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Methodology for Estimating Reprocessing Costs for Nuclear Fuels

W. L. Carter
R. H. Rainey

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CHEMICAL TECHNOLOGY DIVISION

METHODOLOGY FOR ESTIMATING REPROCESSING COSTS FOR NUCLEAR FUELS

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CONTENTS

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ABSTRACT

A technological and economic evaluation of reprocessing requirements for alternate fuel cycles requires a common assessment method and a common basis to which various cycles can be related. A methodology is described for the assessment of alternate fuel cycles utilizing a side-by-side comparison of functional flow diagrams of major areas of the reprocessing plant with corresponding diagrams of the well-developed Purex process as installed in the Barnwell Nuclear Fuel Plant (BNFP). The BNFP treats 1500 metric tons of uranium per year (MTU/yr). Complexity and capacity factors are determined for adjusting the estimated facility and equipment costs of BNFP to determine the corresponding costs for the alternate fuel cycle. Costs of capacities other than the reference 1500 MT of heavy metal per year are estimated by the use of scaling factors. Unit costs of reprocessed fuel are calculated using a discounted cash flow analysis for three economic bases to show the effect of low-risk, typical, and high-risk financing methods.

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1. SUMMARY

The Alternate Fuel Cycle Evaluation Program (AFCEP) includes technical and economic assessments of fabrication, reprocessing, and refabrication for a number of reactor fuel cycles for water reactors, breeder reactors, gas-cooled reactors, and certain advanced reactors. A methodology has been developed for estimating capital and operating costs of reprocessing plants that have the capability of treating spent fuel from any of the reactor cycles. The method is based on a comparison of reprocessing requirements of the various alternate fuel cycles with the well-developed Purex process for which a large-scale plant [1500 metric tons per year (MT/yr)] is nearly complete at Barnwell, South Carolina. Cost data for

this plant are proprietary, but it is estimated that the completed facility will constitute an $800 million investment (in 1976 dollars).

The Barnwell Nuclear Fuel Plant (BNFP) and its associated capital investment are regarded as the base case to which all alternate fuel cycles are compared. The $800 million investment is apportioned among the primary areas -- head end, solvent extraction, product conversion, off-gas treatment, common facilities, and waste treatment -- according to a technological evaluation of the relative complexity and difficulty of the individual operations. Functional flow diagrams are drawn for the major areas of the reprocessing plant, which treats the spent fuel from the candidate fuel cycle. A side-by-side comparison of these diagrams with corresponding diagrams for the BNFP allows a technological assessment to be made of the relative complexity of the various operations so that a complexity factor can be assigned to the candidate cycle. The total amount of material (structural plus fissile and fertile) to be treated in each of the major areas is determined and compared with the corresponding material flow for light water reactor (LWR) fuel in BNFP. A scaling factor is applied to the ratio of the material flow rates to determine capacity factors for each plant area for the candidate fuel cycle. Facility and equipment capital costs are estimated for each plant area by multiplying the corresponding BNFP cost by the complexity and capacity factors. Capital costs at other plant capacities are found by using a scaling factor of 0.6 for throughputs of 1200 to 3000 MT/yr and 0.35 for throughputs of 300 to 1200 MT/yr.

Operating costs for the BNFP are not available because the plant has not started operation; however, it was estimated that total direct annual costs (in 1978 dollars) would be $32.6 million. Operating costs for the alternate fuel cycles are estimated relative to this cost by considering the complexity, number of operations, maintenance requirements, and other pertinent characteristics.

A discounted cash flow analysis is recommended to determine a levelized unit price for the reprocessed fuel. The influence of financing methods on the charge that must be made for products is shown by adopting low-risk, typical industrial, and high-risk economic bases that correspond to annual amortization rates of 10.8, 22.6, and 31.6% respectively.

2. INTRODUCTION

The Alternate Fuel Cycle Evaluation Program (AFCEP) includes numerous fuel cycles for several reactors such as LWRs, spectral shift control reactors (SSCRs), heavy water reactors (HWRs), fast breeder reactors (FBRs), high-temperature gas-cooled reactors (HTGRs), and certain advanced reactors. These cycles are being evaluated in support of the nonproliferation objectives of the United States; the evaluation includes both technical and economic assessments. The AFCEP schedule is not compatible with the time needed to prepare detailed assessments for each fuel cycle, especially with regard to cycle economics that require considerable engineering and design to provide reliable cost data. However, an economic comparison of the various fuel cycles can be made without time-consuming design studies by relating each fuel cycle to a reference cycle for which economic data are available. This methodology constitutes only a nominal design effort and will furnish adequate cost data for an initial comparison of the fuel cycles.

All elements of the fuel cycle are encompassed in AFCEP: fuel fabrication, reactor utilization, spent fuel reprocessing, and refabrication. This report addresses only reprocessing, and it documents the methodology employed in estimating facility capital costs and operating costs.

3. REFERENCE FUEL CYCLE

The uranium-plutonium (U-Pu) fuel cycle for the LWR was chosen as the reference cycle. This fuel is reprocessed by the well-developed Purex process, and a plant (BNFP) to treat 1500 MTU/yr has almost been completed at Barnwell, South Carolina. A process flow diagram of the BNFP facility is included in the Final Safety Analysis Report[1] for the facility.

The reference reprocessing cycle is for LWR fuel that has been irradiated to about 30,000 MWd per metric ton of heavy metal and cooled for 160 days or longer. Fuel elements are removed from pool storage for

size reduction in a mechanical shear that first removes structural end pieces before the fuel-bearing section is sheared into 2- to 5-in. lengths. Uranium and bred-plutonium values are leached from these small pieces with nitric acid and, after clarification, the solution is sent to a solvent extraction area. Cladding hulls and other fuel element hardware are packaged for waste disposal.

The BNFP solvent extraction area consists of a U-Pu partitioning cycle to remove the bulk of the fission products and to separate uranium and plutonium. This step is followed by one cycle of additional uranium purification and two cycles of additional plutonium purification, which ensures that the products have sufficient decontamination for direct handling. The plutonium product is concentrated and stored; the uranium product is sent to the uranium hexafluoride (UF_6) facility to prepare the UF_6 for subsequent enrichment in a gaseous diffusion plant. Gaseous wastes are treated to remove nitrogen oxides and iodine before release to the environment. Liquid wastes are stored in large tanks.

Since the BNFP is used as the reference, the ground rules for developing the economic data conform to the characteristics of this plant. In areas where the BNFP facility is incomplete, appropriate bases were assumed that would enable the plant to complete the reprocessing cycle. The bases given in Table 1 are part of the methodology for these cost estimates.

4. LIMITATIONS OF BNFP

The BNFP was designed and built to employ a minimum amount of remote maintenance and to have relatively thin biological shielding in the product storage areas. These design standards conformed to the Code of Federal Regulations governing nuclear fuel reprocessing plants at the time that the plant was constructed. However, new (and proposed) regulations decrease the allowable exposure level to operating personnel to a standard to which the BNFP design will no longer comply. Any advanced technology reprocessing plant will use thicker shielding, more areas of remote maintenance, and will require more complete cleanup of all plant effluents.

Table 1. Reference bases for reprocessing plant cost estimation

General	
Plant capacity	1500 MT heavy metal/yr
Operating time	300 days/yr
Operating schedule	24 hr/day operation for 7 days/week
Maintenance procedure	Direct
Fuel cooling time	≥160 days
Type of storage	Pool
Storage capacity for spent fuel	250 MT heavy metal
Head end	
Size reduction	Mechanical shearing
Tritium removal[a]	Voloxidation
Dissolution	Continuous; standard Purex procedure
Solvent extraction	
U-Pu fuel	Purex process for U-Pu purification and partitioning
U storage	Surge capacity of 150 MT of heavy metal
Pu storage	Stored as nitrate solution
U-Th fuel[a]	Thorex process or modified Thorex process for U-Th purification
Th storage[a]	Surge capacity of 150 MT maximum
Product conversion to oxides[a]	
$UO_2(NO_3)_2 \rightarrow UO_2$	Gel-sphere process
$Pu(NO_3)_4 \rightarrow PuO_2$	Gel-sphere process
$Th(NO_3)_4 \rightarrow ThO_2$	Gel-sphere process
Storage capacity	(1) 30 days production (2) 20-yr thorium storage required for nonrecycle thorium cases
Off-gas treatment	
BNFP treatment	I and NO_x removal only
Additional treatment[a]	^3H, Kr, Rn, $^{14}CO_2$ removal
Particulate removal	HEPA filtration
Waste treatment[a]	
Extent of treatment	Prepare all wastes for ultimate disposal as immobile solids
Storage capacity	30-day surge capacity before solidification
Reserve storage	Always one empty waste tank available for liquid waste
Solidified waste storage	≥5-yr capacity

[a]Facilities and/or process not included in reference BNFP.

The BNFP flowsheet does not include facilities for oxide conversion and waste treatment. In the BNFP concept, purified uranium is converted to UF_6 for return to an enrichment plant, and wastes are routed to interim storage in large tanks. Present regulations require that high-level aqueous wastes be converted to solids and encapsulated in a form suitable for ultimate disposal; this treatment must occur within 5 years after the spent fuel has been processed. Also, the off-gas treating capability at the BNFP removes only iodine and nitrogen oxides before dispersal in the atmosphere. Future plants will be required to treat off-gases for removal of krypton, tritium, radon, and ^{14}C, as well as iodine and nitrogen oxides.

In the BNFP concept, recovered plutonium is stored as a nitrate solution and the plant contains no facilities for converting plutonium to a solid oxide. Regulations do not permit shipment of plutonium in any state other than as a solid (PuO_2); hence, conversion facilities must be included in current fuel cycle evaluations.

5. REFERENCE COST DATA

Actual cost data for the BNFP have not been published; however, it is estimated that inclusion of waste treatment and plutonium conversion facilities will require a total investment of $800 million (1976 dollars). Process operations of the BNFP were categorized on a flowsheet that divided the plant into major functional areas -- head end, solvent extraction, product conversion, off-gas treatment, common facilities, and waste treatment. The total plant investment (facilities plus equipment costs) was apportioned among these functions as follows: $150 million for head end, including fuel receiving and storage; $150 million for solvent extraction; $80 million for product conversion; $110 million for off-gas treatment; $250 million for waste treatment; and $60 million for common facilities. This cost breakdown is the reference to estimate costs of other fuel cycles. Functional flow diagrams that present the various areas of the plant in equivalent degrees of detail are used as the basis of this apportionment. Subfunctions or unit operations are standardized in terms of complexity and magnitude and in terms of uncertainty, both technological and regulatory. The relatively large portion

of the cost of the BNFP assigned to waste treatment reflects the uncertainty of the requirements for a final waste management program, especially with regard to an acceptable form for wastes and possible treatment of transplutonium nuclides.

A division of the capital costs for the BNFP between facilities and equipment is not available. For these studies it is assumed that a fraction of the capital investment of each area will be associated with equipment capital costs, as follows: head end, 25%; solvent extraction, 25%; product conversion, 30%; off-gas treatment, 30% waste treatment, 27%; common facilities, 40%.

6. ALTERNATE FUEL CYCLE

The fuel cycles for LWRs, HWRs, SSCRs, and FBRs include U-Pu, U-Th, and Pu-Th fuels; for HTGRs, the cycles include only the U-Th and Pu-Th fuels. The fuels that contain uranium for certain reactor systems may be either fully enriched or denatured to varying degrees depending on the requirements of the specified fuel cycle. The treatment of these fuels in a reprocessing plant introduces several reprocessing options that may affect costs in one or more areas of the plant. For example, head-end costs are influenced primarily by the type of cladding, the heavy metal content of the fuel element, and the presence of thorium; solvent extraction costs depend on such reprocessing options as degree of decontamination, partitioned products vs coprocessed products, plutonium recovery or rejection to waste, and separate or coincident treatment of core and blanket materials. The methodology employed in these evaluations allows an assessment of the various options and requirements of a fuel cycle, because each principal area of the reprocessing plant is compared individually to the equivalent functional area of the reference plant.

7. HEAVY-METAL AND FUNCTIONAL FLOW DIAGRAMS

The initial requirement for a technological and economic assessment of an alternate fuel cycle is a heavy-metal flow diagram. Characteristics of this diagram determine the requirements for the functional flow diagrams of fuel fabrication, reprocessing, and refabrication.

7.1 Heavy-Metal Flow Diagram

A heavy-metal flow diagram of a candidate LWR fuel cycle utilizing denatured U-Th fuel is given in Fig. 1. This diagram relates all components of the fuel cycle including uranium enrichment, fuel fabrication, spent-fuel reprocessing, and refabrication. Interfaces between the components are identified with respect to material and composition crossing the interface. With regard to reprocessing, Fig. 1 shows that uranium, thorium, and plutonium are partitioned. Uranium and thorium are recycled, and plutonium is routed to secure storage or burned in other reactors. It is timely to note that the fuel cycle shown in Fig. 1 is only one of several schemes that might be applied to an LWR operating on denatured U-Th fuel.

7.2 Functional Flow Diagrams

Functional flow diagrams identify the principal steps in each major area of the reprocessing plant. They are prepared to assist a side-by-side comparison of the alternate fuel cycle with the reference BNFP cycle. The following diagrams are typical of those that are required for each major area. Alternate fuels and/or specific requirements of a fuel cycle could necessitate either minor or significant alterations in these representative figures.

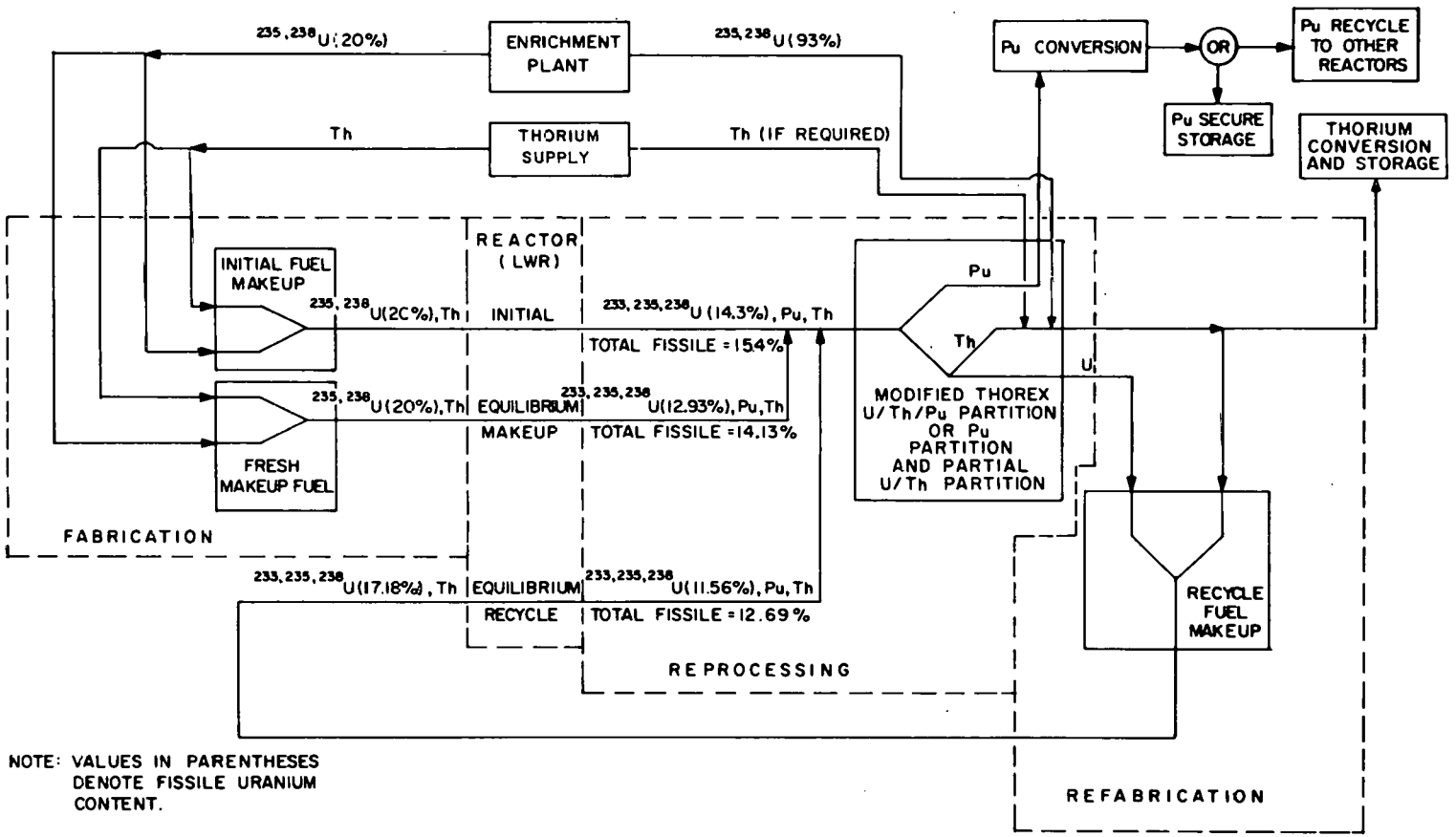

Fig. 1. Heavy-metal flow diagram for an LWR fueled with denatured uranium-thorium.

7.2.1 Head-end treatment

A functional flow diagram for the head-end treatment of metal clad U-Th fuel is shown in Fig. 2. After the fuel element has been received from the storage pool, the first step is to cut the inactive end pieces for disposal as solid waste. The fueled portion of the element is chopped into ∿2-in. lengths, which are roasted at an elevated temperature in the presence of oxygen to cause tritium migration from the fuel; other fission gases partially migrate out of the fuel during the thermal soaking. The tritium removal step is followed by dissolution in nitric acid catalyzed by fluoride ion to leach fuel values from the cladding hulls. The hulls are separated from the nitrate solution and packaged for disposal as solid waste. The liquor is clarified to remove insoluble fines, adjusted to the appropriate composition for solvent extraction, and analyzed for heavy metal accountability. The head end of the reference BNFP facility does not include a tritium removal step.

7.2.2 Solvent extraction

The steps that are required to purify the fissile and fertile materials in a denatured U-Th fuel are shown in Fig. 3. The initial solvent extraction cycle removes the bulk of the fission products and partitions plutonium, thorium, and uranium from each other. Subsequent cycles are needed for additional decontamination of thorium and uranium products; however, the plutonium product is not purified further since it is not recycled immediately. The functional flow diagram also indicates the steps needed to recycle off-specification products and the recovery of acid and solvent for reuse in the process.

7.2.3 Product conversion

The operations shown in Fig. 4 are the steps in the conversion of uranium, thorium, or plutonium nitrate solutions to oxide spheres for refabrication into fuel by the gel-sphere-pac method. Alternate processes that might be used when oxide powders are required for refabrication are denitration of the nuclear materials by established procedures such as the ammonium diuranate process, oxalate precipitation, or thermal denitration.

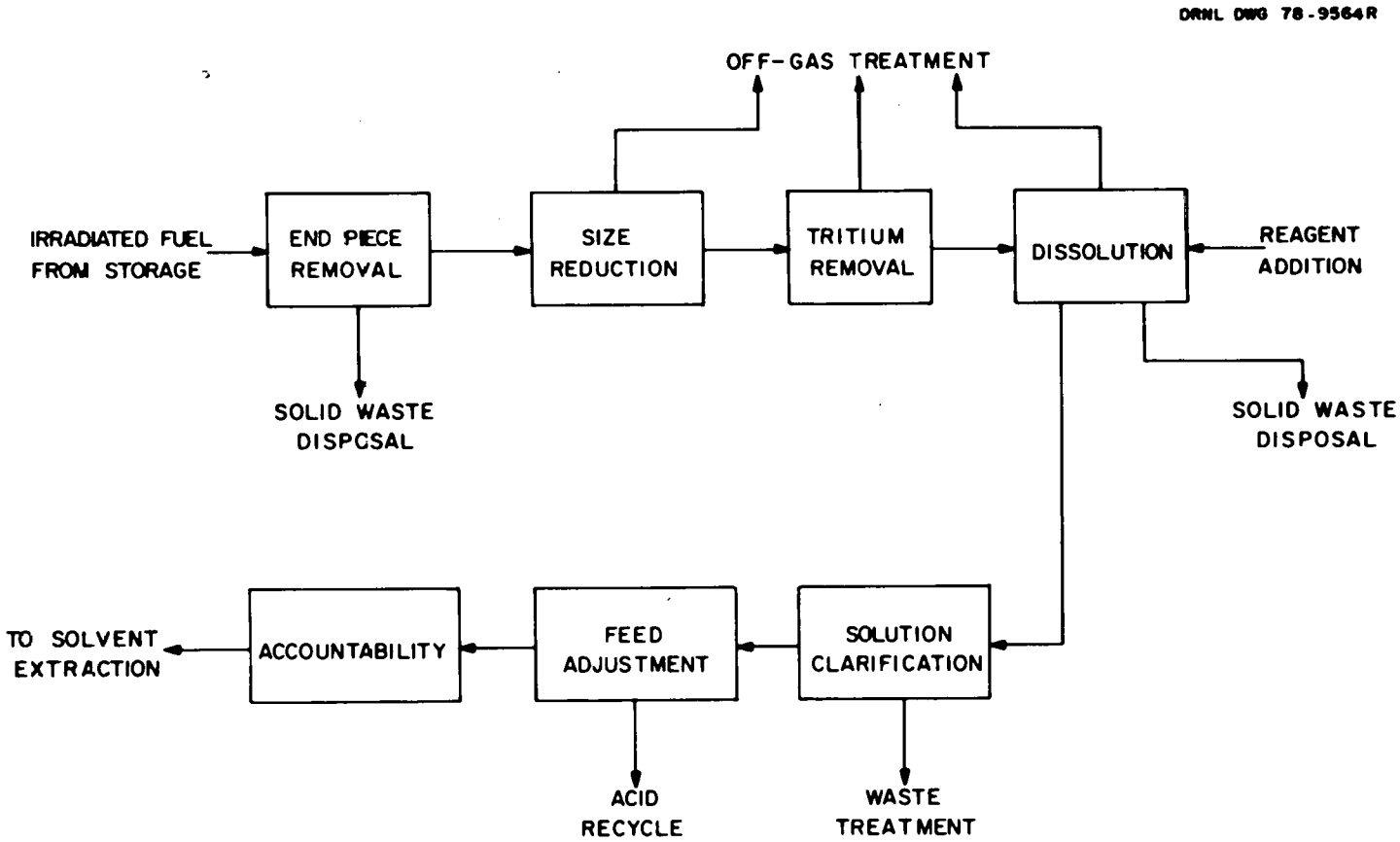

Fig. 2. Functional flow diagram of head-end treatment of uranium-thorium fuel.

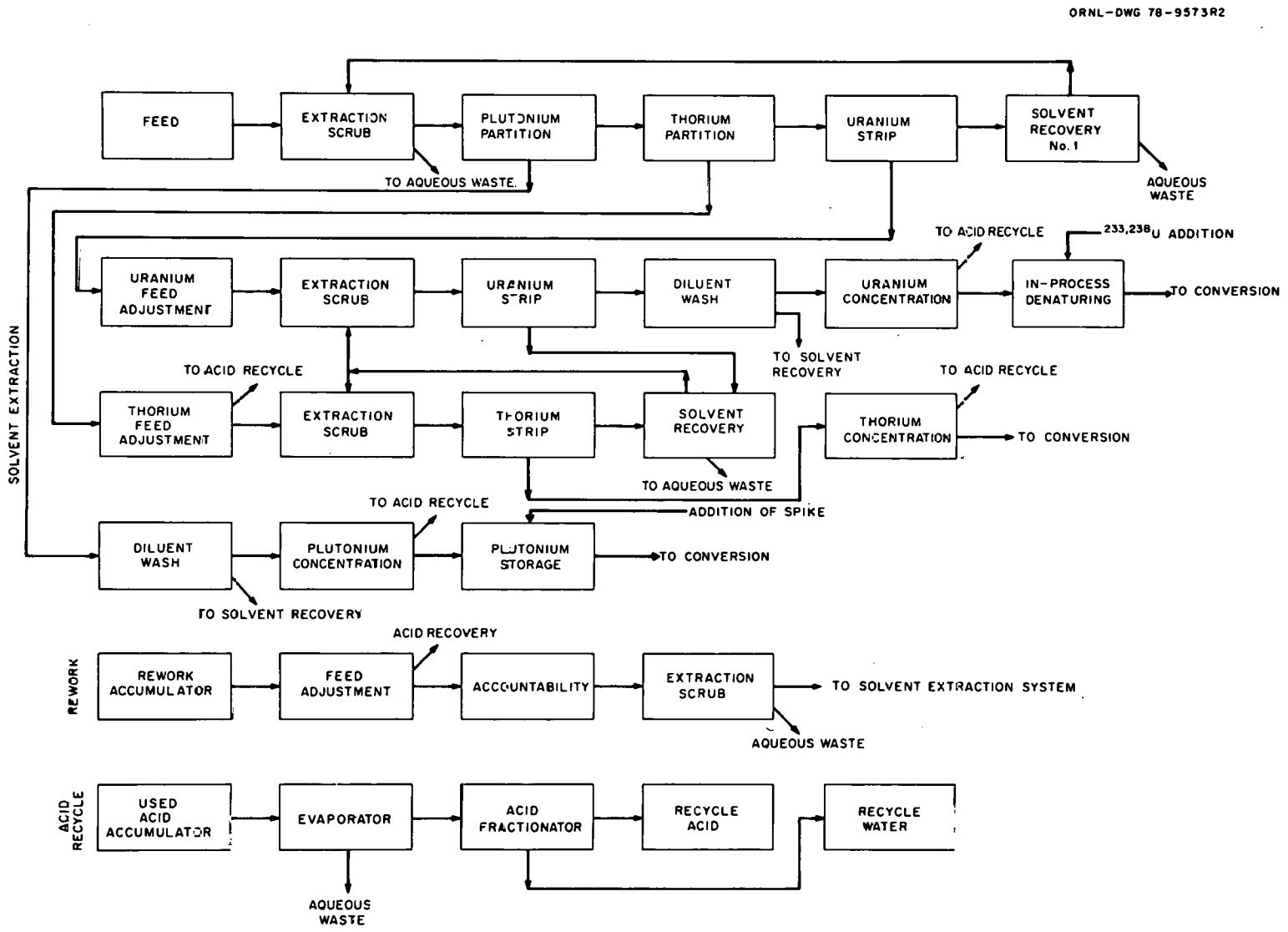

Fig. 3. Functional flow diagram for the purification of denatured uranium-thorium fuel by solvent extraction.

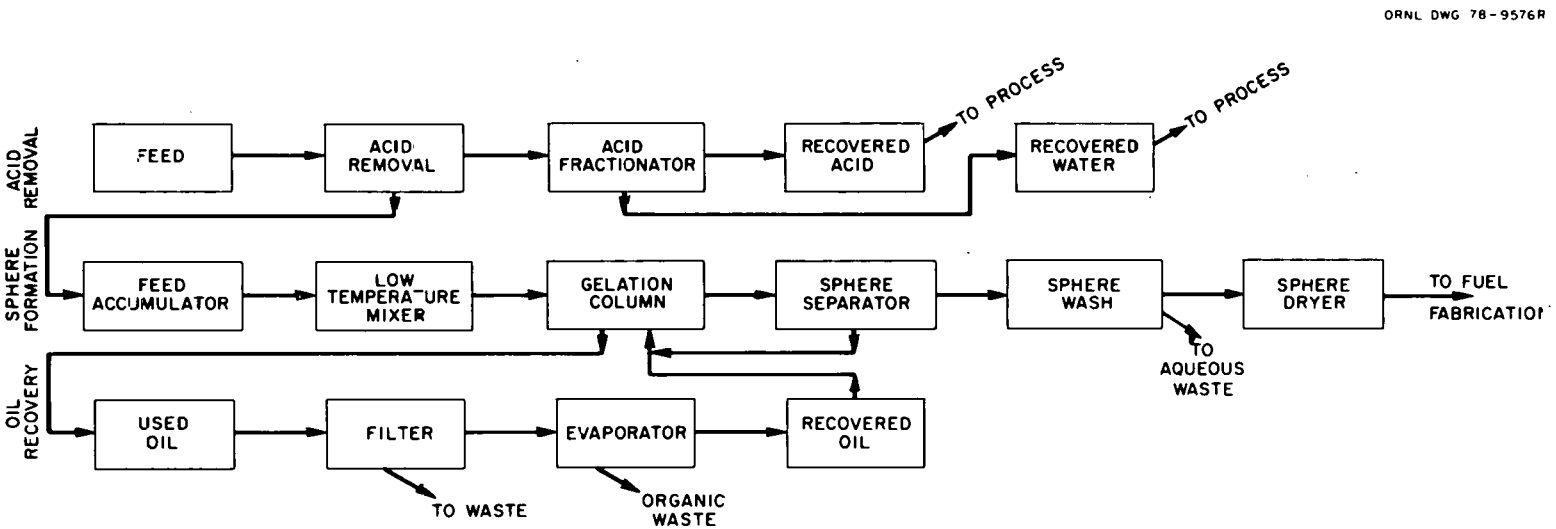

Fig. 4. Functional flow diagram for product conversion by the gel-sphere process.

Since the reference plant does not include product conversion, there is no reference functional flow diagram that can be used for comparison. It was assumed that if product conversion were added to the BNFP it would be a process for the preparation of oxide powders.

7.2.4 Off-gas treatment

The three principal sources of radioactive off-gases are shown in Fig. 5 along with the steps that are necessary to purify the carrier gas sufficiently for release to the environment. The diagram is constructed on the assumption that future regulations will require a high decontamination factor for all radioactive species. The volumetric concentrations of the radioactive gases in the carrier are in the parts-per-million and parts-per-billion range, which allows convenient removal by gas-solid reactions for most species. Krypton is removed by sorption in a refrigerant from which it is concentrated for long-term storage. The reference BNFP includes only iodine, nitrogen oxide, and particulate removal.

7.2.5 Waste treatment

Regulations for waste treatment given in CFR 10, Part 50, Appendix F, require that high-level liquid wastes be converted to solids that are suitable for permanent disposal; the conversion must occur within 5 yr after reprocessing, and transfer of waste solids to a repository must take place within 10 yr of reprocessing. The bulk of the fission products is contained in the aqueous raffinate from the first solvent extraction column, and minor amounts come from subsequent solvent extraction and solvent cleanup cycles. The principal steps for treating these wastes are shown in the functional flow diagram of Fig. 6. Waste treatment is also a recovery operation for recyclable chemicals.

In the waste-treatment process, cladding hulls and fuel-element end pieces are removed from the dissolution area to be packaged for disposal. The pieces are dropped into a container of cement grout for immobilization and containment. Small pieces of failed equipment may be handled in the same way. A 55-gal drum is the standard container for this disposal.

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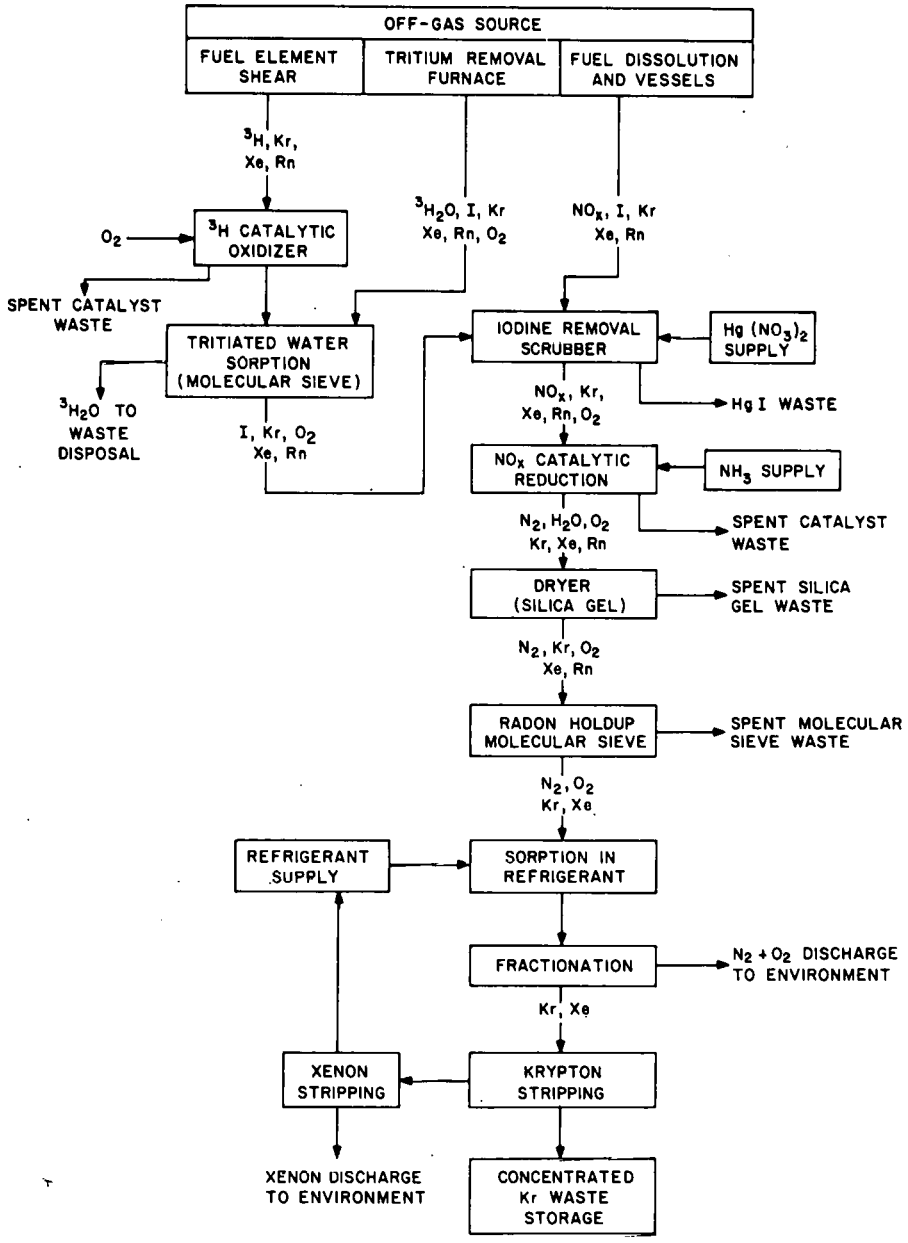

Fig. 5. Functional flow diagram for treating off-gases from reprocessing uranium-thorium fuels.

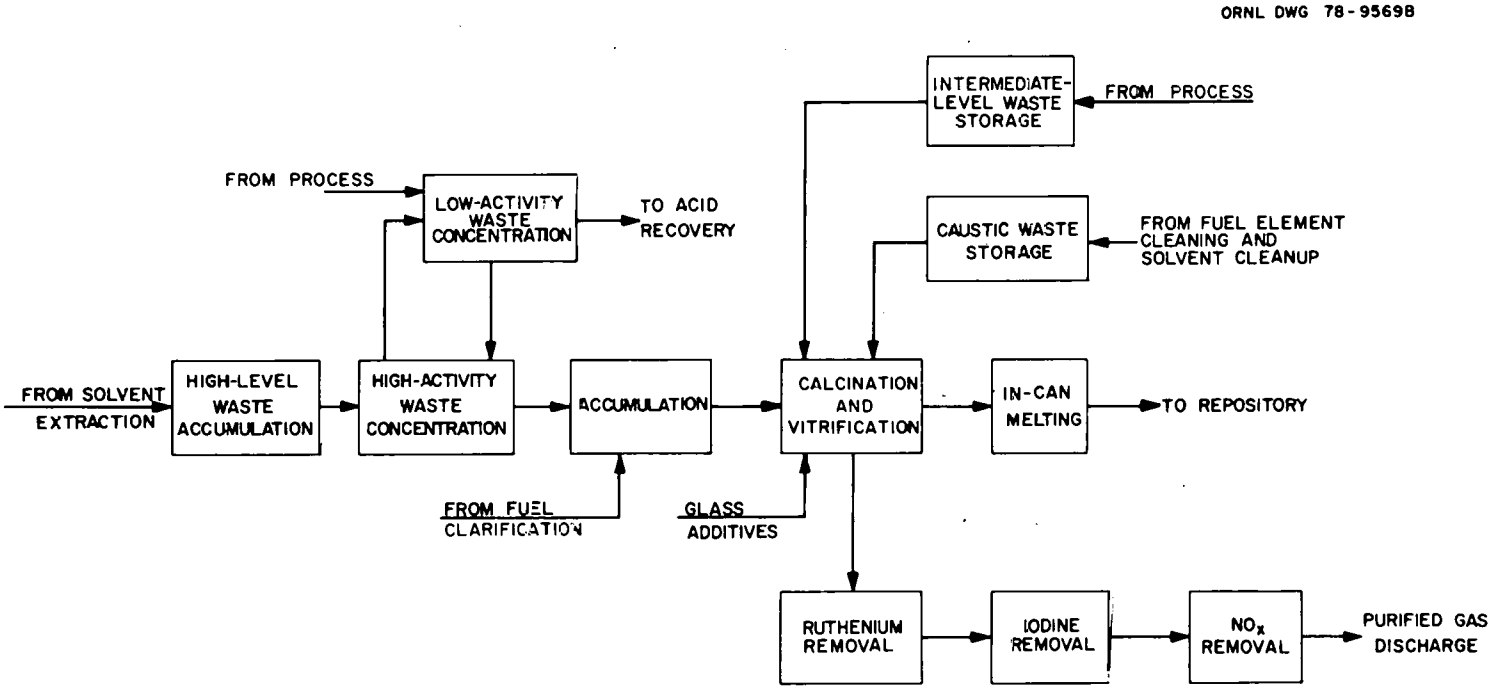

Fig. 6. Functional flow diagram for treating liquid wastes from reprocessing.

Combustible wastes and trash are burned and the ash is incorporated in the vitrified high-level waste.

The economics of waste treatment--waste storage with regard to the most favorable time to convert liquid wastes to solids--have not been resolved; however, it is anticipated that lower costs will result from conversion to solids as soon as it is technologically feasible. In these evaluations, a nominal 30-day holdup for liquid wastes has been assumed to preclude large liquid inventories. As stated earlier, the reference BNFP has no comparable waste treatment facility; the current procedure is to store liquid wastes pending the definition of waste treating requirements.

8. FUEL CYCLE ASSESSMENT

Corresponding functional flow diagrams are drawn for each alternate fuel cycle for which cost estimates are needed. Side-by-side comparisons are made of the diagrams of the alternate and reference fuel cycles for each major area of the plant. Based on this comparison, complexity and capacity factors are determined for these areas of the reprocessing plant. All flow diagrams are constructed on a standardized basis so that normalization of related functions to the reference case is fair and impartial.

8.1 Complexity Factor

The complexity factor for a given system is determined with respect to process chemistry, number of operations, material handling, state of development of each unit operation, ease of operation and maintenance, and size and type of equipment. In head-end treatment, consideration is given to the type of fuel cladding or matrix (stainless steel, Zircaloy, or graphite), size reduction procedure, and dissolution requirements. The solvent extraction assessment considers modifications to developed procedures, the degree of purification required, the number of nuclear materials to be recovered, and whether coprocessing or full partitioning is required. The increased complexity of off-gas treatment over the

reference cycle is caused by the requirement that all radioactive species, including radon and tritium, must be removed. An additional complexity factor is introduced when graphite fuels are treated because copious quantities of carbon dioxide are produced. Liquid waste treatment is similar for all metal-clad fuels, except that thorium fuel wastes are more complex because of the presence of fluoride ion. For the waste treatment of graphite fuels, a major consideration is immobilization of large quantities of carbon dioxide. In product conversion, the major influence on complexity occurs in the treatment of denatured thorium fuels for which ^{232}U and ^{228}Th activity necessitates remote operation and maintenance. If plutonium from these fuels is recycled, an additional remotely operated conversion line is required. This line may also require remote maintenance.

8.2 Capacity Factor

The capacity factor relates the total throughputs of the reference and alternate fuel cycles for the various areas of the reprocessing plant. Its determination is analogous to the customary scaling procedure used to relate capital costs and capacity. In these evaluations the capacity factor is defined as follows:

$$\text{Capacity factor} = \left[\frac{\text{throughput of alternate system}}{\text{throughput of corresponding BNFP system}}\right]^{n} .$$

The scaling factor, n, is assumed to be 0.6 for head-end and product conversion systems and for off-gas treatment of graphite fuels; a factor of 0.35 is used for the solvent extraction, off-gas treatment for metal-clad fuels, and waste treatment systems. In each case the throughput of a system is considered to be the total mass of inert and nuclear materials that are handled in that particular system. The effect is most noticeable in the head end where the amounts of structural material accompanying the reference 1500 MT per year of heavy metal varies considerably among the several fuel types. The higher scaling factor (0.6) is chosen for the operations that require application of undeveloped technology, considerable

mechanical equipment, and/or solid materials handling. The lower factor (0.35) is used for the operations that are characterized primarily by the flow of liquids and gases.

8.3 Use of Complexity and Capacity Factors

Complexity and capacity factors are used to adjust facility and equipemnt costs of the reference BNFP to obtain cost estimates for each major area of the plant for the several alternate fuel cycles. The alternate cycle cost is obtained by multiplying the reference cost by the product of the complexity factor and the capacity factor. In some instances, the reference facility costs are not adjusted by the same complexity and/or capacity factors as the reference equipment costs for a particular area; for example, the candidate fuel cycle might require complex equipment and operations but the facility requirements need not be as strongly influenced. In general, facility costs are influenced more by the space required for equipment than by the complexity of the process. For each fuel cycle, facility and equipment requirements are assessed independently to determine the appropriate complexity and capacity factors.

Reference cost data given in 1976 dollars for the BNFP are adjusted to a 1978 dollar base by assuming an inflation rate of 7%/yr. Thus the estimated $800 million investment in 1976 dollars escalates to $915 million in 1978 dollars.

8.4 Operating Costs

There are no base data for the annual cost of operating a 1500-MT/yr reprocessing plant. Direct operating costs were derived for the reference plant by estimating the number of personnel required to operate the plant and the annual cost of chemicals and other consumed items. It was estimated that a staff of 835 persons would be required at an annual cost of $29.3 million; consumable items added an additional $3.3 million/yr for a total direct cost of $32.6 million/yr (1978 dollars). These costs do

not include amortization of capital, escrow fund for decommissioning, equipment replacement, taxes, or interest during construction. These latter costs are calculated separately for the alternate fuel cycles to indicate the influence of various financing methods on the charge that must be made for the products of the plant.

Direct operating costs for the alternate fuel cycles are estimated from the above data and include a side-by-side comparison of the functional flow diagrams of the alternate and reference fuel cycles. Complexity and capacity factors are not used to adjust the reference cost, because it is believed that the operating costs would not be influenced in exactly the same way as facility and equipment costs. However, cognizance is taken of the complexity and number of operations in a process area to determine the factor by which the reference costs should be adjusted. Operating costs are estimated for each major area of the reprocessing plant and are summed to give the total cost.

9. FINANCING METHODS

The method of financing the reprocessing facility is the most significant factor used to determine the price that must be charged for the products. Under AFCEP, the economic and technical data on alternate fuel cycles receives international distribution among nations whose financing methods for reprocessing plants may vary considerably. It is not feasible to apply multiple financing procedures to a set of economic data; however, it is germane to compute product prices that are representative of the anticipated extremes in financing. This is conveniently done by choosing three types of financing (Table 2) that are representative of a high-risk venture, a typical venture, and a low-risk venture. In the first case, the reprocessor must resort to complete equity financing and demand a higher after-tax return on the investment. In the second case, where nominal risk is taken, the required capital is obtained through equity and debt financing for which the average cost of money is lower than for complete equity financing. The low-risk case is probably typical of government financing for which all capital is supplied by debt at a low cost.

Table 2. Financing methods for treating estimated capital and operating costs of reprocessing plants

	Type of financing		
	Low-risk venture	Typical industrial venture	High-risk industrial venture
Project life, yr			
Construction period	6	6	6
Operating period	20	20	20
Decommissioning period	3	3	3
Capital structure			
Equity, %	0	65	100
After-tax return on equity, %/yr	0	14	15
Debt, %	100	35	0
Interest rate on debt, %/yr	7.5	8.3	0
Weighted average cost of money, %/yr	7.5	12.0	15.0
Taxes			
Federal income, %	0	48	48
State income, %	0	3	3
Property taxes and insurance, %	0	3	3
Federal investment tax credit, %	0	7	7
Tax depreciation method		SYD[a]	SYD[a]
Tax depreciation life, yr		16	16
Equipment replacement and maintenance charge, % of initial equipment cost/yr	5	5	5
Charge rate during construction, %/yr	7.5	10.5	10.5
On-stream efficiency, %			
Years 1-6	0	0	0
Year 7	33	33	33
Year 8	67	67	67
Years 9-26	100	100	100
Owner's cost during construction, % of annual operating cost			
Year 1	5	5	5
Year 2	10	10	10
Year 3	20	20	20
Year 4	30	30	30
Year 5	40	40	40
Year 6	40	40	40
Capital costs, % of total			
Year 1	2.5	2.5	2.5
Year 2	6.5	6.5	6.5
Year 3	18.2	18.2	18.2
Year 4	44.2	44.2	44.2
Year 5	27.1	27.1	27.1
Year 6	1.5	1.5	1.5
Derived fixed-charge rate, %/yr	10.8	22.6	31.6
Charges during construction, fraction of total cost			
Capital expenditures	0.249	0.366	0.366
Owner's cost	0.209	0.303	0.303

[a] Sum of years digits.

10. UNIT COST DETERMINATION

The unit cost ($/kg) of the products of the reprocessing plant are derived by the application of the data in Table 2 to the capital cost estimates of the facility and equipment and the annual operating cost. The relationship for calculating the unit cost is

$$\text{Unit cost (\$/kg)} = \frac{(C_D + C_O + C_C)R + O + M + E_R + D}{T} ,$$

where

$$C_D = C_F + C_E$$

$$C_C = (IDC_O)(C_O) + (IDC_D)(C_C)$$

$$E_R = (A_R)(C_E)$$

$$T = XF$$

and

C_D = design and construction costs, $ million

C_F = facility cost (excludes process equipment), $ million

C_E = equipment cost, $ million

C_O = owner's cost during construction, $ million

$C_O + C_D$ = direct capital

C_C = charge on direct capital during construction, $ million

IDC_D = fractional charge on design and construction cost during construction

IDC_O = fractional charge on owner's cost during construction

R = annual fixed charge rate on capital, fraction/yr

O = annual operating cost, $ million/yr

M = annual hardware and expendable material cost, $ million/yr

A_R = annual maintenance and replacement rate on equipment, fraction/yr

E_R = annual maintenance and replacement cost

D = annual payment to establish fund for decommissioning, $ million/yr

T = annual throughput achieved, millions of kg/yr

X = design capacity of plant, millions of kg/yr

F = average fraction of design capacity achieved

The basis of this formula is a discounted cash flow analysis that provides for recovery of all capital and operating expenses plus a return on investment by establishing a levelized price for recovering the customer's fuel. Thus, total income over the life of the plant will equal the total expenditures plus the specified return on investment.

11. CAPITAL COSTS AT OTHER CAPACITIES

Evaluations of alternate fuel cycles include various types of reactors (and even symbiotic relationships between reactors) such that reprocessing requirements need to be satisfied by either larger or smaller plants than the reference 1500 MT/yr facility. It is inconvenient and time consuming to prepare cost estimates for every fuel cycle, and experience has shown that a satisfactory correlation between capital cost and plant capacity can be made with the expression

$$C = C_o\left(\frac{R}{R_o}\right)^n ,$$

where

C_o = capital cost of reference facility

R_o = throughput of reference facility

C = capital cost of a similar facility for which the required throughput, R, is known

n = scaling factor.

It is clear that the utility of this expression depends strongly on the choice of n, the scaling factor, and a high-confidence number can only be obtained from estimates based on detailed designs at two or more plant

capacities. Furthermore, the range of R-values over which n applies needs to be specified to preclude questionable extrapolation.

Experience in the chemical industry has shown that a value of 0.6 for n gives a good correlation of cost and capacity data; however, it is not certain whether this value applies to nuclear fuel reprocessing plants for which a large portion of the cost is independent of or only slightly dependent on capacity. Judkins and Olsen[2] surveyed and analyzed cost data for nuclear fuel reprocessing plants that are reported in the literature to determine if a reliable value of the scaling factor could be identified. Their study indicated that reported data were developed for different bases and assumptions and that different design and operating philosophies were employed; also, some estimates included costs that were omitted in other studies. Reported values for n were in the range 0.3 to 0.7. The Judkins and Olsen study did indicate that a single value of n is probably not appropriate over the entire capacity range (~300 to 3000 MT/yr) that will be met in the evaluation of alternate fuel cycles. The point of discontinuity in scaling factor cannot be fixed without further study, but it is suggested that the following values be used:

for $300 \leq R \leq 1200$, use $n = 0.35$;

for $1200 \leq R \leq 3000$, use $n = 0.6$;

where R is the reprocessing plant capacity in MT heavy metal/yr.

12. REFERENCES

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