IMPLICATIONS OF PLUTONIUM UTILIZATION STRATEGIES ON THE TRANSITION FROM A LWR ECONOMY TO A BREEDER ECONOMY[a]

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DISCLAIMER

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ABSTRACT

The plutonium interface between the LWR and LMFBR fuel cycles is examined for typical nuclear growth projections both with and without plutonium recycle in LWRs. In order to guarantee a fuel supply for projected LMFBR growth rates, significant multiple Pu recycle in LWRs will not be possible. However, about 78% of the benefit of multiple plutonium recycle between now and the turn of the century is realized by one recycle and then stockpiling spent MOX for the LMFBR. LMFBR reprocessing schedules are estimated based on accumulation of reprocessing load. These schedules are used to estimate the amount of plutonium recovered from LMFBR fuels and determine the residual LWR plutonium required to meet LMFBR demand. The stockpile of LWR produced plutonium in spent MOX is sufficient to fuel the LMFBR until commercial LMFBR reprocessing can be justified. After that time, recycle of plutonium in LWRs will be significantly limited by a continuing LMFBR demand for LWR plutonium due to the projected high LMFBR growth rate.

LWR reprocessing requirements are estimated for the assumed condition that LWR plutonium recycle is not approved, but the LMFBR is still pursued as an energy option. The uncertainties presented by this condition are addressed qualitatively. However, in our judgment these uncertainties in the plutonium market would likely delay LMFBR growth to levels significantly below current projections.

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INTRODUCTION

Historically the evaluation of plutonium recycle in Light Water Reactors (LWRs) has been separated from the Liquid Metal Fast Breeder Reactor LMFBR).[1,2] Whereas this approach may have its programmatic rationale, one never observes a true indication of plutonium logistics and use strategies during the transition, the LWR recycle industry requirements related to breeder growth, or an analysis of the LMFBR reprocessing capacity requirements to avoid shortfall in the LMFBR fuel supply.

Previous studies have shown that plutonium recycle is technically feasible[3] and contributes significantly to uranium resource utilization.[1] When one considers the LWR as a source of fuel for LMFBRs, the benefits of plutonium recycle in LWRs are obviously affected. Conversely, decisions to recycle plutonium now will affect the quantity and quality of plutonium available to the LMFBR to support its growth prior to the time that it is self-sufficient. Since neither the LMFBR itself nor the back end of the LMFBR fuel cycle are proven technologies, the possible growth rate of the LMFBR may be more sensitive to the LWR plutonium supply than is indicated by examining its anticipated breeding ratio and doubling time characteristics. Experience gained closing the back end of the LWR fuel cycle would tend to mitigate similar problems for the LMFBR. However, it may be optimistic to assume that LMFBR reprocessing will be available on demand and that the projected doubling times will be experienced in the early growth years.

In this paper the relationships between LWR recycle decisions and LMFBR fuel supply are examined with the emphasis on contingency rather than strategy optimization. Optimization will be considered in follow-on studies. In this context we have examined the interface between LWR and LMFBR fuel cycles for both the conditions where LWR plutonium recycle is allowed, and where it is not allowed.

BACKGROUND

In Figures 1 and 2 the impact of plutonium and uranium recycle options on annual U_3O_8 and separative work demand is shown graphically. These results are based on a nuclear growth projection used internally at ERDA for planning purposes (Figure 3). In Table I the cumulative U_3O_8 and separative work requirements are shown for these same recycle options over the 1976 through 2001 time frame. When the fuel cycle unit cost figures in Table II are applied, these savings are reflected in the industry wide fuel cycle costs and cash flows in Table I. The unit costs listed in Table II are consistent with those used in a recent ERDA study of plutonium recycle incentives[4] with the exception that reprocessing costs have been lowered from $280/Kg to $220/Kg to reflect the economy of scale of large (2-3000 MT/kg) reprocessing plants.

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In these cases, where LMFBR plutonium requirements are not considered, multiple recycle of plutonium and uranium reduces U_3O_8 demand by 384.4 thousands of short tons (23%), reduces separative work requirements by 108.4 millions of SWUs (15%), and reduces the total fuel cycle cash flow $20 billion (9%). The magnitude of these savings is sensitive to the assumed industry growth and unit costs for fuel cycle services; however, the relative benefits for the recycle options are not expected to be particularly sensitive to these assumptions.

LMFBR AND LWR GROWTH ASSUMPTIONS

The reference nuclear growth assumptions used for our evaluations are shown in Figure 3. In this case the LWR installed capacity is ~500 GWe in the year 2000. The first commercial LMFBR is introduced in 1995, and LMFBRs have captured the nuclear market by 2007. The delayed schedule (Figure 4) assumes a 5 year delay in the LMFBR schedule while maintaining the same total nuclear capacity. The maximum LMFBR growth schedule (Figure 5) is achieved by introducing the first commercial LMFBR in 1995 (the same date as for the reference scenario) and by constraining LMFBR capacity additions in succeeding years to no more than twice the additions in the previous years. In addition, LWR additions are constrained to be no less than 50% of the previous year's additions.

In Figure 6 the cumulative LMFBR core and blanket discharges are plotted versus time for the three cases. If we assume that commercial reprocessing of LMFBR fuels will start when discharges accumulate to 1500 MT, or when the annual discharge rate would feed a 1500 MT/yr fuels reprocessing plant starting up on 1/3, 2/3 and full plant capacity in its first three years of operation, then commercial reprocessing would start in 2000 for the reference case, 1999 for the accelerated case, and in 2005 for the delayed case. In the following sections we discuss the utilization of plutonium for these cases primarily in the time preceeding these commercial reprocessing dates.

PLUTONIUM RECYCLE AND LMFBR DEMAND

If plutonium recycle is approved for LWRs, the ultimate benefits of that decision will be modified by the LMFBR demand for plutonium from the LWR systems. Previous studies of the LWR-LMFBR plutonium relationship have either been performed on growth projections that are not consistent with current estimates and/or LMFBR fuel cycle models that assume almost instantaneous reprocessing capability. It is our contention that the latter assumption is not only optimistic, but also ignores a possible real constraint to LMFBR growth if LMFBR reprocessing hits a technical snag or for some other reason experiences schedule delays.

The above considerations pose some interesting questions. If plutonium is recycled in LWRs and we want to assure an LMFBR fuel supply,

(1) what is the net benefit (reduction in U_3O_8 and separative work) of Pu recycle?

(2) what are the impacts if LMFBR reprocessing slips significantly? and

(3) what will be the cost of plutonium purchased for the LMFBR?

These questions are obviously difficult to address in a general context. It is, however, interesting to note from Figures 1 and 2 and the cumulative values in Table I, that fully 78% of the potential benefit of plutonium recycle between now and 2001 can be realized by one recycle. Since the plutonium contained in irradiated LWR MOX is of inherently higher neutronic value in an LMFBR, we consider the case in which plutonium is recycled once in LWRs and then stockpiled, without reprocessing, for the LMFBR.

Plutonium Supply and Demand

In Figure 7 LMFBR plutonium demand is compared to the plutonium available in spent LWR MOX for the reference growth conditions. By the year 2000 the LMFBR would require plutonium from reprocessing its own fuel. Recalling that commercial LMFBR reprocessing could be justified in 2000 for this growth condition, it would appear that this plutonium use strategy gives a good indication of the true LWR benefit of plutonium recycle, i.e., savings in U_3O_8 and separative work, that can be realized if the LMFBR develops as currently anticipated. This savings amounts to approximately 300 x 10^3 ST of U_3O_8 and 80 x 10^6 Kg of SWU by year 2001. For our cost numbers, this represents approximately 0.47 mills/kw-hr on an industry wide average, or approximately 15.7 x 10^9 undiscounted 1977 dollars. Our analysis indicates that if plutonium recycle were halted in 2000, the LMFBR could be supported an additional two to three years before a true plutonium shortfall would occur. Thus, there is a 3 year window after LMFBR reprocessing could be justified before LMFBR reprocessing capability would be mandatory to support the projected growth.

After LMFBR reprocessing begins, there will be a continuing demand for LWR plutonium to feed LMFBRs. This occurs because the large demand for initial LMFBR cores and reloads exceeds the rate at which plutonium becomes available and can realistically be recovered from the LMFBR spent core and blanket materials. This is demonstrated graphically in Figure 8 where LMFBR reprocessing is assumed to come on line in discrete steps as determined by LMFBR core and blanket discharges. In this analysis plutonium recovery from the LMFBR is based on core and blanket mass flows from the Hanford Engineering Development Laboratory 2500 MWt small pin design.[5] This design is an advanced oxide LMFBR concept which has an equilibrium plutonium compound doubling-time of 12.7 years. For these conditions, the LMFBR is not self-sufficient until beyond 2020. While there is never a plutonium shortage, this continuing demand for plutonium will significantly limit the extent to which plutonium can be recycled in LWRs beyond 2000.

Delaying the LMFBR introduction date for 5 years extends the time that the MOX stockpile could supply the LMFBR by approximately seven years, or until 2007. Under these conditions the first commercial LMFBR reprocessing plant could be justified in 2005. This 7 year time extension allows greater latitude in plutonium utilization strategies for LWRs. At this time, we have not closely evaluated the benefits of a second recycle in LWRs for this growth assumption. However, it is correct to say that this decision, i.e., the decision to undertake multiple recycle is not required until approximately 1988-1990 when significant amounts of plutonium would be available for second recycle.

If the LMFBR growth rate is accelerated, the once-recycled plutonium stockpile can support the LMFBR only until 1998, or almost to the time an LMFBR reprocessing plant could be started. Under these conditions, there would be little or no room for delayed LMFBR reprocessing.

Plutonium Transfer Price

Since the plutonium in spent LWR MOX fuel represents a resource to the LWR community, the LMFBR will have to pay for the loss in savings that could be realized by multiple recycle. The LMFBR requires approximately 320 MT of plutonium through 2000, or approximately 12287 MT of spent LWR MOX fuel. If this fuel were reprocessed and recycled it would provide a net additional benefit of $\sim$\$4.3 x 10^9. Therefore, the LMFBR must pay to ship, reprocess, and dispose of waste from this fuel at a total of \$251/Kg and pay the LWR owners \$4.3 x 10^9 in lost benefits. This amounts to \$7.4 x 10^9 for 320 MT of plutonium or \$23/g of Pu. Although this treatment ignores several factors such as discounting effects, external market pressures, and the fact that LMFBR and LWR operators are likely the same utilities, it does give a first order indication of plutonium transfer price for our assumed cost conditions.

It would appear from the above discussion that multiple plutonium recycle in LWRs is not compatible with providing plutonium to fuel the LMFBR unless the LMFBR growth rate is substantially lower than projected. This results from both the late date at which plutonium would be available for second recycle and the lower neutronic value of once-recycled plutonium to LWRs. Nevertheless substantial savings in U_3O_8 and separative work can be realized by a single plutonium recycle, and this strategy is consistent with fueling the LMFBR through the year 2000.

THE LWR "STOWAWAY" OPTION

In the current political context, it would appear that plutonium recycle in LWRs is no longer an inevitable step in the utilization of this source of energy. The accepted rationale for this position is based on nonproliferation arguments which require a moratorium on separating plutonium from spent fuel. Nevertheless, there is residual interest in the fast breeder reactor with some recent discussion of developing breeder fuel cycles that do not require separated plutonium. Basically, this scenario assumes that there are available acceptable means of recovering and handling plutonium by the time it is required for LMFBR fuel. If it is assumed that these means do not now exist, this can be achieved by either development of new technologies, changes in standards of acceptability, or some combination of these factors.

Reprocessing to Supply the LMFBR

The total amount of plutonium potentially available to the LMFBR is maximized by this LWR option. Since there is no competitive market for plutonium, the LMFBR can likely have LWR spent fuel for the taking. However, this in itself presents an interesting situation. If the driving force behind this strategy is to minimize plutonium availability, then there is an obvious incentive to delay reprocessing, while on the other hand the LMFBR must be guaranteed a fuel supply. In Figure 8 the annual LMFBR plutonium requirements are compared to that which can be recovered with an optimistic LMFBR reprocessing schedule beginning in year 2000. The difference between these curves must be supplied annually by reprocessing LWR UO_2 fuels. If one translates this to spent fuel reprocessing requirements, approximately 27 x 10^3 MT of spent fuel must be reprocessed by 1999. This amount of fuel represents 18 years of operation for a 1500 MT/yr reprocessing plant regardless of the plutonium recycle decision. This would be roughly equivalent to the AGNS reprocessing plant beginning operation in 1981. There are, of course, alternative approaches to meeting the anticipated plutonium demand. Between 2000 and 2020 an LWR reprocessing capacity of approximately 1100 MT/yr would be required. By introducing some of this needed capacity in the early 1990s, the anticipated LMFBR fuel demands for plutonium could also be met. However, the longer this capability is delayed, the less confidence there will be in the LMFBR as a viable option.

The conflict in the above discussion is apparent. In practical terms industry must be assured of the demand for their product before investing in LWR reprocessing. On the other hand, utilities must be assured of a fuel supply to order LMFBRs. Operating AGNS with government plutonium buyback would be contrary to the desire to avoid large stockpiles of separated plutonium. Not having the LWR as a flexible source and user of plutonium renders the plutonium market unstable and can only slow the anticipated growth rate of LMFBRs. Moreover, accelerated LMFBR reprocessing could support LMFBR growth only to a maximum of its actual fuel doubling-time which is significantly lower than current projections.

"Stowaway" Plutonium Transfer Price

By definition of the "stowaway" option, plutonium would have no value to LWRs. Therefore, the price of the plutonium transferred to the LMFBR would be determined by the cost of reprocessing, waste management and transportation of the spent UO_2 fuel minus the credit for the recovered uranium that would be returned for re-enrichment. In the time frame from 1976 through 2001, nearly 126 thousand metric tons of spent UO_2 fuel would be discharged from LWRs assuming the reference growth scenario shown in Figure 3. This spent fuel contains about 1.04 thousand metric tons of plutonium, or about 8.3 g of Pu/Kg, and about 121 thousand metric tons of slightly enriched uranium. If we assume that the residual ^{235}U enrichment above natural assay compensates for the ^{236}U penalty, the returned uranium has the value of natural uranium. The average price of uranium in the time frame 1976-2001 is about \$40/lb U_3O_8, or about \$103/Kg U. Therefore, the net cost for recovery of 8.3 g of plutonium is the difference between the \$251 charge for reprocessing, waste management, and transportation and the $100 uranium credit. The net cost to the LMFBR would be approximately $18/g of Pu.

SUMMARY AND CONCLUSIONS

In order to guarantee a fuel supply for projected LMFBR growth rates, significant multiple Pu recycle in LWRs will not be possible. However, it is possible to realize ∿78% of the benefit of multiple plutonium recycle between now and the turn of the century by one recycle and then stockpiling spent MOX for the LMFBR. This stockpile is sufficient to fuel the LMFBR until commercial LMFBR reprocessing can be justified. Before the turn of the century, the plutonium transfer price would be approximately $23/g of Pu in undiscounted 1977 dollars. Beyond the year 2000 plutonium recycle in LWRs will be significantly limited by a continuing LMFBR demand for LWR plutonium due to the projected high LMFBR growth rate.

If plutonium recycle is not allowed in LWRs, the plutonium supply to the LMFBR is limited by LWR fuels reprocessing capability. The effects of the uncertainties presented by this condition have not been analyzed quantitatively. However, in our judgment perceived uncertainty in the plutonium market by both the utilities and the reprocessing industry would likely delay LMFBR growth to levels significantly below current projections.

REFERENCES

(1) "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, ES, U. S. Nuclear Regulatory Commission (August 1976).

(2) "Final Environmental Statement: Liquid Metal Fast Breeder Reactor Program," ERDA-1535, U. S. Energy Research and Development Administration (December 1975).

(3) B. A. Zolotar and J. T. A. Roberts, "EPRI Plutonium Recycle Program," Trans. Am. Nucl. Soc., 23, 238 (1976).

(4) "Benefit Analysis of Reprocessing and Recyling Light Water Reactor Fuel," ERDA-76/121, U. S. Energy Research and Development Administration (December 1976).

(5) D. A. Cantley, R. W. Hardie, M. R. Shay, and R. P. Omberg, "Core Design Parameters for the HEDL 2500 MWt Small Pin, Large Pin, and Advanced Large Pin Oxide LMFBR Designs," private communication, Hanford Engineering Development Laboratory, Richland, Washington (November 1976).

TABLE I. Impacts of Recycle Options on Uranium Consumption, Separative Work, and LWR Fuel Cycle Costs

1976-2001

	Cumulative U_3O_8 (10^3 Short Tons)	Cumulative Separative Work (10^6 Kg SWU)	Industry Average Fuel Cycle Costs (mills/kw-hr)	Total Fuel Cycle Cash Flow (Billions of Undiscounted 1977 dollars)
No recycle	1498.1	702.6	6.77	224.8
Recycle U once	1359.4	710.0	6.93	230.2
Recycle Pu and U once	1207.5	620.9	6.32	209.8
Recycle Pu once, Multiple U recycle	1198.9	622.8	6.30	209.1
Multiple Pu and U recycle	1149.7	594.2	6.17	204.8

TABLE II. Fuel Cycle Cost Assumptions

U_3O_8	\$34/lb increasing at \$11/lb/10^6 ST consumed
Separative work	\$100/kg
Reprocessing	\$220/kg
U Fab	\$90/kg
Waste disposal	\$25/kg
Spent fuel disposal	\$90/kg
MOX fab	\$260/kg
Spent fuel transportation	\$6/kg
Spent fuel storage	\$2.3/kg-yr

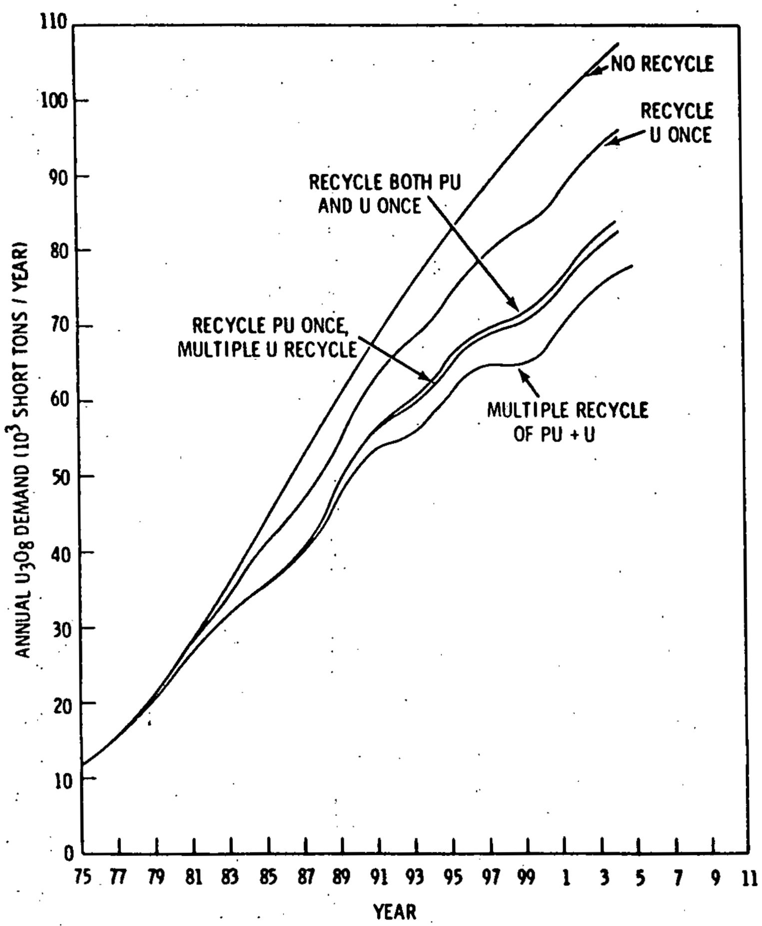

FIGURE 1. Annual U_3O_8 Demand for LWR Recycle Options

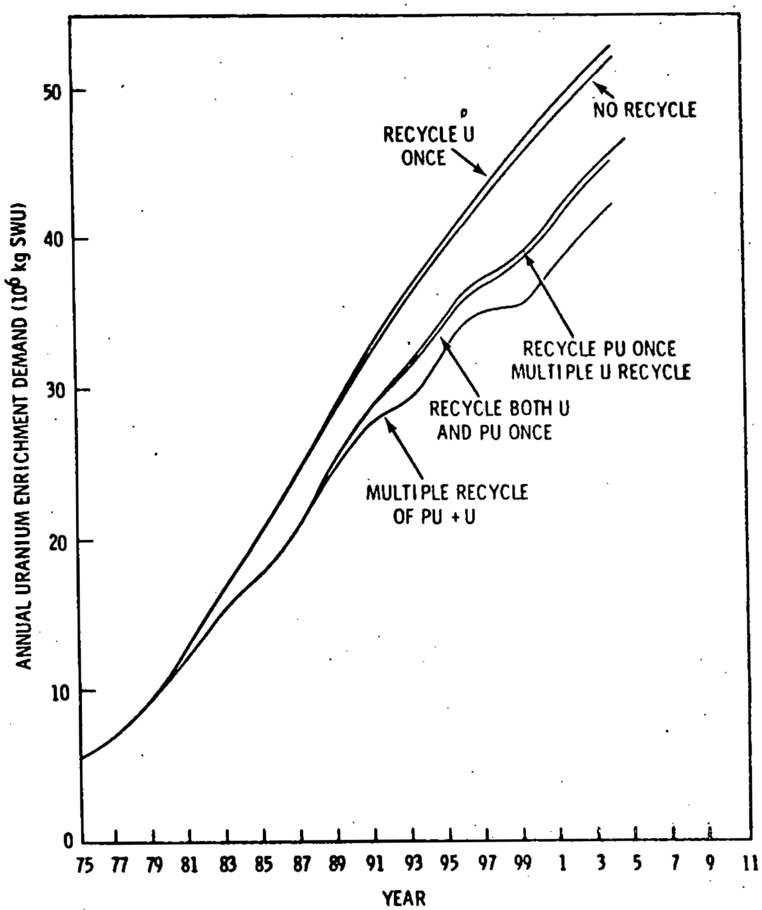

FIGURE 2. Annual Separative Work Requirements for LWR Recycle Options

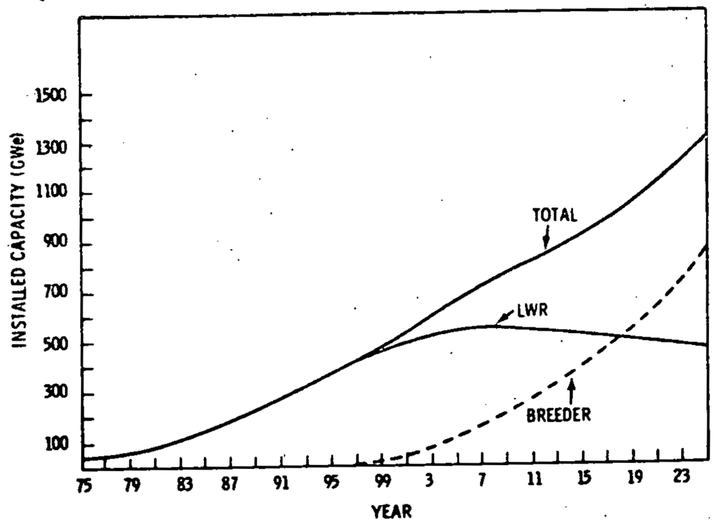

FIGURE 3. ERDA Reference Electrical Generation for Nuclear Sector

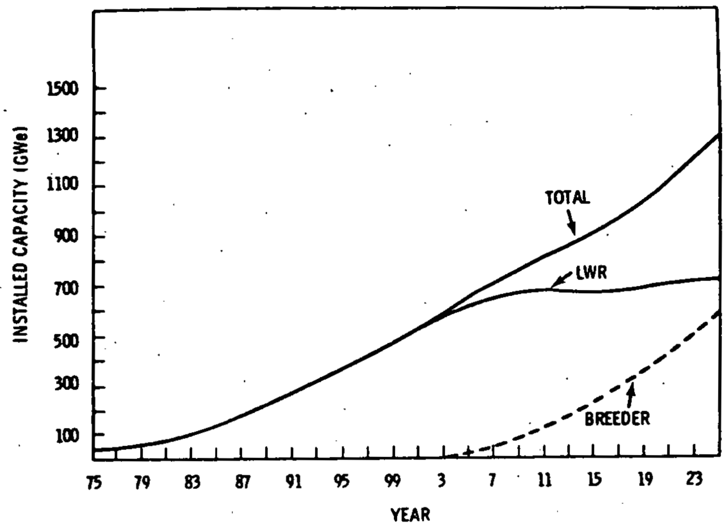

FIGURE 4. Breeder Introduction Delayed 5 Years

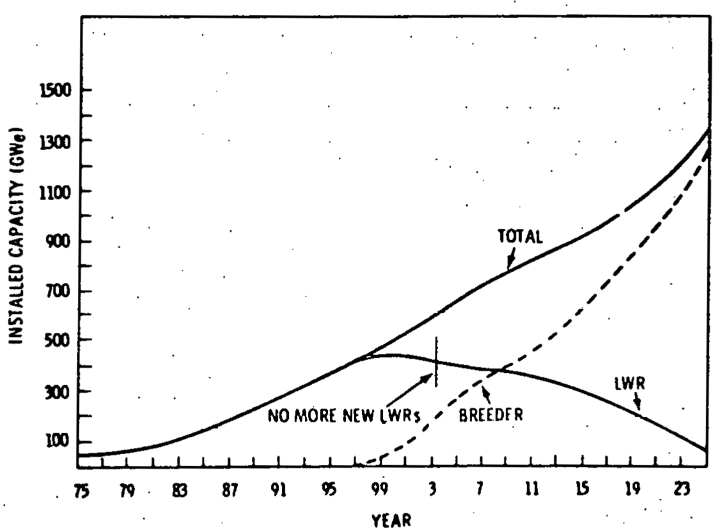

FIGURE 5. Maximum Breeder Growth in Nuclear Electrical Generation Sector

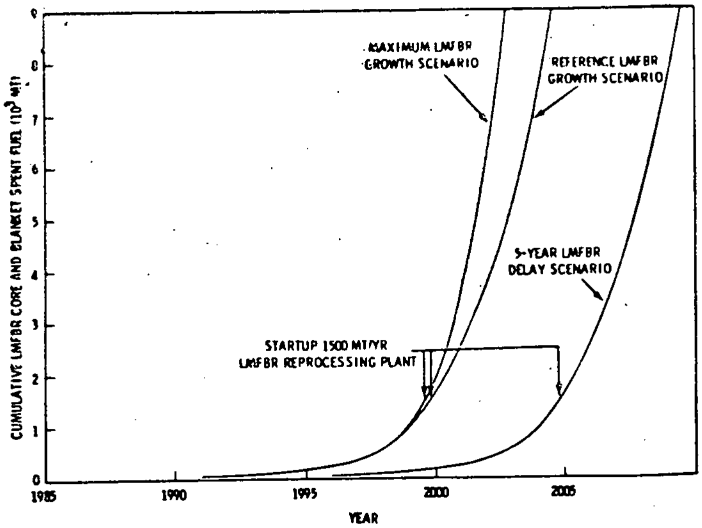

FIGURE 6. Cumulative LMFBR Spent Fuel and Startup of Reprocessing Plant

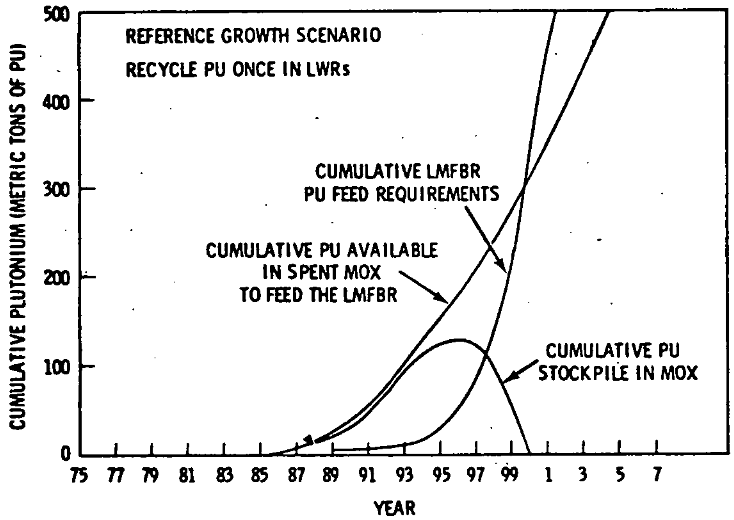

FIGURE 7. Comparison of LMFBR Plutonium Demand to the Plutonium Available in LWR Spent MOX

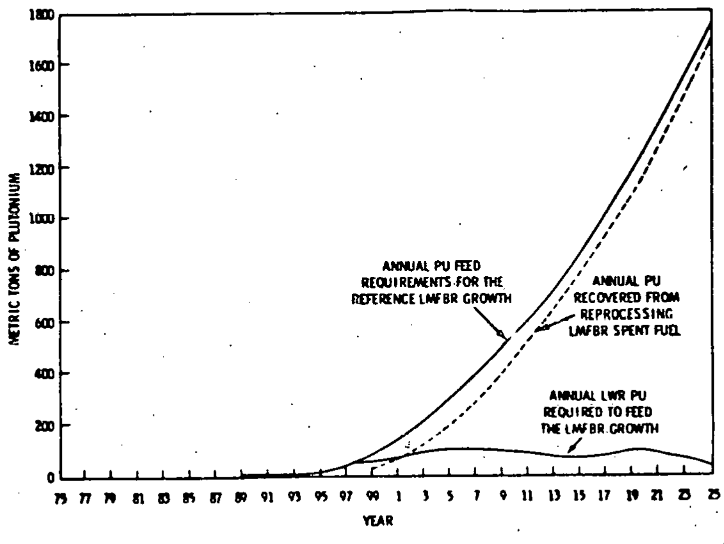

FIGURE 8. Annual LMFBR Plutonium Requirements for the Reference Growth Scenario