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ECONOMIC EVALUATION OF CLOSE-COUPLED
FUEL PROCESSING WITH PLUTONIUM RECYCLE

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for Plutonium and Uranium

ECONOMIC EVALUATION OF CLOSE-COUPLED
FUEL PROCESSING WITH PLUTONIUM RECYCLE

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ECONOMIC EVALUATION OF CLOSE-COUPLED FUEL PROCESSING WITH PLUTONIUM RECYCLE

1.0 INTRODUCTION

In recent years there has been considerable discussion of the relative advantages of close-coupled reactor fuel reprocessing and fabrication as compared to reprocessing in a large central plant. A close-coupled reprocessing plant is a single purpose plant located on the same site as the reactor or reactor complex it serves. A central plant having capability for processing a wide variety of reactor fuels might be located hundreds of miles away from some of the reactors it serves.

The primary potential advantages of a low throughput, close-coupled plant are its simplified process requirements, elimination of most shipping charges, and reduced out-of-reactor inventory charges. Some additional advantages of close-coupled processing that cannot be quantitatively evaluated include:

- a. Increasing public safety through minimized long distance shipment of irradiated fuels and plutonium
- b. Establishing a closed-loop recycle system with improved reactor performance through better technical feedback (burnup analyses, postirradiation examination, etc.)
- c. Providing as part of the basic facility the potential for remote refabrication of fuel to capitalize on technical progress in fuel rejuvenation and cladding reuse techniques.

A close-coupled plant could be based on a completely different technology from that used for central plant processing for which the highly flexible and efficient solvent extraction processes are so well adapted.

At Hanford extensive effort has been devoted toward development of the Salt Cycle Process, an electrolytic fused-salt process concept adaptable to close-coupled plutonium-recycle processing. Because of the recognized need to quantitatively define objectives and incentives for development work, a study was initiated to: (1) determine the magnitude of the economic incentives for close-coupled plutonium-recycle process development, (2) define essential or minimum process features and capabilities required, and

(3) define the reactor types and fueling concepts most attractive to close-coupled reprocessing.

To fully evaluate the relative costs of fuel reprocessing by two different methods, it is desirable to compare them on the basis of optimized costs for the entire fuel cycle. This is because of the interacting effects of various fuel cycle costs and the ability, in a plutonium recycle system, to minimize the effect of higher costs associated with mixed oxide ($\text{PuO}_2\text{-UO}_2$) fuels by adjusting the proportion of fuel containing plutonium. In addition, the full effect of reprocessing cost variances cannot be assessed without evaluating fuel inventory carrying charges* during irradiation. The problem was programmed for computer solution to speed the large number of repetitive calculations required to optimize a reprocessing scheme and evaluate a range of costs.

* Because of recent passage of the "Private Ownership of Special Nuclear Materials Act" which requires that special nuclear material be distributed by the AEC only by sale after 1970, and because application of close-coupled process technology before that time--except possibly for a brief period--is unlikely, only "private ownership" economics are considered in this report. However, companion cases based on current AEC lease ground rules were also evaluated and the results are available from the author's files.

2.0 SUMMARY AND CONCLUSIONS

This report investigates the relative fuel cycle costs (and elements thereof) of two alternative reactor fuel cycles employing light water moderated reactors and either central plant reprocessing refabrication or close-coupled reprocessing refabrication. Three reactor types, a typical water reactor (TWR) with zirconium clad fuel, a typical water reactor with stainless steel (SS) clad fuel, and an advanced pressurized water reactor with SS clad fuel were examined. Two fuel management concepts were considered: one with several reactors at a single site with staggered fuel discharges averaging 1 to 3 months between discharges, and the other, a single reactor discharging fuel at 12 month intervals.

Cost input data were grouped as high-range and low-range costs. The costs were based in part on those in TID-7025,¹ proposed NFS charges,² AEC conceptual plant charges,¹ a fuel fabrication cost study,³ and objective estimates and judgments of other cost elements and trends. Since few of these values have been proven in the market place and a competitive fuel cycle business is only now beginning to evolve, no claim is made that any single cost represents an exact value. The intent was to bracket possible future costs.

One of the principal findings of this study was that the fuel exposure for a close-coupled plant cycle optimizes (depending on input data) at 15,000 to 20,000 MWd/ton resulting in an annual throughput of 40,000 to 50,000 kg/yr per 1000 MW_e installed capacity. This optimum is largely independent of close-coupled plant investment.

During the terminal stages of this study, a scope design and preliminary cost estimate was made of the construction cost of a close-coupled plant serving a 1000 MW_e reactor complex and providing the process functions of reprocessing, remote fabrication of mixed oxide fuels, and by-product UO₂ to UF₆ conversion. Approximately \$6,200,000 was indicated. The study results indicate that a \$6.2 million close-coupled plant serving a 1000 MW_e reactor complex can be competitive with central plant processing. Since the close-coupled plant shares with most chemical operations, a great economic sensitivity to throughput, increased throughput (more reactor capacity)

rapidly escalates profits and incentives, but lower throughput (less reactor capacity) can eliminate the incentives.

The results of this study in terms of allowable plant investment are interpreted in terms of 1000 MW_e reactor capacity, but are linearly scalable to other reactor capacities. A recently released National Power Survey by the Federal Power Commission⁴ states "Construction of mammoth nuclear electric power stations with several reactor units at one site may be anticipated." A 2000 MW_e reactor station would permit twice as large an investment or a moderate increased investment and a marked increase in savings.

Using the high range costs and high decontamination factor input data, the annual fuel cycle savings with a \$6.2 million close-coupled plant and with exposures of up to 20,000 MWd/ton in a 1000 MW_e reactor, ranged from \$0.6 million to \$1.6 million (0.09 to 0.22 mills/kWh) depending on reactor type. Using low range cost inputs and a close-coupled plant decontamination factor of 6, the maximum annual savings for a \$6.2 million plant were \$0.3 million (0.037 mills/kWh), and in the worst case, the maximum plant investment was reduced to \$4.9 million just to break even. It should be noted that the savings quoted are over and above normal profits, amortization, taxes, insurance, etc.

If fuel exposure is limited to 15,000 MWd/ton in the central-plant cycle, the incentive for close-coupled processing is substantial (possibly as high as 0.4 mills/kWh) but drops off sharply at higher fuel exposures.

The most attractive prospects for close-coupled plutonium-recycle processing are relatively high enrichment reactors, such as a pressurized water reactor (PWR) using stainless-steel clad fuel. If fuel exposures in the central-plant cycle do not exceed 20,000 MWd/ton an investment of \$6 to \$7 million per 1000 MW_e capacity can be allowed for close-coupled processing facilities with a savings advantage of around 0.1 mill/kWh.

If fuel exposures much higher than 20,000 MWd/ton are practical, or if relatively low enrichment reactors using zirconium-clad fuel are considered, it then appears that 2000 to 3000 MW_e capacity will be required before close-coupling is attractive. For low-enrichment zirconium-clad-fuel reactors, it

may be more advantageous to sell rather than recycle plutonium because of its lower value, hence plutonium recycle per se may not be attractive.

A single large reactor with partial core discharges at 1 yr intervals is a much less attractive prospect for close-coupled processing than a group of three or more reactors operating with staggered discharge schedules where fuel would be discharged at least every 4 months. The difference in fuel cycle costs would be about 0.05 mills/kWh because of differences in inventory costs.

3.0 REPROCESSING ALTERNATIVES

The fuel cycles for the two reprocessing alternatives being compared in this study are illustrated in Figure 1.

FIGURE 1

Schematic Diagram of Conventional and Close-Coupled Fuel Cycle

For the economics calculations, it was assumed that a complete fuel service is provided to the reactor operator by the reprocessor, either central or close-coupled, with ownership of the spent fuel passing to the reprocessor at reactor discharge and to the reactor operator as new fuel is charged to the reactor. Appropriate adjustments in inventory carrying charge rates are made at the time of change of ownership. The economics would be somewhat more favorable for a close-coupled plant incorporated with a utility company's operation because of lower capital charges. However, this possibility was not evaluated because of uncertainties regarding the feasibility of this type of operation.

Process losses and inventory periods for the central-plant and close-coupled fuel cycles are presented in Appendix A, Tables I-A, II-A, and III-A.

3.1 Central Plant

In the central-plant case the spent fuel is shipped to a central plant where plutonium is separated from uranium and both are separated from fission products with a high degree of efficiency. This plant could be a solvent extraction plant serving a number of widely scattered reactor sites. The uranyl nitrate product is then converted to UF_6 and returned to the AEC or other enriched uranium supplier. Plutonium nitrate from the central plant is converted to mixed oxide fuel in an off-site conversion and fuel fabrication plant. Both mixed-oxide and UO_2 -only fuel elements are produced at the conversion and fuel fabrication plant using the recycled plutonium and with the enriched uranium components purchased as UF_6 and converted to oxide. Following fabrication, the new fuel is shipped to the reactor site. The requirement for both mixed-oxide and UO_2 -only fuels or the two-fuel concept, is discussed in more detail under Plutonium Fuel Zoning in Section 5.

3.2 Close-Coupled Plant

In the close-coupled process case the spent fuel is sent to a reprocessing and fuel fabrication plant at or near the same site as the reactor. The assumptions made regarding the close-coupled process for this study are (1) it is a batch process capable of producing a fuel-grade mixed-oxide (PuO_2 - UO_2) which consists of a portion of the spent fuel uranium enriched with all (except for losses) of the spent fuel plutonium at an enrichment level suitable for recharging to the reactor, (2) fission product decontamination is sufficient (a factor of 6 to 10) to reduce parasitic neutron capture to a low level, but relatively poor gamma decontamination is achieved so that remote fabrication of the new mixed-oxide fuel is required, and (3) the balance of the uranium is produced as a by-product UO_2 and sent to permanent storage, or, if sufficiently valuable, it is processed through a small fluoride volatility unit for further fission-product decontamination and sold as UF_6 . The mixed-oxide fuel elements are returned to the reactor and, for the balance of the new fuel requirement, additional UO_2 -only fuel elements are obtained from a central source as in the case of central plant processing.

The Salt Cycle Process currently under development at the Pacific Northwest Laboratory—Battelle Memorial Institute (formerly Hanford Laboratories, General Electric Company) is the model for the assumed process, though other processes with similar "external" attributes could also be assumed. In the Salt Cycle Process, a spent oxide-fuel core is dissolved in a molten LiCl-KCl salt bath and then either UO_2 or a mixture of UO_2 - PuO_2 is recovered by electrolysis with only moderate decontamination from fission products.

4.0 REACTOR CONSIDERATIONS

4.1 Reactor Type

The present study was confined to consideration of reprocessing oxide fuel from water moderated thermal reactors. Since fuel enrichment influences fuel-cycle and fuel reprocessing economics, particularly in a plutonium recycle system as employed here, three reactor cases operating at different enrichment levels were selected for evaluation. This is not to say that every possible case has been covered by these three cases, but only that they are broadly representative of future fuel-cycle requirements and that study of other cases would be unlikely to lead to conclusions fundamentally different from those arrived at in this study.

4.2 Reactor Size

Preliminary estimates indicated that less than 1000 MW_e reactor capacity would probably not provide sufficient fuel load to justify a close-coupled plant. As recently confirmed in the "National Power Survey, 1964" report of the Federal Power Commission,⁴ it appears likely that single reactors as large as 1000 MW_e will be built soon or that two or three smaller reactors with a total capacity of 1000 MW_e or greater will be constructed at a common site. Consequently, 1000 MW_e was selected as the basic unit of reactor capacity for this study. However, the study results, in terms of allowable investment in close-coupled plant facilities, are applicable to any capacity basis through multiplication by reactor capacity ratios.

4.3 Fuel Management

Two broad categories of fuel management have been considered: (1) partial core discharges at 1 yr intervals, and (2) more frequent discharge approaching a graded cycle operation. The latter category was examined in far greater detail in this study. Current indications are that fuel management programs for the larger reactors being planned today will be based on some form of a partially graded cycle with periodic partial core replacements and possible fuel reshuffling. A 1 yr frequency appears to be favored at present rather than the shorter periods but if more frequent fuel discharges are realized, the incentive for close-coupled process development

will materially increase. This question is discussed further under Results in Section 10.4. Similarly, close-coupling would be more attractive in association with several reactors operating with staggered discharge schedules.

An important feature of the close-coupled process can be its ability to process short-cooled fuel providing a significant source of fuel cycle cost savings through reduced inventory carrying charges on the spent fuel. If long periods of time elapse between reactor fuel discharges, as in a batch-fueled reactor, a close-coupled plant cannot fully capitalize on this short-cooled processing capability. Synchronization of in-reactor and out-of-reactor cycle times becomes increasingly important with infrequent discharges, and a more detailed study may show that some processing over-capacity might be desirable in the close-coupled plant. However, this latter aspect was not the subject of detailed investigation here.

4.4 Reactor Case Descriptions

The basic features of the three reactor cases evaluated in this study are summarized in Table I. All three cases are large, 1000 MW_e, light-water-cooled light-water-moderated reactors or reactor combinations operating with

TABLE I
REACTOR CASE DESCRIPTIONS

Case	Typical Water Reactor		Advanced Pressurized Water Reactor
	I	II	III
Cladding Material	Stainless Steel	Zirconium	Stainless Steel
Cladding Thickness	0.010 in.	0.020 in.	0.0162 in.
Fuel	UO ₂ -PuO ₂	UO ₂ -PuO ₂	UO ₂ -PuO ₂
Fuel Diameter	0.5 in.	0.5 in.	0.375 in.
Fuel Density	95% theoretical	95% theoretical	95% theoretical
Fuel to Moderator Ratio	0.483	0.483	0.598
Specific Power	15 MW/ton	15 MW/ton	20 MW/ton
Total Power	3000 MW _t	3000 MW _t	3000 MW _t
Net Electrical Power*	1000 MW	1000 MW	1000 MW
Thermal Efficiency	33.3%	33.3%	33.3%
Plant Use Factor	0.80	0.80	0.80
Fuel Management	Graded cycle with partial core discharge at 1 month intervals or at 3 month intervals if a three-reactor complex is assumed.		Graded cycle with partial core discharge at 3 month intervals or at 9 month intervals if a three-reactor complex is assumed.

* The study results are developed in terms of allowable investment in close-coupled plant facilities for a 1000 MW_e reactor complex but can be converted to any capacity basis through multiplication by reactor capacity ratios.

33-1/3% thermal efficiency and an 80% plant use factor. All cases were examined in detail for operation on a modified graded fuel cycle. In Case III, preliminary and less comprehensive attention has been given to a cycle involving partial core discharges at 1 yr intervals.

Case I is designated a typical water reactor (TWR) with SS-clad oxide fuel operating at 15 MW/ton specific power. The design parameters were based on other Hanford fuel cycle studies.⁵ For calculation of inventory carrying charges, it was assumed that part of the fuel is discharged every month. The same inventory carrying charges are realized if a two-reactor complex is assumed with each discharging fuel at 2 month intervals on alternate months or with a three-reactor complex with each discharging fuel at 3 month intervals on alternating months.

Case II is the same as Case I except for substitution of zirconium for stainless steel fuel cladding, thus reducing fissile enrichment requirements.

Case III is designated as an advanced pressurized water reactor (APWR) and is based on a Westinghouse reactor described in MITNE-28.⁶ It has a harder spectrum, operates at a higher specific power, 20 MW/ton, has thicker cladding and requires more fissile enrichment than Case I. To provide for inventory charges more nearly in line with current technology, a longer interval, 3 months, between fuel discharges was assumed for calculation of inventory carrying charges in Case III. This would be equivalent to discharging fuel at 9 month intervals from each reactor in a three-reactor complex at alternating 3 month periods. Thus the inventory carrying charge savings for close-coupled processing in Case III are not as large as Cases I and II.

The difference in enrichment requirements for the three reactor cases is shown in Figure 2 where enrichment for the initial uranium-only step is plotted against fuel exposure.

FIGURE 2

Fuel Enrichment Requirements for the Three Reactor Cases
(Fully Graded Fuel Cycle)

4.5 Fuel Burnup Calculations

For each reactor case, the reactor is fueled initially with enriched uranium only and subsequent refueling is with a mixture of recycled self-generated plutonium and enriched uranium with the total enrichment adjusted to result in the same exposure as the initial step. Fuel burnup data was calculated using the MELEAGER⁷ computer program for four to five different fuel exposures ranging from approximately 10,000 to 40,000 MWd/ton.

Early in the study, it was feared that the assumption of plutonium recycle equilibrium might lead to erroneous conclusions. Although the results obtained since have indicated that an assumption of plutonium recycle equilibrium would very likely result in only minor error, sufficient recycle steps were calculated at each exposure to provide for a 15 yr reprocessing operation which was the assumed amortization period for the close-coupled plant. (A recycle step is one complete fuel cycle in a series of consecutive

plutonium recycles.) Another reason for limiting the evaluation period to 15 yr was the recognition that the plant use factor for the reactor would probably begin to drop off after 15 yr as newer and more efficient reactors were brought into the utility's system.

Because a close-coupled process is particularly adapted to recycle of self-generated plutonium and because of the complications of price, isotopic composition and availability for bringing plutonium in from outside the system, this study was limited to consideration of recycling self-generated plutonium only.

Constant exposure recycle steps were concluded to be the most practical and realistic basis for evaluation rather than constant enrichment or constant reactivity. The MELEAGER program was not designed to automatically simulate burnup to a constant fuel exposure. The computation required trial and error solution for initial reactivity of each recycle step for the desired goal exposure. Fuel exposures for successive recycle steps do not agree exactly since a $\pm 2\%$ variation from the initial step was considered acceptable for this study.

The graded fuel cycle computation with the MELEAGER program assumes that fuel is being continuously replaced in the reactor. If appropriate fuel reshuffling takes place at each discharge, it can be shown that discharging as much as one-sixth of a fuel core at one time will result in essentially the same fuel compositions as a fully graded fuel cycle. Thus the assumptions of a fully graded fuel cycle for the burnup calculation and a partially graded cycle for the economics calculations are compatible within the limits of accuracy required for this study.

Since the close-coupled separations process is not expected to be a high efficiency process in removing fission products, it is important to evaluate the effect on fuel cycle costs of recycling some of the fission product poisons. To provide data for this evaluation, two sets of burnup data were developed for each reactor case. In one, all of the fission product poisons were removed before recycling plutonium to the next step; in effect an infinite decontamination factor (DF). In the other, one-sixth of the fission product poisons present in the spent fuel from each recycle step were recycled with the plutonium to the next step. This fission-product poison DF of six is considered to be a reasonable goal for a close-coupled process.

5.0 PLUTONIUM FUEL ZONING

Because of the hazards associated with handling plutonium, fabrication costs are higher for plutonium-bearing fuels than for uranium-only fuels. This is true even for highly decontaminated plutonium but for the partially decontaminated product from the close-coupled process postulated here, the plutonium fabrication penalty is even higher since completely remote fabrication is required. To avoid paying this plutonium fabrication penalty on 100% of the fuel, a fuel zoning technique was employed in which two types of fuel are charged to the reactor. One fuel is a mixed $\text{PuO}_2\text{-UO}_2$ fuel and the other is a UO_2 -only fuel, but each of the fuel types have the same total fissile enrichment; one is largely plutonium enriched and the other is entirely U^{235} enriched.

Generally, there is an optimum mixed-oxide zone fraction where fuel cycle costs are minimized. As the mixed-oxide fuel fraction is reduced, the fabrication cost is reduced since the fabrication penalty is paid on a smaller fraction of the total fuel. At the same time, however, it also results in splitting the uranium into two enrichment components which increases costs, since more diffusion cascade separative work is involved. For example, 1 kg of 2% U^{235} costs \$146.50, but the same amount of U^{235} obtained as one-half of a kilogram of 1% and one-half of a kilogram of 3% U^{235} would cost \$151. The cost of converting UF_6 to UO_2 is also affected by enrichment with higher charges associated with higher enrichments.

An optimum mixed-oxide fuel zone size was calculated automatically by the computer program for both central and close-coupled plant processing. Different techniques were employed for the central and closely-coupled system zoning calculations since uranium of any enrichment was available to the central plant system and only mixtures of the two spent-fuel uranium enrichments were available to the close-coupled system. This calculation is explained more fully in Appendix B.

The variation of fuel cycle cost with mixed-oxide zone fraction is illustrated in Figures 3 and 4 for central plant and close-coupled processing respectively.

FIGURE 3

Variation of Fuel Cycle Cost with Mixed-Oxide Zone Fraction for Central Plant Processing

FIGURE 4

Variation of Fuel Cycle Cost with Mixed-Oxide Zone Fraction for Close-Coupled Processing

6.0 FUEL CYCLE COST CALCULATIONS

The two computer programs developed for this study provide for a detailed calculation of the out-of-reactor fuel cycle costs for the two fuel reprocessing concepts being compared. The in-reactor costs (burnup and inventory) are less detailed but are believed to accurately reflect the result of differences in out-of-reactor costs and of differences in fuel components. It was intended that the calculations provide an accurate basis for comparing the relative cost of the two process concepts but not necessarily an accurate total cost for either concept.

The calculation starts at the point of reactor discharge. A salvage value at point of reactor discharge was determined by subtracting reprocessing, shipping, conversion, and inventory charges from the market value of the recovered fuel components were they to be sold. Costs are then added for various processing, loss and shipping charges in the order they are accrued. Inventory carrying charges, based on a cost of money interest rate, are also accumulated as a function of time as the various costs are accumulated. Each cost is assumed to occur at the time midpoint required for that particular operation. The main cost stream follows the plutonium. Inventory carrying charges on all costs outside this stream are adjusted for their appropriate time relationship to the plutonium stream.

All the costs of reprocessing and fabrication are summed at the point the new fuel is charged to the reactor. An inventory carrying charge during irradiation is calculated assuming that the average investment in the fuel during irradiation is the mean value between the investment in fresh fuel at reactor charging and the spent-fuel salvage value at discharge. The final total fuel cycle cost is calculated both in terms of \$/kg fuel and mills/kWh.

The program is designed so that the reprocessor can be considered a separate entity providing a complete fuel service to the reactor operator.

All fuel-cycle cost comparisons have been based on an average cost of enough recycle steps to equal 15 yr of reactor and reprocessing plant operation at a particular fuel exposure. In the nomenclature used here, step one is a UO_2 -only cycle and step two is the first plutonium recycle. Except for

step one which starts with procurement of UF_6 from the diffusion plant, each cycle starts with discharge of spent fuel from one cycle and ends at fuel discharge of the next cycle. Plutonium present in the fuel discharged from one cycle is in effect purchased for recovery and generation of power in the next cycle. An averaging procedure was adopted because of variations in fuel cycle costs from step to step and because of the 15 yr amortization period assumed for the close-coupled plant. A more detailed description of the average fuel-cycle cost calculation procedure is presented in Appendix C.

To fully evaluate effects of variations in out-of-reactor time cycles on inventory charges and overall fuel cycle costs, it is necessary to assign a value to the plutonium inventory. In this study plutonium was valued on the basis of its worth as a substitute for U^{235} enrichment. A description of the break-even plutonium valuation procedure is presented in Appendix D.

The computer programs carry the fuel cycle cost calculations to the point of an optimized cost for each cycle. All subsequent calculations, from determination of average cost for 15 yr of operation to determination of allowable plant investment, discussed in Section 8.0 were done by hand.

7.0 ECONOMICS CASE DESCRIPTIONS

There are rather wide differences in available cost projections for some of the major out-of-reactor fuel cycle costs such as spent-fuel shipping, separations, fabrication, inventory carrying charges and chemical conversions. A privately financed and competitive fuel cycle business is only now beginning to evolve, and these costs can be expected to change as the nuclear power industry matures. To avoid the complexity of a parameterized study of each of these variables and yet to give recognition to these differences and provide a simplified basis for evaluating their effects on the two fuel cycles under consideration, these costs were divided into two groups. All of the high estimates were grouped together and all of the low estimates were grouped together so that there were only two basic economics cases for each of the three reactor cases evaluated: a high-range cost case and a low-range cost case. Single values for other cost elements were used uniformly in all of the calculations.

In general, high costs for the various fuel cycle components tend to favor close-coupling. They show larger savings or allow higher close-coupled processing costs, since any advantage for close-coupling results from by-passing these costs with at least a portion of the fuel. This is not uniformly true, however. For example, inclusion of the high range fabrication costs with the high group tends to reduce any savings because this includes the highest penalty for low-decontamination mixed-oxide fuel fabrication which must be sustained by the close-coupled plant product. In effect the spread between the high and low cost cases is narrowed.

The high and low cost estimates for the major fuel cycle components are listed in Tables II and III along with some comments as to source. These costs are expressed terms of unit costs, \$/kg uranium or \$/kg fuel (uranium + plutonium), and are intended to include a profit as well as other capital charges for that particular operation. All other cost inputs are listed in Table IV and are used uniformly in all the calculations. These other costs, mostly shipping costs based on nominal 1000-mile shipments, are all set at values obtained from a limited survey of these cost areas.

TABLE II
HIGH AND LOW UNIT-COST ESTIMATES

Cost Description	Low Estimate		High Estimate	
	Unit Cost	Comments	Unit Cost	Comments
Spent Fuel Shipping to Central Plant	\$ 5.00/kg Fuel	See Note (1)	\$16.00/kg Fuel	TID-7025 VOL4 ¹
Central Separations Plant Processing	\$25.00/kg Fuel	See Note (2)	\$35.00/kg Fuel	Estimate of range for next 10 to 15 yr. See Note (2)
Total Shipping and Separations See Note (3)	\$30.00/kg Fuel		\$51.00/kg Fuel	
Inventory Carrying Charges				
Reactor Irradiation Period	10%/yr	See adjacent comment	10.0%/yr	Representative of investor-owned utility.
Reprocessing-Fabrication Period	12.5%/yr	Average chemical industry rate for nondepreciating assets.	15%/yr	Represents a more selective investor who requires a higher rate of return.
UF ₆ to Fuel Grade UO ₂ Conversion				
Below 0.9% Enrichment	\$ 4.50/kg U	Based on same incremental factor as high-range costs but assuming that one-half of the high-range costs for <0.9%, natural and 1% enriched uranium would be reasonable future costs.	\$ 9.00/kg U	Based on mid-range cost shown on Figure 450-1 in TID-7025 VOL4 ¹ with conversion cost for natural uranium reduced to reflect conversion from ore concentrate to UO ₂ rather than UF ₆ conversion.
Natural Uranium as Ore Concentrate	\$ 3.50/kg U		\$ 7.00/kg U	
Above 0.9 to 10% Enrichment	(\$2.50 + 2.50 x % enrichment)/kg uranium		(\$7.50 + 2.50 x % enrichment)	
High DF Mixed Oxide Preparation	(\$0.35/g Pu + above UF ₆ conversion charge)	Based on \$0.25/g Pu estimate for conversion of Pu(NO ₃) ₄ to PuO ₂ + \$0.10/g Pu allowance for mixed oxide preparation	(\$0.70/g Pu + above UF ₆ conversion charge)	Based on assumption that possibility of rigid specifications on mixed-oxide quality could double Pu portion of mixed-oxide preparation cost.
UNH to UF ₆ Conversion				
Below 0.9% Enrichment	\$ 2.75/kg U	Based on assumption that conversion of UNH to UF ₆ at low enrichments should cost no more than conversion of natural U ore concentrate to UF ₆ . The enrichment factor is adjusted so that conversion cost equals \$5.60/kg at 3% enrichment. (Spent fuel enrichment was always well below 3%)	\$ 5.60 kg/U	TID-7025 VOL4 ¹
Above 0.9% to 5.0% Enrichment	(\$2.75 + 0.95 x % enrichment)/kg U		\$ 5.60 kg/U	TID-7025 VOL4 ¹
Close-Coupled Process By-Product UO ₂ Conversion to UF ₆ (High γ DF). See Note (4).				
Below 0.9% Enrichment	\$ 5.50/kg U	Twice UNH to UF ₆ charge assumed. Based on same enrichment factor as UNH to UF ₆ conversion but with cost equal to twice the UNH to UF ₆ cost at 3% enrichment.	\$11.20/kg U	Twice UNH to UF ₆ charge assumed.
Above 0.9% to 5.0% Enrichment	(\$8.25 + 0.95 x % enrichment)/kg U		\$11.20/kg U	Twice UNH to UF ₆ charge assumed.

NOTES:

- (1) Determination of spent-fuel shipping cost is an involved economics problem that must consider such factors as irradiation history, method and distance of shipment, federal and state regulations, insurance charges, cask design, utilization and amortization, possible criticality problems and handling costs. Representative costs are not readily available but indications are that costs will probably range from \$5 to \$10/kg of fuel rather than the \$16/kg suggested in TID-7025 VOL4.¹ A cost of \$5/kg was selected as the probable minimum rate for spent-fuel shipments at a distance of 1000 miles. Recently published information⁸ indicates fuel shipping cost for the Oyster Creek Station, at a distance of 400 miles, at approximately \$4.50/kg.
- (2) A range of \$25 to \$35/kg was selected as representative of probable separations plant charges over the next 10 to 15 yr. This is based on consideration of AEC conceptual plant charges, which would be approximately \$25/kg including turnaround for fuel enrichments used here, and on consideration of NFS published charges which range from \$30 to \$35/kg including turnaround for the fuel enrichments of interest here.
- (3) Except for small differences in inventory carrying charges, spent fuel shipment and separation charge can be considered a single cost. For example, the low case could be considered \$10.00/kg shipped and \$20.00/kg separation and the high case could be considered \$10.00/kg shipped and \$41.00/kg separation.
- (4) This is considered to be a small process unit designed to convert a fraction of UO₂ by-product to UF₆ with a high γ DF after plutonium has been removed in close-coupled process. Only by-product with sufficient enrichment value to justify extra process cost would be processed to UF₆, otherwise it would go to storage. This unit cost adds to the close-coupled separations charge in determination of allowable plant investment as discussed in Section 8.0. The precise division of unit charges between the main close-coupled process and this by-product process is not too critical but it does provide the criteria for a choice between storage or recovery of by-product uranium.

TABLE III

FUEL FABRICATION COST ESTIMATES

(In Dollars Per Kilogram of Contained Uranium and Plutonium)

Cladding Material	Fuel Exposure MWd/ton	Low-Range Cost Estimates			High-Range Cost Estimates		
		UO ₂	PuO ₂ -UO ₂ High γ DF	PuO ₂ -UO ₂ Low γ DF	UO ₂	PuO ₂ -UO ₂ High γ DF	PuO ₂ -UO ₂ Low γ DF
Zirconium	15,000	46.00	51.00	66.00	70.00	78.00	100.00
	22,000	56.00	61.00	76.00	85.00	93.00	115.00
	30,000	66.50	71.50	86.50	101.00	109.00	131.00
	40,000	78.50	83.50	98.50	119.50	127.50	149.50
Stainless Steel	11,000	20.00	25.00	40.00	30.00	38.00	60.00
	15,000	22.00	27.00	42.00	33.00	41.00	63.00
	18,000	24.00	29.00	44.00	36.00	44.00	66.00
	22,000	26.00	31.00	46.00	39.50	47.50	69.50
	26,000	28.50	33.50	48.50	43.00	51.00	73.00
	30,000	31.00	36.00	51.00	46.50	54.50	76.50
	34,000	33.50	38.50	53.00	50.00	58.00	80.00
	40,000	36.50	41.50	56.50	55.00	63.00	85.00
	42,000	38.00	43.00	58.00	57.50	65.50	87.50

NOTES: Fuel fabrication costs here include only direct fabrication costs and do not include cost of core material or inventory charges on core material which are handled separately, nor do they include any conversion charges for uranium or plutonium compounds to fuel grade oxide which are also handled separately. Capital charges for the fabrication plant are included.

Fabrication costs for the zirconium-clad UO₂ and high γ DF PuO₂-UO₂ fuel at 15,000 MWd/ton exposures are based on detailed estimates for vibrationally-compacted rod-bundle-type fuel assemblies in a 1 ton/day plant presented in HW-74304.³ For stainless-steel-clad fuel the same basic estimate is used with an appropriate adjustment for cladding material costs. Fabrication costs at other exposures were based on the assumption that the cladding material cost portion of the fabrication cost would be proportional to the fuel goal exposure.

For the low γ DF mixed-oxide fuel fabrication the estimates were adjusted to reflect the low throughput rate (0.1 to 0.2 tons/day) of the close-coupled plant and remote operation. Capital charges are 4-fold greater per kg and operating costs are 1.5-fold greater per kg compared to the high γ DF mixed oxide. Other appropriate increased costs are also factored in.

To provide a consistent basis for the estimates, the low-range costs were based on a 19-rod assembly and the high-range costs were based on a 37-rod assembly but in using these estimates it is only intended that the low- and high-range costs represent a range of possible future fabrication costs without necessarily specifying details of the actual assembly.

TABLE IV
FIXED UNIT COSTS

Uranium Cost:

Current AEC price schedule for enriched and depleted UF_6 based on natural uranium at \$8/lb U_3O_8 and cost of separative work at \$30/kg.

Minimum cost of depleted uranium at \$3/kg for less than 0.38% enrichment.

Natural uranium available as ore concentrate at \$8/lb U_3O_8 or \$2.75/kg less than price as UF_6 .

Shipping Costs:

Fresh UF_6 to Central Fabrication Plant: (See Note 1)

- (a) Below 0.9% enrichment = $(0.39 + 0.0005 \times \text{value})$, \$/kg uranium
- (b) Natural uranium as ore concentrate = $(0.11 + 0.0005 \times \text{value})$, \$/kg uranium
- (c) Above 0.9% but < 12.5% enrichment = $(0.95 \times 4.7 \times \text{enrichment fraction} + 0.0005 \times \text{value})$, \$/kg uranium

Recovered UF_6 to AEC: (See Note 2)

- (a) Below 0.9% enrichment = $(0.35 \times 0.0005 \times \text{value})$, \$/kg uranium
- (b) Above 0.9% enrichment but < 12.5% = $(0.86 \times 4.3 \times \text{enrichment fraction} + 0.0005 \times \text{value})$, \$/kg uranium

Fabrication Plant to Reactor: (See Note 3)

- (a) UO_2 -only fuel from central plant = \$1.50/kg uranium
- (b) Mixed-oxide fuel from central plant = \$2.00/kg uranium + plutonium
- (c) Mixed-oxide fuel from close-coupled plant = \$0.00/kg uranium + plutonium

Recovered $Pu(NO_3)_4$ from Central Separation to AEC: (See Note 4)

$$= (0.020 + 0.0005 \times \text{value}), \text{ $/g}$$

Recovered $Pu(NO_3)_4$ from Central Separation to Central Fabrication:

$$= (0.020 + 0.0005 \times \text{value}), \text{ $/g}$$

Permanent Storage Costs:

UNH from Central Separation Plant: (See Note 5)

- (a) Below 0.9% enrichment = \$0.15/kg
- (b) Above 0.9% up to 5% enrichment = \$0.75/kg

By-Product UO_2 from Close-Coupled Plant: (See Note 6)

- (a) Below 0.9% enrichment = \$0.65/kg
- (b) Above 0.9% up to 5% enrichment = \$3.00/kg

Notes:

1. Fresh UF_6 shipping costs are based on 1000 mile shipments and include an approximation for withdrawal and packaging charges and an allowance of \$0.05/\$100 value for property insurance. A 10% allowance for return of recycled scrap is also included. Natural uranium is assumed to be shipped as ore concentrate rather than UF_6 .
2. Shipping costs for recovered UF_6 are the same as for fresh UF_6 except that the 10% allowance for return of recycled material is deleted.
3. Cost of shipping new UO_2 fuel elements from fabricator to reactor is taken as the \$1.50/kg uranium as recommended in TID-7025 VOL4.¹ Cost of shipping new PuO_2 - UO_2 fuel elements was increased to \$2.00/kg (uranium + plutonium) to reflect greater hazards associated with plutonium handling.
4. Plutonium shipping cost is based on approximating shipping cost of small lots of high enrichment uranium.
5. UNH storage cost estimates are based on perpetual storage in stainless steel tanks at \$2.00/gal for enrichments below 0.9% U^{235} and \$10.00/gal for higher enrichments in geometrically safe vessels.
6. By-Product UO_2 from the close-coupled plant is assumed to be highly radioactive due to low fission product decontamination. Storage costs are consequently high due to remote handling and heat dissipation requirements.

It should be emphasized that all out-of-reactor costs are treated for inventory carrying charge purposes as if these services were provided by a business separate from the utility operating the reactor.

The unit charge for the close-coupled separations process was maintained as a variable in each economics case. Two or three unit costs for the close-coupled process were selected for each economics case, and fuel costs were calculated using the computer program. Fuel cycle costs for other close-coupled process unit costs were obtained by interpolation since a straight-line relationship exists between these two variables.

8.0 ALLOWABLE PLANT INVESTMENT CALCULATIONS

It is difficult to evaluate the feasibility of a given unit processing cost standing by itself. Thus, after establishing the relationship between close-coupled process unit cost and overall fuel cycle costs, it was then desirable to relate unit cost to some more readily evaluated term. The approach used in this study was to relate unit processing cost to plant capital cost per 1000 MW_e reactor capacity. It was then possible to determine the investment in close-coupled plant facilities that could be allowed and still be competitive with central-plant processing. A judgment could then be made as to whether or not the allowable investment or capital cost was sufficient to build the required plant facilities and as to the probability of realizing a net fuel cycle cost savings through close-coupled processing. To provide a reference point to aid in evaluating results of this study, a preliminary rough design and cost estimate for a close-coupled plant was also developed. However, it was beyond the scope of this study to develop definitive cost estimates for a close-coupled facility.

To relate unit processing cost to plant capital cost, a range of fixed capital charges for the high- and low-range cost cases was first developed. A breakdown of these fixed charges is shown in Table V where total fixed charges range from 18.8%/yr for the low-range case to 20.9%/yr for the high-range case.

It is also necessary to make an allowance for operating costs. Here it was assumed that operating costs would be proportional to the plant capital cost and relatively insensitive to throughput. This assumption is based on the premise that capital cost is relatively insensitive to throughput for a small plant. The operating force would be more closely related to plant complexity, and hence capital cost, than to throughput for a small plant. Such things as chemical costs, power costs, etc., that are directly related to throughput would have secondary effects on total operating costs. Based on a variety of published estimates, an allowance of 15% of the capital cost per year was allocated for direct operating costs of the close-coupled separations plant.

TABLE V

ESTIMATED PERCENT CHARGES FOR CLOSE-COUPLED PLANT*

	Low-Range Estimates, %/yr	High-Range Estimates, %/yr
Return on Investment before Income Taxes**	12.5	15.0
Sinking Fund Depreciation Allowance (15 yr depreciation period)***	4.0	3.6
Interim Replacements	0.3	0.3
Local Taxes and Insurance	2.0	2.0
Total Fixed Charges on Capital Investment	18.8	20.9
Operating Costs for Chemical Reprocessing and UO ₂ → UF ₆ Conversion	15.0	15.0

* E. B. Hutchins. Personal communication. March 27, 1963.

** These rates of return are applied to both average investment in inventory and the first cost of plant and equipment. A rate of 12.5% is slightly higher than the average for the Basic Chemicals Industry in 1961, and is equivalent to 17.5% of stockholder's equity, a more common measure of return. The 15% return is representative of a more selective investor.

*** These rates, expressed as a percentage of plant and equipment first cost, are based on the actual proportion of income taxes, 44.2% of profits before taxes, for the Basic Chemicals Industry in 1961. Hence, the depreciation sinking fund factors are derived from a respective 7.0 and 8.4% return after taxes on 12.5 and 15% return before taxes. (The so-called sinking fund depreciation allowance is a useful calculational short-cut which, in conjunction with the return on the constant base of plant and equipment first cost, yields the equivalent of straight line depreciation and a constant rate of return on a declining investment.)

Adding the fixed charge and operating cost allowance together, the required gross income on investment (gross income factor) was estimated at 33.8%/yr for the low-range case and 35.9%/yr for the high-range case. Multiplying yearly throughput by unit processing cost and dividing by the gross income factor gives an allowable investment or capital cost for that particular set of conditions. This procedure is used to calculate allowable investment for the main reprocessing facility and for the by-product volatility unit. In the latter case throughput is lower since the recovered by-product uranium is only a fraction of the total fuel, and the unit cost is influenced by enrichment as shown in Table II.

For the close-coupled fuel fabrication facility a slightly different procedure was used. Here a breakdown of the fabrication cost was available.³ Each low gamma DF fabrication cost estimate in Table III, regardless of cladding material or fuel exposure, includes an \$11/kg fixed capital charge on investment allowance in the low-range estimates and \$15/kg fixed capital charge on investment allowance in the high-range estimates with a separate

allowance for operating costs. Thus, only the fixed charge on investment factor (18.8% or 20.9%/yr) are required to determine allowable investment in the fabrication facility since an approximation for operating costs is not necessary.

In determining allowable plant investment, the close-coupled facilities were considered as a single plant and included the separations plant, the fabrication plant for the high gamma activity recycled fuel and the small volatility unit for recovery of by-product uranium. The allowable investment for the three components of the close-coupled facility were summed up to determine the total allowable investment in close-coupled plant facilities. Although, in arriving at the total allowable investment a breakdown into the three component parts was used, it is not necessary to restrict the allowed investment in each component to the original amount. The final total represents the allowable investment per 1000 MW_e reactor capacity in the complete close-coupled plant facility regardless of how it may be subdivided.

By calculating the total allowable investment per 1000 MW_e at several different fuel exposures and for a number of close-coupled separations plant unit costs, a plot of allowable investment versus exposure with unit cost parameters was developed for each economics case. A breakdown of calculated allowable investment into the component parts over a range of exposures and separations plant unit costs is illustrated for a selected case in Table VI. The total allowable investment per 1000 MW_e for this example case is correlated with exposure and separations plant unit cost in Figure 5. A similar plot was prepared for each case. Data read from these plots were then used in optimizing the close-coupled cycle as described in the next section.

TABLE VI

TOTAL ALLOWABLE INVESTMENT CALCULATION FOR CLOSE-COUPLED PLANT

APWR Reactor Case, Private Ownership of Enriched Uranium and Low-Range Cost Inputs

Exposure MWd/ton	Total Fuel Throughput, kg/yr	Separations		Mixed-Oxide Fuel Fabrication		By-Product Recovery			Total Allowable Investment, \$/1000 MW _e
		Unit Cost, \$/kg	Allowable Investment, \$	Zone Fraction	Allowable Investment, \$	Recovered By-Product Fraction	Average Unit Cost, \$/kg*	Allowable Investment, \$	
10,000	79,460	15.00	3,526,000	0.597	2,775,000	0.375	9.89	872,000	7,173,000
15,000	52,970	15.00	2,351,000	0.509	1,578,000	0.455	7.74	552,000	4,481,000
20,000	39,730	15.00	1,763,000	0.426	990,000	0.533	7.47	468,000	3,221,000
25,000	31,780	15.00	1,410,000	0.354	658,000	0.602	8.17	463,000	2,531,000
10,000	79,460	20.00	4,701,000	0.597	2,775,000	0.375	9.89	872,000	8,348,000
15,000	52,970	20.00	3,134,000	0.509	1,578,000	0.455	7.74	552,000	5,264,000
20,000	39,730	20.00	2,351,000	0.426	990,000	0.533	7.47	468,000	3,809,000
25,000	31,780	20.00	1,881,000	0.354	658,000	0.602	8.17	463,000	3,002,000
10,000	79,460	25.00	5,877,000	0.597	2,775,000	0.375	9.89	872,000	9,524,000
15,000	52,970	25.00	3,917,000	0.509	1,578,000	0.455	7.74	552,000	6,047,000
20,000	39,730	25.00	2,938,000	0.426	990,000	0.533	7.49	468,000	4,396,000
25,000	31,780	25.00	2,351,000	0.354	658,000	0.602	8.17	463,000	3,472,000
30,000	26,490	25.00	1,959,000	0.303	470,000	0.646	8.50	430,000	2,859,000
12,000	66,210	30.00	5,877,000	0.562	2,177,000	0.407	8.87	707,000	8,761,000
15,000	52,970	30.00	4,702,000	0.509	1,578,000	0.455	7.74	552,000	6,832,000
20,000	39,730	30.00	3,526,000	0.426	990,000	0.533	7.49	468,000	4,984,000
25,000	31,780	30.00	2,821,000	0.354	658,000	0.602	8.17	463,000	3,942,000
30,000	26,490	30.00	2,351,000	0.303	470,000	0.646	8.50	430,000	3,251,000
12,000	66,210	35.00	6,856,000	0.562	2,177,000	0.407	8.87	707,000	9,740,000
15,000	52,970	35.00	5,485,000	0.509	1,578,000	0.455	7.74	552,000	7,615,000
20,000	39,730	35.00	4,114,000	0.426	990,000	0.533	7.49	468,000	5,572,000
25,000	31,780	35.00	3,291,000	0.354	658,000	0.602	8.17	463,000	4,412,000
30,000	26,490	35.00	2,743,000	0.303	470,000	0.646	8.50	430,000	3,643,000

* Unit cost for by-product recovery changes with enrichment of recovered by-product according to formula in Table II.

Unit cost shown is weighted average for two components of by-product uranium from the two fuel zones.

FIGURE 5

Total Allowable Investment in Close-Coupled Plant Facilities
as a Function of Fuel Exposure
and Close-Coupled Separations Plant Unit Costs

9.0 OPTIMIZATION OF THE CLOSE-COUPLED CYCLE

To insure that the maximum incentive for close-coupled processing is defined, allowable close-coupled plant investment should be based on optimum or minimum-cost fuel exposure. At least two methods of calculating allowable investment at optimized fuel exposure are possible:

(1) minimum fuel cycle cost determination based on constant unit process charge parameters followed by calculation of allowable investment at the optimum, or (2) minimum fuel cycle cost determination based on constant allowable-plant-investment parameters. In either case a relationship between allowable plant investment and an optimized fuel cycle cost is obtained.

The first method assumes a constant unit process charge can be maintained in a close-coupled plant over a wide range of fuel exposures. This would not be a valid assumption since unit cost would undoubtedly be very sensitive to throughput. Throughput is inversely proportional to fuel exposure and changes by a factor of 3 over a range of 10,000 to 30,000 MWd/ton.

The second method assumes a constant plant investment requirement irrespective of throughput. This assumption is not exact but probably is reasonably accurate since at the low throughput requirements for a close-coupled plant serving a 1000 MW_e reactor complex (88 down to 29 tons/yr over the range of 10,000 to 30,000 MWd/ton) a large part of the plant facilities such as site, building, hot cells, auxiliary facilities and equipment, etc., would be sized close to an irreducible minimum. The actual process equipment cost would vary but probably would not shift total plant cost very much one way or the other. For these reasons, the constant plant investment basis was used to minimize fuel cycle costs for close-coupled processing.

To determine the optimum fuel cycle cost for close-coupled processing, a plot of fuel cycle cost versus exposure with close-coupled separations unit cost parameters was first prepared using data from the computer calculations. Then by cross plotting allowable investment parameters with data points taken from the allowable investment versus exposure plot (Figure 5),

an optimum fuel cycle cost for any specified investment could be obtained. An example is shown in Figure 6.

FIGURE 6

Optimized Costs for Central-Plant
and Close-Coupled-Plant Fuel Cycles

One constraint placed on this optimization procedure was an assumption that unit costs below \$15/kg were eliminated from consideration as being unrealistic. Thus, for the very low allowable investment values a true optimum was not always obtained.

The fuel cycle cost with central plant processing for the same economics case is also shown in Figure 6.

It should be noted in Figure 6 that the optimized exposures for close-coupled processing based on plant investment are around 15,000 MWd/ton compared to greater than 30,000 MWd/ton for central plant processing. This is characteristic of all the economics cases evaluated. This could be considered

an advantage for close-coupling since it would mean less rigorous fuel performance requirements, but it also illustrates a major problem for the close-coupled process concept, which is providing enough throughput or yearly revenue to pay out an investment. The revenue requirement forces exposure down to a level where throughput is high enough to provide the required revenue at a reasonable unit cost. Only that portion of the fuel cycle cost not associated with the close-coupled plant is affected by exposure so the cycle optimizes at a lower fuel exposure. Actually, it costs so much to run the plant regardless of exposure and the throughput. The throughput problem that faces any close-coupled process is illustrated by plotting throughput against exposure in Figure 7.

FIGURE 7

Effect of Fuel Exposure on Fuel Throughput for a 1000 MWe Reactor
at 33% Thermal Efficiency and 80% Plant Use Factor

10.0 RESULTS

10.1 Allowable Investment Results

The calculated central-plant-processing fuel cycle costs for 15,000 and 20,000 MWd/ton fuel exposures as well as optimum fuel exposure are shown in Table VII. These costs are the basis of comparison for the close-coupled processing costs. The calculated break-even plutonium values are also shown in Table VII.

TABLE VII
CENTRAL-PLANT REPROCESSING FUEL CYCLE COSTS

Reactor Case	Economics Case	Break-Even Plutonium Value, \$/g Fissile	Fuel Cycle Cost at 15,000 MWd/ton, Mills/kWh	Fuel Cycle Cost at 20,000 MWd/ton, Mills/kWh	Optimum Fuel Cycle	
					Exposure, MWd/ton	Cost, Mills/kWh
APWR	Low-Range and Purchase U	10.50	1.943	1.817	31,000	1.739
	High-Range and Purchase U	9.65	2.315	2.085	35,000	1.920
TWR	Low-Range and Purchase U	10.36	1.542	1.468	24,000	1.452
SS Clad	High-Range and Purchase U	9.35	1.865	1.720	28,000	1.653
TWR	Low-Range and Purchase U	9.03	1.410	1.353	23,000	1.345
Zirconium	High-Range and Purchase U	8.00	1.840	1.703	28,000	1.647

The difference between the fuel cycle cost with central-plant-processing and close-coupled processing at a specific plant investment represents a savings (either plus or minus) for that set of conditions. If fuel cycle savings with close-coupled processing are taken at the optimum for each of several allowable investment values and plotted against allowable investment, a nearly straight line relationship is found between allowable investment and fuel cycle cost savings. The point of zero savings represents the maximum investment that can be allowed in a close-coupled facility and still remain competitive with the central plant cycle. The allowable investment at the point of zero savings is referred to here as the break-even investment.

Data plots of allowable investment in close-coupled processing facilities for a 1000 MW_e reactor complex versus fuel cycle savings are included in the appendix as Figures 1-E through 18-E. This comparison is made relative to three distinct central-plant cycle fuel exposure levels: 15,000 MWd/ton on Figures 1-E through 6-E, 20,000 MWd/ton on Figures 7-E

through 12-E, and optimum central-plant cycle exposure (25,000 to 35,000 MWd/ton) on Figures 13-E through 18-E. Two plots are presented for each of the three reactor cases at each central-plant cycle exposure: one for complete removal of fission product poisons in the close-coupled cycle ($DF = \infty$), and one where 1/6 of the fission products are recycled in the close-coupled cycle ($DF = 6$). Both the low- and high-range economics cases are shown on each plot. These data are summarized in Table VIII where the range of allowable investment represents the low- and high-range cost cases. Both the break-even investment and the allowable investment for an 0.1 mill/kWh savings advantage are shown for each case, and the data for both an infinite fission product poison DF and for a poison DF of 6 at three specified central-plant-cycle fuel exposures are included.

TABLE VIII
CLOSE-COUPLED PLANT ALLOWABLE INVESTMENT
FOR A 1000 MW_e REACTOR COMPLEX

Central-Plant Fuel Exposure MWd/ton	Fission Product Poison DF	Fuels Cycle Savings, Mills/kWh	Allowable Investment, \$ Millions		
			APWR Reactor Case	TWR Reactor Cases	
				SS Clad	Zirconium Clad
15,000	∞	0.0	9.4 to 13.2	7.8 to 11.5	7.5 to 10.3
		0.1	7.8 to 11.8	5.9 to 9.7	4.9 to 8.5
	6	0.0	9.0 to 13.1	7.0 to 10.3	6.0 to 9.1
		0.1	7.3 to 11.5	5.2 to 8.7	3.9 to 7.5
20,000	∞	0.0	7.3 to 9.9	6.4 to 8.9	6.1 to 7.8
		0.1	5.6 to 8.2	4.5 to 7.1	3.6 to 6.0
	6	0.0	6.8 to 9.4	5.7 to 8.0	4.9 to 6.9
		0.1	5.1 to 7.7	3.8 to 6.4	2.9 to 5.3
Theoretical Optimum	∞	0.0	6.0 to 7.3	6.1 to 7.7	5.8 to 6.8
		0.1	4.2 to 5.6	4.1 to 6.0	3.3 to 5.0
	6	0.0	5.5 to 6.8	5.3 to 6.9	4.7 to 6.0
		0.1	3.7 to 5.0	3.6 to 5.3	2.7 to 4.4

To aid in evaluating results of this study, a preliminary rough design and cost estimate for a close-coupled reprocessing-refabrication plant was developed. The design was based on fabricating inverted-cluster fuel assemblies, which would simplify remote fabrication, on some optimistic projections of Salt Cycle Process capability and on serving 1000 MW_e of reactor capacity. A circular cell process line provides the least costly and most

flexible type of facility. Considering what would be required of a close-coupled fuel fabrication facility, it was assumed that the operation could be simplified and costs reduced by purchasing the fuel assembly components from a central supplier. It was assumed that utility services would be available from the nearby power reactor. Cost of construction including design services and 25% for contingencies was estimated at \$6.2 million. Although the \$6.2 million estimate should not be considered a firm estimate, it does indicate that a \$6 to \$7 million cost for a close-coupled plant serving 1000 MW_e reactor capacity is a reasonable basis for evaluating the allowable investment results developed in this study.

To further visualize the incentive for close-coupled processing, another table was prepared, using data from Figures 1-E through 18-E, showing fuel cycle savings for a fixed close-coupled plant investment of \$6.2 million. These data for all three reactor cases and for the same central-plant-cycle fuel exposures as in Table VIII are shown in Table IX.

TABLE IX
FUEL CYCLE SAVINGS WITH CLOSE-COUPLED PROCESSING
WHEN ALLOWABLE INVESTMENT IS FIXED AT \$6.2 MILLION

Central-Plant Fuel Exposure MWd/ton	Fission Product Poison DF	Savings, Mills/kWh		
		APWR Reactor Case	TWR Reactor Cases	
			SS Clad	Zirconium Clad
15,000	∞	0.192 to 0.462	0.083 to 0.300	0.049 to 0.223
	6	0.162 to 0.431	0.045 to 0.260	-0.008 to 0.180
20,000	∞	0.066 to 0.223	0.010 to 0.155	-0.005 to 0.089
	6	0.037 to 0.186	-0.029 to 0.110	-0.064 to 0.045
Theoretical	∞	-0.013 to 0.067	-0.007 to 0.088	-0.014 to 0.032
Optimum	6	-0.043 to 0.032	-0.050 to 0.044	-0.076 to -0.012

Although data for both an infinite fission-product poison DF and a poison DF of 6 are shown in Tables VIII and IX, the incentive for close-coupled processing should be judged primarily on the latter. Technologically, an overall fission-product poison DF of 6 is considered to be a reasonable assumption for the Salt Cycle Process. The penalty for incomplete removal of the fission-product poisons is indicated to be approximately of \$0.5 to \$1.0 million in allowable investment per 1000 MW_e or 0.03 to 0.05 mills/kWh

at a fixed investment. Although substantial, this is not an excessive penalty, and it was concluded that a poison DF of 6 is reasonable, economically and technologically.

As fuel exposure in the central-plant cycle increases from 15,000 MWd/ton to the theoretical optimum, the allowable investment in the close-coupled plant is reduced sharply. This is further illustrated by the plots of break-even investment versus exposure on Figures 19-E through 24-E in the appendix. This effect is primarily the result of the throughput problem which causes the close-coupled-cycle optimum exposure to lie at about 15,000 MWd/ton; whereas, in the central-plant cycle the fuel cycle cost can be further reduced by increasing exposure up to 25,000 or 35,000 MWd/ton.

If fuel exposure in the central plant cycle is limited to 15,000 MWd/ton, the prospect for close-coupled processing would look quite attractive. The data in Table VIII indicate that with a DF of 6, the allowable investment is large enough to build the required facilities and realize a savings of 0.1 mill/kWh or more in both the APWR and the TWR (SS clad) cases. In the TWR (zirconium clad) case, the prospect of a fuel cycle savings is more marginal, but close-coupled processing appears to be at least a break-even situation. This conclusion is borne out by Table IX where a substantial savings is indicated for the APWR case but where the TWR (zirconium clad) case appears more marginal. However, it is not realistic to assume that fuel exposure would be limited to less than 20,000 MWd/ton. For example, the fuel guarantee for Jersey Central's planned Oyster Creek Station, is reported⁸ to be 15,000 MWd/ton for the first core and 20,000 MWd/ton for the second core.

With fuel exposure in the central-plant cycle increased to 20,000 MWd/ton, an investment of \$6 to \$7 million/1000 MW_e and a 0.1 mill/kWh savings for the APWR case appears reasonable. In the TWR cases, however, a more nearly break-even situation between close-coupling and central-plant processing is indicated.

If fuel exposure in the central-plant cycle is carried to the theoretical optimum, a break-even prospect for close-coupling even with the APWR case appears marginal.

In the above conclusions more weight was given to the low-range cost cases than the high-range cases since it was felt that they are more representative of future costs.

The allowable investment data in Tables VIII and IX and the discussion up to this point is based on serving a 1000 MW_e reactor complex. If the reactor capacity being served is doubled (2000 MW_e), the allowable investment would also double, but the cost of a close-coupled facility probably wouldn't increase more than 30 to 40%. Thus, even the TWR (zirconium clad) case at the theoretical optimum exposure could become an attractive prospect for close-coupling if a 2000 or 3000 MW_e reactor complex is considered. As indicated in the Federal Power Commission Study,⁴ the situations where this much reactor capacity might be concentrated at one site are expected to develop.

It was concluded that the most attractive prospects for close-coupled processing are relatively high enrichment reactors such as a PWR using SS clad fuel. If fuel exposures in the central-plant cycle are limited to around 20,000 MWd/ton, an investment of \$6 to \$7 million per 1000 MW_e can be allowed for close-coupled processing facilities with a savings advantage of around 0.1 mill/kWh.

If fuel exposures much higher than 20,000 MWd/ton are practical or if relatively low enrichment reactors using zirconium clad fuel are considered, it then appears that 2000 to 3000 MW_e capacity would be required before close-coupling would be attractive. Actually, in the case of low-enrichment zirconium-clad-fuel reactors, it may be more advantageous to sell rather than recycle plutonium because of its lower value, as shown in Table VII.

Discussion of fuel cycle cost savings here has been limited to the relatively small savings in terms of mills/kWh. To assist in evaluating the importance of small mills/kWh savings, the relationship between mills/kWh and dollars/yr is shown in Figure 8. For a 1000 MW_e reactor complex, 0.1 mill/kWh savings amounts to close to \$3/4 million/yr which would be substantial, considering the magnitude of the investment required in close-coupled plant facilities.

FIGURE 8

Conversion of Fuel-Cycle Savings
from Mills/kWh to \$/yr
for a 1000 MW_e Reactor at 80% Plant Use Factor

10.2 Allowable Operating Costs

A better understanding of the feasibility of close-coupled processing is gained by an examination of allowable operating costs as well as allowable investment. For this purpose the case was selected for illustration where the central-plant-cycle fuel exposure is 20,000 MWd/ton, a fission product poison DF of 6 is achieved in the close-coupled cycle, and the capital cost is the break-even value. The allowable operating costs for all three reactor cases for these conditions are shown in Table X. The operating and capital charges include the total allowance for all three components of the close-coupled process: separations, by-product recovery, and mixed oxide fuel fabrication.

The allowable operating costs ranging from \$1.2 to \$2.0 million/yr appear to be a reasonable allowance for the size and type of plant under

consideration. A detailed design and cost study would be required to establish precise operating cost and capital requirements.

TABLE X
CLOSE-COUPLED PLANT ALLOWABLE OPERATING COSTS,
\$ MILLIONS/yr/1000 MW_e

Based on Break-Even Investment Cases with Fuel Exposure of 20,000 MWd/ton in the Central-Plant Fuel Cycle and a Poison DF of 6 in the Close-Coupled Cycle

	APWR Reactor Case	TWR Reactor Cases	
		SS Clad	Zirconium Clad
Allowable Operating Costs	1.4 to 2.0	1.3 to 1.9	1.2 to 1.6
Allowable Capital Charges	1.3 to 2.0	1.1 to 1.7	0.9 to 1.4
Cladding Material Cost for Mixed-Oxide Fuel	0.2 to 0.3	0.2 to 0.3	0.9 to 1.1
Total Allowable Yearly Costs	2.9 to 4.3	2.6 to 3.9	3.0 to 4.1
Break-Even Capital Investment, \$ Million/1000 MW _e	6.8 to 9.4	5.7 to 8.0	4.9 to 6.9

10.3 Differences Between Close-Coupled and Central-Plant Fuel Cycle Costs

The cost disadvantages of close-coupled processing tend to be offset because plutonium is returned to the reactor more quickly, and because a fuel-grade mixed-oxide is produced directly from the separations process and a portion of the spent fuel uranium is reused in the next fuel cycle. This short-circuits some of the normal out-of-reactor costs. Any advantage for close-coupling is magnified with higher enrichment fuel cycles since inventory and processing costs increase with enrichment.

To further illustrate the differences in fuel cycle costs between close-coupled and central-plant processing, a cost breakdown for a low- and high-range cost case is shown in Tables XI and XII. They show an example APWR case when the allowable investment for the close-coupled plant is fixed at \$6.2 million/1000 MW_e and fuel exposure is 20,000 MWd/ton in the central-plant cycle. To provide a complete picture, fuel cycle costs are shown both in terms of \$/kg of total fuel and mills/kWh, but direct comparisons can be

TABLE XI
COMPARISON OF CENTRAL PLANT AND CLOSE-COUPLED PLANT
FUEL-CYCLE COST COMPONENTS
APWR CASE WITH LOW-RANGE COSTS

Central-Plant-Cycle Fuel Exposure = 20,000 MWd/ton
 Close-Coupled Plant Investment = \$6.2 Million
 Close-Coupled Process Fission Product Poison DF = 6
 Optimum Fuel Exposure for Close-Coupled Cycle = 15,000 MWd/ton

Fuel-Cycle Cost Components	Average Fuel Cycle Costs*				
	\$ /kg of Total Fuel		Mills/kWh		Savings or (Penalty)
	Central Plant Processing	Close- Coupled Processing	Central Plant Processing	Close- Coupled Processing	
Processing Costs					
Separations**	25.00	26.00	0.142	0.197	(0.055)
UNH to UF ₆	3.63	--	0.021	--	0.021
UNH Storage	--	--	--	--	--
UO ₂ to UF ₆ **	--	3.63	--	0.027	(0.027)
Mixed-Oxide mfg	4.80	--	0.027	--	0.027
UO ₂ -Only mfg	7.61	5.05	0.043	0.038	0.005
Fabrication***					
Mixed-Oxide**	8.81	21.21	0.050	0.161	(0.111)
UO ₂ -Only	<u>17.66</u>	<u>10.89</u>	<u>0.100</u>	<u>0.082</u>	<u>0.018</u>
Total Processing	67.51	66.78	0.383	0.505	(0.122)
Shipping Costs	8.65	1.71	0.049	0.013	0.036
Out-of-Reactor Inventory Carrying Charges	32.26	14.20	0.183	0.107	0.076
In-Reactor Inventory Carrying Charges	79.10	52.70	0.448	0.399	0.049
Net Enrichment Costs Including Losses	<u>133.00</u>	<u>100.04</u>	<u>0.754</u>	<u>0.756</u>	<u>(0.002)</u>
Total Fuel Cycle Cost	320.52	235.43	1.817	1.780	0.037

* Average costs for 15 yr of plutonium recycle operation.

** Components of the close-coupled plant process include separations, by-product UO₂ to UF₆ and mixed-oxide fuel fabrication.

*** The mixed-oxide fuel fraction is 0.294 in the central-plant case and 0.505 in the close-coupled case.

TABLE XII
COMPARISON OF CENTRAL PLANT AND CLOSE-COUPLED PLANT
FUEL-CYCLE COST COMPONENTS
APWR CASE WITH HIGH-RANGE COSTS

Central-Plant-Cycle Fuel Exposure = 20,000 MWd/ton
 Close-Coupled Plant Investment = \$6.2 Million
 Close-Coupled Process Fission Products Poison DF = 6
 Optimum Fuel Exposure for Close-Coupled Cycle = 18,000 MWd/ton

Fuel-Cycle Cost Components	Average Fuel Cycle Costs*				
	\$ / kg of Total Fuel		Mills / kWh		Savings or (Penalty)
	Central Plant Processing	Close- Coupled Processing	Central Plant Processing	Close- Coupled Processing	
Processing Costs					
Separations**	35.00	33.00	0.199	0.208	(0.009)
UNH to UF ₆	3.80	--	0.022	--	0.022
UNH Storage	0.04	--	0.0002	--	0.0002
UO ₂ to UF ₆ **	--	5.70	--	0.036	(0.036)
Mixed-Oxide mfg	9.70	--	0.055	--	0.055
UO ₂ -Only mfg	11.16	8.62	0.063	0.054	0.009
Fabrication***					
Mixed-Oxide**	13.45	30.03	0.076	0.189	(0.113)
UO ₂ -Only	26.65	19.62	0.151	0.124	0.027
Total Processing	99.80	96.97	0.566	0.611	(0.045)
Shipping Costs	19.58	1.85	0.111	0.012	0.099
Out-of-Reactor Inventory Carrying Charges	36.76	17.34	0.208	0.109	0.099
In-Reactor Inventory Carrying Charges	77.58	63.05	0.440	0.397	0.043
Net Enrichment Costs Including Losses	133.06	121.25	0.754	0.764	(0.010)
Total Fuel Cycle Cost	366.78	300.46	2.079	1.893	0.186

* Average costs for 15 yr of plutonium recycle operation.

** Components of the close-coupled plant process include separations, by-product UO₂ to UF₆ and mixed-oxide fuel fabrication.

*** The mixed-oxide fuel fraction is 0.294 in the central-plant case and 0.476 in the close-coupled case.

made only on the basis of mills/kWh since fuel exposures are different in the two cycles. In both cases, total processing costs are higher in the close-coupled cycle even though some processing costs are completely eliminated. This is primarily the result of higher mixed-oxide fuel fabrication costs resulting in turn from higher unit costs and from fabrication of a larger fraction of the fuel as mixed-oxide. In both cases, however, the disadvantage in processing costs is more than offset by lower shipping costs and inventory charges. Only minor differences in enrichment or burnup costs are indicated.

10.4 Fuel Management Considerations

Relatively frequent reactor fuel discharges, as discussed in Section 4.3, were assumed in calculating the close-coupled fuel cycle costs. If long periods elapse between fuel discharges, the special capability of the assumed close-coupled process to handle short-cooled fuels could not be fully utilized. Most of the fuel would remain in the storage basin waiting for the low-capacity close-coupled plant to work off the accumulated inventory of fresh fuel where the first fuel produced must wait in storage for a considerable time period until the reactor is next charged.

Current technology appears to be headed toward discharge frequencies of about once per year. If this trend prevails, and it doesn't appear that close-coupled processing could offer sufficient incentive to change it, the potential for close-coupled processing associated with a single reactor would be materially reduced. A once per year discharge frequency would mean an average spent fuel inventory of about 6 months and an average pre-reactor inventory for the mixed-oxide fuel of about 6 months also. This would result in an increase of approximately 50% in the out-of-reactor inventory carrying charges over those previously cited in this study. Referring to the examples in Tables XI and XII, this would amount to an approximate 0.05 mills/kWh increase in fuel cycle costs. If this effect is interpreted in terms of investment in a close-coupled plant rather than fuel cost, it would mean a reduction of about \$1 million in allowable investment per 1000 MW_e of reactor capacity.

A single large reactor with partial core discharges at 1 yr intervals would be a much less attractive prospect for close-coupling than a group of three or more reactors operated with a staggered or rotating discharge schedule. Three reactors with 1 yr discharge schedules but rotating discharges on a uniform schedule would result in fuel discharges every 4 months with essentially the same inventory charges as the APWR case where a once every 3 months schedule was assumed.

10.5 Mixed-Oxide Zone Size and By-Product Recovery

The calculated minimum-cost mixed-oxide fraction for close-coupled processing for all three reactor cases is shown in Figure 9 as a function of fuel exposure. The fractions shown are averages for 15 yr of recycle operation, and the fractions for individual recycle steps are scattered around the average. The APWR case has the highest mixed-oxide fraction primarily

FIGURE 9

Mixed-Oxide Zone Fraction for Close-Coupled Process

because there is more fissile plutonium in the spent fuel: about 8.5 g fissile/kg fuel compared to 5 to 6 g fissile/kg fuel in the TWR case at the end of 15 yr. Considering the variations in the individual recycle steps and that optimum exposure for close-coupled processing is in the range of 15,000 to 20,000 MWd/ton, these data show that a close-coupled process designed to recycle self-generated plutonium must have the capability of concentrating all the plutonium in 30 to 60% of the spent fuel uranium.

The mixed-oxide fraction for central-plant processing is not dependent on the spent-fuel uranium enrichment and shows more variation with the economics cases at any specified exposure. The data does not show a simple correlation with exposure and the mixed-oxide fraction ranges from 20 to 50% of the total fuel.

The amount of spent-fuel by-product uranium from the close-coupled process valuable enough for recovery ranges from zero to all of the uranium not used in the mixed-oxide fuel. In the zirconium-clad TWR case, the value of the uranium by-product was too low for recovery in nearly every case. In the APWR case, the value of the uranium by-product was high enough that all or most of it was worth recovering. Generally, about one-half to two-thirds of the by-product uranium was worth recovering in the SS-clad TWR case. It is apparent from these results, when considering self-generated plutonium recycle, that provision must be made in the close-coupled process for further decontamination and recovery of by-product uranium over and above the partial decontamination possible with a salt-cycle-type process.

If outside plutonium can be purchased for make-up enrichment, rather than using U^{235} , it should be possible to fully utilize the spent fuel uranium and eliminate the need for by-product uranium recovery. However, savings from this source would need to be balanced against increased fabrication costs due to larger proportions of mixed-oxide fuel.

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APPENDIX A
PROCESS VARIABLES

TABLE I-A
PROCESS LOSSES ASSUMED, %

Central Separation Plant:	Uranium	1
	Plutonium	1
Close-Coupled Separations Plant:	Uranium	1
	Plutonium	1
	Plutonium to By-Product UO_2	1
Mixed-Oxide Manufacture:	Uranium	1
	Plutonium	1
UNH Conversion to UF_6 :	Uranium	0.3
UO_2 Conversion to UF_6 (Close-Coupled)	Uranium	1.3
UF_6 Conversion to UO_2 :	Uranium	1
UO_2 -Only Fuel Fabrication:	Uranium	1
UO_2 - PuO_2 Fuel Fabrication (Conventional):	Uranium	1
	Plutonium	1
UO_2 - PuO_2 Fuel Fabrication (Remote):	Uranium	1
	Plutonium	1

TABLE II-ACENTRAL-PLANT-PROCESS INVENTORY PERIODS, DAYS

Spent Fuel Cooling	120
Spent Fuel Shipment	20
Preprocess Separation Inventory*	120
In-Process Separation Inventory	5
Postprocess Separation Inventory for Plutonium	10
Plutonium Shipment to Fabrication	20
Preprocess Mixed-Oxide Manufacture Inventory	20
In-Process Mixed-Oxide Manufacture	5
Postprocess Mixed-Oxide Manufacture Inventory	25
Fuel Fabrication	28
Postfabrication Inventory	4
New Fuel Shipment	20
Prereactor Inventory	<u>60</u>
Total Out-of-Reactor Time for Plutonium Recycle	457
Postseparation UNH Inventory	30
UNH to UF ₆ Conversion	5
Post-UF ₆ Process Inventory	20
UF ₆ Shipment to AEC	20
UF ₆ Shipment from AEC to Converter	20
Pre-UO ₂ -Process Inventory	20
UF ₆ to UO ₂ Conversion	5
Post-UO ₂ -Process Inventory	25

* Preprocess inventory depends on time required to accumulate a processing batch. If four round trips with the shipping casks at 30 days per round trip are required, it would take 120 days to accumulate a batch.

TABLE III-A
CLOSE-COUPLED PROCESS INVENTORY PERIODS
AND LIMITING PROCESS VARIABLES

	<u>TWR Case,</u> <u>Days</u>	<u>APWR Case,</u> <u>Days</u>
Spent Fuel Cooling, Average	15	45
Spent Fuel Shipment	0	0
Preprocess Inventory	0	0
In-Process Inventory	10	10
Postprocess Inventory and Preprocess Fabrication Inventory	25	25
In-Process Fuel Fabrication	28	28
Postfabrication Fuel Inventory for PuO ₂ -UO ₂	0	0
PuO ₂ -UO ₂ Fuel Shipment	0	0
Prereactor Inventory, Average	<u>20</u>	<u>45</u>
Total Out-of-Reactor Time for Plutonium Recycle	98	153
Postprocess By-Product UO ₂ Inventory	10	
By-Product UO ₂ to UF ₆ Conversion	5	
By-Product UF ₆ Inventory	20	
By-Product UF ₆ Shipment to AEC	20	
Make-Up UF ₆ Shipment to UO ₂ Conversion	20	
Pre-UO ₂ Process Inventory	20	
UF ₆ to UO ₂ Conversion	5	
Post-UO ₂ Process and Precentral Fabrication Inventory	25	
Central Fabrication Process	28	
Prereactor Inventory, Central Plant Fuel*	20	45

* A larger prereactor inventory may be required for the portion of fuel supplied from central fabrication source. A 60 day prereactor inventory on this fuel would increase close-coupled fuel cycle costs from 0.005 to 0.02 mills/kWh.

Limiting Process Variables

Minimum By-Product Heel	10% of Full By-Product Batch
Minimum Product Heel	5% of Full Product Batch
Minimum Product	20% of Full Product Batch

APPENDIX BPLUTONIUM FUEL ZONING CALCULATIONS

To minimize the effect of higher fabrication costs associated with plutonium bearing fuels, a fuel zoning technique was employed in which plutonium is recycled in an optimum fraction of the fuel to the next step. Zoning, as used in this study, does not mean that the mixed-oxide and uranium-only fuels are charged to separate sections of the core; both fuels are assumed distributed relatively uniformly throughout the core. Both the $\text{PuO}_2\text{-UO}_2$ and the UO_2 -only fuels have the same total fissile enrichment which is also equal to the total fissile enrichment when plutonium is fully mixed through all the fuel. The net fuel burnup is assumed to be the same with zoning as with the fully mixed fuel.

By making this assumption, any number of zoning combinations can be calculated for each recycle step by material balance procedures after obtaining the basic burnup data for the fully mixed case with the MELEAGER program. The U^{235} enrichment in the two fuels or zones is, of course, different and different from the U^{235} enrichment that would be required for a fully mixed fuel. To calculate the composition of the spent fuel uranium from each zone, it is assumed that the U^{235} and U^{238} burnup in each zone is proportional to the U^{235} and U^{238} burnup in the fully mixed fuel.

The smallest possible mixed oxide zone fraction would result from mixing fully depleted uranium with the plutonium. Increasing the enrichment of the uranium mixed with the plutonium will increase the mixed-oxide zone fraction and reduce the UO_2 -only zone fraction. However, for a given recycle step the UO_2 -only fuel elements always have the same enrichment (equal to the total fissile enrichment for the fully mixed case) regardless of the zoning fractions.

An optimum fraction of mixed-oxide fuel was calculated automatically by the computer program for each recycle step and for both reprocessing methods. By making these calculations over a range of several different fuel exposures, the fuel cycle costs for the two reprocessing methods can then be compared at any specified exposure on the basis of a minimized cost in each case.

For central plant processing, the minimum cost mixed-oxide fuel fraction was selected from testing a broad range of enrichments, assumed available from a central source of supply, for blending with the recycled plutonium. An example of a mixed-oxide fuel zoning material balance for central plant processing is shown in Figure 1-B.

For close-coupled processing, the minimum-cost zone fraction was also selected automatically by the computer program, but here a portion of the spent fuel uranium was recycled with the plutonium. The range of enrichments tested for blending with the recycled plutonium was limited to possible combinations of the two spent fuel uranium components. A check was also made for any possible cost advantage through blending fresh make-up uranium at any enrichment into the close-coupled process, but no instance was found where this was attractive.

With the batch Salt Cycle Process model used for this study and with the process charged alternately from the two fuel zones, a certain amount of intermixing of the two spent fuel components was assumed because of residual process heels. Thus, the range of enrichments for recycle was further limited. This effect is illustrated in Figure 2-B. The process variables that control these blending calculations are tabulated in Table III-A of the appendix. In nearly every case calculated in this study, the minimum-cost mixed-oxide zone fraction was obtained by recycling the maximum possible amount of the highest enrichment component of the spent fuel as in Figure 2-B. The mixed-oxide zone fraction was generally larger in the close-coupled cases than in the central plant cases since the savings from direct reuse of a maximum amount of the spent fuel uranium offset larger mixed-oxide fabrication penalties.

FIGURE 1-B

Mixed-Oxide Fuel Zoning Example for Central Plant Processing

FIGURE 2-B

Mixed-Oxide Fuel Zoning Example for Close-Coupled Processing

APPENDIX CAVERAGE FUEL-CYCLE-COST CALCULATION PROCEDURE

In a recycle system such as the fuel cycle model in this study, reprocessed recycled fuel is not available at the time the first spent fuel is discharged. Consequently, additional new step-one fuel must be charged to the reactor until the out-of-reactor reprocessing and fabrication is completed on the first unit of discharged step-one spent fuel. At this point, step-two fuel (the first recycled fuel) charging can be started. The same situation applies to step two in relation to step-three fuel and so on. This results in each fuel step being charged for more than one reactor core loading by the proportion that the total fuel-cycle time exceeds the in-reactor time. For example, at 20,000 MWd/ton fuel exposure, 20 MW/ton power level and an 80% plant factor, fuel life in the reactor would be $(20,000)/(20 \times 0.8) = 1250$ days or 3.42 yr. If 457 days are required for the out-of-reactor portion of the cycle, each step would be charged for $(3.42 + 1.25)$ or 4.67 yr and $(15)/(4.67)$, or 3.21 recycle steps would be required for 15 yr of operation with each step being charged for $(4.67)/(3.42)$ or 1.37 core loadings. If only 153 days are required for out-of-reactor processing, 3.91 recycle steps would be required for 15 yr of operation. Thus, more recycle steps are required for a given period of reprocessing when the out-of-reactor cycle is shorter. This is illustrated in Table I-C where the number of recycle steps and weighted average fuel cycle costs for both central plant and close-coupled plant processing are shown for one of the APWR case calculations.

No correction is made for reactor startup variations in fuel composition. In an actual reactor start-up, it would take some time to establish a graded fuel-cycle equilibrium, with the initial core loading probably being some form of a graded enrichment charge. Because of the complications involved, this reactor-start-up phase of fuel reprocessing was not evaluated. Both central plant and close-coupled plant fuel cycle costs are evaluated after an assumed step-one graded cycle equilibrium is established.

TABLE I-C

WEIGHTED AVERAGE FUEL CYCLE COST

APWR Reactor Case, Private Ownership of Uranium and Low-Range Cost Inputs

Plutonium Valued at \$10.50/Fissile Gram Based on Break-Even Value at Optimum Exposure of 31,000 MWd/ton

<u>Recycle Step</u>	<u>Exposure, MWd/ton</u>	<u>In-Reactor Time for Single Fuel Element, (a) Years</u>	<u>Out-of-Reactor Fuel Processing, (b) Years</u>	<u>Processing Campaign Period for Each Step, (c) Years</u>	<u>Proportion of Each Step Recycled in 15 yr</u>	<u>Minimum Fuel Cycle Cost, Mills/kWh</u>	<u>Weighted Average Fuel Cycle Cost for 15 yr Reprocessing (e)</u>
<u>CENTRAL PLANT PROCESSING</u>							
1	17,985	3.079	1.252	4.331	1.000	(d)	
2	17,895	3.064	1.246	4.310	1.000	1.846	
3	17,795	3.047	1.239	4.286	1.000	1.854	
4	17,910	3.066	1.247	4.313	0.481	1.864	
5	17,970					1.876	1.858 Mills/kWh at 3.481 Recycles
<u>CLOSE-COUPLED PLANT PROCESSING</u>							
(Poison DF = ∞; Unit Process Charge = \$30/kg)							
1	17,985	3.079	0.419	3.499	1.000	(d)	
2	17,895	3.064	0.417	3.481	1.000	1.733	
3	17,795	3.047	0.415	3.462	1.000	1.713	
4	17,910	3.066	0.418	3.484	1.000	1.708	
5	17,970	3.077	0.419	3.496	0.308	1.712	
6	17,945					1.720	1.717 Mills/kWh at 4.308 Recycles

(a) At 80% plant factor

(b) A slight variation in reprocessing time (5 days) is accepted to balance fuel availability since the quantity of step-one fuel defines amount of recycle fuel available for subsequent steps. Variations result from exposure variations.

(c) This is also the time period during which recycled fuel for next step is charged to the reactor. After step one, processing time is proportional to fuel exposure.

(d) Fuel cycle cost for step one omitted because it does not affect relative recycle costs.

(e) The last of the recycled fuel will be in the reactor some 4 yr after the end of the 15 yr processing period.

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APPENDIX DPLUTONIUM VALUE CALCULATION PROCEDURE

An important difference in fuel cycle costs between central-plant and close-coupled plant processing results from the difference in inventory carrying charges as influenced by the out-of-reactor time cycles. Since the value of plutonium in the fuel cycle inventory is substantial, an arbitrarily selected plutonium value might misstate this carrying charge difference. Also, it is important to establish the relative plutonium values for different reactor cases in order to evaluate the prospects for plutonium recycle--a high plutonium value would indicate good prospects for recycle, but a low value would indicate probable sale to others rather than recycle of the plutonium. For these reasons an effort was made to assign realistic plutonium values. However, extreme accuracy is not essential since, for example, a \$0.50/g fissile error would not change fuel cycle cost differences by more than 0.005 mills/kWh.

The method selected to determine plutonium values is based on valuing plutonium as a replacement for U^{235} enrichment. The result is termed the break-even plutonium value and represents a value of fissile plutonium as nitrate, that results in an average fuel cycle cost that equals (over a 15-yr period of plutonium recycle fueling at optimum exposure) the fuel cycle cost for step one at optimum exposure when fuel enrichment is entirely U^{235} . The calculation is based on central-plant fuel reprocessing, and a separate break-even value is calculated for each economics and reactor case. The same plutonium value is used in the fuel cycle cost computation for a corresponding close-coupled plant reprocessing case. The spent-fuel salvage value calculation, which is the point of beginning or ending for a recycle fuel cost calculations, is based on the option in either process concept of recovering the plutonium for sale to others (presently the AEC) via central-plant processing.

The break-even method of plutonium valuation is a technique used for assigning value in the absence of an established market price because plutonium would be worth that much to the reactor operator relative to

alternative U^{235} enrichment. It is the maximum price which could be paid and still justify plutonium recycle. If the actual market price of plutonium should turn out to be higher than the break-even value, plutonium would be sold if a buyer could be found rather than recycled. Any evaluation of plutonium recycle fuel costs for that case would be of questionable validity since it would be cheaper to utilize U^{235} enrichment. The break-even value is similar to the indifference value term used by Eschbach⁹ except for the method of averaging values over several recycle steps. This study is concerned more with the overall effect on inventory charges rather than with plutonium value at any particular step or of any specific composition.

A simplifying assumption is that plutonium value is entirely a function of fissile plutonium content and that fissile plutonium value determined at optimum exposure can be used as the value at other exposures. Plutonium value is influenced by the relative amounts of all the plutonium isotopes but the major value factor is fissile plutonium content. In addition, for a given reactor case, the change in average plutonium composition over a fixed period of reactor operation (15 yr) is relatively small regardless of the exposure per recycle step, and it was felt that this effect could be neglected, particularly since the effect on inventory charges would undoubtedly be very slight. Another small error is possible through use of the same average plutonium value for both close-coupled and central-plant reprocessing for a given economics case. The number of recycle steps in a 15-yr processing period is not exactly the same for both reprocessing methods and a slight difference in average isotopic composition would result.

The break-even plutonium value is obtained by computing central-plant fuel cycle costs for three different arbitrarily assigned plutonium values and several different fuel exposures. Fuel cycle costs with each plutonium value are then plotted against fuel exposure for both uranium-only (step one) and plutonium recycle operation (15 yr average) as in Figures 1-D and 2-D. Minimum fuel cycle costs at the three assigned plutonium values are then selected from these plots for both uranium-only and plutonium-recycle operation. Another plot is then prepared of minimum fuel cycle cost versus plutonium value for uranium-only and for plutonium recycle as in Figure 3-D.

FIGURE 1-D

Minimum Fuel Cycle Cost Determination
for U235 Enriched Fuel at Three Plutonium Values

FIGURE 2-D

Minimum Fuel Cycle Cost Determination
for Plutonium Recycle Fuel at Three Plutonium Values

FIGURE 3-D

Break-Even Plutonium Value Determination

With uranium-only fueling, fuel cycle cost decreases with increasing plutonium value (more value in the spent fuel), but with plutonium recycle, fuel cost increases with increasing plutonium value (increased cost of feed enrichment). The point of intersection represents the break-even plutonium value and the fuel cycle cost for central-plant processing at optimum exposure.

APPENDIX E

ALLOWABLE INVESTMENT DATA PLOTS

FIGURE 1-E

Allowable Close-Coupled-Plant Investment Compared with Average Fuel-Cycle-Cost Savings Relative to Central-Plant Cycle at 15,000 MWd/ton

FIGURE 2-E

Allowable Close-Coupled-Plant Investment Compared with Average Fuel-Cycle-Cost Savings Relative to Central-Plant Cycle at 15,000 MWd/ton

FIGURE 3-E

Allowable Close-Coupled-Plant Investment Compared with Average Fuel-Cycle-Cost Savings Relative to Central-Plant Cycle at 15,000 MWd/ton

FIGURE 4-E

Allowable Close-Coupled-Plant Investment Compared with Average Fuel-Cycle-Cost Savings Relative to Central-Plant Cycle at 15,000 MWd/ton

FIGURE 5-E

Allowable Close-Coupled-Plant Investment Compared with Average Fuel-Cycle-Cost Savings Relative To Central-Plant Cycle at 15,000 MWd/ton

FIGURE 6-E

Allowable Close-Coupled-Plant Investment Compared with Average Fuel-Cycle-Cost Savings Relative to Central-Plant Cycle at 15,000 MWd/ton

FIGURE 7-E

Allowable Close-Coupled-Plant Investment Compared with Average Fuel-Cycle-Cost Savings Relative to Central-Plant Cycle at 20,000 MWd/ton

FIGURE 8-E

Allowable Close-Coupled-Plant Investment Compared with Average Fuel-Cycle-Cost Savings Relative To Central-Plant Cycle at 20,000 MWd/ton

FIGURE 9-E

Allowable Close-Coupled-Plant Investment
Compared with Average Fuel-Cycle-Cost
Savings Relative to Central-Plant Cycle
at 20,000 MWd/ton

FIGURE 10-E

Allowable Close-Coupled-Plant Investment
Compared with Average Fuel-Cycle-Cost
Savings Relative to Central-Plant Cycle
at 20,000 MWd/ton

FIGURE 11-E

Allowable Close-Coupled-Plant Investment
Compared with Average Fuel-Cycle Cost
Savings Relative to Central-Plant Cycle
at 20,000 MWd/ton

FIGURE 12-E

Allowable Close-Coupled-Plant Investment
Compared with Average Fuel-Cycle-Cost
Savings Relative to Central-Plant Cycle
at 20,000 MWd/ton

FIGURE 13-E

Allowable Close-Coupled-Plant Investment
Compared with Average Fuel-Cycle-Cost
Savings Relative to Central-Plant Cycle
at Optimum Exposure

FIGURE 14-E

Allowable Close-Coupled-Plant Investment
Compared with Average Fuel-Cycle-Cost
Savings Relative to Central-Plant Cycle
at Optimum Exposure

FIGURE 15-E

Allowable Close-Coupled-Plant Investment
Compared with Average Fuel-Cycle-Cost
Savings Relative to Central-Plant Cycle
at Optimum Exposure

FIGURE 16-E

Allowable Close-Coupled-Plant Investment
Compared with Average Fuel-Cycle-Cost
Savings Relative to Central-Plant Cycle
at Optimum Exposure

FIGURE 17-E

Allowable Close-Coupled-Plant Investment
Compared with Average Fuel-Cycle-Cost
Savings Relative to Central-Plant Cycle
at Optimum Exposure

FIGURE 18-E

Allowable Close-Coupled-Plant Investment
Compared with Average Fuel-Cycle-Cost
Savings Relative to Central-Plant Cycle
at Optimum Exposure

FIGURE 19-E
Effect of Central-Plant-Processed-Fuel
Exposure on Break-Even Investment
for Close-Coupled Plant

FIGURE 20-E
Effect of Central-Plant-Processed-Fuel
Exposure on Break-Even Investment
for Close-Coupled Plant

FIGURE 21-E

Effect of Central-Plant-Processed-Fuel Exposure on Break-Even Investment for Close-Coupled Plant

FIGURE 22-E

Effect of Central-Plant-Processed-Fuel Exposure on Break-Even Investment for Close-Coupled Plant

FIGURE 23-E
Effect of Central-Plant-Processed-Fuel Exposure on Break-Even Investment for Close-Coupled Plant

FIGURE 24-E
Effect of Central-Plant-Processed-Fuel Exposure on Break-Even Investment for Close-Coupled Plant

APPENDIX FCLOSE-COUPLED FUEL-REPROCESSING PLANT COST ESTIMATETABLE I -FBASISReactor Case:

- a. 1000 MW_e reactor at 33% thermal efficiency and 80% use factor.
- b. Fuel Exposure = 15,500 MWd/ton (optimum for APWR case with low-range costs).
Thus, fuel discharge rate = 51,260 kg/yr.

Process Requirements:

- a. Instantaneous reprocessing capacity = 176 kg/day or 80% operating efficiency.
- b. Fission Product Poison DF = 6.
- c. By-product recovery facilities for 75 kg uranium/day as UF₆.

Fabrication Requirements:

- a. 50 to 55% of fuel fabricated in close-coupled plant as mixed PuO₂-UO₂.
- b. From 2/3 to 4 complete fuel assemblies produced per day depending on fuel design.
- c. Assume inverted cluster fuel assembly with complete assembly purchased from offsite vendor so that filling, final closure and leak testing are only operations required.

Facilities Furnished by Reactor:

- a. Cooling basin
- b. Utilities
- c. Site

Process Equipment Required:

- a. One fuel bisecting machine
- b. One decladding machine
- c. Two oxidizers with 5 kW resistance furnaces and associated controls
- d. Four 220 liter fused silica salt pots and associated induction heaters (30 kW), and instrumentation
- e. Off-gas facilities including two parallel drying columns and filters, two chlorine condensers and one HCl condenser, two parallel absolute-filter charcoal-absorber combinations and a caustic scrubber
- f. By-product process equipment for conversion and decontamination of UO₂ to UF₆, including a 6 in. diam x 6 ft long fluid bed fluorinator, filter and cold trap
- g. Product treatment equipment including an electrode stripper, small roll crusher, wash columns, screen separator, scale and blender
- h. Two vibrational compaction machines, a welding machine for the final closure, and leak testing equipment
- i. Miscellaneous quality control and testing equipment.

FIGURE 1-F
Schematic Flow Diagram
Close-Coupled Fuel Reprocessing Plant

FIGURE 2-F

Close-Coupled Fuel Reprocessing Plant Floor Plan

TABLE II-F

CLOSE-COUPLED FUEL-REPROCESSING PLANT COST ESTIMATE

Installation and Erection:Construction Costs:

Buildings and/or Structures	\$2,215,000
Equipment	1,935,000
Yardwork and Utilities	50,000
Demolition and Removal	20,000
Subtotal Construction Cost	\$4,220,000
Supervision of Construction (Title III)	70,000
Project Startup	150,000
Contingency (25%)	1,110,000
Total Construction Cost	\$5,550,000
Design Services (Titles I and II)	650,000
TOTAL PROJECT COST	\$6,200,000

Construction Cost Breakdown:Yardwork

Landscaping	\$ 12,000
Parking, Roads, and Walks	10,000
Piping	18,000
Electrical	10,000
	\$ 50,000

Building

Structure - 15,350 sq ft	615,000
Basement - 11,856 sq ft	295,000
Exhaust and Stack	50,000
Heat and Vent	100,000
Furniture	40,000
Crane, 10 Ton	25,000
Paint and Coatings	20,000
Communications and Alarm	30,000
Elevators (3)	150,000
Cell Structure - 4900 sq ft	735,000
Instrumentation	75,000
Electrical and Fire Protection	80,000
	\$2,215,000

Equipment

Viewing Windows (26)	415,000
Manipulators (20 pairs)	300,000
Cell Cranes (2 each)	40,000
Shop Equipment	30,000
Cell Doors (4)	150,000
Process Equipment	1,000,000
	\$1,935,000

F-4

BNWL-28

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