Parametric study on the effects of spent fuel storage time on the economics of nuclear fuel recycling

by

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A Thesis Submitted to the

Graduate Faculty in Partial Fulfillment of

The Requirements for the Degree of

MASTER OF SCIENCE

Department: Chemical Engineering and
Nuclear Engineering
Major: Nuclear Engineering

Iowa State University
Ames, Iowa

1977

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INTRODUCTION

The ability of nuclear power to produce the needed energy for the future will center around having adequate supplies of fuel. Recently the price of fuel for nuclear reactors has increased as a result of supply and demand. One solution to this increase in price is to recycle the spent fuel and recover the uranium and generated plutonium. This technology is available for use but has not been implemented on the commercial level due to delays in government regulatory decisions and licensing.

The purpose of this study is to evaluate the economics of recycling as affected by a delay between discharge of the spent fuel from the reactor and recycling to future fuel cycles. This evaluation is of interest because of the recent fluctuations in uranium and plutonium values and the escalating costs of reprocessing, waste disposal, spent fuel storage, shipping and reconversion. The technique used for evaluation was an incremental cost-value approach in which escalation and time valuing were used.

REVIEW OF LITERATURE

The economics of the nuclear fuel cycle, in particular the economics of recycling, is constantly changing due to the interlocking nature of the fuel cycle. These changes are the result of changing costs, technical advances, safety regulations, and the socio-political implications related to nuclear power. Effective fuel management requires an understanding of how variations in such parameters as value of plutonium, time in storage, cost of reprocessing, and the cost of U_3O_8 change the cost of electrical energy. The range of values for the parameters must be known consequently finding and evaluating the most recent articles and paper dealing with these subjects were of great importance.

Perspective for the study was provided by articles concerning the costs of electricity as generated by nuclear, coal, and oil (16, 13, 35). Other articles of value were concerned with the delay in availability of nuclear power generating capacity and the associated escalation of the plant cost (35, 26). These works provided a basis upon which to evaluate the nuclear industry and the fuel cycle.

General readings on the makeup of the nuclear fuel cycle (15, 32, 18) were important in providing an understanding of the processes that take place within the cycle. Articles on the economics of the fuel cycle (10, 23, 36, 5, 16, 28, 17, 37, 29, 7, 12) provided insight into the capital involved and the interrelationship of various economic variables such as the effect of enrichment cost on the total fuel cycle cost.

The costs of U_3O_8, enrichment, and fabrication along with the core physics review provided the input information for the initial calculation of the value of spent fuel at the time of discharge from the reactor core.

Due to the recent change in the uranium ore market, evaluation of information on U_3O_8 costs and contracts was a key study in arriving at the most realistic and up-to-date prices for U_3O_8. Information on the switch from fixed price to market value contracts for U_3O_8 was found in two Nuclear News articles (20, 23). Articles on uranium reserves and resources (38, 8, 11, 21) provided definitions of the above terms and the latest information on the magnitude of these reserves and resources.

Evaluation of information concerned with the availability and techniques of enrichment was necessary to determine the cost of enrichment that was to be used in the base case calculation. Articles and papers concerned with the availability and costs of enrichment services provided part of the information necessary to arrive at a cost for enrichment (1, 19). Present day costs of enrichment services (30, 19) and the latest news on privately owned enrichment facilities provided additional information.

Future fabrication cost estimations were taken from papers by Allied General Nuclear Services (3) and the Nuclear Regulatory Commission (14). Information from References 15 and 4 was used for the fabrication process and helped explain some of the problems associated with the fabrication of mixed oxide fuels.

Core physics characteristics were taken from "Current Status and Future Technical and Economic Potential of Light Water Reactors" (31) and "Reactor Fuel Cycle Costs for Nuclear Power Evaluation" (36). Data on plutonium isotope buildup as a function of burnup were found in "The Proceedings of the Conference on Commercial Plutonium Fuels" (31).

Basic to this differential economic study was the cost and timing of the recycling phase of the fuel cycle. Papers such as "Plutonium Recycle, the Impact of Indecision" (26) and "Nuclear Fuel Cycle Closure Alternatives" (3) emphasized the importance of timing on the economics of recycling. From these papers and others (24, 39, 27), it became clear that many of the problems are not technical but social and political in nature.

One of the key parameters in carrying out parametric studies on the effect of recycling delay was the cost of reprocessing. Papers on the economics of plutonium recycle by Allied General Nuclear Services (3) and the Nuclear Regulatory Commission (14) provided the most current estimates on reprocessing costs. The reprocessing cost is of major importance because of the large contribution it will make to the total cost of recycling.

Basic to this study was the review of literature specifically concerned with evaluation of the economic worth of plutonium as a fuel for thermal reactors. A review of these articles (3, 14, 25, 9) revealed that the use of plutonium as a fuel in thermal reactors will involve higher fabrication costs, special and perhaps costly handling due to the toxicity of plutonium, and increased costs to provide protection against theft. Many of the factors listed above have not been investigated to the extent necessary to provide good cost estimates. Thus the economic value of plutonium cannot be given to a high degree of certainty.

References 33 and 18 provided information on the costs associated with waste management. Due to the fact that waste management plans have not been implemented, the above costs are at best engineering estimates. A paper entitled "Radioactive Waste Management Alternatives" (2) provided valuable insight into the present waste management alternatives.

ECONOMIC ANALYSIS OF THE RECYCLE FUEL CYCLE

A differential study on the economics of recycling as affected by storage costs, reprocessing costs, post-irradiation inventory costs, and yellowcake costs is concerned with evaluation of those costs and any benefits directly connected with recycling. Included in this study were the costs of shipping, storage, post-irradiation inventory, reprocessing, waste disposal, and reconversion along with the values of uranium and plutonium. An incremental evaluation of this type is appropriate because other costs associated with the nuclear fuel cycle have no direct effect on the economics of recycling. This technique was chosen also because of its simplicity and the ease with which parametric studies can be performed and evaluated.

Due to the interlocking nature of the steps in the nuclear fuel cycle (Figure 1), it was necessary to evaluate each step prior to the performing of the differential study. After combining the results of evaluation with core data such as burnup, efficiency, and fuel consumption, it was possible to generate input data for the differential study.

By using the analysis that follows, it was possible to carry out two types of economic comparisons. One was a cost-value comparison between recycling and the throwaway cycle. The other was a cost-zero alternative comparison.

Basic Assumptions

The economic evaluation of recycling was based on the following assumptions:

1) The study was concerned only with the initial economics of transition to recycling. Thus this study was based on the timing of a

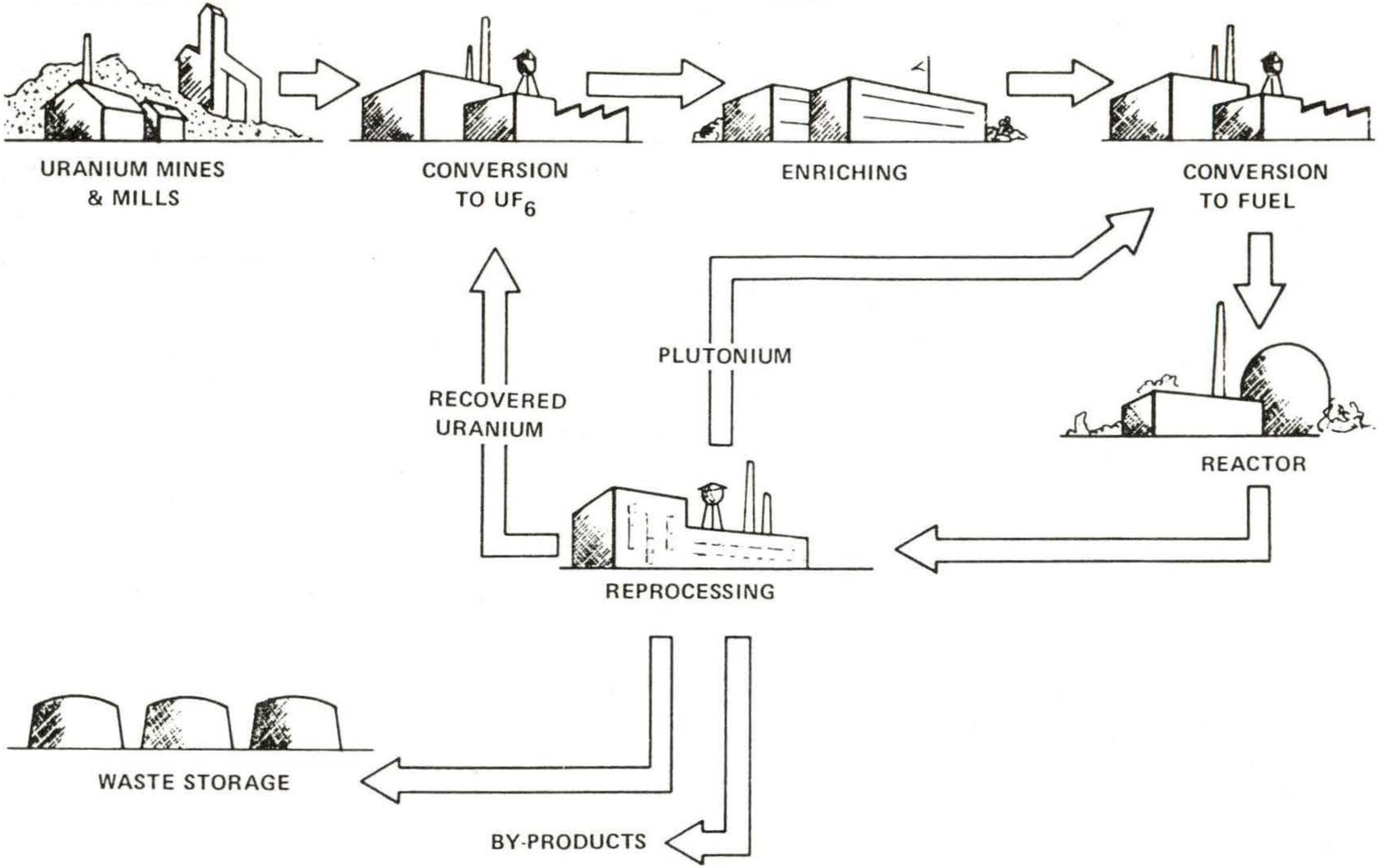


Figure 1. The nuclear fuel cycle

Nuclear Regulatory Commission (NRC) decision on "The Generic Environmental Impact Statement on Mixed Oxide Fuels."

2) The evaluation was based on economic considerations only, that is, no penalty was attached to lost energy as a result of the throw-away cycle.

3) All costs and values were time valued because of escalation and the time value of money.

4) The evaluation was based on one cycle of a single reactor fueled with UO_2.

5) Use of the recycled uranium and plutonium was not restricted to recycling into the reactor under consideration. It was assumed that any net benefit or cost would be related back to the original batch of fuel.

6) An equilibrium pressurized water reactor fuel cycle, which allowed for burnup data already developed, was used.

7) A post-irradiation inventory charge associated with money tied up in the spent fuel was used.

Differential Costs and Values

For the purpose of clarity and conciseness, it is necessary to define the basic terms associated with this economic analysis. Two basic divisions, costs and values, are defined as follows:

Value - Monetary worth of an item based on the costs of processes that would lead to the product from raw materials.

Cost - The outlay of money for services or, in the case of post-irradiation inventory, money tied up which cannot be used for other investments at that time.

Based on these definitions, it was possible to place the costs and values into centers. The following is a list of the cost and value centers along with appropriate definitions.

Reprocessing cost - Cost of reprocessing spent fuel with an inclusion of an adjustment for the cost of waste disposal.

Shipping cost - Cost associated with spent fuel storage and shipping. Storage includes both on- and offsite costs for the batch under consideration.

Reconversion cost - The cost associated with reconversion of the recovered uranium.

Post-irradiation inventory cost - The charge associated with the net value of the spent fuel which cannot be recovered until after reprocessing.

Uranium value - The value associated with savings of U_3O_8, separative work, and conversion costs.

Plutonium value - The value of plutonium minus a penalty for mixed oxide fuel fabrication.

Cost Components

Proper economic evaluation for this study was based on careful evaluation of the worth of uranium and plutonium along with the associated costs. As was stated previously, it became necessary to evaluate each of the steps in the fuel cycle because of the indirect affect on the economics of recycling.

U_3O_8 supply and cost

From early investigations (15), it became apparent that the cost of U_3O_8 would be one of the major determining factors in evaluation of the worth of uranium in spent fuel.

The definition of uranium value and the expression for the cost of enriched uranium is

$$C_E = F \cdot C_F + S \cdot C_S$$

where F = mass of feed material,
C_F = cost of feed material/unit mass,
S = units of separative work,

and C_S = cost of enrichment per separative work unit.

Using the above information, it was possible to go through a simple calculation using present day costs for an enrichment of 3 percent. The ore cost was found to be about 30 percent of the total enriched uranium cost.

Evaluation of the present and future yellowcake costs was based on the availability of ore along with current market trends. The effect of availability on the price of yellowcake has become a topic of major concern due to the recent difficulties that utilities have had in contracting for U_3O_8. This problem and the associated upward turn in the U_3O_8 prices are apparently the result of deficiencies within the exploration and mining phase. First of all there is a definite lack of detailed knowledge as to the quality and quantity of uranium reserves and resources. However, recently the Energy Research and Development Administration (ERDA) has started a multiyear program NURE (National Uranium Resource Evaluation) to perform a complete evaluation of uranium reserves and resources. Secondly, up until recently there has been no incentive for new exploration and mining due to low ore prices. But with the rapid upswing in the uranium market, a marked increase in exploration can be expected. It should be kept in mind that even if exploration does increase, there is a lag in time of eight to ten years between exploration and the actual mining.

A recent report on the availability of U_3O_8 (20) showed that in order to operate all the existing and committed reactors for their lifetimes will require 1.4 billion kilograms of U_3O_8. The latest ERDA report shows the reserve level is 0.64 billion kilograms. There is a need for expanded mining and exploration in order to provide for the remaining needed reserves.

Combining the above information with prices used by Allied General Nuclear Services (3) and the Nuclear Regulatory Commission (14) in similar studies, a range of prices of \$66/kg (\$30/lb) to \$132/kg (\$60/lb) U_3O_8 was chosen for this study. All of the information used in this cost determination is given in much greater detail in the bibliography (38, 8, 21, 11, 20).

Conversion

The purpose of the conversion operation is to separate the remaining impurities from the uranium and to convert the uranium to a very highly purified uranium hexafloride gas. The uranium hexafloride is fed to the gaseous diffusion plants for isotopic enrichment. Conversion is achieved by either solvent extraction or volatilization and fractionation, neither of which pose any technical or operational problems. Also plants of either type are relatively inexpensive to build and operate. The cost of conversion has little effect on the worth of uranium. For the preliminary calculations which were performed to generate data for the differential study, a value of \$7.70/kgU (\$3.50/lbU) was assigned to the cost of conversion. This value agrees well with costs used by the Nuclear Regulatory Commission in their most recent fuel cycle cost calculations (14).

Enrichment

In order to determine the worth of the uranium in the spent fuel, one must sum all the savings associated with recycling. Therein lies the importance of proper analysis of the availability and cost of enrichment.

To evaluate the availability of enrichment, one must determine not only how much separative work will be required but also who will be doing the separation. Tied directly to the question of who will be providing the enrichment services is the question of how much would commercial services cost as compared to government services.

The present government plants with the Cascade Improvement and Uprating Programs will be able to supply 27.6 million separative work units annually by about 1986 (18). Due to recent delays in the building of nuclear power plants, it appears that increased separative work will not be needed until 1983. The apparent shortage of separative work after 1983 bring to point the question of who will be providing this needed enrichment service.

The major difficulty with any private venture is the investment loss if for technical reasons the gaseous diffusion plant fails to operate or if it becomes uneconomical due to the gaseous centrifuge technology. The possibility of the gaseous diffusion plant being replaced by the gaseous centrifuge could indeed become a possibility due to recent plans to design and build demonstration gaseous centrifuge plants in this country and several foreign countries.

For purposes of this study, it was assumed that all of the enrichment services for the early 1980's will be provided by the government. The enrichment costs for this study were taken from a Nuclear Regulatory Commission study on plutonium recycling (14).

Burnup

The cost of any service connected with the generation of electricity is usually based on the revenue for the electrical energy produced. For this reason it was necessary to carefully develop and evaluate fuel consumption, plutonium production, and electrical energy produced for the batch of fuel under consideration.

The variables associated with burnup in an equilibrium cycle in a PWR were determined. The variables included such things as plant efficiency, electrical energy production, uranium consumed, and discharged masses of uranium and plutonium. With the purpose of this study and the variables needed in mind, it was determined that use should be made of already available burnup data. The above decision was also based on the close similarity between the type of information desired and that found in WASH-1099 and WASH-1082 (36, 34). In particular, the data matched the desired burnup of approximately 20 MWd/kg.

The choice of 20 MWd/kg was based on actual burnup data. From the data taken from WASH-1099, it was necessary to assume that there was uniform fuel burnup and that the power generated during the time under consideration was constant.

During the course of development of burnup data, the question arose as to what affect the time in storage would have on the amount of plutonium present at recycling due to the decay of Pu^{241}. By performing a simple calculation, it was determined that for the case under consideration the Pu^{241} lost by decay in even a 5-year delay would cause only a minor perturbation in the plutonium available at reprocessing.

Plutonium value

The economic consideration of plutonium recycle is based largely upon some justifiable range of values for the plutonium recovered. However, after evaluation of articles on plutonium recycle (26, 3, 9), it became clear that this range of values was very wide. It must be assumed that the Nuclear Regulatory Commission will rule in favor of mixed oxide fuel, otherwise it makes no sense to place any value on plutonium. The value will have some relationship to the availability of reprocessing as well as the value of uranium which plutonium could replace. Finally, it could be a function of such things as the type of reactor under consideration and even social pressures against using plutonium recycle. Because of these uncertainties, it was necessary to vary the value of plutonium.

Waste disposal

Waste disposal costs were taken into account in the reprocessing cost center. As a result, the uncertainty of the reprocessing cost center increased. The increased uncertainty is a direct result of the decision upon plutonium recycle and the uncertainty of the Energy Research and Development Administration as to the best disposal plan for radioactive waste. Waste disposal plans as they now stand will probably include retrievable storage followed by permanent storage in an underground salt bed. However, the final solid form of the high level waste has not been decided, but extensive work is being done with calcined glass. More detailed information can be found in Reference 2.

Shipping and storage

Costs for shipping and storage were grouped into one cost center. Thus, it was possible to express the total cost for the center as

$$T = C + SM$$

where T = total cost of shipping and storage,
C = cost of shipping,

and S = cost per month of storage,
M = number of months.

With the use of the above expression, a parametric study on the effects of time in storage upon the economics of recycling was performed.

Most of the information on shipping and storage costs was taken from a study done by Allied-General Nuclear Services (AGNS) (3). It should be pointed out that the costs of storage given in the AGNS report could be markably low due to continual buildup of spent fuel which cannot be reprocessed. However, it is a small fraction of the total cost of recycling.

Procedural Analysis

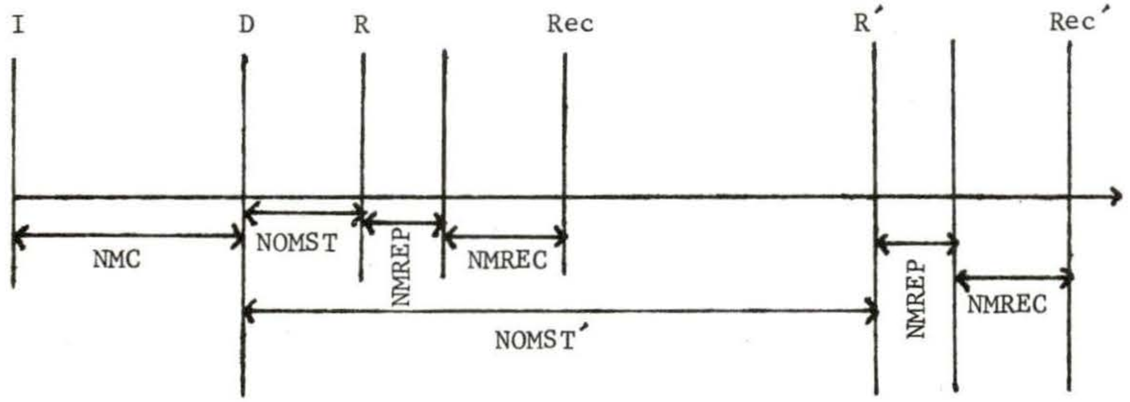
The procedure for this differential study was based on the concept that all of the major costs and values directly associated with the recycling of spent fuel could be grouped and assigned to cost centers. The utility of the cost centers concept is the ease with which one can assign a particular value a location in time. This facilitates the movement of the cost centers though time for the purpose of economic evaluation.

Considering the cost centers and the parametric studies on time in storage, reprocessing costs, plutonium values, and escalation rates that were to be performed, it was necessary to develop a base case. This gave initial values and times to each cost center and provided a basis upon which to carry out the parametric studies.

In order to generate the base data for this study, it was necessary to adapt CINCAS, a fuel cycle cost code, to the Iowa State Computer System. CINCAS is a very general and quite powerful fuel cycle cost code. This code has the capability of being used for either engineering economic predictions of fuel cycle costs or forecasting of such costs.

Tied directly to the development of input data for the differential study was the placing of each cost and value on a time line. First, the original cost centers were placed on the time line (Figure 2) according to their definition. Then an arbitrary second set of cost centers was defined and located. The second set of cost centers represented the original cost centers time valued.

Once each of the cost centers was calculated and moved in time to their appropriate position, it was necessary to move all of the costs to a common time in order to perform the economic evaluation. Because of the necessary operation of moving money through time, it was important to evaluate the time value of money and the escalation rates to be used. The results of the evaluation of the escalation rates showed that it was necessary to escalate some of the cost and value centers at different rates. Secondly, the evaluation revealed that the time value of money could range greatly. However, for the purpose of this study, a constant rate of 7 percent was chosen for the time value of money.



I - Insertion into core
D - Discharge
R - Reprocessing
Rec - Reconversion and post-irradiation inventory
R' - Reprocessing prime
Rec' - Reconversion and post-irradiation inventory prime
NMC - Number of months in core
NOMST - Number of months in storage
NMREC - Months between reprocessing and reconversion
NOMST' - Number of months in storage prime

Figure 2. Time line for differential costs and values

PROCEDURE

A parametric investigation of the differential value of recycling spent fuel for a model pressurized water reactor with characteristics shown in Table 1 was conducted using the algorithm shown in Figure 3.

Table 1. Pressurized water reactor characteristics, equilibrium cycle

Item	Rate
Electrical output	1000 MW
Thermal output	3077 MW
Efficiency	32.5%
Enrichment	2.548%
Discharge assay	1.016%
Burnup	20.3 MWd/kg
Mass of uranium in core	77,905 kg
Refuel batch size (1/3 core)	25,968 kg
Plutonium at insertion	none
Plutonium at discharge	143.9 kg fissile
Capacity factor	60%

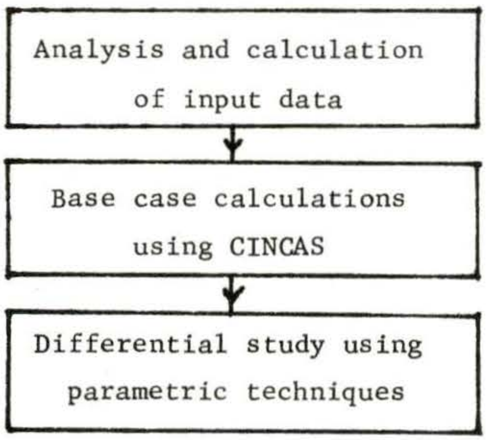


Figure 3. Algorithm of the basic procedures used in the calculation of the differential value of recycling

The parameters which were varied in this study were: (1) time in storage, (2) yellowcake value, (3) plutonium value, (4) reprocessing cost, and (5) the escalation rate on plutonium. The study was so designed that it was possible to investigate the effects of time in storage in conjunction with each of the other parameters.

The basic procedure used in this study was to develop a base case in which each of the costs and values was defined with respect to both amount and position in time. Once the events and costs were placed in time, it was possible to move them through time in order to represent the variation of the parameters under consideration. The time line in Figure 2 shows the base case along with a primed system which represents an arbitrary set of costs which have been moved through time. Using the time line as a guide, each of the original cost locations in time was defined as follows:

Reprocessing cost - Cost of reprocessing at original time of reprocessing.

Reconversion cost - Cost of reconversion at original time of reconversion.

Shipping and storage cost - Cost at time of discharge.

Post-irradiation inventory cost - Post-irradiation cost was recalculated each time and was located at the time of the reconversion under consideration.

Similarly the original values of uranium and plutonium were located in time as follows:

Uranium value - Value of uranium at original time of discharge.

Plutonium value - Value of plutonium at original time of discharge.

With the cost centers defined and located in time, the analysis of input data was undertaken. Once the various parameters for the base case were evaluated, the data were organized and used as input into CINCAS.

CINCAS generated present worth values at the time of discharge for uranium and kilowatt hours of electricity along with uranium and plutonium masses at discharge. This code also calculated costs, burnup data, and levelized fuel cycle costs which were used to provide checks for later calculations. The values calculated by CINCAS and input data developed previously were used to carry out the differential parametric studies.

The steps involved in the calculation of the differential costs and values are found in Figure 4. As shown in the figure, the first step in this calculation was to calculate the monthly escalation and time value rates for each of the costs and values. It should be mentioned that the time value and escalation rates were effective annual rates. Once the monthly rates were determined, the costs associated with the particular time in storage were calculated. For example, if the time in storage was increased by five months, it would be necessary to escalate each of the costs and values to its appropriate time in relation to this change in storage time. These new costs and values are represented by the primed letters in Figure 2. After each cost was relocated in the prime system, it was then necessary to move them to a common time for summation. For convenience, all costs and values were moved to the time of reconversion prime. It was then possible to calculate the post-irradiation inventory cost according to the definition. This was followed by the calculation of total costs and values, which were then moved through time to the time of insertion of the batch into the reactor. These values then were used in conjunction with the present worthed energy output in kilowatt hours, and the net differential values were calculated.

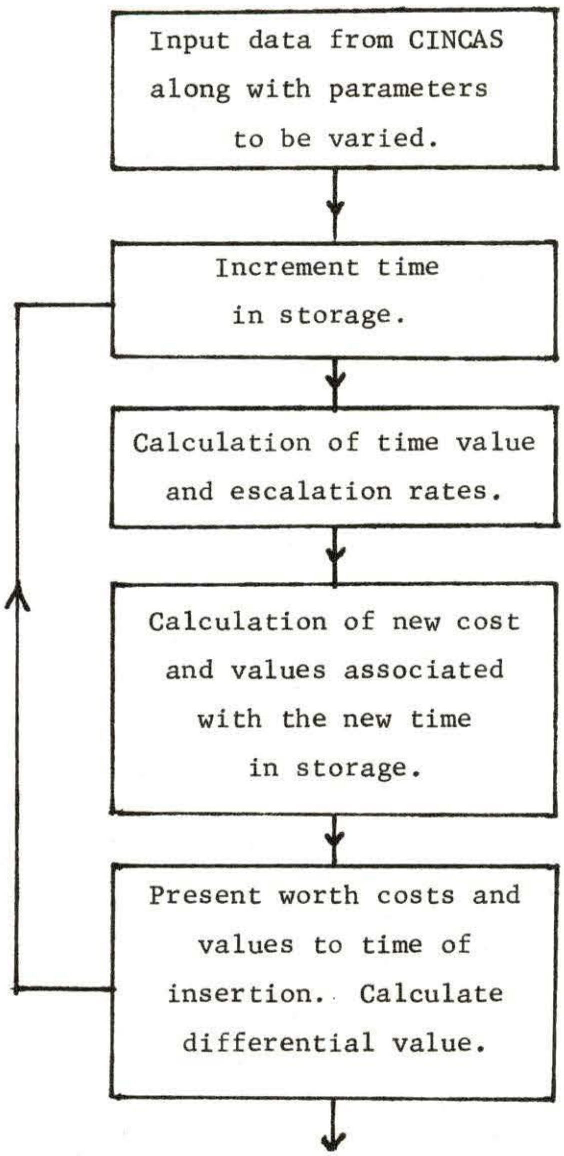


Figure 4. Flow diagram of differential value calculation

RESULTS

The results of this study are presented as a series of figures of the differential values (costs) as a function of time in storage. The series of curves found on each figure represent the effects of variation of the parameters under consideration for various times in storage. This means that each one of the figures illustrates the results of a particular parametric study.

All of the costs and values represented by the curves in the figures have been time valued to the time of insertion for purposes of comparison. By combining the results shown in the figures with the burnup data in Table 2, one can properly evaluate the results. This evaluation included comparison of the differential value to that of the throwaway cycle cost and the zero alternative. The zero alternative refers to comparison only on a cost-value basis.

Table 2. Batch characteristics

Item	Rate
Fuel enrichment at insertion	2.548%
Fuel enrichment at discharge	1.016%
Burnup	20.3 KWd/kg
Plutonium at discharge	143.9 kg
Mass of uranium at insertion	25,968 kg
Mass of uranium at discharge	25,158 kg

Throwaway Cycle Cost

The cost for the throwaway cycle based on a ten-year cooling down period followed by permanent storage was found to be about 1.4 mills/KWh. The above cost was calculated based on the data shown in Table 3 and the same time valuing techniques used in the other portions of this study. However, it was assumed that the cost of temporary storage increased stepwise every two years. The amount of the step was based on the yearly escalation rate shown in Table 3.

Table 3. Throwaway cycle cost data

Item	Rate
Temporary storage cost[a]	\$0.50/kg-HM[b]
Permanent storage cost	\$150/kg-HM
Transportation cost	\$15/kg-HM
Rate of escalation of costs	10%
Time value	7%

[a]All costs are costs at time of discharge.

[b]HM - heavy metal, uranium, or plutonium.

Recycle Results

Figures 5 and 6 illustrate the effect of time in storage upon the differential value for a range of plutonium values. As one might expect, the incentive for recycling becomes greater as the costs of yellowcake increases. More importantly it appears that even for the case of \$66/kg (\$30/lb) U_3O_8 and \$10/g Pu fissile, recycling is economical especially if

U_3O_8-$132/kg
Reprocessing cost-$200/kg-HM
Pu value-$10-$50/g fissile
Time value-7%
Pu and U escalation-10%

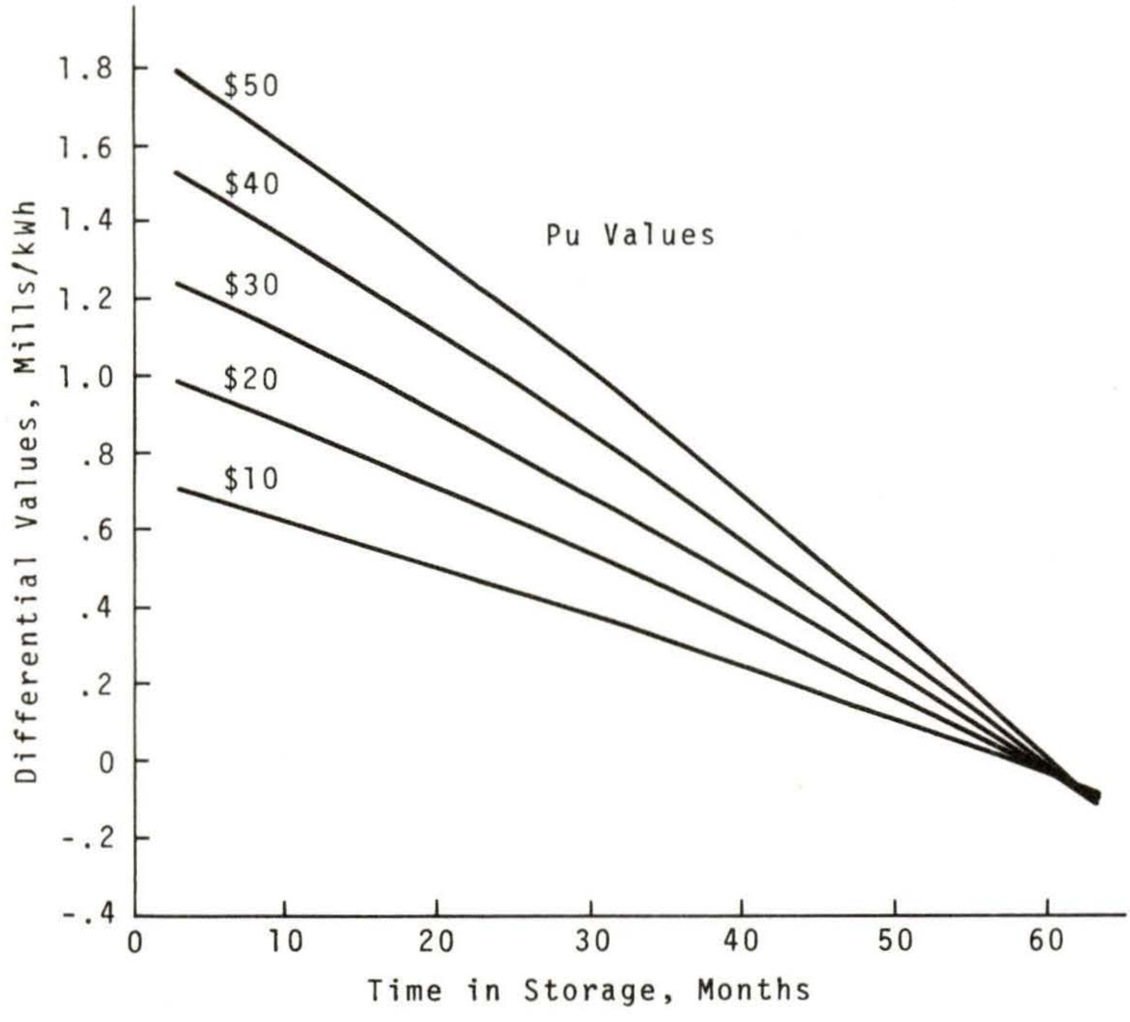


Figure 5. Differential value as a function of months in storage and plutonium value

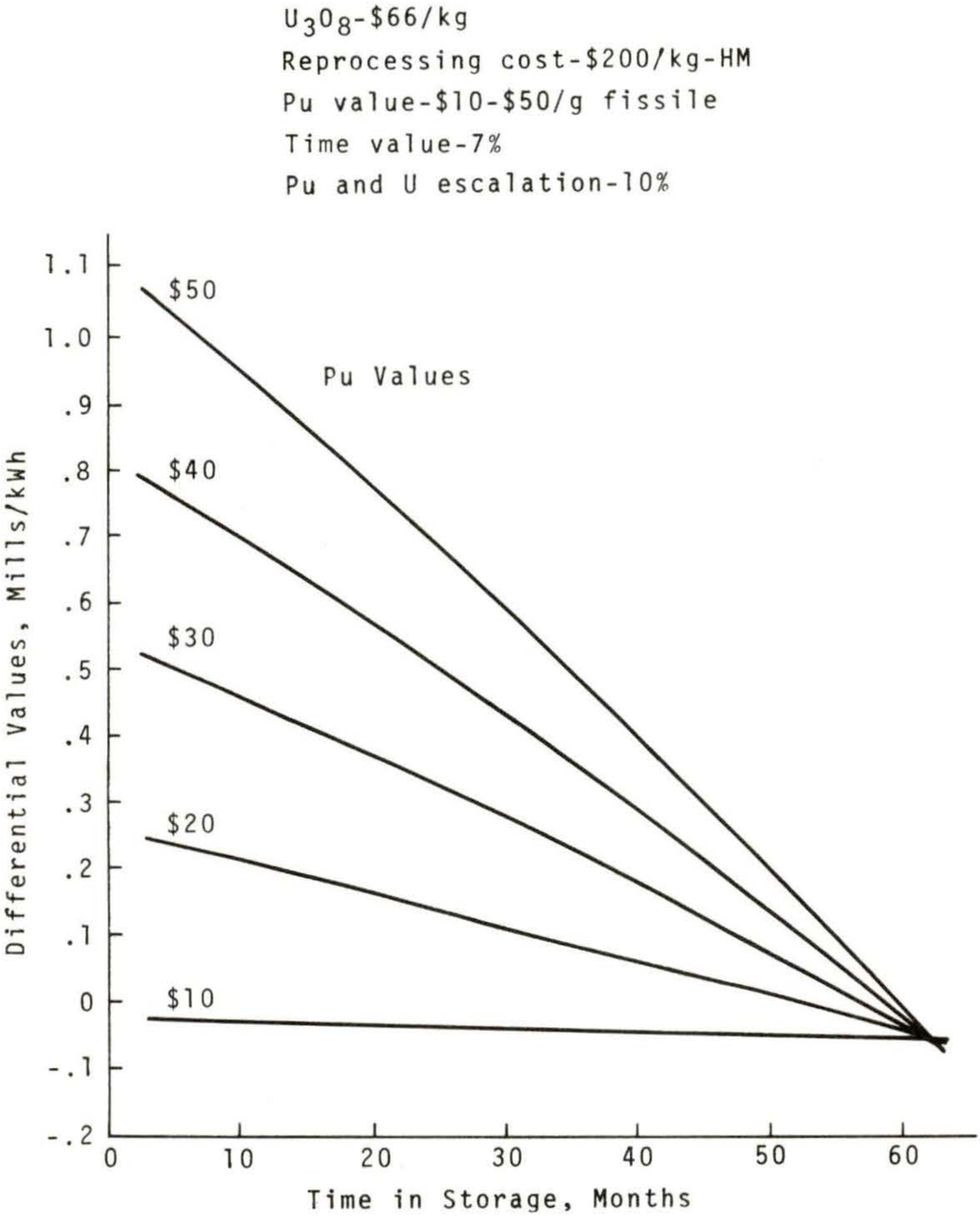


Figure 6. Differential value as a function of months in storage and plutonium value

one compares the throwaway cost. It should be pointed out that the convergence of the curves is followed by divergence if the time in storage is extended.

The effects of time in storage on the differential value for various reprocessing costs are shown in Figures 7 and 8. From the figures it appears that the higher the cost of U_3O_8, the more expensive reprocessing can become before recycling becomes uneconomical. This is a result of the effect that increased ore prices has on the value of enriched fuel.

Fundamental to a proper understanding of the economics of recycling was the development of figures showing how the individual costs varied in relation to the total cost as functions of time in storage, reprocessing cost, and plutonium value. Figures 9 through 12 illustrate the variation of individual cost ratios as a function of time in storage.

Figures 9 and 10 illustrate the variation of the post-irradiation inventory cost ratio for various reprocessing costs. It should be noted that an increase in the cost of reprocessing results in a decrease in the post-irradiation inventory cost ratio. This is a result of a direct increase in reprocessing cost as compared to an indirect decrease in the post-irradiation inventory cost. This indirect decrease is caused by the decline in the net value of the spent fuel which when multiplied by the offsite carrying charge gives a reduced post-irradiation inventory cost and ratio.

From Figure 10 one can see that for the cases of \$300 and \$350 reprocessing, the post-irradiation inventory went negative. However, a negative post-irradiation inventory has no true meaning because by definition post-irradiation inventory cost is that cost associated with the net value tied

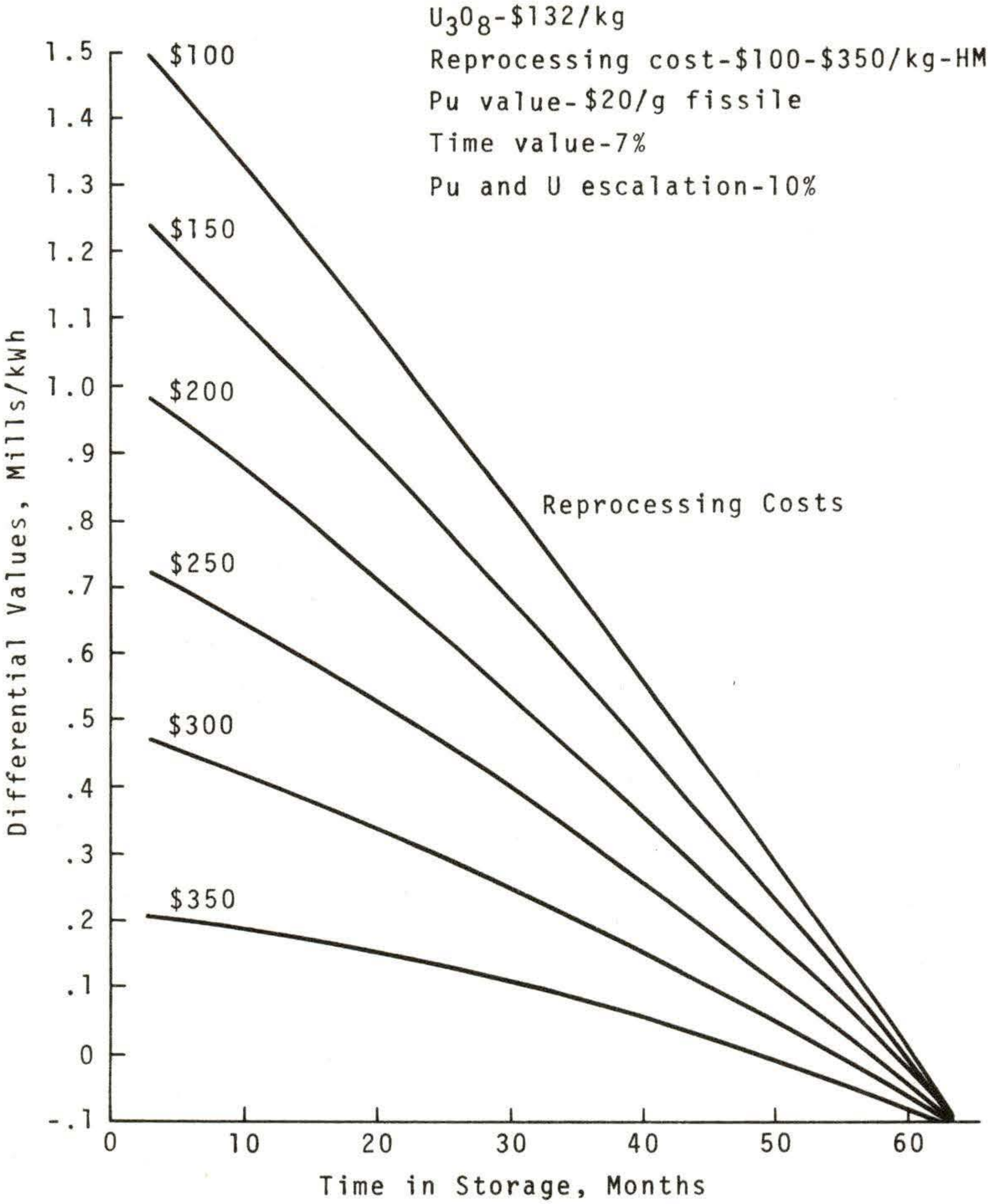


Figure 7. Differential value as a function of months in storage and reprocessing cost

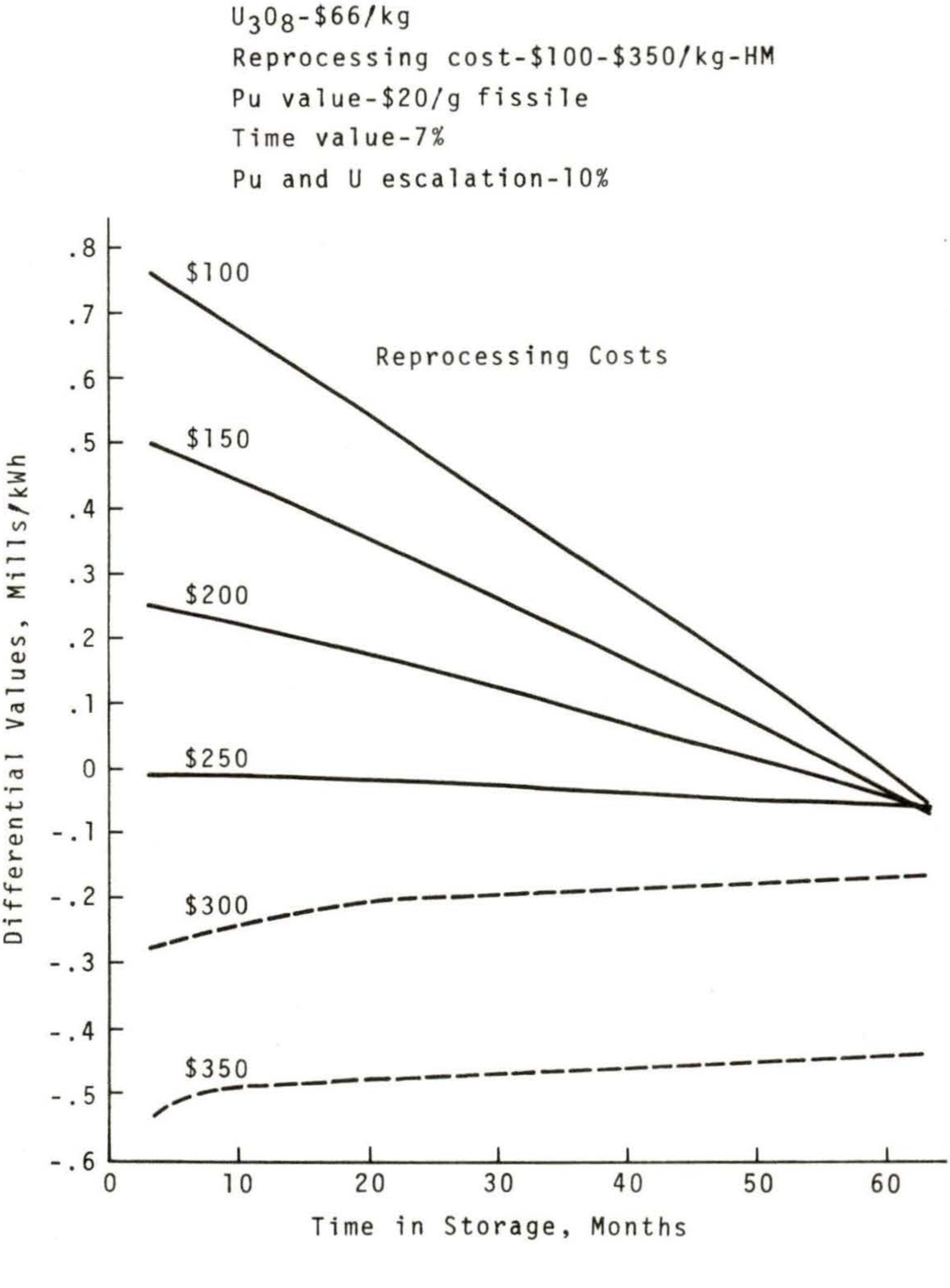


Figure 8. Differential value as a function of months in storage and reprocessing cost

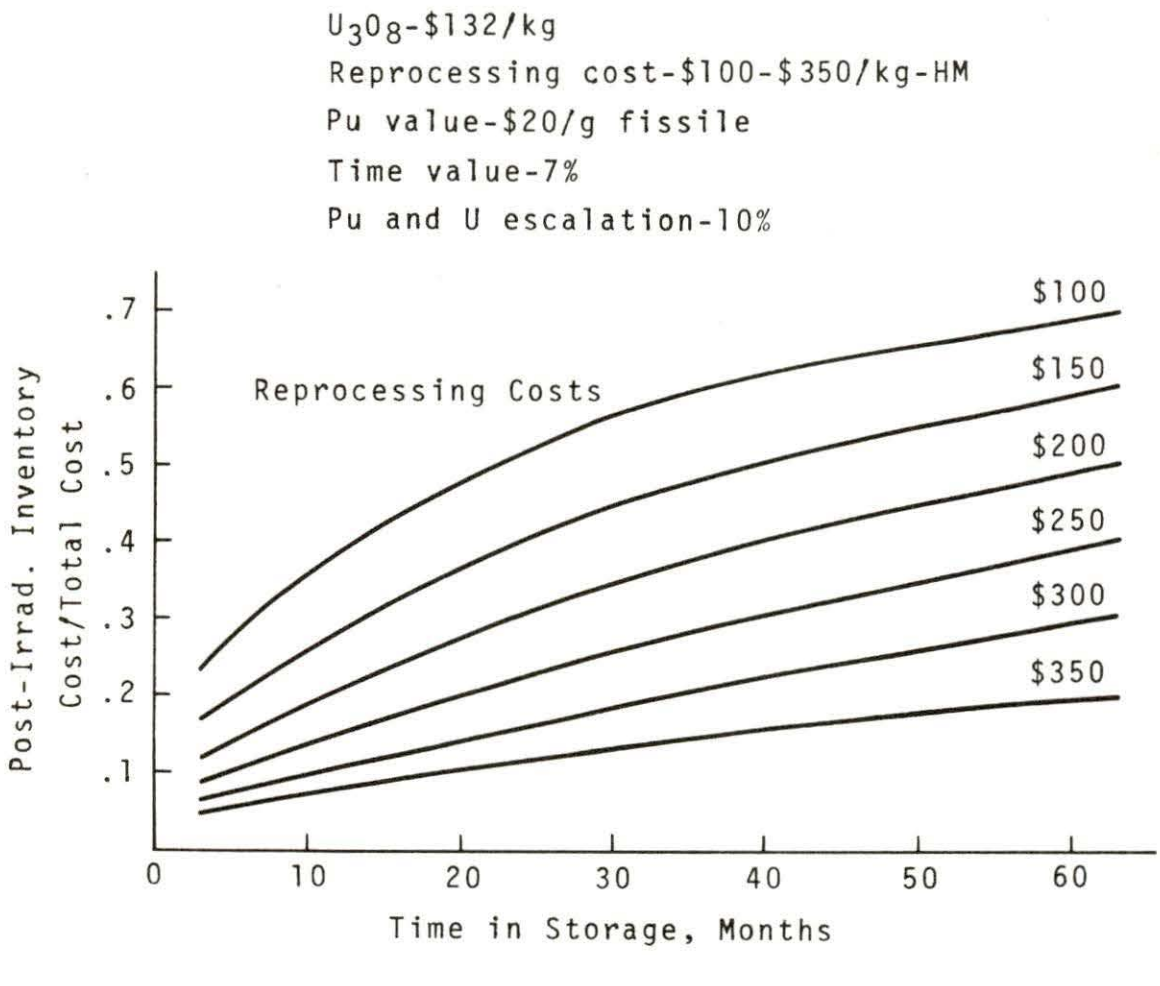


Figure 9. Post-irradiation inventory cost ratio as a function of months in storage and reprocessing cost

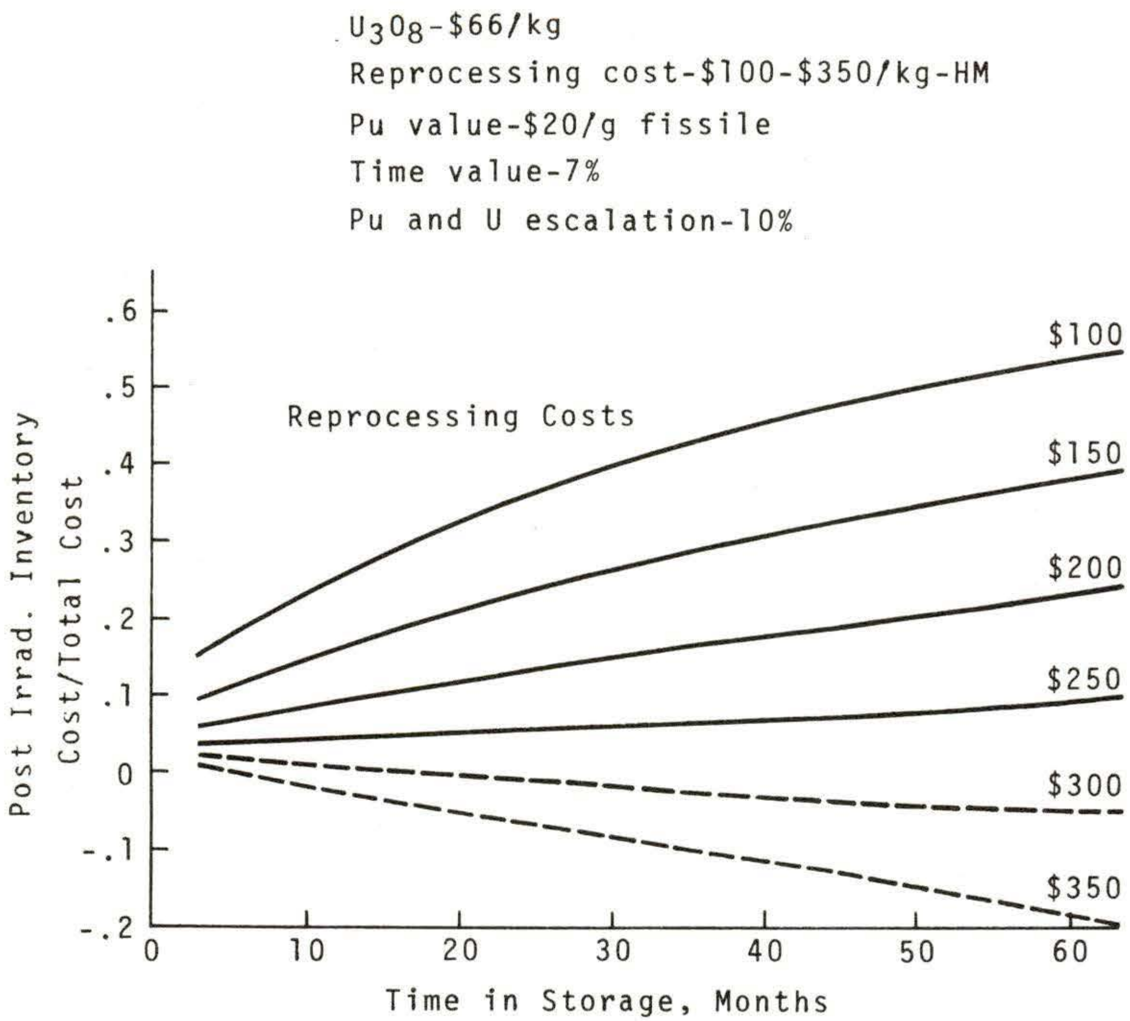


Figure 10. Post-irradiation inventory cost ratio as a function of months in storage and reprocessing cost

up in the spent fuel. This means that since the offsite carrying charge is positive, the net value of the spent fuel must be negative. Thus it makes no sense to attach a carrying charge onto a cost. The fact that the net value of the spent fuel is negative does tell one that recycling is no longer economical when compared to the zero alternative.

From the \$132/kg (\$60/lb) U_3O_8 curves in Figure 11, it can be seen that in all but the \$10/g Pu fissile case the post-irradiation inventory becomes the dominate cost in the time of storage under consideration. This can be compared to the \$66/kg (\$30/lb) U_3O_8 curves in Figure 12 from which one can see that only for the \$50/g Pu fissile value does the post-irradiation inventory become the dominate cost. This shows that for a fixed reprocessing cost, variation in the U_3O_8 cost can have a major influence on which cost is dominate.

In Figures 13 and 14 are illustrated the effects of variation in the escalation rate of plutonium. From these figures it appears that the variation of the plutonium escalation rate has only minor effects on the results. One would expect, however, that the higher the initial value of plutonium the greater the effect of variation in the escalation rate would have on the economics.

Figures 15 through 18 show clearly the dominance of the reprocessing cost for various economic conditions. From these figures it appears that only when one has high yellowcake costs and low reprocessing costs does the reprocessing cost fail to be dominant. This tells us that the economics for recycling is determined mainly by the reprocessing costs.

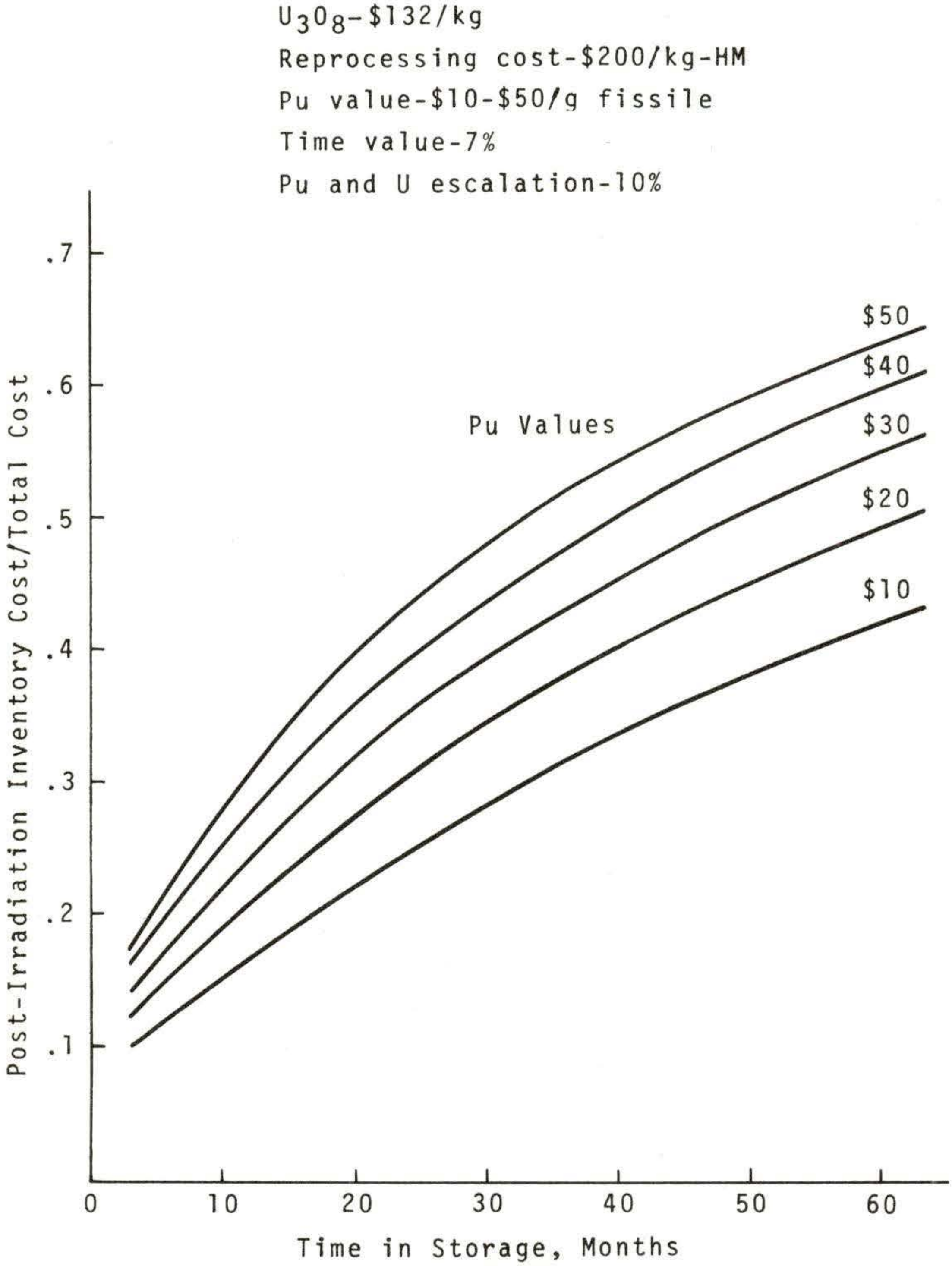


Figure 11. Post-irradiation inventory cost ratio as a function of months in storage and plutonium value

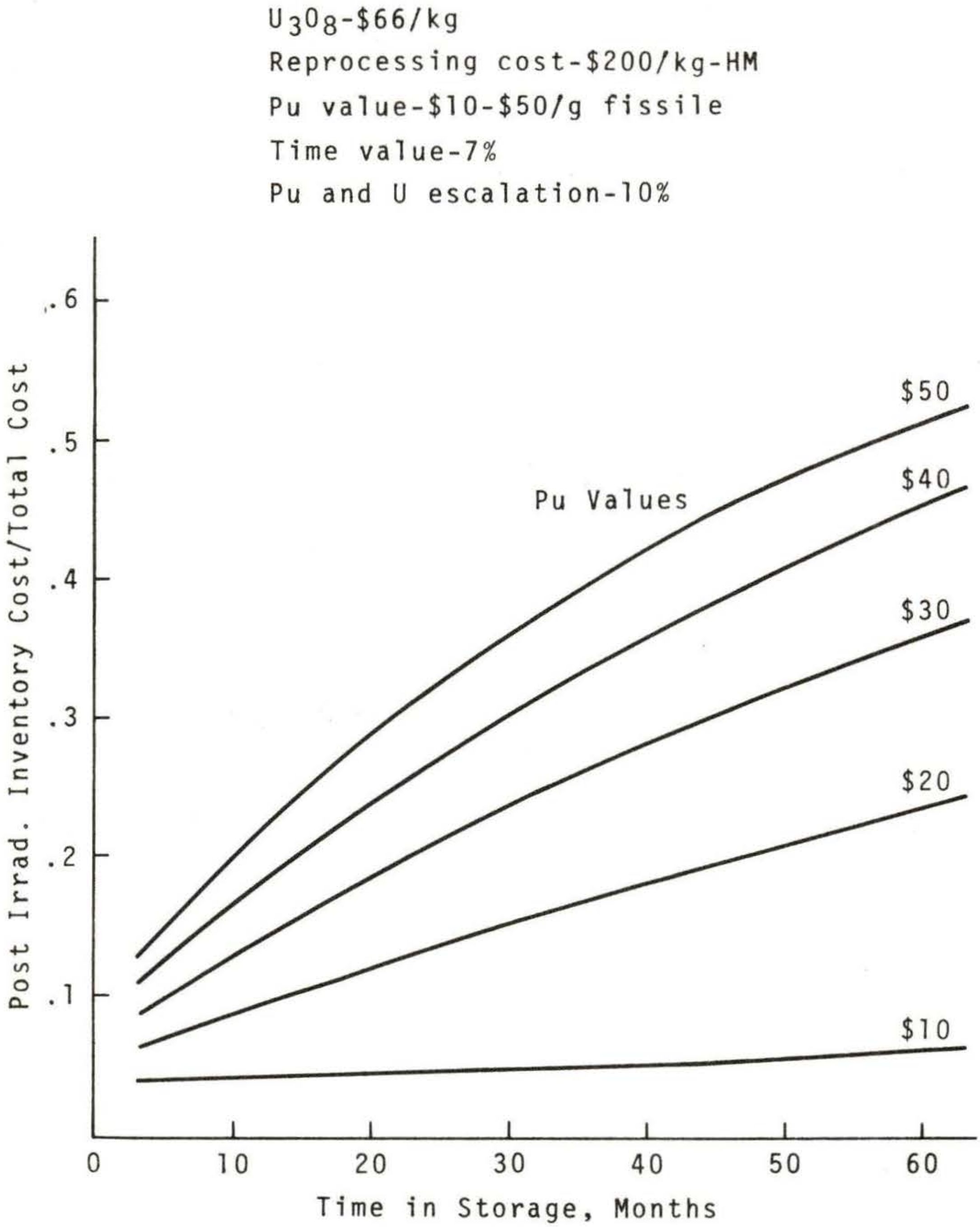


Figure 12. Post-irradiation inventory cost ratio as a function of months in storage and plutonium value

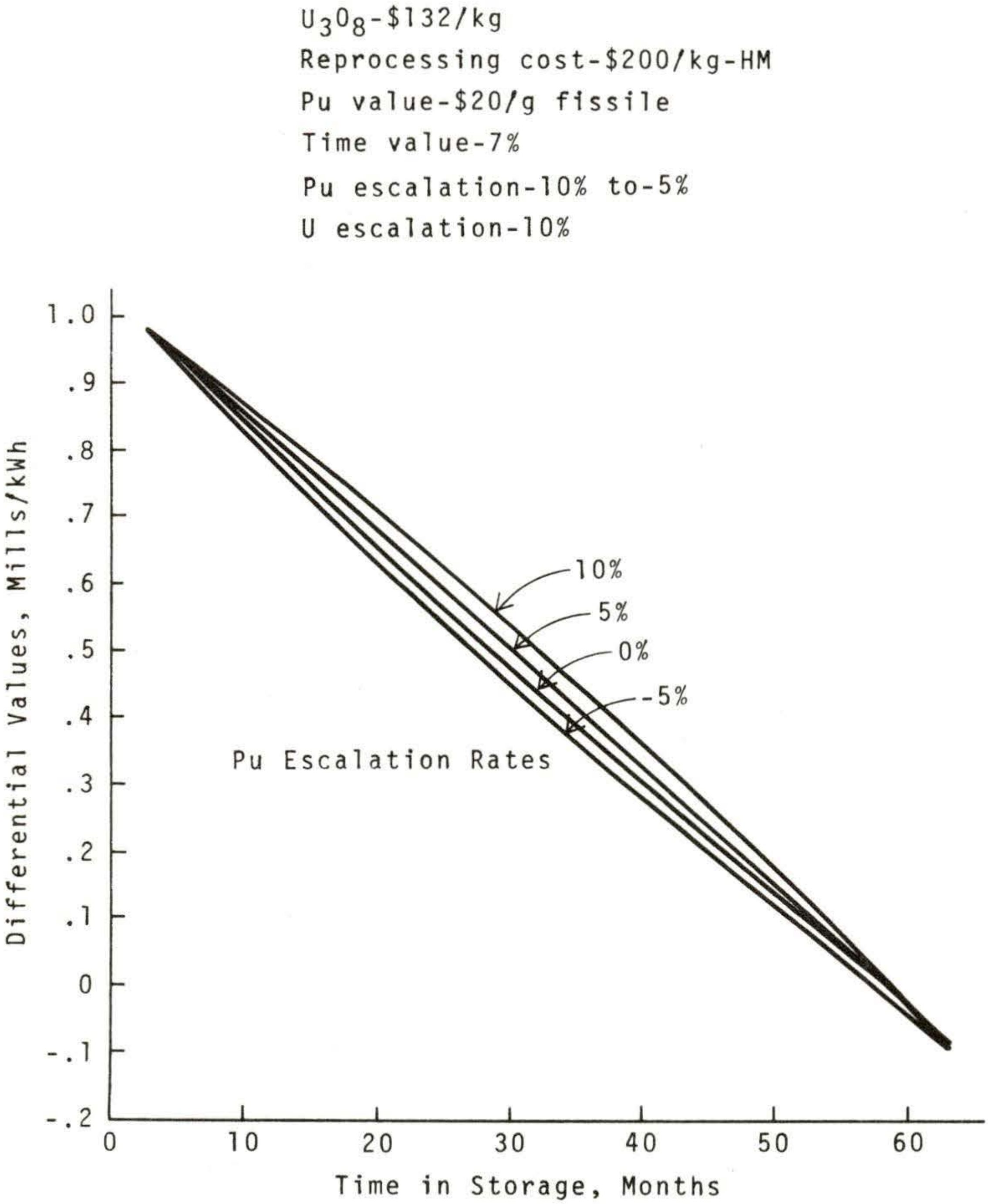


Figure 13. Differential value as a function of months in storage and plutonium escalation rate

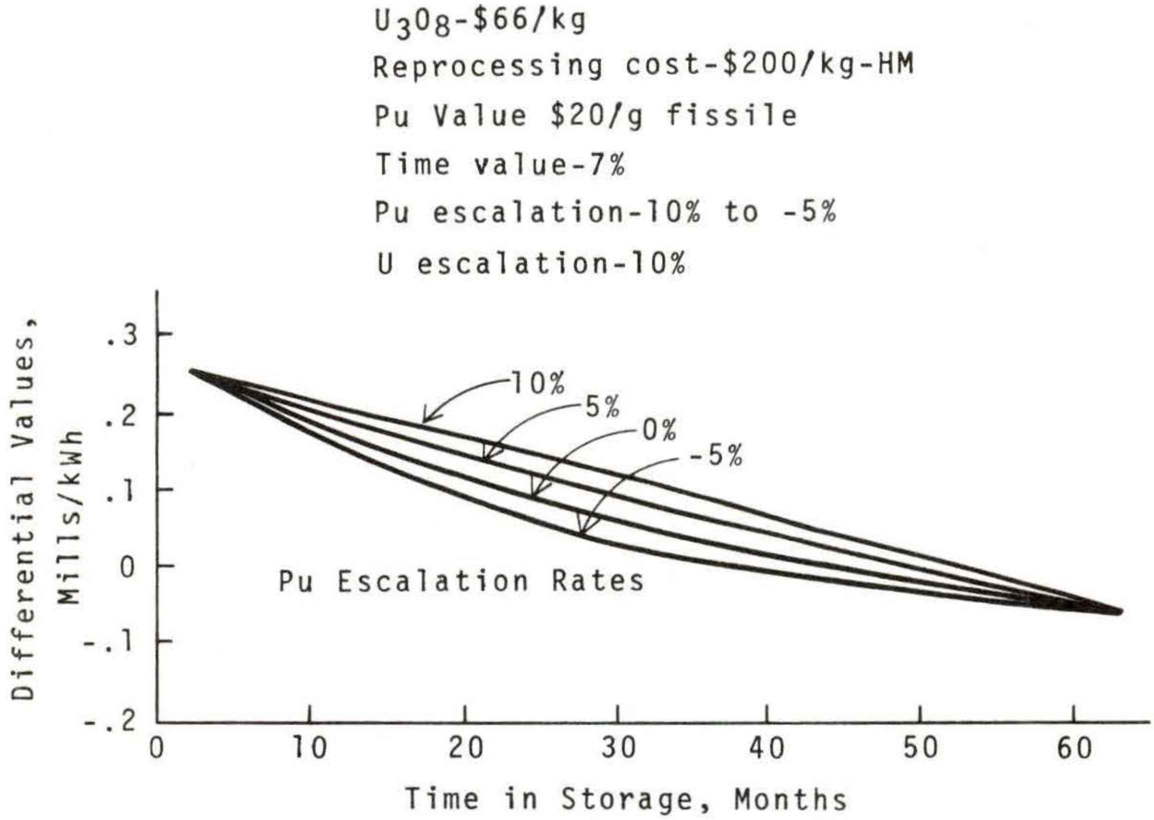


Figure 14. Differential value as function of months in storage and plutonium escalation rate

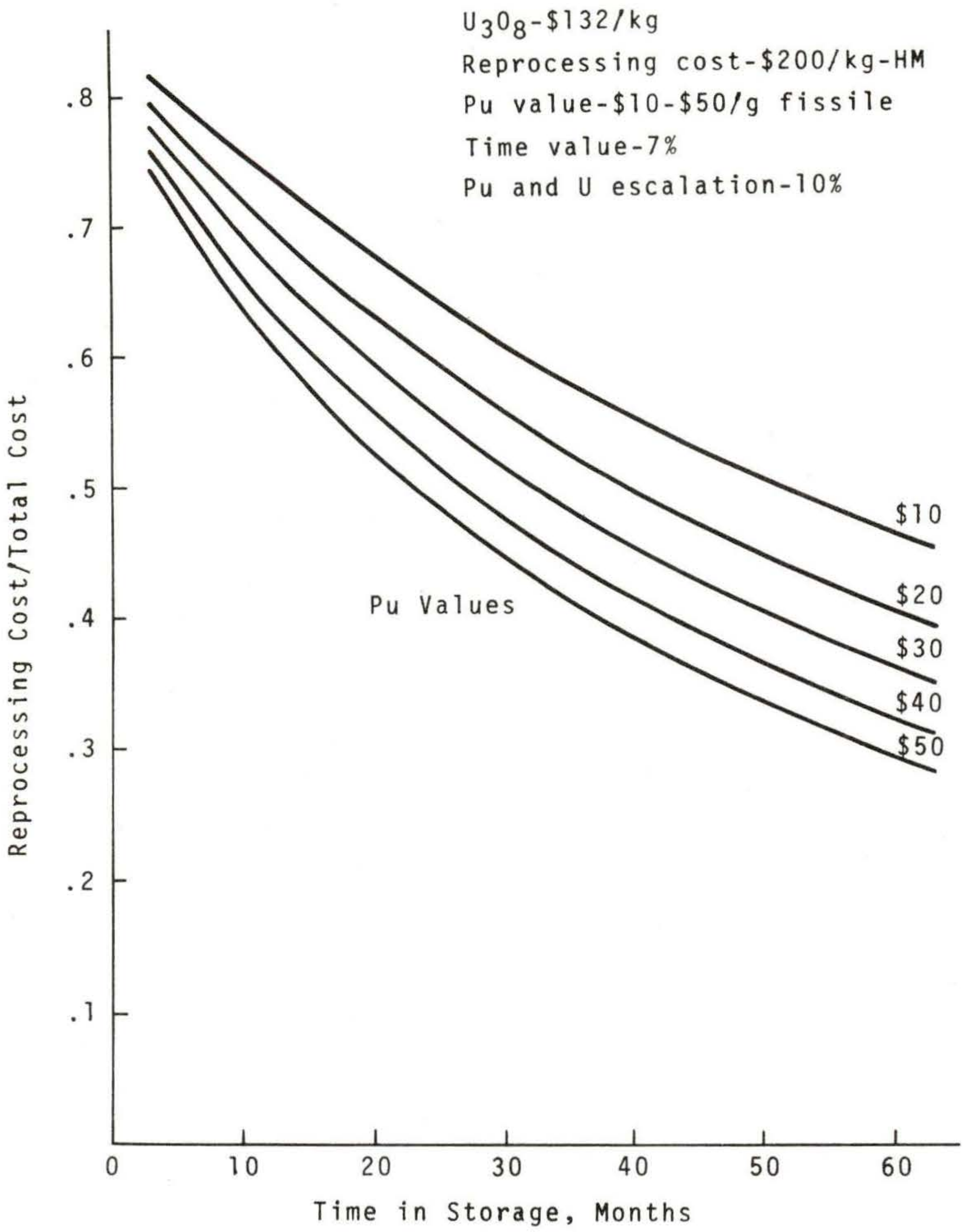


Figure 15. Reprocessing cost ratio as a function of months in storage and plutonium value

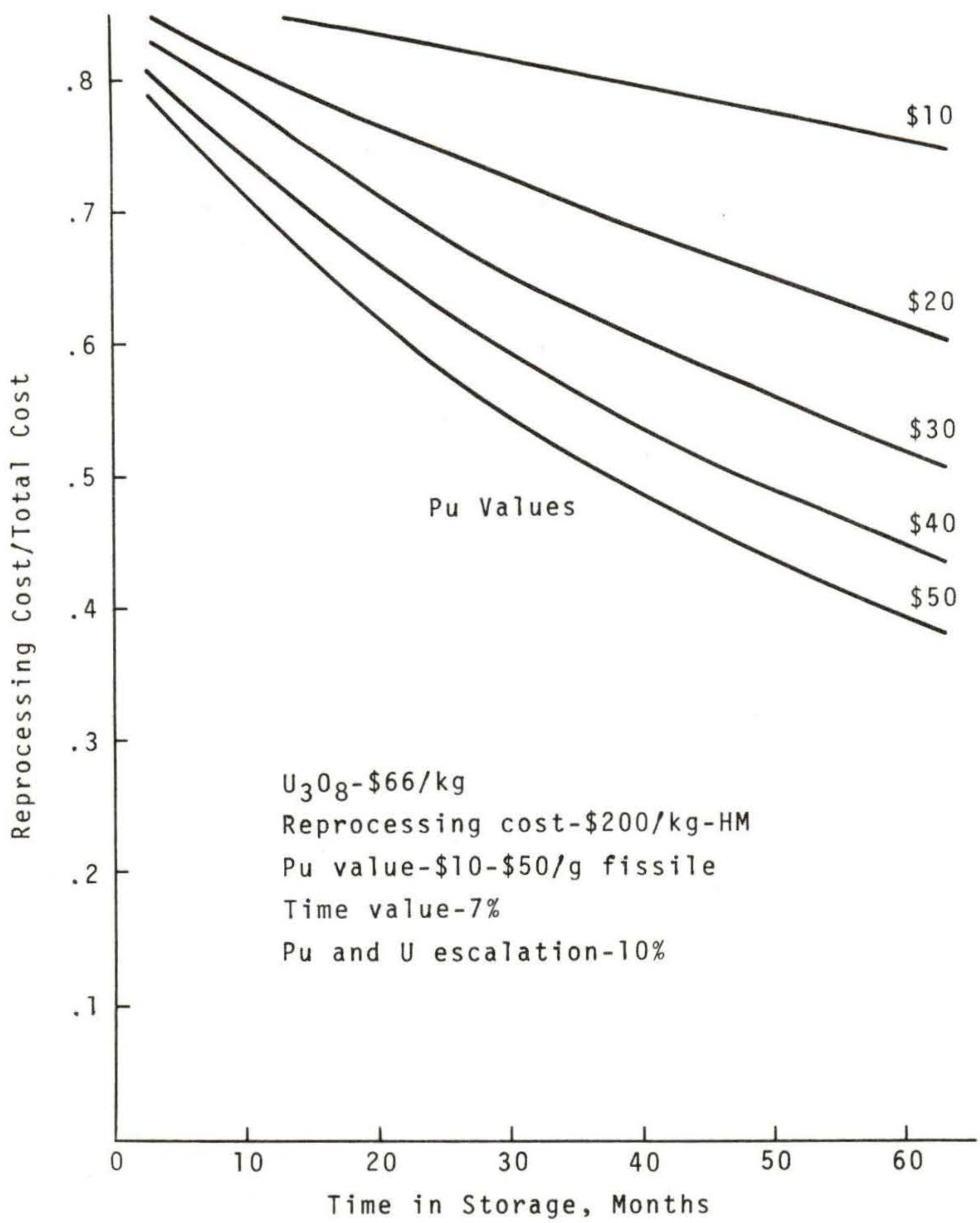


Figure 16. Reprocessing cost ratio as a function of months in storage and plutonium value

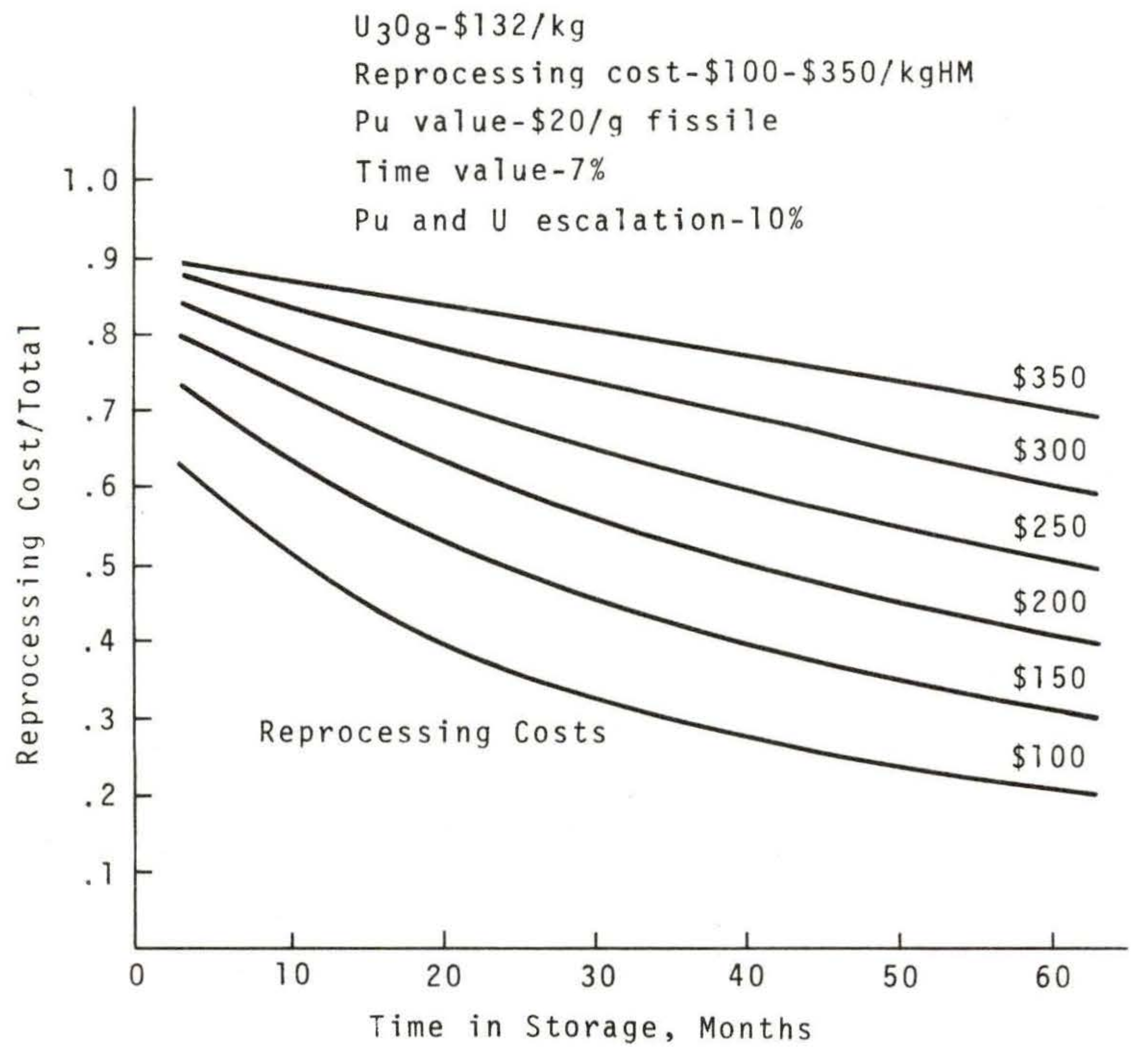


Figure 17. Reprocessing cost ratio as a function of months in storage and reprocessing cost

U_3O_8-\$66/kg
Reprocessing cost-\$100-\$350/kg-HM
Pu value-\$20/g fissile
Time value-7%
Pu and U escalation-10%

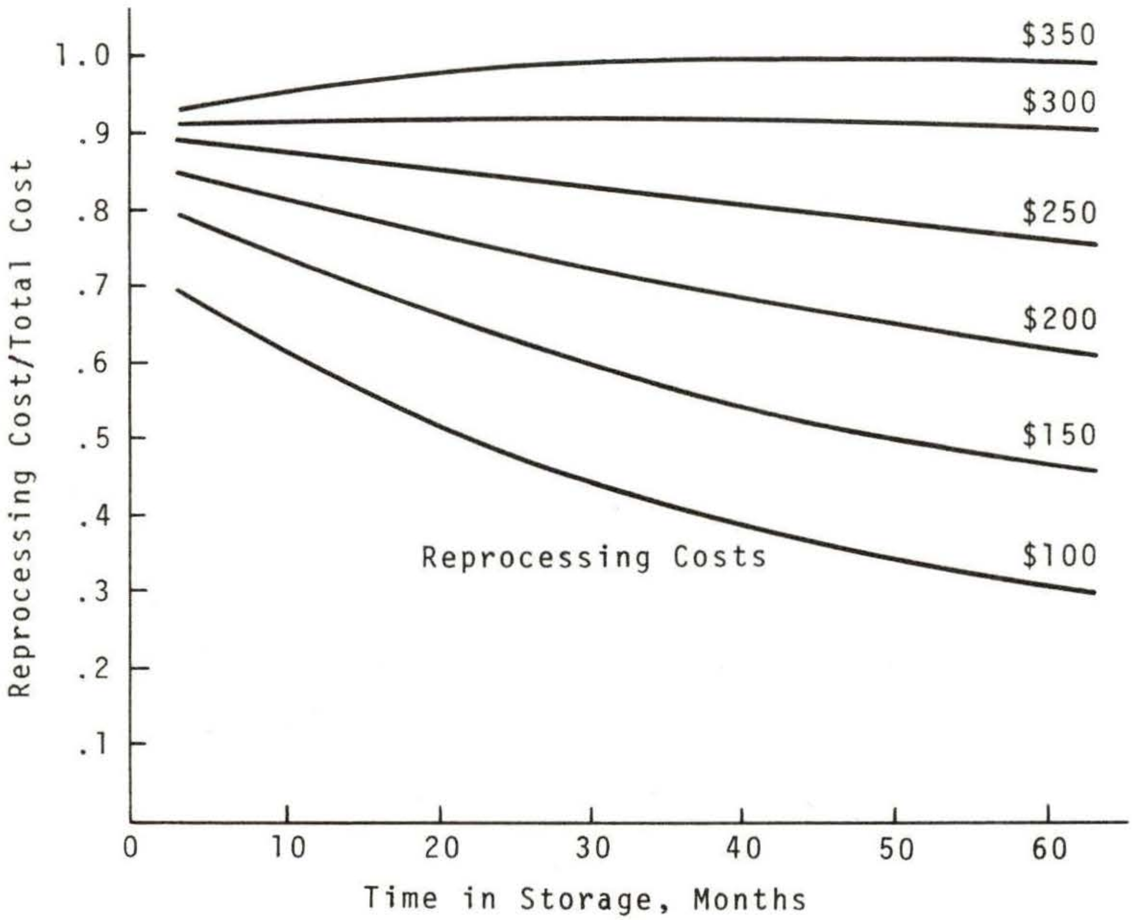


Figure 18. Reprocessing cost ratio as a function of months in storage and reprocessing cost

SUMMARY AND CONCLUSIONS

The differential values have been calculated for duration in storage, reprocessing costs, plutonium values, and escalation rates.

Some conclusions drawn from this study are as follows:

1) As expected the value of plutonium has a sizable effect on the differential values. However, the figures do show that recycling is economical for a wide range of plutonium values. This is especially true if one compares the differential value to the throwaway cycle cost.
2) The costs associated with shipping, storage, and reconversion are minor in comparison to either the post-irradiation inventory or reprocessing costs.
3) The effect of time in storage is such that reprocessing should be carried out as soon as possible after a batch is removed from the core.
4) If for some reason the Nuclear Regulatory Commission decides against plutonium recycle, it appears that it might become economical to recycle uranium. This is based on the idea that if recycling of plutonium is not allowed one might expect a gradual but long term increase in the cost of yellowcake.
5) For the cases considered, it would be necessary to increase the storage cost tenfold before there would be anything but a minor effect on the economics of recycling.
6) Comparing the results of the various parametric studies to the cost associated with the throwaway cycle, one can conclude that

for all cases under consideration it is more economical to recycle.

7) Variation in the rate of escalation on plutonium during the time in storage has only minor effects on the differential value.

8) Reprocessing is the dominant cost except when one has high yellow-cake costs and low reprocessing costs. This tells one that the economics for recycling are determined mainly by reprocessing costs.

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ACKNOWLEDGMENTS

The author is indebted to his major professor, Dr. Alfred F. Rohach, for the guidance he provided throughout the investigation and preparation of the thesis. The author also wishes to acknowledge and thank the Power Affiliates for financial support provided through a research assistantship.

The author wishes to express his gratitude to his fiancée and parents for their encouragement and help in preparing the manuscript.

APPENDIX A:

APPLICATION OF RESULTS

The parametric curves given in the results could be used to provide a rough estimate, in terms of present worth costs, of the effects of changes in reprocessing cost, plutonium value, or U_3O_8 cost. Application of the results require that characteristics of the batch under consideration be similar to the characteristics given in Appendix B. Also required are uniform fuel burnup and a post-irradiation inventory cost.

Example 1

Estimate the effect of a delay in reprocessing due to an inability to ship spent fuel to a fuel reprocessing facility.

Assume that the storage time doubled from 12 months to 24 months and that the other variables have the values shown in Table 4.

Table 4. Example batch characteristics

Item	Value
U_3O_8	\$66/kg
Pu and U escalation rate	10%
Escalation rates for:	
Shipping	7%
Storage	7%
Reconversion	7%
Reprocessing	7%
Time value	7%
Reprocessing cost	\$200/kg-H
Plutonium value	\$20/g fissile

Proceed to the figures in the results and by comparing Table 4 to the legends, locate the most appropriate figure. (Figure 5 in this particular case.) Reading the results for 24 months and a plutonium value of \$20/g fissile one obtains a value of .43 Mills/kwh. Comparing this to the savings due to recycling after 12 months storage, .6 Mills/kwh, one obtains an approximate loss in the value of recycling of .17 Mills/kwh. Note that all values shown in the figures are present worth values.

Example 2

Estimate the effect of increasing the reprocessing cost from \$200 to \$300/kg-H. Assume a storage time of 20 months and a U_3O_8 cost of \$132/kg. Let the other variables have the values shown in Table 4.

Locate the appropriate figure using the technique given in Example 1. Figure 7 would be used and gives a value of .34 Mills/kwh for a storage time of 20 months and a reprocessing cost of \$300/kg-H. Comparing this to the value of .71 Mills/kwh for \$200/kg-H reprocessing, one obtains a loss in the value of recycling of .37 Mills/kwh.

APPENDIX B:

INPUT AND CORE CHARACTERISTICS

Table 5. Input characteristics

Characteristic	Value
U_3O_8 ore cost	\$66/kg or \$132/kg
Enrichment cost	\$85.00/swu
Fabrication cost	\$80.00/kg U
Storage cost	\$0.50/kgH-mo
Shipping cost	\$15.00/kgH
Reprocessing cost	\$100-\$350/kgH
Plutonium value	\$10-\$50/gr fissile
Uranium escalation rate	10%
Plutonium escalation rate	-5% to 10%
Time value rate	7%

Table 6. Core characteristics

Characteristic	Value
Electrical output	1000 MW
Thermal output	3077 MW
Efficiency	32.5%
Enrichment	2.548%
Discharge assay	1.016%
Burnup	20.3 MWd/kg
Mass of uranium in core	77905 kg
Refuel batch size (1/3 core)	25968 kg
Plutonium at insertion	none
Plutonium at discharge	143.9 kg (fissile)
Capacity factor	60%
Load factor	85%