NUCLEAR FUEL REPROCESSING COSTS

M. Jonathan Haire
Nuclear Science and Technology Division
Oak Ridge National Laboratory*
Oak Ridge, TN, USA 37831-6179

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ABSTRACT

Perhaps the most sensitive aspect of any project is information regarding costs. The capital and operating costs of reprocessing irradiated nuclear fuels that are presented in this paper were developed in the early 1980s but were never made public because of confidentiality concerns at the time. At the time this information was developed, the capital cost of a facility that reprocesses conventional light-water-reactor fuel at a rate of 1500 metric tons of heavy metal (MTHM) per year was estimated to range from 1.5 to 2.4 billion 1983 dollars. The annual operating costs for this plant were estimated to be ~6% of the capital cost. The capital cost of reprocessing fast reactor fuel is about 50% higher than that of reprocessing fuel from LWRs. This paper describes the variations in capital cost associated with different plant sizes and throughput capabilities. The cost of reprocessing nuclear fuels was established based on data from four sources available in the early 1980s: (1) the Allied-General Nuclear Services Plant at Barnwell, South Carolina, as well as the conceptual designs of facilities by (2) Exxon Nuclear Company, (3) E. I. du Pont de Nemours and Company, and (4) Oak Ridge National Laboratory.

The familiar rule-of-thumb scaling law [i.e., capital costs are proportional to the *n*th (~0.6) power of capacity] is not valid over wide ranges of plant throughput. The large capital costs required to establish a basic reprocessing capability cause capital costs to be nearly constant for small-capacity plants (i.e., *n* is near a value of 0.1 or lower). There is little economic advantage in increasing the capacity of a plant that processes uranium-based light-water fuels beyond 2500 MTHM/year or one that processes fast breeder fuels beyond 1150 MTHM/year. At these large throughput rates, doubling the capacity nearly doubles the capital costs (i.e., *n* is about 0.9). The economics of scale favor plants of large size (- 1500 MTHM/year).

The choice of overall facility design and operation (maintenance) philosophy can have a major impact on capital costs.

The present-day Advanced Fuel Cycle Initiative has identified a number of ways to reduce the costs predicted in 1983 [1].

I. INTRODUCTION

This paper summarizes the cost data from four major design studies and, by normalizing these data to a common basis or reference plant design, establishes a range of capital costs reflecting the diverse design and maintenance philosophies for each of eight fuel types to be processed.

During the 1970s and early 1980s, it was believed that reprocessing of fuel was an essential part of the nuclear fuel cycle, because the amount of fissile material in natural uranium resources is limited. The recovery and recycle of unused ^{235}U and bred ^{239}Pu fuel remaining in spent conventional light-water-reactor (LWR) fuel assemblies could extend these uranium resources by -50% in conventional reactors and, in breeder reactors, by a factor of -100% (assuming 2% losses during reprocessing and refabrication). If used as a blanket fertile material in breeder reactors, the uranium tailings accumulated from the uranium enrichment cascades could supply more energy than the total U.S. coal reserves, which are yet to be mined. The long-term national energy plan promoted breeder reactors that would be fueled initially with plutonium recovered from conventional light-water converter reactors. Later, breeder reactors would be supplied with plutonium fuel from the recycle of their own discharged spent fuel. Advanced converter reactors would derive fuel from the recycle of their own fuel and from excess fissile material recovered from breeder reactor fuel. Consequently, it was expected that fuel from a variety of reactor types (i.e., light water, advanced converter, and breeder) would require reprocessing.

The objective of this work was to estimate the costs of reprocessing eight types of nuclear fuel. Costs are estimated for plants dedicated to the reprocessing of a single fuel type at an annual average throughput rate of 1500 metric tons of heavy metal (MTHM)/year. The constituents of capital and operating costs are given. The impact on capital costs of varying the plant size or throughput rate is discussed, and the influence of various plant design philosophies is noted.

The work, performed at Oak Ridge National Laboratory under the Consolidated Fuel Reprocessing Program (CFRP) during the late 1970s and early 1980s, was a major effort to establish credible costs for reprocessing nuclear fuel. The overall objective of the CFRP was to develop the technology required for reprocessing a variety of possible nuclear fuels. The program coordinated U.S. research and development activities and demonstrated prototypes, advanced processes, and equipment. Close liaison was maintained with industry and with the reprocessing development activities of other countries.

Cost data from four sources were combined in a single presentation. The most credible reprocessing cost estimates available for commercial-scale (1500-MTHM/year) facilities in the United States are those from the Allied-General Nuclear Services (AGNS) plant located near Barnwell, South Carolina, and the conceptual designs of reprocessing facilities by Exxon Nuclear Company and E. I. du Pont de Nemours and Company. The AGNS facility provides a base of actual cost experience. Exxon Nuclear's cost data are based on 7 years of design effort, including over 200 man-years of architect engineering [2]. About 200 man-years of effort went into the DuPont conceptual design effort. The CFRP developed conceptual designs for smaller-scale (150-MTHM/year or less) demonstration facilities [3].

Several studies conducted in the early 1980s explore economic issues related to reprocessing. Laughon and Goodman describe the economics of various scenarios for operation of the Barnwell reprocessing plant in the United States [4]; de l'Estang and Peterson report reprocessing costs at the UP2 facility at La Hague, France [5]; Sandburg and Braun place the economics of reprocessing in a U.S. context [6]; and Duda and Frank describe worldwide views concerning reprocessing [7].

II. THE INFLUENCE OF PLANT DESIGN PHILOSOPHY ON COSTS

The capital costs of the AGNS facility and the Exxon Nuclear facility are essentially the same, ~1.5 billion 1983 dollars. The capital cost of the DuPont conceptual facility is ~2.4 billion 1983 dollars. The design bases and, subsequently, the estimated costs for all three facilities were adjusted to the common basis described in Table 1. A comparison indicates that the DuPont facility costs are 1.6 times greater than those for the AGNS and the Exxon Nuclear facilities. This difference is broadly interpreted as resulting from a more conservative design philosophy.

Much of the additional cost in the DuPont design is attributable to the redundancy of process equipment. Instead of a single set of equipment for a given functional area, the design calls for several sets. For example, the DuPont design contains a solvent treatment system for each of six solvent extraction cycles, three independent high-level-waste (HLW) solidification systems, and three low-level liquid waste evaporation systems.

A significant portion of the difference in costs is attributable to different maintenance philosophies. The DuPont design assumes a "canyon-type" facility, which would have the capability for replacing all process equipment remotely through the use of an overhead crane. The AGNS and Exxon facility designs assume that only the first solvent extraction cycle and the HLW process stream would be remotely operated and maintained. The Exxon design places failure-prone equipment in shielded "niches" for easier access in the contact-maintained portions of the plant. Contact maintenance plants can employ a more compact arrangement of equipment, thus resulting in a smaller process building and, consequently, lower capital costs. A design philosophy that calls for the capability for extensive use of in-situ maintenance beyond that of the DuPont concepts may increase capital costs even more. On the other hand, such a philosophy may increase plant on-line availability and ultimately reduce unit product costs.

Table 1. Major design bases for an LWR fuel reprocessing plant

Spent fuel reprocessing capacity	1500 MTHM/year
Fuel exposure, maximum	40,000 MWd/t
Minimum fuel age at receipt	90 d
Minimum fuel age at processing	150 d
Fuel enrichment, maximum	5.0 wt % ^{235}U equivalent
Principal product forms	UF_6, PuO_2
Process	
Fuel core exposure	Bundle shears
Uranium and plutonium separation and purification	Tributyl phosphate solvent extraction (PUREX)
Uranium conversion	Thermal denitration and direct fluorination
Plutonium conversion	Thermal denitration
Waste forms	
HLW	Borosilicate glass
Intermediate-level waste	Incorporated with HLW
Zirconium cladding hulls	Uncompacted and packaged
Miscellaneous combustible transuranic waste	Incinerated and packaged
Miscellaneous noncombustible transuranic waste	Compacted and packaged
Krypton-85	Packaged gas bottles
Tritium	Packaged as tritiated water
Ruthenium	Packaged on adsorbents
Iodine	Packaged on adsorbents
Storage capacity	
Spent fuel	465-t equivalent
HLW	15,000-t equivalent
Fuel cladding and hardware	15,000-t equivalent

It is clear that the choice of overall facility design philosophy has a prominent impact on capital costs.

III. CAPITAL COSTS

The capital and operating costs of reprocessing low-enriched uranium fuel from conventional LWRs were developed in detail and are used as the base case or the reference plant costs. The capital cost of a 1500-MTHM/year LWR fuel reprocessing plant ranges from 1.5 to 2.4 billion 1983 dollars. As discussed in the preceding section, this range reflects the diverse design philosophies. Table 1 defines the design bases for this reference plant. The facilities were designed to meet the security and regulatory requirements in effect in 1976.

The capital cost of a 1500-MTHM/year facility for processing fast breeder reactor (FBR) plutonium- and uranium-based fuels was found to be about 50% greater than that for LWR fuel. Table 2 and Fig. 1 present the constituent costs for LWR and FBR fuel reprocessing facilities developed from the Exxon Nuclear Company data base. Although this table and figure are based on only one of the three data sources, the relative cost estimates for constituent functions are believed to be roughly applicable to any facility design. Table 2 introduces the term “module.” A module here is defined as all of the equipment considered dedicated to or exclusively required of a given functional area, extending to and including cell shielding walls. Differences in LWR and FBR fuel module costs in Table 2 and Fig. 1 reflect the number and sizes of modules needed to maintain a 1500-MTHM/year capacity. The number of modules impacts the building space and plant operation requirements and is again reflected in the balance-of-building and balance-of-facility costs.

Figure 1 illustrates the major constituents of total cost. In general, the process equipment contained within the modules constitutes 15% of the total capital cost. The major components of total building costs are the receiving and storage facility (-25%) and the chemical processing facility (-60%). The utilities and support facilities, which comprise the major balance-of-plant costs, are -10 and 8%, respectively, of the total plant cost.

Another cost breakdown is in terms of direct and indirect costs. Direct construction costs (that is, the costs of materials and equipment and the labor for their installation) are -50% of the total facility capital cost. Indirect costs are divided into two categories—engineering services and distributable field cost. Engineering services, including cost engineering, engineering design, procurement, project management, construction management, and a burden factor (sick leave, overtime, etc.) are assumed to be 25% of the direct costs. Distributable field costs, which consist of temporary buildings, services and consumables, equipment rentals, and benefits, are assumed to be 30% of direct costs. Owner-operator costs during construction (including the owner’s responsibility for project management) are small and estimated to be about $22 million.

Table 2. Relative capital costs for the constituent modules of a 1500-MTHM/year plant

Module function	Relative capital cost (%)	
	LWR[a]	FBR[b]
Receiving	7.8	4.69
Sodium deactivation		2.92
Mechanical feed preparation	13.0	15.6
Tritium confinement	3.65	3.13
Dissolution	8.16	9.79
Feed preparation	0.69	0.73
Dissolver off-gas	4.17	3.54
Vessel off-gas	1.22	0.83
Solvent extraction, uranium	1.39	0.42
Solvent extraction, plutonium	1.56	1.88
Solvent treatment	1.04	0.31
Acid and waste recovery	1.91	1.35
HLW concentration	1.04	0.94
Intermediate-level waste concentration	1.39	0.94
Low-enriched uranium purification	0.69	
Low-enriched uranium conversion	3.99	
Fissile conversion	2.26	14.0
Head-end off-gas	0.35	0.31
Fertile conversion		0.63
HLW solution storage	3.13	1.77
HLW solidification	4.86	2.92
Fuel and waste storage	26.9	18.7
Fissile product storage	0.35	2.92
Fertile oxide storage		2.92
Cladding storage	10.4	8.75
Total	100.0	100.0[c]

[a]Fuel is low-enriched uranium.
[b]Fuel is plutonium-uranium oxide.
[c]The ratio of the total cost of FBR modules to LWR modules is 1.67.

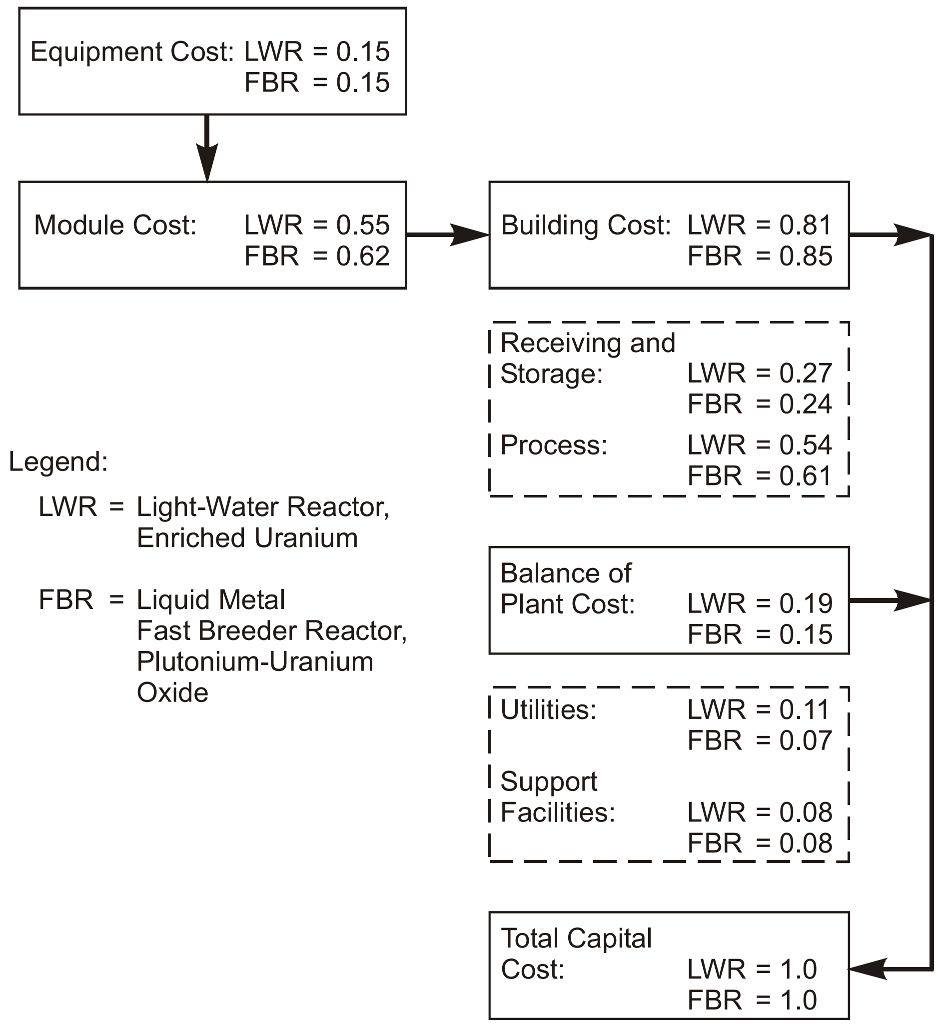

Fig. 1. Composite fractions of capital costs for facilities that process LWR or FBR fuel at 1500 MTHM/year.

A 30% contingency is applied to all direct and indirect cost estimates.

The difference in costs between the processing of LWR and FBR uranium-based fuels results primarily from differences in the physical design of the fuel assemblies and in the amount and concentration of fissile material. The amount of heavy metal per FBR fuel assembly is about half that of LWR fuel (178 vs 461 kg). Many operations in the head-end of a reprocessing facility (fuel receiving, fuel transfer, and shearing) are throughput limited by the number of pieces handled per day. Therefore, breeder fuel, with less heavy metal per fuel assembly, is more costly to process in this portion of the plant because additional parallel equipment is required to maintain the throughput rate.

The higher concentration of fissile material in breeder fuels increases the cost of processing because of the precautions necessary to prevent criticality. In this study, criticality is prevented by one or more of several mechanisms: by maintaining a specified distance between fuel assemblies, by limiting the amount and/or concentration of fissile materials in solutions, or by geometric restrictions on process equipment. A cursory examination of the use of soluble poisons to control criticality indicated only a small (roughly ±3%) impact on capital costs. When the processing capacity of equipment is limited by geometric restrictions, as in fissile production conversion, parallel lines of equipment must be used to process the much larger quantities of fissile material present in breeder fuels. Differences in product form (conversion of uranium to UF_6 for LWR fuel vs conversion to UO_3 for FBR fuel) and more compact UF_6 storage account for some differences in costs. Also, the additional step of removing the sodium-coolant contamination from fuel assembly surfaces adds to the cost of processing breeder fuels.

Table 3 presents the capital costs calculated for all eight fuel types examined in this study. The capital cost of facilities for reprocessing thorium-based fuels are factors of - 1.9 and 2.1 higher than those for uranium-based fuels (case 8 vs case 6 and case 3 vs case 1, respectively). Reprocessing thorium-based fuel introduces another fuel design parameter that influences costs, that is, the chemical composition of the fuel. Thorium-based fuels are more refractory than uranium-based fuels: (1) more dissolvers are needed, (2) dilute flowsheets impose a greater evaporation load, (3) more equipment replacement is required because of the corrosive effects of the fluoride catalyst needed to promote dissolution, and (4) an increased volume of HLW is present because of the complexants added to inhibit the fluoride corrosion. However, thorium-based fuel reprocessing is less developed than that of uranium-based fuel, and potentially greater reductions (or increases) in costs are possible.

Table 3. Relative capital costs for processing various fuels

Case	Fuel type[a]	Capital cost ratio
1	LWR, enriched uranium	1.0
2	LWR, plutonium-uranium	1.1
3	LWR, denatured uranium in thorium fuel	1.9
4	Heavy-water reactor, plutonium-thorium	2.2
5	Heavy-water reactor, denatured uranium in thorium fuel	2.1
6	FBR, plutonium-uranium	1.5
7	FBR, plutonium-uranium core, thorium blankets	2.5
8	FBR, denatured uranium in thorium core, thorium blankets	3.2

[a]Classified by reactor type, principal fissile material, and fertile material.

IV. THE INFLUENCE OF PLANT CAPACITY ON CAPITAL COSTS

The variation of capital cost with changing plant sizes is presented in Fig. 2. Capital cost estimates for the 1500-MTHM/year commercial-scale facilities, discussed in the preceding sections of this paper, are plotted in the figure. The CFRP completed a conceptual design of a 150-t/year (0.5-t/d) prototype plant, named the Hot Experimental Facility, in 1981. The process design basis for this smaller-scale experimental facility was adjusted to that of the 1500-MTHM/year commercial-scale facilities to obtain a direct comparison of capital costs. For example, the capability to process thorium and carbide fuel was deleted. The volume of the process building was reduced -40%. The capital cost of the optimized experimental facility was 1.0 ± 0.25 billion 1982 dollars.

The cost of a very small-scale [15-t/year (0.1-t/d)] reprocessing plant, designed to provide reprocessing services for just one or two demonstration breeder reactors, was scoped. The cost for such a stand-alone facility, built for and dedicated to reprocessing, was 0.8 ± 0.2 billion 1982 dollars.

The line drawn in Fig. 2 is calculated using a computer code based on cost information provided by the Exxon Nuclear Company; the line should not be construed as being a fit to the cost data. Computer code calculations indicate that there are virtually no capital cost differences in processing LWR and liquid-metal breeder-reactor fuels at throughput rates <300 MTHM/year. The cost of reprocessing FBR fuel increases at a faster rate with increasing capacity. At a 1500-MTHM/year throughput rate, the capital costs for FBR fuel reprocessing are 50% greater than those for LWR fuel.

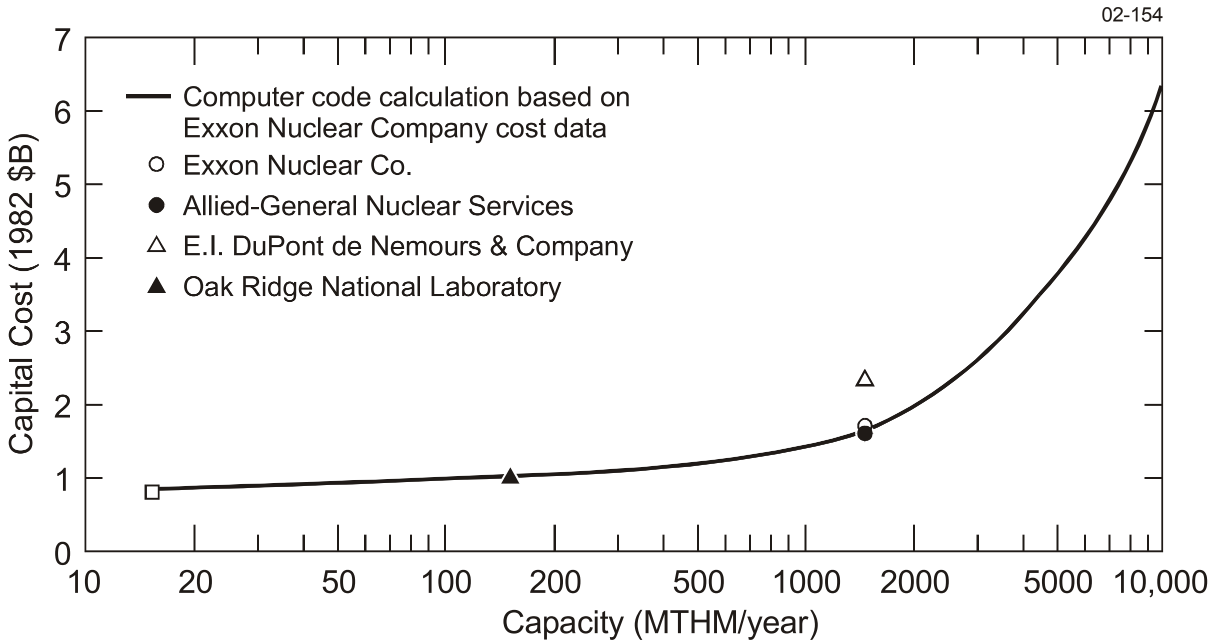

Fig. 2. Capital cost as a function of yearly throughput capacity.

Small plants are disproportionately expensive. As Fig. 2 indicates, no large difference in capital costs exists between experimental-scale and commercial-size plants. This is because such items as receiving stations, shears, and radiation shielding must be large and durable enough to handle individual shipping casks and fuel assemblies, regardless of the number handled per day. On the other hand, increasing a plant's capacity causes various modules to be duplicated, because each equipment module reaches its maximum throughput capability. Maximum module size is established by material-handling limitations, by criticality prevention requirements, or by equipment replacement feasibility (e.g., process concentrators). As a plant increases in size, its cost approaches a linear relationship with size.

In the familiar rule-of-thumb scaling law, capital costs are proportional to the nth powers of capacity; however, n is not a constant. The value of n approaches 0.1 for very small-capacity plants and 0.9 for very large plants. Thus, there is an upper limit to the axiom that states that the larger the plant size, the smaller the unit cost. For example, doubling the throughput rate of a large-capacity plant nearly doubles capital costs, and unit costs are largely dependent on capital recovery and interest on capital. The upper limit for minimizing unit cost is about 2500 and 1150 MTHM/year for LWR and FBR fuels, respectively. Should the fuel load exceed this capacity, consideration should be given to building a separate second facility. This construction may result in a slight increase in capital and unit costs; however, the redundancy would reduce the risk of losing total reprocessing capability.

The "economics of scale" is an inducement for building large-capacity plants. The magnitude of the capital costs associated with the massive shielding and specialized equipment of a reprocessing facility argues that capital costs should be distributed over as much fuel throughput as is practical to minimize the price per unit product. If the amount of fuel requiring reprocessing from a single reactor type is not large enough to fully utilize the throughput capability of a large-capacity plant, "campaigning" is a possibility. If such a strategy is used, the plant is designed to process fuels from other reactor types sequentially through the same process line. On the other hand, if the total fuel load is large and requires the paralleling of equipment modules, an economic advantage may exist in building separate, complete parallel process lines, with each line dedicated to a particular fuel type. Both of these reprocessing facility configurations are likely to be less costly than building separate facilities to process each type of fuel, unless the quantity of each fuel type is large enough to fully load relatively large, individual, single fuel-type plants.

V. ANNUAL OPERATING COSTS

The estimated relative annual operating costs for each constituent for reprocessing LWR fuel in a 1500-MTHM/year facility are given in Table 4. The annual operating costs are about 6% of the total capital costs. The labor force for the reference LWR fuel reprocessing case is projected to be about 500 persons. Labor costs for this study are assumed to be $40,000 per man-year including benefits. Consumables include product and waste containers and chemicals used directly in the process. Utility costs consist of steam (0.32¢/kg, or 0.7¢/lb) and electricity (1.3×10^{7}¢/J, or 3.5¢/kWh). Waste disposal costs are not included in this annual operating cost: the terminal isolation of radioactive wastes is considered to be a "pass-through" cost to the customer and is not a part of the reprocessing costs per se. The miscellaneous cost category includes property taxes, insurance, and decommissioning.

VI. UNIT PRICE

The unit prices for reprocessing low-enriched uranium fuel in a 1500-MTHM/year facility range from $370 to $585 per kilogram of heavy metal, depending on whether the facility is of the type designed by AGNS/Exxon Nuclear Company or is a DuPont-type design. This range of costs reflects different fundamental judgments concerning the reliability of process equipment and the amount of repair time required. Prices are given in terms of constant 1982 dollars.

Table 4. Relative annual operating cost estimates for a 1500-MTHM/year facility

Item	Percentage of total
Labor	23
Consumables	9
Utilities	13
Equipment replacement[a]	13
Taxes and miscellaneous	42
Total	100

[a]Five percent of initial equipment cost per year.

Unit price is basically the yearly expenditure of funds divided by the number of tonnes of fuel processed. Capital and operating costs given in the preceding sections are used as input data for calculating unit prices. Annual payments for the retirement of capital debit interest on invested capital and high-level radioactive waste disposal costs are the major contributors to the unit price. The methodology [8] used to calculate unit prices is based on a discounted cash flow analysis that provides for the recovery of all capital and operating expenses (plus a return on investment) by establishing a leveled price for the sale of processing services. The method assumes a 6-year design and construction period and a 20-year plant operating lifetime. The type of financing for a project has a prominent impact on the unit costs. Key financing parameters in this unit price calculation were a 0.35 to 0.65 debt-to-equity ratio, at 12% weighted average cost of money and a 54% federal and state income and property tax. The net derived fixed change rate was 0.226.

Relative unit prices for processing various fuel types are, to a close approximation, the same as that for relative capital costs (Table 3) because of the predominant influence of capital cost on unit prices. Therefore, the unit price for processing FBR fuel is about 50% greater than that for processing the corresponding fuel from thermal reactors.

VII. APPROACH USED IN ESTABLISHING COSTS

The capital costs for commercial-scale facilities previously provided in this paper were originally developed as part of the Nonproliferation Alternative System Assessment Program [9]. The Exxon Nuclear Company analysis is the only data base that presents results for breeder and other advanced reactor fuels. It is the Exxon Nuclear Company analysis [10,11] that is the basis for the constituent cost estimates.

A detailed regimen is used in developing cost estimates for reprocessing plants. The reprocessing plant is divided into functional areas or modules. Process flowsheets (i.e., block flow diagrams and stream data sheets) are prepared for each module. Equipment requirements, conceptual equipment arrangements, and equipment sizes are then established for each module corresponding to some established instantaneous throughput rate (e.g., 8 MTHM/d of conventional LWR reactor fuel).

The types and numbers of modules required to process each fuel at a rate of 1500 MTHM/year are identified and arranged in a logical plant layout. The required number and size of each module are calculated from the daily processing rate capability of each process cell, taking into consideration the maintenance time requirements, the time reserved for semiannual flushing for material accountability inventories, and an allowance for operation at less than maximum plant rates. Capital costs are estimated for the "balance of building" (e.g., control room, laboratory, maintenance shops, radioactive solid waste storage, and access corridors). Utility and ventilation requirements are estimated for building layouts and process flowsheets. The estimated balance-of-plant capital costs include site development, utility supply systems (electric, water and heating, steam plant, emergency utilities, etc.) support facilities (tank farms, warehouses, cold maintenance shops, guard houses, office buildings, parking, etc.), and (in the case of conventional LWR low-enriched uranium fuel only) fluorine generation facilities. Capital cost estimates include a 30% contingency. Annual operating costs are estimated for labor, consumables, utilities, equipment replacements, local and state taxes, and a sinking fund for subsequent decommissioning.

VIII. COST INDICES FOR 1983 AND 2003

Labor, materials, equipment, and construction costs have risen by approximate factors of 2, 2.1, 1.5, and 1.3, respectively, since 1983 [12].

IX. THE PERSPECTIVE FROM YEAR 2003

The central issue in plant design during the early 1980s was the reliability of processing equipment. Chemical reprocessing plants ran well when they were operational. However, a critical equipment failure could shut down a plant for months or even years. Two approaches were used to address this problem. A canyon-like plant design, such as that used at the Savannah River reprocessing plant, had the capability for quickly and remotely replacing plant equipment. The assumption was that of the thousands of items comprising the radioactive hot cell environment, at least some were likely to fail during the plant lifetime. Providing for rapid, remote replacement of failed equipment is capital cost intensive. The other approach, which was used at Barnwell, South Carolina, was to place the failure-prone equipment of a reprocessing plant in niches for easy access and removal. The Barnwell plant design had many small processing cells;

lower cell volume; and, thus, lower capital costs. Because the canyon and niche designs had disparate capital costs, the relevant question today is whether there have been technological changes that would tilt the approach toward one plant design philosophy or the other.

The present-day Advance Fuel Cycle Initiative [1] has identified a number of ways to dramatically reduce the reprocessing costs predicted in 1983. The cost-reduction steps include minimizing the number of process steps and simplifying the process steps needed. Furthermore, the use of automated processes and robotic techniques should be maximized. Most importantly, reprocessing costs must be evaluated within the context of the whole back-end of the nuclear fuel cycle. Collocating chemical processing, fuel fabrication, and waste storage facilitates the use of shared functions (e.g., security) and minimizes transportation costs. This is essentially the “energy center” concept of the late 1970s and early 1980s. Separation of heat-generating fission products (^{137}Cs and ^{90}Sr) would lower the heat load of the spent nuclear fuel repository and thus lower the (size) cost of the repository itself [13], thus lowering overall back cycle systems costs.

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