall present only the cost estimates which a utility will use when choosing between a breeder and a light water reactor. These relate to the direct costs and benefits. The justifiable extra investment in a breeder increases with increasing uranium costs. If the average unescalated lifetime cost of U_3O_8 is $20/lb (75$), a utility would be justified in spending about one-third more in capital cost for a breeder than an LWR. The lifetime cost is the single value of U_3O_8 that would result in the same accumulated cost of U_3O_8 as the **actual** year by year costs when both are present-valued to the year of plant startup. If the lifetime real cost of U_3O_8 is $60/lb, the breeder plant could cost about 75% more, while for the case of U_3O_8 at $100/lb the breeder could cost about 2.2 times as much as an LWR.

The following table summarizes the allowable capital cost of the breeder over the LWR for three U_3O_8 cost levels:

* T. R. Stauffer, H. L. Wyckoff, R. S. Palmer, *An Assessment of Economic Incentives for the Liquid Metal Fast Breeder Reactor.*

ALLOWABLE CAPITAL COST OF BREEDER OVER LWR

Levelized U_3O_8 Value of Plant Lifetime Supply (75$) ($/lb)	Projected Year of Occurrence	Allowable Ratio of Total Plant Costs[1,2] (Any Year and Any Rate of Inflation)[3] (Breeder/LWR)
20	1965 to 1970	1.29
60	1985 to 1990	1.73
100	2000 to 2005	2.18

[1] The reference case cost for an LWR is $400/kW(e) in 1975 dollars [$600/kW(e) for a plant installed in 1982].

[2] These ratios are for a plant design capacity factor of 70%. The comparable numbers for an 80% capacity factor are: U_3O_8 @ $20/lb — 1.34, U_3O_8 @ $60/lb — 1.84, U_3O_8 @ $100/lb — 2.09.
factor of 65%: U_3O_8 @ $20/lb — 1.27, U_3O_8 @ $60/lb — 1.69, U_3O_8 @ $100/lb — 2.09.

[3] This table is valid for any year when the value of U_3O_8 is in 75$'s. For years other than 1975, it may prove more convenient to convert the U_3O_8 values to current dollars.

It is projected that lifetime real costs of U_3O_8 will reach about $60/lb (75$) for reactors installed in 1985 to 1990, and $100/lb after the turn of the century A lifetime real cost of $20/lb (75$) will be incurred by reactors that were started up 5 to 10 years ago The actual year in which uranium costs achieve any given levelized value is sensitive to the uranium supply curve See Figure 1 However, the relationship between a uranium cost and the premium a utility will pay for a breeder reactor — for example, 29% more if U_3O_8 costs $20/lb — is independent of the rate of uranium depletion or assumptions regarding the extent of the uranium resource base

The calculations and assumptions are discussed in more detail later It must be emphasized that the allowable extra investment cost is based upon a utility financial analysis focused upon the decision to build a reactor A national economic analysis, which includes the indirect benefits accruing to all utilities and consumers collectively, would indicate greater benefits and a higher justifiable investment/kW(e) for each uranium cost

FUEL CYCLE COSTS FOR LWR AND BREEDER

The financial arithmetic that is applicable to the breeder, and all nuclear plants and their fuel cycles is neither unique nor unusual Nevertheless, considerable care is necessary to ensure that the calculations are internally consistent, especially when using cost data based upon projected inflation rates For example, it is not uncommon in cursory analyses to treat plant and fuel costs as constant (which is economically equivalent to an assumption of zero inflation) but then to use current carrying charge cost rates for capital, which embody a current rate of inflation Unfortunately, the results of such hybrid calculations are seriously in error

Our goal here is to preview the comparative economics of a breeder plant versus an LWR plant on a consistent basis, as viewed by an investor-owned utility faced with choosing between the two types of reactor * Table 1 shows the coordinated financial assumptions that are used in this analysis for investor-owned utilities The cost of debt and equity as well as the debt/equity ratio are based on the industry's past experience Column A summarizes the "real" financial parameters, i e , corrected for inflation and applicable to constant dollar capital outlays Column B shows the comparable values for the case of a steady-state inflation rate of 6%

The breeder reactor that is used as a reference for this assessment has the following key characteristics

Electrical Output (MWe)	1000
Capacity Factor (%)	70
Overall Plant Efficiency (%)	38
Breeding Ratio (at equilibrium)	1 25
Compound System Doubling Time (at equilibrium) (years)	18

This breeder is conservative, the fuel performance is achievable with oxide fuels without significant metallurgical development Sufficient information is provided in Table A-5 of Appendix A so that analysts can make their own calculations

* Appendices A and B describe details of the method of analysis used in this study

Table 1
COORDINATED FINANCIAL ASSUMPTIONS FOR INVESTOR OWNED UTILITIES

		A (%)	B (%)
1	Rate of Inflation	0	6
2	Cost of debt money for zero inflation	2 75	2 75
3	Cost of debt money with inflation (1 x 2), e g , [(1 06 x 1 0275)−1] x (100) = 8 92%	2 75	8 92
4	Cost of equity money for zero inflation	5 5	5 5
5	Cost of equity money with inflation (1 x 4), e g , [(1 06 x 1 055)−1] x (100) = 11 83%	5 50	11 83
6	Assumed debt/equity ratio for utility industry capitalization	55/45	55/45
7	Assumed federal plus state tax as percent of total earnings[1]	50	50
8	Return on debt (cost for use of debt portion of money), (3 x 6), e g , (0 55 x 8 92) = 4 91%	1 52	4 91
9	(a) Return on equity (cost for use of equity portion of money), (5 x 6) e g , (0 45 x 11 83%) = 5 32%, and,	2 48	5 32
	(b) Federal tax plus state tax (for 50% total tax on earnings)[1]	2 48	5 32
10	(a) Weighted-average interest rate (net-of-taxes), (8 + 9)	4 00	10 24
	(b) Discount rate for utility decision making process (net of taxes), (8 + 9)	4 00	10 24
11	Level annual revenue requirement excluding depreciation (effective interest rate plus taxes) (10a + 9b)	6 48	15 56
12	Level annual revenue requirement with depreciation, 32-year book-life and 16-year tax life (determined by calculations using the above assumptions — not shown) [2]	5 89	11 83
13	Charge for property tax plus plant insurance	0 85	1 70
14	Level annual revenue requirements with depreciation, property tax and insurance (12 + 13)	6 74	13 53

[1] At 50%, assumed federal plus state income tax is equal to return on equity

[2] This annual charge is derived from the preceding financial assumptions and duly incorporates the effects of the normalization of accelerated tax depreciation, 16 year asset depreciation range (ADR) tax life, and a capital recovery period of 32 years This represents the capital charge that a tax-paying regulated electrical utility might apply

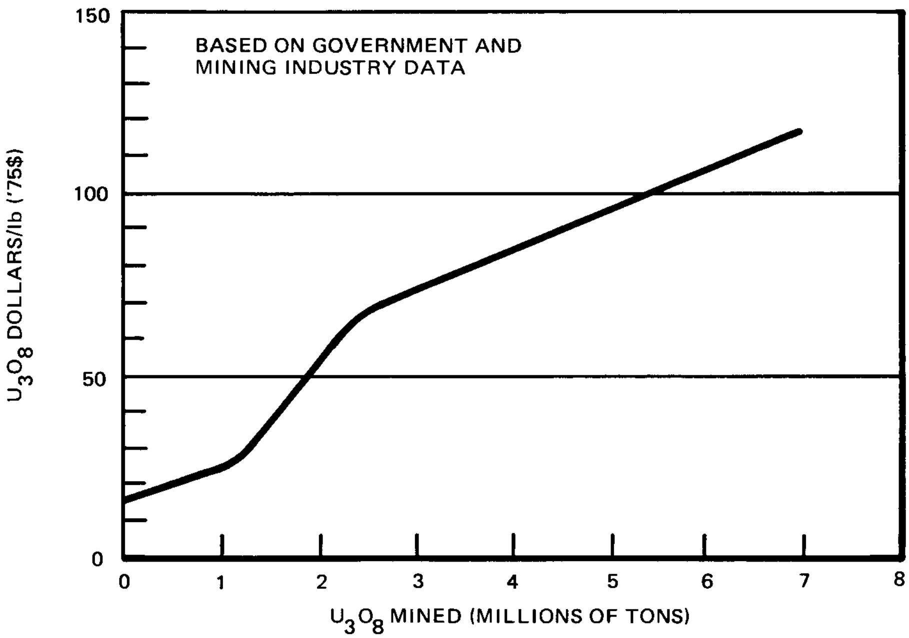


Figure 1 Projection of U_3O_8 Price versus Cumulative Consumption

based on their assessments of any of the parameters

For the LWR, it is assumed 1) that one fuel cycle lasts 4 years (including downtime), 2) that U_3O_8 is purchased 2 years before reactor loading, and 3) that enrichment is purchased 1 year before loading For the breeder, one fuel cycle lasts 2 years, and plutonium is purchased 1 year before reactor loading For both the LWR and the breeder, fuel fabrication costs are incurred 1 year before reactor loading, and reprocessing is paid for and plutonium credit received 1 year after spent fuel is discharged The design fuel loading and control reactivity are assumed to vary with the plant capacity factor, so that there results a fixed length fuel cycle (including downtime) permitting annual refueling on a scheduled basis

The future costs of nuclear power and thus the need for a breeder reactor depend upon what uranium will cost in the decades ahead Figure 1 is a projection, based on ERDA and industry estimates of the nation s uranium resources, of U_3O_8 market prices as a function of cumulative consumption This projection is based on the effort that will be needed to recover the various grade ores It places the present market price of U_3O_8 at about $15/lb, and the price at the point of transition to the lower grade ores (shales) lies in the range of $65/lb (75$) This estimated supply curve for uranium includes a large fraction of speculative resources whose existence is still unproven

The lower curve on Figure 2 traces the cost of U_3O_8 over time as lower-cost reserves are consumed Note that already in 1990, when the commercial breeder will first be available, the price of U_3O_8 is expected to be around $25/lb (75$) Considering that offer prices for future delivery of U_3O_8 are already approaching this range, this projection may be unduly conservative

The upper curve on Figure 2 is of particular significance, this is the present-value-weighted price of U_3O_8 for a reactor versus the year it comes on line During the 30-year life of a nuclear plant, the cost of U_3O_8 will rise as one resorts to ever lower grade ores This is quite apart from any effects of inflation, reflecting only the steady depletion of the better ores The proper cost of U_3O_8 to use in evaluating the lifetime cost of power from the plant is the 30-year levelized real cost of U_3O_8 This is the equivalent constant cost of U_3O_8 over the lifetime of the plant which would result in the same total plant lifetime cost of power as the actual costs of U_3O_8 which increase steadily

The upper curve on Figure 2 is a projection of the 30-year real costs of U_3O_8 for a plant which goes into operation in any year up to 2010 By 1990, the levelized cost of U_3O_8 is in the range of $60 to 70/lb (75$), and by 2000 it is $100 to 110/lb It is these costs of U_3O_8 against which the breeder will be competing unless additional major deposits of high grade uranium ore are discovered

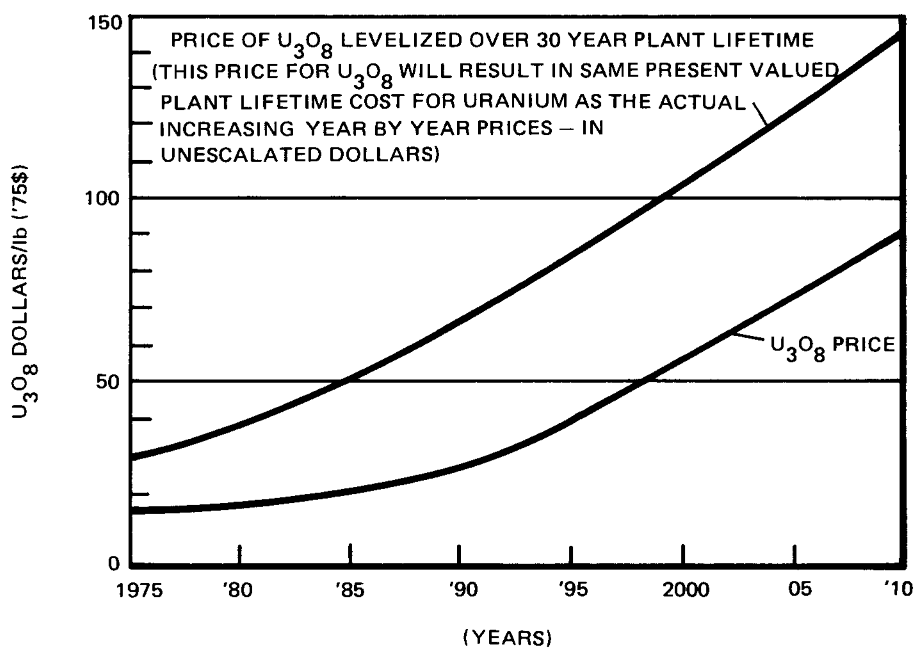


Figure 2. Projection of U_3O_8 Price versus Years

Tables 2 and 3 are the final product of the analysis — the comparative fuel cycle costs for the breeder and the LWR, for both zero inflation and a 6% rate of inflation. These tables also indicate the additional capital cost that is justified for a breeder because of its fuel cycle cost advantage.

For a plant lifetime levelized "real" (not including inflation) U_3O_8 cost of $20/lb (Table 2), the breeder lifetime levelized fuel cycle cost is 1.50 mills/kWh for zero inflation and 3.00 mills/kWh for 6% inflation. The comparable numbers for the LWR are 2.75 mills/kWh and 5.58 mills/kWh.

The magnitude of the fuel costs for the 6% inflation case are larger than those for the zero inflation case for two reasons. First, with inflation, fuel prices in current dollars will continue to increase during the life of the plant, hence average lifetime costs (actually levelized costs) — in inflated dollars — will be about 1.7 times larger than costs at the time of plant start-up. Second, with inflation the carrying charge cost for capital are over twice as large (Table 1, line 11) as for the zero inflation case. Of course, the present-values of the plant's total lifetime fuel costs are the same for both rates of inflation (and in fact any assumed rate of inflation when treated consistently as was done here).

We determine the extra capital cost which exactly offsets the lower fuel cycle cost of the breeder as follows. For the case of U_3O_8 at $20/lb (see Table 2), the levelized fuel cycle differential (6% inflation) is (5.58 − 3.00) = 2.58 mills/kWh(e). If the breeder operates at a 70% capacity factor, the annual fuel savings per kW(e) of capacity becomes:

$$\frac{2.58}{1000} \times 8760 \times 0.7 =$$

$15.82 per year per kW(e)

Capitalized at a charge rate of 0.1353 (see Column B, Table 1), $15.82/year translates into a capital cost difference of $116.93 ($15.82 ÷ 0.1353) which rounds up to $117/kW(e). An analogous computation, using the fuel cycle differential and the capital charge appropriate to the zero-inflation case, yields an allowable capital cost difference of $114.

While the net fuel cycle cost advantage for the breeder is 1.25 mills/kWh for zero inflation, and 2.58 mills/kWh for a 6% inflation case, the resulting amounts by which the initial capital cost of the breeder can exceed the LWR and still remain competitive are essentially the same for both rates of inflation — $114 versus $117/kW(e).* This is because the as-

* The small discrepancy in the capital cost differential between the two cases arises because of certain inflation-related tax effects.

Table 2
FUEL CYCLE COSTS FOR LWR AND BREEDER
(LEVELIZED OVER PLANT LIFETIME — $75)

U_3O_8 @ $20.00/Pound

	Zero Inflation mills/kWh(e) (A)	6% Annual Rate of Inflation mills/kWh(e) (B)
LWR		
Use Costs		
U_3O_8[3]	1 11	1 64
Enrichment	0.75	1.18
Fabrication	0.27	0.41
Reprocessing	0.43	0.96
Plutonium Credit	−0.38	−0 90
	2 18	3.29
Carrying Charge Costs		
U_3O_8	0.34	1 35
Enrichment	0.18	0 71
Fabrication	0 06	0.25
Reprocessing	−0.07	−0.32
Plutonium	0.06	0.30
	0.57	2 29
Total (LWR)	2 75	5 58
Breeder		
Use Costs		
Fabrication	0 53	0.87
Reprocessing	0.63	1.32
Plutonium, Net Created	−0 38	−0.82
Plutonium, Plant Constant Lifetime Inventory	—	−0.27
	0 78	1.10
Carrying Charge Costs		
Fabrication	0.09	0.37
Reprocessing	−0.05	−0.28
Plutonium, Net Created	0 03	0.17
Plutonium, Plant Constant Lifetime Inventory	0.65	1.64
	0 72	1 90
Total (LMFBR)	1.50	3 00
Fuel Cycle Cost Differential	1 25 mills/kWh(e)	2.58 mills/kWh(e)
Equivalent Capital Cost Differential: LMFBR versus LWR (75$)	$114/kW(e)[1]	$117/kW(e)[2]

[1] The small discrepancy between the zero inflation and 6% inflation values arises because of certain inflation related tax effects

[2] Compared to a capital cost of $400/kW(e) for an LWR starting up in 1975 — equivalent to $600/kW(e) for a 1982 startup

[3] See Table A-3 of Appendix A for explanations of various components of cost

sumed rate of inflation plays a role in determining the financial parameters, such as carrying charge cost and discount rate, that are used when converting both plant capital costs, and fuel costs, to their equivalent mills/kWh.

Thus, except for the minor tax-induced discrepancy, the effects of inflation cancel in any comparison between plant and fuel costs and the real capital cost differences are the same for the zero and 6%-inflation cases, as one should expect.

Table 3
FUEL CYCLE COSTS FOR LWR AND BREEDERS (LEVELIZED OVER PLANT LIFETIME — $75)

U_3O_8 @ $60.00/Pound

	Zero Inflation mills/kWh(e) (A)	6% Annual Rate of Inflation mills/kWh(e) (B)
LWR		
Use Costs		
U_3O_8[3]	3.33	4.92
Enrichment	0.75	1.18
Fabrication	0.27	0.41
Reprocessing	0.43	0.96
Plutonium Credit	−0.99	−2.32
	3.79	5.15
Carrying Charge Costs		
U_3O_8	1.02	4.05
Enrichment	0.18	0.71
Fabrication	0 06	0.25
Reprocessing	−0.07	−0.32
Plutonium	0.15	0.78
	1.34	5.47
Total (LWR)	5.13	10.62
Breeder		
Use Costs		
Fabrication	0.53	0.87
Reprocessing	0.63	1.32
Plutonium, Net Created	−0 97	−2.12
Plutonium, Plant Constant Lifetime Inventory	—	−0 70
	0.19	−0 63
Carrying Charge Costs		
Fabrication	0.09	0 37
Reprocessing	−0.05	−0.28
Plutonium, Net Created	0 09	0 45
Plutonium, Plant Constant Lifetime Inventory	1 68	4.25
	1 81	4 79
Total (LMFBR)	2 00	4 16
Fuel Cycle Cost Differential	3 13 mills/kWh(e)	6 46 mills/kWh(e)
Equivalent Capital Cost Differential LMFBR versus LWR (75$)	$285/kW(e)[1]	$293/kW(e)[2]

[1 2 3] See Table 2 for footnotes

As a point of reference, it is interesting to compare the LWR fuel cycle cost of 5.58 mills/kWh that is shown in Table 3 (for 6% inflation) with current industry statements that LWR fuel cycle costs are currently about 2.00 mills/kWh. The fuel cycle costs on Table 2 are based on U_3O_8 at $20/lb, enrichment at $50/SWU, and plutonium at $16.42/gm. These assumptions reflect conservative projections of the expected cost picture within the next several years. The higher figures may be reconciled with the currently reported lower values. First, if the LWR fuel cycle cost of Table 2 is modified to reflect the recent past (U_3O_8 at $10/lb), enrichment at $35/SWU, and plutonium at $10/gm — the levelized fuel cycle cost that reflects a plant lifetime of 6% inflation — would decrease from 5.58 mills/kWh to 3.34 mills/kWh. Second, if the fuel cycle cost is *converted from the lifetime levelized* value to the current cost (divide by 1.66), the present LWR fuel cycle cost would be 2.01 mills/kWh. This is in agreement with the level of LWR fuel cycle costs the utility industry has been reporting.

The fuel cycle costs and the justifiable capital cost premium for the case of U_3O_8 at $60/lb are detailed in Table 3. For this cost of U_3O_8, a utility would be economically justified in selecting a breeder over an LWR even if its capital cost were as much as $290/kW(e) *more than an LWR* (75$). Further calculations show that for a plant lifetime levelized "real" U_3O_8 cost of $100/lb, the capital cost differential between the breeder and the LWR could be about $470/kW(e), i.e., a cost premium of 118%.

The allowable ratio of breeder plant *capital costs to LWR plant capital costs* is valid regardless of the year of plant startup and assumed rate of inflation because: 1) the reference U_3O_8 costs exclude inflation (are in constant dollars referenced to the year of plant startup), 2) plant capital costs are inherently referenced to the year of plant startup, and 3) it is assumed that over the long run, inflation affects all components of real cost (plant and fuel) uniformly. Any intrinsic increase in real uranium costs, for example, due to resource depletion rather than monetary inflation, is included explicitly in the calculation of the levelized U_3O_8 price.

CONCLUSIONS

Five conclusions emerge from this close examination of the fuel cycle economics of the breeder and the LWR.

1. At today's market value of U_3O_8, a utility would be justified in investing about one-third more for a breeder than for a LWR, even if the real cost (75$) of U_3O_8 might never increase.

2. At the time the breeder is commercially available — circa 1990 — it appears probable a utility would find it economically attractive to select a breeder, even if its capital cost were twice that of an LWR.
   Moreover, this spread very likely will continue to increase during the years that follow the breeder's commercial introduction.

3. Economic comparisons of nuclear alternatives for supplying electricity must be based on analyses that are internally consistent.
   An excellent method of checking the overall consistency of the economic technique being used is to make test analyses using several assumed rates of inflation. When the technique is correct, the results will be essentially independent of the assumed rate of inflation.

4. These calculations understate the permissable "break-even" capital cost penalty for a breeder **nuclear system**, since a large part of the plant costs are for hardware and systems that are present in any nuclear plant, and not specific to the breeder plant. Thus, for example, a 30% premium justified for the breeder plant implies that the nuclear island might cost up to 60% more than the comparable part of an LWR plant.

5. A national economic cost-benefit calculus would suggest still larger cost premia for a breeder over a LWR for any given level of U_3O_8 costs.
   These added indirect benefits from breeders due to reduced long-term U_3O_8 prices for all reactors are not included herein.

*

APPENDIX A
ESTIMATING NUCLEAR FUEL CYCLE COSTS

This appendix describes details of the method used in this study to determine fuel cycle costs We develop here a general methodological framework for computing fuel costs consistent with analytical techniques used by the electrical utilities This methodology is generally applicable to all nuclear fuel cycle cost calculations, and it is particularly useful because it provides for a rigorous and internally consistent treatment of inflationary effects

Three problem areas require special attention The first is inflation, where previous studies have used discounting procedures which are internally inconsistent with their own assumptions — implicit or explicit — as to the underlying rate of inflation The second is the need to identify and treat properly those components whose "real" uninflated costs may be expected to rise over the lifetime of the plant The third complication arises because different parts of the fuel cycle involve significantly different patterns of payments and credits, which therefore involve different financial treatment

INFLATION

Perhaps the most serious error in estimating and comparing nuclear fuel cycle costs has stemmed from a failure to handle inflation in a financially consistent manner When handled properly, the present-value of the year by year costs (carrying charge + depreciation) for a plant item or stream of expenses is independent of the assumed rate of inflation This means the present-value of a nuclear plant s estimated total lifetime fuel costs will not be affected by the assumed rate of inflation It is necessary that all carrying charge costs and discount rates be consistent with the assumed rate of inflation and that all costs be escalated at that same rate of inflation Nuclear fuel cycle cost estimates are traditionally made using a carrying charge cost which reflects the prevailing rate of inflation However, this leads to an error unless costs are consistently escalated over the life of the plant, and this is not always done One reason for this is the desire to avoid the extensive arithmetic that is needed to handle year by year escalation This shortcut fails to escalate fuel cycle costs in accord with the assumed rate of inflation and thus introduces a bias against plants with low fuel-cycle costs

LIFETIME COSTS VS PRESENT COSTS

Apart from inflation, there is evidence that the ' real" cost (constant dollars) of certain components of the fuel cycle will rise because of depleting reserves or other problems Examples of components that might be affected are uranium, enrichment, and reprocessing In order to accommodate these items, it is first necessary to convert the stream of rising real costs (where costs for each year are in unescalated dollars) into a lifetime levelized real cost for the plant This levelization must be carried out using the inflation-corrected (zero inflation) discount rate The levelized real cost becomes the point of reference, and the effects of any assumed rate of inflation are superimposed on this

CARRYING CHARGE COST

Determination of the carrying charges which enter into the cost calculation for each component of the fuel cycle, becomes complicated because each element of the fuel cycle is characterized by a unique time pattern of expenditures and credits For example, U_3O_8 for one fuel cycle of a LWR might typically be purchased 2 years before the fuel rods are loaded into the reactor Then, the fuel will be depreciated (due to burnup) over the 4 year fuel cycle The carrying charges for these 6 years must be "levelized" over the 4 years that the fuel is in the reactor in order that these costs can be recovered from the electricity that is generated This pattern then repeats for the seven or eight fuel cycles that will occur during the plant s lifetime, but with the further complication that the costs (in current dollars) for each successive fuel cycle will increase if some rate of inflation has been assumed Finally, the other elements of the fuel cycle enrichment, fabrication, reprocessing, plutonium recovery, etc each have their own unique pattern, and, different reactor types have fuel cycles of different duration Therefore, each major element of the fuel cycle must be treated separately

These problem areas are major in that they have made fuel cycle cost estimating an expensive, time-consuming task when handled properly We develop here a method which greatly reduces the complexity of fuel cycle estimating while introducing internal consistency into the financial calculations The key is the fact that the plant lifetime fuel cycle costs can be expressed as multiples of the unescalated costs for a single fuel cycle *

Paralleling utility industry practice, we differentiate between two categories of fuel cycle cost The "use" costs for one fuel cycle are akin to depreciation charges For example, if for one cycle, X dollars of U_3O_8 will make Y kWh(e), the use charge per kWh(e) is X/Y The use cost for the plant lifetime for any rate of inflation, can be shown to be a multiple of the zero inflation use cost for one fuel cycle

The second cost category is the carrying charges attributable to the various components of the fuel cycle These cover the costs of money and federal taxes related to carrying the inventory — for example U_3O_8 — until it is fully depreciated (used up) As above, it may be shown that the carrying charge costs for both one fuel cycle, and for the plant lifetime, are also constant multiples of the zero-inflation use costs for one fuel cycle This affords a major simplification because it means that one needs to compute only the use costs for a single cycle The plant lifetime costs are then determinable multiples of this

* Different multiplicative factors must be used for different rates of inflation and for each element of the fuel cycle

We refer to the constant multipliers that are used to generate lifetime fuel cycle use costs and lifetime fuel cycle carrying charge costs, from one cycle use costs, as "translators." Each component of the fuel cycle — U_3O_8, enrichment, fabrication, reprocessing, plutonium — must have its own translator. Reactors with different lengths, or patterns of fuel cycles (LWR, HTGR, breeder) must each have their own set of translators. But once the translators have been determined, plant lifetime fuel cycle analyses reduce to simple hand calculations, and it is possible with a minimal effort to investigate a wide range of reactor parameters and costs for the various elements of the fuel cycle.

We shall here recapitulate the four steps that are required to determine lifetime fuel cycle costs, and then we shall present an illustrative example. These are:

1. Reduce each component of the nuclear fuel cycle whose real (unescalated) costs are expected to rise substantially during the life of the plant, to a plant lifetime *levelized real cost.* Each year's real costs, measured in unescalated dollars, are present-valued using the inflation corrected (zero inflation) discount rate. This step is a must for fuel such as U_3O_8 where real costs are expected to rise and it may be desirable for items such as enrichment. For example, in Figure 2 of the report it is projected that the price of U_3O_8 will rise from $16/lb in 1975 to $65/lb in 2005. These prices are in 1975 dollars and represent the real costs of mining ever lower grade ores; escalation is not included. Figure 2 also shows that the plant lifetime levelized "real" cost for this 30 year period is $30/lb.* Thus, an analysis can be made on the basis that the unescalated cost of U_3O_8 during the life of the plant is a constant $30/lb. If some rate of escalation is assumed, it would be superimposed on this, starting in 1975.
2. Determine the one-fuel-cycle zero inflation use costs for the various components of the fuel cycle — U_3O_8, enrichment, etc., using the lifetime *levelized real costs, or constant real* costs should this be the case. The fuel cycle costs are typically expressed as mills/kWh(e), hence the costs incurred by the utility must be divided by the kWh(e) that will be generated during one fuel cycle. The one-fuel-cycle use costs should be determined assuming zero inflation, which means the lifetime real costs need no adjustment for escalation. (The translators, to be discussed below incorporate all necessary adjustments for the effects of inflation.)
3. Determine the translators for the various components of the nuclear fuel cycles under consideration. The translators are principally a function of the costs of money and assumed rate of inflation. There is a need to modify the translators only if the assumptions regarding these quantities are *changed. The details of determining* the translators are covered in the sections that follow.
4. Multiply the one-fuel-cycle use costs for each of the various components (U_3O_8, enrichment, etc.) by the appropriate translators to determine:
   - Lifetime levelized fuel cycle use costs.
   - Lifetime levelized fuel cycle carrying charge costs.

The final step of the procedure is to sum all of the cost elements to arrive at the total levelized fuel cycle cost over the plant lifetime.

*The reader may verify this through direct calculation

$$P(\text{levelized}) = \sum_{i=1}^{30} \frac{P^{(1975+i)}(1+d)^{-i}}{a(30, d)}$$

where.

a (30, d) is the present value of one dollar per year for 30 years discounted at rate d.

AN ILLUSTRATION OF PRINCIPLES

We shall highlight the application of these principles and the method of analysis with a very-much simplified example and sample calculations. Let us consider the uranium costs for a hypothetical nuclear plant that has an 8-year lifetime and which during its life burns two loads of fuel, each of which last 4 years (see Figure A-1). We assume that the U_3O_8 is burned at the rate of $100/year and that the uranium is bought 2 years before being loaded into the reactor at the price current at the time of payment. Figure A-1 indicates the purchase and use of U_3O_8 during the plant's 8 year lifetime. A set of three observations that simplify the task of analyzing the cost of nuclear fuel cycle alternatives will be presented based upon this example.

Observation 1 — **The present-value of a given period of fuel cycle costs is independent of the assumed rate of inflation.**

The costs of U_3O_8 consists of two components, the use charges (treated here as depreciation charges), and the inventory charges for carrying the yet to be burned U_3O_8. The determination of the present values for these two components of cost is indicated on Figure A-1, along with the explanations of the various expressions and terms that are used.

The equation for the use costs (PVU), is the present value of the uranium use charge, discounted at the current discount rate "d." For a constant load factor this is constant over each 4-year period. The second equation (PVCC), specifies the present value of the annual charges necessary to yield a return of "d%" (including income tax), to the capital investment. The sum of the two expressions describes the present value of the total pre-tax cash flow which provides for recovery of the investment and the targeted return on capital ("d" = "c").*

The point of note is that the sum of the present values of the use costs and carrying charge costs for the plant lifetime is the same regardless of the rate of inflation.** We may illustrate this numerically; consider a zero inflation situation where the carrying charge rate and discount rate are both 0.04.

*This representation, as well as those that follow, include three simplifying assumptions concerning the operation of the reactor and the physics of the fuel cycle. 1) assumes total core is refueled once every 4 years rather than one-fourth every year, 2) assumes equilibrium cycle throughout life of plant, and 3) assumes constant load factor To refine these is not warranted in the context of this type of analysis

**This result is rigorously true when the discount rate and carrying charge rates (including taxes) are identical. It is essentially true for the range of carrying charge rates and discount rates germane to the electric utility industry

Then referring to the example of Figure A-1 we have

$$z = 0\ 00$$
$$\bar{d} = 0\ 04$$
$$\overline{cc} = 0\ 04$$

and

$$PVU = \$673\ 27$$
$$PVCC = \$129\ 19$$
$$PVU + PVCC = \$802\ 46$$

The present value cost for two successive 4-year fuel cycles, where U_3O_8 is purchased 2 years before use and burned at the rate of $100 00/year (year 0 dollars, Figure A-4) is $802 46

Let us consider the same situation, but for a 6% annual rate of inflation The new carrying charge rate and discount rate is 0 1024 This comes about because for each $100 00 invested, an investor would first want to receive $6 00 to compensate for inflation, and he then would want the basic interest rate (0 04) times $106 00 (= $4 24), as return on his investment Thus the total carrying charge on each $100 00 would be $10 24 The classical relationship for describing this is

$$cc = [(1 + z)(1 + \overline{cc}) - 1]$$

which for our example would be

$$cc = [(1\ 06 \times 1\ 04) - 1] = 0\ 1024$$

Our example with inflation included looks as follows

$$z = 0\ 06$$
$$d = 0\ 1024$$
$$cc = 0\ 1024$$

$$PVU = \$520\ 56$$
$$PVCC = \$281\ 90$$
$$PVU + PVCC = \$802\ 46$$

Thus when the economic analysis is carried out in an internally consistent manner, the present value of the total U_3O_8 costs ($802 46) is independent of the rate of inflation It should be noted that when the calculation is based on an inflation scenario, all costs must be recorded at the price at the time of purchase and must include the effects of inflation In our example, the equations provide that the

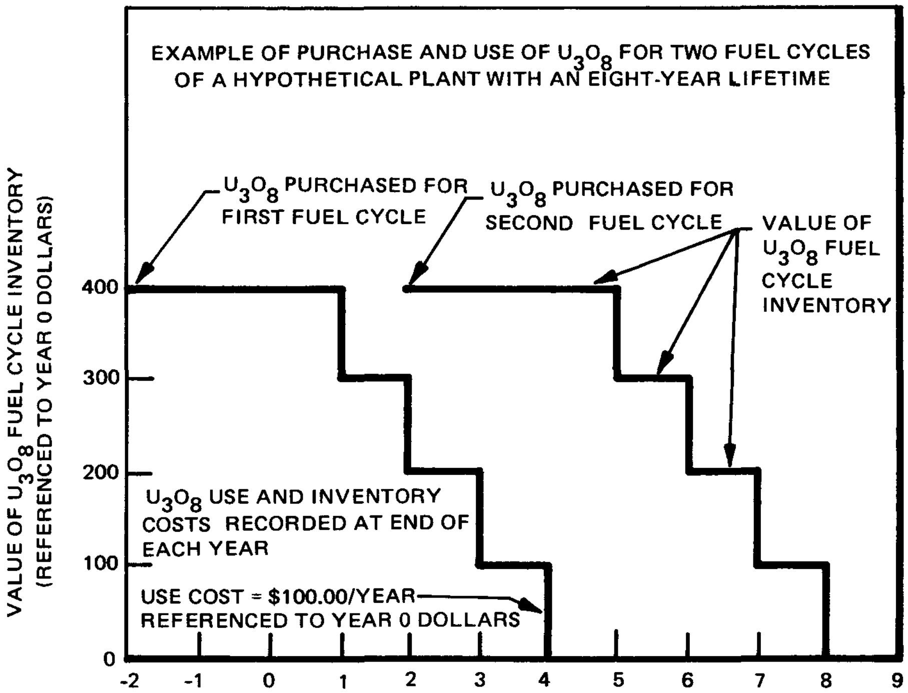


Figure A-1. Economic Techniques for Analyzing Nuclear Plant Fuel Cycle Costs

Financial Equations for Figure A-1

$$PVU = \left(\frac{1}{(1+z)^2}\right)\left[\frac{100}{(1+d)} \frac{100}{(1+d)^2} \frac{100}{(1+d)^3} \frac{100}{(1+d)^4}\right]\left(1 + \frac{(1+z)^4}{(1+d)^4}\right)$$

One Fuel Cycle Use Cost

Adjustment for Inflation Because U_3O_8 is Purchased Two Years before Use

This expression causes the second fuel cycle to be included One additional term, with the exponent increased successively by 4, is needed for each additional 4 year fuel cycle Enough additional terms would cause a full 28 or 32 year plant lifetime of fuel cycles to be included

One Fuel Cycle Carrying Charge Cost

$$PVCC = \left(\frac{1}{(1+z)^2}\right)\left[400(1+d)cc + 400cc + \frac{400cc}{(1+d)} + \frac{300cc}{(1+d)^2} + \frac{200cc}{(1+d)^3} + \frac{100cc}{(1+d)^4}\right]\left(1 + \frac{(1+z)^4}{(1+d)^4}\right)$$

where

PVU = present value of U_3O_8 use costs for 8 year life of plant

PVCC = present value of U_3O_8 inventory carrying charge costs for 8 year life of plant

cc = carrying charge rate

z = annual rate of inflation

d = discount rate to be used for present valuing costs = $(1+\bar{d})(1+z) - 1$

$\bar{d}$ = inflation corrected (real) discount rate cost of U_3O_8 for the first fuel cycle is reduced by dividing by $(1.06)^2$ because the purchase is 2 years before year zero (the reference year), and the price for the U_3O_8 *for the second fuel cycle must be increased* by $(1.06)^2$ to reflect the effect of inflation on a purchase 2 years after plant startup

Observation 2 — **Economic analyses of nuclear plant fuel cycles are most easily handled if fuel cycle costs are levelized.**

The frame of reference used by the utility industry in comparing fuel cycle costs (and power costs) is "mills/kWh." This is the value, which when levelized over the kilowatt hours generated, yields the same present-valued total cost for making a given amount of electricity as the actual costs incurred by the utility. The levelized value equals the present value of the actual costs divided by the present value of the number of kilowatt hours that will be generated

The adjacent expression indicates how the **use** costs for **one fuel cycle** of the example of Figure A-1 would be converted to a levelized yearly cost.* The denominator, a_n, is the annuity factor for the period of the levelization. These costs would be divided by the number of kWh(e) made during 1 year, to yield mills/kWh(e)

Because the zero-inflation use costs for one fuel cycle will serve as the basis for determining plant lifetime fuel cycle use costs, and carrying charge costs, it is worth noting its properties. The levelization annuity factor (denominator) is identical to the sum of the present value terms (numerator), and they cancel each other. Further, for zero inflation, the fact that the U_3O_8 is purchased 2 years before its use does not affect the price paid ($z = 0$). Hence, the zero inflation use costs for one fuel cycle are merely the actual costs incurred by the utility divided by the number of kilowatt hours made during the fuel cycle. The fortunate simplicity of this relationship greatly eases the task of the analyst

When some non-zero rate of inflation is assumed, the factor $[1/(1 + z)^2]$ which embodies the fact that the U_3O_8 is purchased 2 years before use, and hence will cost less than at the zero reference time (time of plant startup), will have a value other than unity. This term is included in the determination of the translator. Hence when the zero-inflation one-cycle-use cost is multiplied by the translator to obtain plant lifetime fuel cycle costs, this aspect of the effect of inflation is included

The levelized **carrying charge** costs for **one fuel cycle** from the example of Figure A-1 are defined as the equation for PVCC divided by the annuity factor.*

$$\text{Levelized yearly carrying charge cost for one fuel cycle} = \frac{PVCC}{a_n}$$

$$= \frac{\left[\frac{cc}{(1+z)^2}\right]\left[400(1+d) + \frac{400}{} + \frac{400}{(1+d)} + \frac{300}{(1+d)^2} + \frac{200}{(1+d)^3} + \frac{100}{(1+d)^4}\right]}{\left[\frac{1}{1+d} + \frac{1}{(1+d)^2} + \frac{1}{(1+d)^3} + \frac{1}{(1+d)^4}\right]}$$

Again, dividing by the kWh(e) generated in 1 year would convert the results to mills/kWh(e)

It can be noted that because it is necessary to purchase U_3O_8 about 2 years before it enters the reactor, there are 6 years of carrying charges. This cost must be recovered over the 4 years during which the fuel is in the reactor, hence 4 years is the period of the levelization

The important point to note from these equations is that the ratio between the carrying charge cost for one fuel cycle (above) and the use costs for one fuel cycle (100) is totally independent of the cost of the U_3O_8 (or in the general case, the cost of whatever component of the fuel cycle that is being considered). Hence, this basic ratio is fully determined once the carrying charge rate (cc), the discount rate (d), and the time patterns for the specific element of the cycle are assigned. This means that for subsequent estimates, the analyst need only determine the use cost for one fuel cycle, which is a relatively easy task. The carrying charge cost can be determined by multiplying the use cost by the predetermined ratio

$$\text{Levelized yearly use cost for one fuel cycle} = \frac{\left[\frac{100}{(1+z)^2}\right]\left[\frac{1}{(1+d)} + \frac{1}{(1+d)^2} + \frac{1}{(1+d)^3} + \frac{1}{(1+d)^4}\right]}{\left[\frac{1}{(1+d)} + \frac{1}{(1+d)^2} + \frac{1}{(1+d)^3} + \frac{1}{(1+d)^4}\right]}$$

$$= \frac{100}{(1+z)^2}$$

$$\text{and for zero inflation} = 100$$

Observation 3 — **The levelized fuel-cycle cost over the entire plant lifetime, including inflation, can be determined by multiplying the levelized costs (mills/kWh) for one-fuel-cycle by an appropriate factor.**

This observation provides a powerful tool for simplifying the task of making plant lifetime fuel cycle analyses that reflect inflation and that are internally consistent. When evaluating generating capacity alternatives, the nation's utilities invariably use carrying charge rates that are based on current costs of money. As previously discussed, today's interest rates reflect a high rate of inflation, and any economic analysis using these rates must be based on plant fuel cycle costs which are escalated at the same implicit rate, over the future life of the plant

*

$$a_n = \left(\frac{1}{1+d}\right)\left[\frac{1 - \left(\frac{1}{1+d}\right)^n}{\left(\frac{1}{1+d}\right)}\right]$$

$$= \left[\frac{1}{d}\quad 1 - (1+d)^{-n}\right]$$

* A constant load factor is assumed

It may be shown that a relatively simple factor can be used to multiply the levelized costs for one fuel cycle (mills/kWh) in order to yield the levelized costs for the plant lifetime in a way that the effects of inflation are properly accounted for. This factor makes unnecessary the calculational tedium of summing, present-valuing, and levelizing a full plant lifetime of escalating fuel cycle costs. This factor is:

$$F = \frac{\left[1 - \left(\frac{1+z}{1+d}\right)^{n_{lt}}\right] \times \left[1 - \left(\frac{1}{1+d}\right)^{n_{fc}}\right]}{\left[1 - \left(\frac{1+z}{1+d}\right)^{n_{fc}}\right] \times \left[1 - \left(\frac{1}{1+d}\right)^{n_{lt}}\right]}$$

where:

z = annual rate of inflation
d = discount rate for assumed rate of inflation
n_{lt} = plant life in years
n_{fc} = number of years for one fuel cycle

This factor is derived by dividing the levelized escalated use cost (or carrying charge cost) for the plant lifetime by the comparable cost for one fuel cycle. When similar terms are cancelled, and the remaining terms are summed using the equations for summing a finite series, the given expression for F results.*

Only three values of F are required for this analysis relating the breeder and LWR. These are:

		Factor
Zero Inflation		1
6% Annual Rate of Inflation		
LWR		1 66
Plant Life	32 Years	
Fuel Cycle	4 Years	
Discount Rate	0 1024	
Breeder		1.76
Plant Life	32 Years	
Fuel Cycle	2 Years	
Discount Rate	0.1024	

* Derivation is omitted One may note that each fuel cycle is repeated every n_{fc} years (4 years in the example), so each successive cycle contributes an amount to the present value which is $(1 + d)^{-n_{fc}}$ times the preceding cycle, but scaled up by an inflation factor $(1 + z)^{n_{fc}}$. If $x = [(1 + z) - (1 + d)]^{n_{fc}}$ then the series to be summed is $(1 + x + x^2 + --x^{K-1})$, where K is the number of fuel cycles in the plant lifetime $(n_{lt} - n_{fc})$

To summarize, the translators for each of the various elements of cost for the fuel cycle are a product of two principal factors. One of the factors is the ratio of the plant's lifetime escalated levelized cost to the comparable cost for one fuel cycle (F as defined above). This factor includes the effect of inflation which causes each successive fuel cycle to cost more than the preceding one. The second factor corrects for the effects of inflation on costs because: U_3O_8 is purchased 2 years before use; fabrication is procured 1 year before use, etc. This factor allows all input costs to be referenced to the year of plant startup (equivalent to zero inflation costs for one cycle).

For carrying charge cost translators, there is one additional factor that must be included. This is the ratio between the one-fuel-cycle carrying charge cost, and the one-fuel-cycle use cost. Including this factor creates a translator that will yield a lifetime levelized escalated carrying charge cost.

FUEL CYCLE COST TRANSLATORS FOR LWR AND BREEDER

The preceding section has sketched the economic principles involved in making internally consistent fuel cycle cost calculations. Some of these principles have been demonstrated through a simple example. Also, the system (using "translators") that was devised for the analysis reported herein was described.

The actual cost translators that were used in this analysis are shown in Tables A-1 and A-2. Table A-1 indicates the translators for the LWR fuel cycle for zero inflation and 6% inflation. Table A-2 provides the same information for the breeder. These translators have been developed using the coordinated financial assumptions from Table 1 of the report, and the indicated time patterns for costs and credits for each element in the fuel cycle.

The following illustrates the determination of the translators at a 6% rate of inflation using U_3O_8 as an example. The ratio of the plant's lifetime escalated levelized cost to the cost for one fuel cycle (F) is 1.66 (as previously developed). The correction, because the purchase of U_3O_8 occurs 2 years before reactor loading, is $1/(1.06)^2 = 0.89$; the product of 1.66 and 0.89 is 1.48 — the translator shown in Table A-1 for the plant lifetime U_3O_8 use cost. The ratio between the one-fuel-cycle carrying charge cost, and the one-fuel-cycle use cost is 0.82 and this factor times the other two factors (1.48) is 1.22 — the translator for the plant lifetime U_3O_8 carrying charge cost.

With these translators as a starting point, the determination of fuel cycle costs is a straightforward, two-step affair. The first step is to determine the use costs for one fuel cycle based on prices in effect at the time of plant startup or, if unescalated prices are projected to increase during the plant's lifetime, the use cost should be based on the levelized lifetime real prices. The second step is to multiply these by the appropriate translator to obtain lifetime levelized use costs, and lifetime levelized carrying charge costs, that reflect the assumed inflation rate. Using the translators, it is possible to make quickly a variety of comparative analyses of alternative fuel cycles.

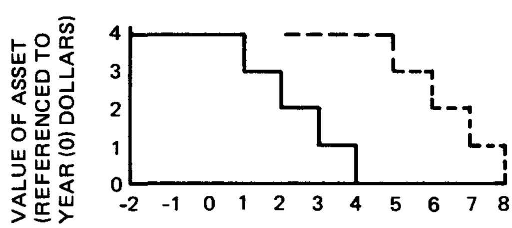
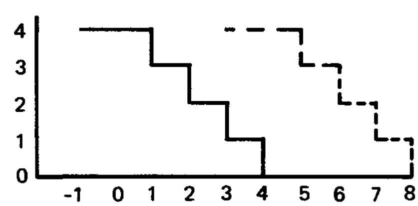
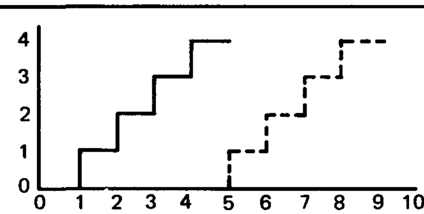
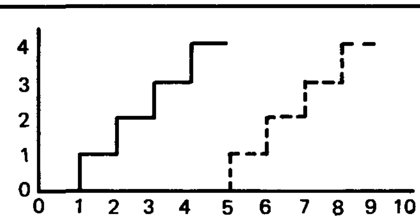
Tables A-3 and A-4 show the results of using the translators to determine the various subcosts of the fuel cycle from the use costs for one fuel cycle. Table A-5 shows the assumptions that are used in the determination of the one-fuel-cycle use costs. Table A-3 is applicable to a levelized lifetime "real" U_3O_8 price of \$20/lb and Table A-4 is for a U_3O_8 price of \$60/lb. Each component of cost (such as U_3O_8) is determined by multiplying the appropriate translator times the use cost for the case of no inflation. For example, the zero inflation use cost for U_3O_8 at \$20/lb is 1.11 mills/kWh (Table A-3). If this is multiplied by the lifetime use cost translator for 6% inflation — 1.48, the product, 1.64 mills/kWh, is the levelized lifetime use cost for 6% inflation. If the zero inflation use cost is multiplied by the lifetime carrying charge translator for 6% inflation (1.11 x 1.22), the product (1.35 mills/kWh) is the levelized carrying charge cost for 6% inflation. The cost for the other components of the fuel cycle is determined in a similar manner.

The indicated values for plutonium have been determined such that the fuel cycle cost for an LWR would be the same regardless of whether it is fueled with uranium or plutonium. (These calculations are not shown, but they use translators that have been developed for the LWR fueled with plutonium.)

Tables A-3 and A-4 provide a further empirical demonstration that the capital cost differential that can be justified for the breeder over the LWR is independent of the rate of inflation, when the financial calculations are internally consistent. For any assumed levelized plant lifetime "real" cost of U_3O_8, the indifference values of plutonium at zero inflation and 6% inflation would be identical, and the allowable capital cost differential at zero inflation and 6% would be identical (except for certain minor tax effects).*

* Without taxes, the carrying charge rate and discount rate for a utility would be identical and the present-value of a plant's nuclear fuel cycle costs for a given number of years would be identical regardless of the assumed rate of inflation. Taxes act to make the carrying charge rate larger than the discount rate and the exact identity no longer holds. Nevertheless, theoretical and computer analyses show that the present-values of a plant's lifetime fuel cycle costs for zero inflation and 6% inflation will be different by no more than 2 to 3% when taxes cause the carrying charge rate to be 50% greater than the discount rate. It is this and several other tax related discrepancies that cause the results for the "with," and "without" inflation cases to be slightly different.
For practical purposes, any effect that the tax structure has on disturbing the internal consistency of these financial calculations can be neglected. The descrepancy is less than the uncertainties inherent in the technical parameters.

Table A-1
FUEL CYCLE COST TRANSLATORS FOR LWR

COMPONENTS OF FUEL CYCLE	ASSUMPTIONS	ASSETS VERSUS YEARS FOR COMPONENTS OF FUEL CYCLE NOTES: ALL USE AND CARRYING COSTS RECORDED AT END OF YEAR ASSETS BASED ON "USE OF COST" OF 1.00 FOR EACH OF 4 YEARS OF FUEL CYCLE	TRANSLATORS (1): ZERO (2) INFLATION: ONE FUEL CYCLE (4 YEARS) AND FULL PLANT LIFETIME (32 YEARS)		6% ANNUAL (3) RATE OF INFLATION: ONE FUEL CYCLE (4 YEARS)		6% ANNUAL (3) RATE OF INFLATION: FULL PLANT LIFETIME (32 YEARS)	
			u (4)	cc (5)	u	cc	u	cc
U_3O_8	PURCHASED TWO YEARS BEFORE LOADING INTO REACTOR		1.00	0.31	0.89	0.73	1.48	1.22
ENRICHMENT FABRICATION	PURCHASED ONE YEAR BEFORE LOADING INTO REACTOR		1.00	0.24	0.94	0.57	1.57	0.95
REPROCESSING	PURCHASED ONE YEAR AFTER DISCHARGE FROM REACTOR		1.00	−0.15	1.34	-0.45	2.23	-0.75
PLUTONIUM CREDIT	SOLD ONE YEAR AFTER DISCHARGE FROM REACTOR		1.00	-0.15	1.34	-0.45	2.23	-0.75

TO USE TRANSLATORS

A Determine "use cost" (mills/kWh(e)) for one fuel cycle based on reference year (0) prices This "use cost" is the purchase cost (referenced to year 0) divided by the kWh(e) that would be generated during one fuel cycle at the design capacity factor

B Multiply the mills/kWh(e) so determined by the appropriate translator to obtain levelized carrying charge costs or levelized use costs, for one fuel cycle or for the plant lifetime, and for either zero inflation or a 6% annual rate of inflation

1 For zero inflation, the non-depreciating carrying charge rate (cc) is 6 48% and the discount rate (d) is 4 00% (See Table 1 of report)

2 For a 6% annual rate of inflation, the non-depreciating carrying charge rate (cc) is 15 56% and the discount rate (d) is 10 24% (See Table 1 of report)

3 "Use cost" of 1 00 referenced to prices at reference year (0) Translators compensate for effects of inflation on purchases and sales before and after reference year

4 Carrying charge cost

Table A-2
FUEL CYCLE COST TRANSLATORS FOR BREEDER

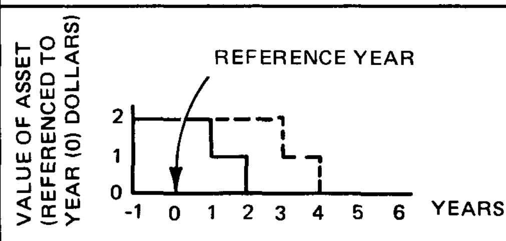
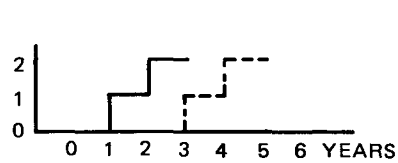
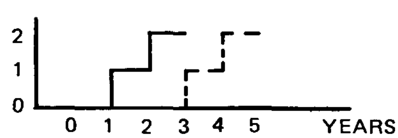
COMPONENTS OF FUEL CYCLE	ASSUMPTIONS	ASSETS VERSUS YEARS FOR COMPONENTS OF FUEL CYCLE NOTES ALL USE AND CARRYING COSTS RECORDED AT END OF YEAR ASSETS BASED ON "USE COST" OF 1.00 FOR EACH OF 2 YEARS OF FUEL CYCLE	TRANSLATORS (1)					
			ZERO (2) INFLATION		6% ANNUAL (3) RATE OF INFLATION			
			ONE FUEL CYCLE (2 YEARS) AND FULL PLANT LIFETIME (32 YEARS)		ONE FUEL CYCLE (2 YEARS)		FULL PLANT LIFETIME (32 YEARS)	
			u (4)	cc (5)	u	cc	u	cc
FABRICATION	PURCHASED ONE YEAR BEFORE LOADING INTO REACTOR		1.00	0.17	0.94	0.39	1.66	0.69
REPROCESSING	PURCHASED ONE YEAR AFTER DISCHARGE FROM REACTOR		1.00	-0.09	1 19	-0.25	2.09	-0.44
PLUTONIUM CREDIT	SOLD ONE YEAR AFTER DISCHARGE FROM REACTOR	APPLICABLE ONLY TO PLUTONIUM CREATED—(LIFETIME INVENTORY TREATED ELSEWHERE) 	1 00	-0.09	1 19	-0.25	2 09	-0.44

Table A-3
FUEL CYCLE COSTS FOR LWR AND BREEDER (LEVELIZED OVER PLANT LIFETIME — 75$)

U_3O_8 @ $20.00/POUND[1]

	Zero Inflation Pu = $15.70/gm		6% Annual Rate of Inflation Pu = $16.42/gm	
	Translators[8]	Mills/kWh(e)	Translators	Mills/kWh(e)
LWR				
Use Costs				
U_3O_8	1 00	1 11	1 48	1 64
Enrichment	1 00	0 75	1 57	1 18
Fabrication	1 00	0 27	1 57	0 41
Reprocessing	1 00	+0 43	2 23	0 96
Plutonium Credit[2,3]	1 00	−0 38	2 23	−0 90
		2 18		3 29
Carrying Charge Costs				
U_3O_8	0 31	0 34	1 22	1 35
Enrichment	0 24	0 18	0 95	0 71
Fabrication	0 24	0 06	0 95	0 25
Reprocessing[10]	−0 15	−0 07	−0 75	−0 32
Plutonium[2,3,10]	−0 15	0 06	−0 75	0 30
		0 57		2 29
Totals (LWR)		2 75		5 58
Breeder				
Use Costs				
Fabrication	1 00	0 53	1 66	0 87
Reprocessing	1 00	0 63	2 09	1 32
Plutonium Net Created[4]	1 00	−0 38	2 09	−0 82
Plutonium, Plant Constant Lifetime Inventory[5]				−0 27
		0 78		1 10
Carrying Charge Costs				
Fabrication	0 17	0 09	0 69	0 37
Reprocessing[10]	−0 09	−0 05	−0 44	−0 28
Plutonium, Net Created[6,10]	−0 09	0 03	−0 44	0 17
Plutonium, Plant Constant Lifetime Inventory[7]		0 65		1 64
		0 72		1 90
Totals (LMFBR)		1 50		3 00
Fuel Cycle Cost Differential		1 25		2 58
Equivalent Capital Cost Differential LMFBR versus LWR (75$)[9]		$114/kW(e)		$117/kW(e)

NOTES FOR TABLES A-3 AND A-4

1 This value of U_3O_8 is the levelized real cost of U_3O_8 during the life of the plant All effects of inflation are excluded It is determined by levelizing the projected lifetime costs of U_3O_8 where the costs for each year are expressed in 1975 dollars To be internally consistent the zero inflation discount rate for utilities cost of money (zero inflation) must be used for the levelization (4%)

2 The plutonium components of fuel cycle cost for zero inflation and 6% inflation are based on the indifference values of plutonium that will result in the same fuel cycle costs for the LWR whether fueled with uranium or plutonium (calculation not shown) The values of plutonium for zero inflation and 6% inflation are slightly different because of certain inflation related tax effects

3 The values of plutonium for the LWR characteristic assumed are
Use Costs
Zero Inflation −0 0245 mills/kWh(e)/$/gm
6% Inflation −0 0546 mills/kWh(e)/$/gm
Carrying Charge Costs
Zero Inflation 0 003675 mills/kWh(e)/$/gm
6% Inflation 0 01840 mills/kWh(e)/$/gm

4 This entry is applicable only to the net plutonium created and removed each fuel cycle
Use Costs
Zero Inflation −0 0239 mills/kWh(e)/$/gm
6% Inflation −0 0500 mills/kWh(e)/$/gm

5 This entry is applicable to the portion of the plutonium (in core and out of core) that can be treated as a plant constant lifetime inventory The core inventory must be deemed sold at the end of the plant lifetime For the zero inflation case, the salvage value equals the original cost and the use cost is accordingly zero
For the case of a 6% annual rate of inflation, the sale reflects 32 years of inflation and is 6 45 larger than the payoff of the original investment The net gain must be levelized over the kWh s generated during the life of the plant as follows

$$\frac{(\text{kgs Pu})\ (\text{g/kg})\ (\text{mills/\$})\ (1\ 06^{32}-1)}{(1+d)^{32}\ (a_n)\ [\text{kWh(e)/yr}]} = -0\ 0164\ \text{mills/kWh(e)/\$/gm}$$

Table A-4
FUEL CYCLE COSTS FOR LWR AND BREEDERS
(LEVELIZED OVER PLANT LIFETIME — 75$)

U_3O_8 @ $60.00/POUND[1]

	Zero Inflation Pu = $40.53/gm		6% Annual Rate of Inflation Pu = $42.47/gm	
	Translators[8]	Mills/kWh(e)	Translators	Mills/kWh(e)
LWR				
Use Costs				
U_3O_8	1 00	3 33	1 48	4 92
Enrichment	1 00	0 75	1 57	1 18
Fabrication	1 00	0 27	1 57	0 41
Reprocessing	1 00	0 43	2 73	0 96
Plutonium Credit[2,3]	1 00	−0 99	2 23	−2 32
		3 79		5 15
Carrying Charge Costs				
U_3O_8	0 31	1 02	1 22	4 05
Enrichment	0 24	0 18	0 95	0 71
Fabrication	0 24	0 06	0 95	0 25
Reprocessing[10]	−0 15	−0 07	−0 75	−0 32
Plutonium[2,3,10]	−0 15	+0 15	−0 75	0 78
		1 34		5 47
Totals (LWR)		5 13		10 62
Breeder				
Use Costs				
Fabrication	1 00	0 53	1 66	0 87
Reprocessing	1 00	0 63	2 09	1 32
Plutonium, Net Created[4]	1 00	−0 97	2 09	−2 12
Plutonium, Plant Constant Lifetime Inventory[5]				−0 70
		0 19		−0 63
Carrying Charge Costs				
Fabrication	0 17	0 09	0 69	0 37
Reprocessing[10]	−0 09	−0 05	−0 44	−0 28
Plutonium, Net Created[6,10]	−0 09	0 09	−0 44	0 45
Plutonium, Plant Constant Lifetime Inventory[7]		1 68		4 25
		1 81		4 79
Totals (LMFBR)		2 00		4 16
Fuel Cycle Cost Differential		3 13		6 46
Equivalent Capital Cost Differential LMFBR versus LWR (75$)[9]		$285/kW(e)		$293/kW(e)

The use cost" and carrying charge cost ' for the plant constant lifetime inventory of plutonium as described herein are internally consistent and the sum of the present values of the two is independent of the assumed rate of inflation (except for certain minor tax effects)

6 Zero Inflation 0 0022 mills/kWh(e)/$/gm
6% Inflation 0 0105 mills/kWh(e)/$/gm

7 The 'carrying charge costs [mills/kWh(e)] associated with the plant constant lifetime inventory of plutonium remain unchanged during the life of the plant The values are
Zero Inflation (cc @ 6 48%) 0 0415 mills/kWh(e)/$/gm
6% Inflation (cc @ 15 56%) 0 1000 mills/kWh(e)/$/gm

8 Translators include effects of inflation on all "use costs' and ' carrying charge costs" that result from purchases and sales before and after year (0)

9 See Table 1, line 14 of report for carrying charge costs for capital

10 The carrying charge cost for reprocessing is negative, representing a credit to fuel cycle costs, because the cost of reprocessing occurs subsequent to the receipt of revenues for the electricity generated The carrying charge cost for plutonium production covers money costs that arise because the electrical user receives credit for plutonium prior to the actual sale of the plutonium

where kgs, Pu = 4300 (see Table A-5)
$(1 + d)^{32}$ = $(1 + 0\ 1024)^{32}$ = 22 639 (present values transaction to year of plant startup)
a_n = 9 33426 (levelizes net gain over 32 years of plant life)
[kWh(e)/year] at design capacity factor

Table A-5
ASSUMPTIONS USED IN DETERMINATION OF "USE COSTS" FOR ONE FUEL CYCLE
(75$)

	Cost Units	Cost	Cost Contribution mills/kWh(e)
LWR			
U_3O_8 @ 27,000 MWd/Te Burnup	$/lb	20	1 11
		60	3 33
		100	5 55
Enrichment	$/SWU	50	0 75
Fabrication, U-Cycle	$/kg	60	0 27
Fabrication, Pu-Cycle	$/kg	155	0 70
Reprocessing	$/kg	100	0 43
Overall Plant Efficiency	%	34	
Net Pu Production, U-Cycle	gm/kWh(e)	2 45 x 10^{-5}	
Net Pu Credit, U-Cycle	mills/kWh(e)/$/gm	2 45 x 10 ^{2}	
Reload Core Inventory, Pu-Cycle	kg(Pu fissile)	3100	
Discharge Core Inventory, Pu-Cycle	kg(Pu fissile)	1600	
Net Pu Consumption, Pu-Cycle	gm/kWh(e)	6 09 x 10 ^{5}	
Net Pu Cost Pu-Cycle	mills/kWh(e)/$/gm	6 09 x 10^{-2}	
Length of Fuel Cycle (including downtime)	years	4	
Breeder			
Fabrication	$/kg/(core)	500	0 53
Reprocessing	*$/kg/(core + blanket)*	200	0 63
Overall Plant Efficiency	%	38	
Breeding Ratio (at equilibrium)		1 25	
Compound System Doubling Time	years	18	
Specific Power (at equilibrium)	kW/kg (fissile)	1000[1]	
Equilibrium Inventory, Pu	kg (fissile)	2600	
Out-of-Reactor Inventory, Pu	kg (fissile)	1700	
Plutonium Fabrication	%/cycle	2	
Net Pu Production Rate	gm/kWh(e)	2 39 x 10^{-5}	
Net Pu Credit	mills/kWh(e)/$/gm	2 39 x 10^{-2}	
Length of Fuel Cycle (including downtime)	years	2	
LWR and Breeder			
Plant Rating	MW(e)	1000	
Design Capacity Factor	%	70	

It is worth noting that the permissible ratios of breeder capital costs to LWR capital costs that are shown on page 1 of this report are highly conservative because of the technique that is used to value plutonium For example, for a levelized plant lifetime U_3O_8 cost of $60 00/lb, the indicated allowable breeder to LWR capital cost ratio is 1 73 This ratio is based on a levelized lifetime plutonium value of $42 47 This is the water reactor indifference value of plutonium that corresponds with a levelized U_3O_8 cost of $60/lb It is assumed that the breeder is inventoried with plutonium of this value which of course would be the case if the U_3O_8 is a constant $60/lb during the life of the plant

In reality though, the value of plutonium will probably rise during the plant life Referring to Figure 2, it can be seen that a levelized U_3O_8 cost of $60/lb will result from U_3O_8 costs that actually rise from about $20 00/lb (uninflated) at the time of plant startup to $120 00/lb at the end of plant life The associated values of plutonium would increase from about $18/gm to $82/gm during the same period, yielding the levelized value of $42 47 Thus, the 4300 kg plant constant lifetime inventory of plutonium for the breeder would actually be purchased at $18/gm rather than $42/gm This of course would result in greatly reduced carrying charges Moreover, the plutonium would be sold at $82/gm at the end of plant life, yielding a credit (negative use charge) Of the various elements of fuel cycle cost, only those related to the breeder constant lifetime inventory of plutonium will be different, and will alter the overall fuel cycle cost results when actual rising uninflated costs are used rather than the single levelized uninflated cost

Detailed calculations show that for a levelized U_3O_8 cost of $60/lb, the allowable ratio of breeder capital cost to LWR capital cost becomes 2 10 when actual rising plutonium values are used for the plant constant lifetime inventory compared to 1 73 when the levelized plutonium value is used For U_3O_8 at $100/lb, the capital cost ratio becomes 2 61 using actual rising plutonium values versus 2 18 when levelized plutonium values are used

While utilities may not wish to depend on a profile of rising plutonium values when they examine the economic incentive for the breeder, in reality plutonium values probably will be increasing and this will act to further substantially increase the economic benefits of the breeder We have chosen not to include this effect because it is to some extent speculative Our results here understate the permissible capital cost of the breeder as a consequence

[1] Equivalent to 900 kW_t/kg at an 80% design capacity factor when design fuel loading and control reactivity are assumed to vary with the design capacity factor so as to maintain a fixed length fuel cycle While the fissile loading would change with design capacity factor, it is assumed the number of fuel rods and the fuel rod heat flux would not significantly change

APPENDIX B
RELATIONSHIP BETWEEN
BREEDER FUEL CYCLE AND LWR FUEL CYCLE

The economic relationship between breeder reactors and LWR's is both one of symbiosis and competition Here we shall examine how the two reactor types are interlinked via the value of plutonium The principal output of both the breeder and LWR is of course electricity, but both also produce plutonium as a very important by-product

The breeder will create about 12 5 kilograms of plutonium for every 10 kilograms of plutonium burned On the other hand, the LWR will create about 6 kilograms of plutonium for every 10 kilograms of U-235 or plutonium burned While the breeder will create excess fissile material that can be used to fuel other reactors, the LWR must always be dependent on external sources of fissile material

Thus both breeders and LWR's will be sellers and buyers of plutonium In fact, during its early commercial years, the breeder will be completely dependent on the LWR for its plutonium fuel supply This dependence will of course decline as the breeder takes hold and begins to create significant quantities of plutonium

Figure B-1 displays the power costs (fuel cycle plus capital charges in mills/kWh) for the breeder, for a LWR burning U-235, and a LWR burning plutonium on recycle The power costs are plotted as a function of plutonium value

When the LWR is burning **U-235**, the value of its by-product plutonium is a credit against its fuel cycle cost, and its power cost goes down as the value of plutonium increases (slopes down to the right) When the LWR is burning **plutonium**, its fuel cycle cost goes up sharply as the value of plutonium goes up On the other hand, the fuel cycle cost (and power cost) of the breeder are relatively insensitive to the value of plutonium They might go up slightly, or down slightly, depending on the breeder's exact characteristics This is because the credit for the excess plutonium produced is of about the same magnitude as the carrying charges for the plutonium inventory and the two essentially offset each other

From Figure B-1 it is possible to surmise how the value of plutonium might behave in a society of mixed reactors Let us first consider the competition between LWR's burning **uranium** and LWR's burning **plutonium** Theoretically there always will be an "indifference" value of plutonium (P_1) for which both fuels result in the same power cost If plutonium were valued at less than P_1, LWR's would preferentially burn plutonium (because of the lower cost) until the increased demand would force the value of plutonium up If the value of plutonium were greater than the indifference value, the lower fuel cycle cost would encourage LWR's to burn U-235 rather than plutonium, and they would become net producers of plutonium until the increased supply of plutonium would bring the value back down to the indifference value The intersection of Curves (A) and (B) in Figure B-1 thus defines an equilibrium value for plutonium in a two-mode system

When LWR's as burners of uranium and net producers of plutonium coexist with the breeder, the indifference value of plutonium (P_2) might be as much as four times higher than the indifference value when plutonium is used as a fuel for LWR's Consequently, the more successful is the breeder the greater is the opportunity cost of plutonium, breeder fuel cycle costs actually rise (from C_3 to C_2) while LWR's benefit from increased by-product credits from sales of plutonium, thereby reducing their apparent power costs from C_1 to C_2 Thus, if the marketplace were ever to reflect this opportunity cost of plutonium, some part of the financial benefits due to the breeder would be transferred to LWR's and would appear as reduced power costs for LWR s P_2 and P_1 *therefore are the upper and lower bounds* for plutonium values, and the actual value

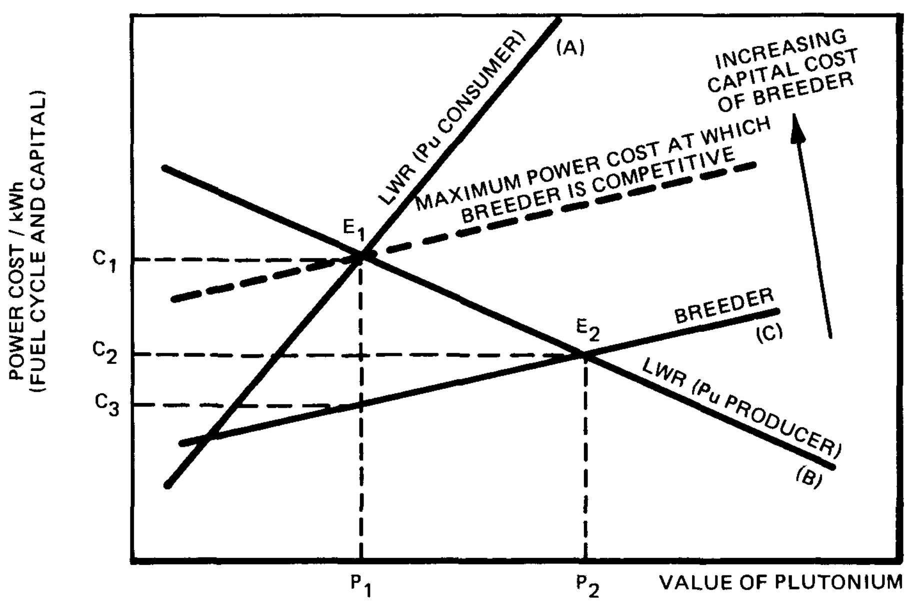


Figure B-1. Power Costs for LWR and Breeder versus Value of Plutonium would be governed by institutional considerations, market forces, and the extent to which the introduction of breeders is constrained by the total availability of plutonium

The value of plutonium will rise above P_1 only to the extent that the breeder's non-plutonium components of power cost are lower than those of the LWR and give the breeder an economic edge For example, the capital cost of the breeder could increase, pushing the breeder power cost line straight upward until it passes through E_1, before it would be more economical to burn plutonium in an LWR than in a breeder From this it can be seen that if **fuel cycle** costs of the LWR and the breeder are both determined using plutonium value P_1 (value when Pu is burned in LWR's), the difference between the breeder and LWR fuel cycle costs will be available to cover an increased capital cost for the breeder over the LWR (See Figure B-2) Thus it is the comparative fuel cycle costs of the breeder and LWR, based upon plutonium valued in LWR recycle, that must be used when determining the additional capital cost that a utility can afford to pay for a breeder over a LWR

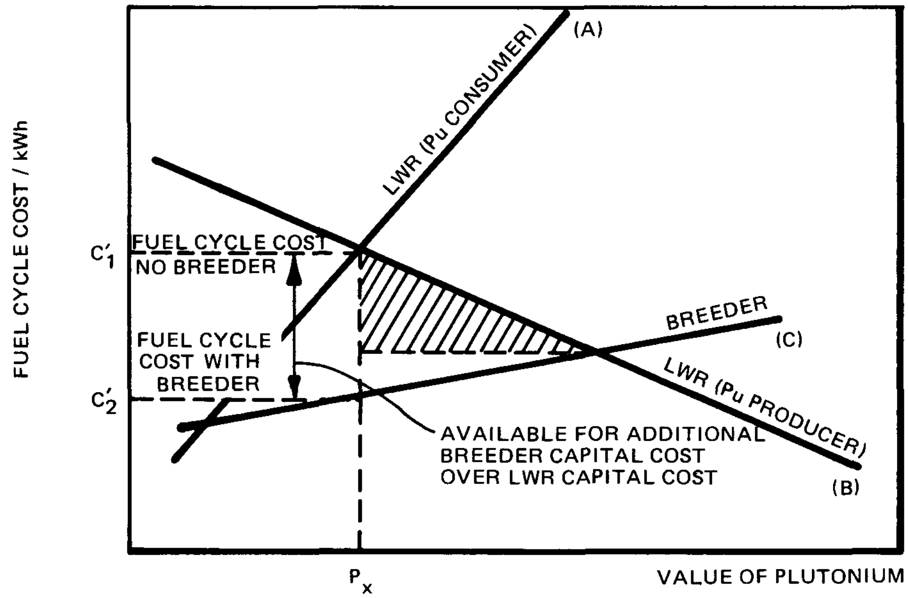


Figure B-2. Fuel Cycle Costs for LWR and Breeder versus Value of Plutonium

*