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MASTER

COST OF REPROCESSING HTGR FUELS IN CENTRAL PLANTS OF VARIOUS CAPACITIES

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INTRODUCTION

Economic studies⁽¹⁾ of nuclear fuel reprocessing indicate that both the reprocessing plant capital costs and the operating costs are relatively insensitive to plant throughput capacity. As a result, the unit reprocessing charges decrease sharply with increased plant throughput if a sufficient quantity of spent fuels exists to allow operation of the plant at its design capacity. A study has been made of the cost of reprocessing High-Temperature Gas-Cooled Reactor (HTGR) fuels in a plant sized to serve a 15,000-MW(e) HTGR economy.⁽²⁾ In a growing HTGR economy, an estimate of reprocessing costs as a function of plant capacity is needed to aid in establishing both the size of a reprocessing plant and when such a plant should be built. With the plant designed for a 15,000-MW(e) HTGR economy as a basis, costs have been developed for plants sized to serve 5,000-MW(e) and 45,000-MW(e) HTGR economies. The results of this cost study are summarized in this report. For discussion purposes, the following designations are used for the various size plants considered in this report:

HTGR Economy Size (MW(e))	Case Designation
15,000	IIIA
5,000	IIIA1
45,000	IIIA2

SUMMARY

Based on the conceptual design and the costs developed for the recovery of thorium and uranium from spent HTGR fuel elements in a central reprocessing plant sized to serve a 15,000 MW(e) HTGR economy, costs have been derived for two other HTGR fuel reprocessing plants of different capacities. These two other central reprocessing plants are sized to serve HTGR economies of 5,000 MW(e) and 45,000 MW(e). The HTGR fuel considered is a hexagonal block element containing pyrolytic-carbon coated fertile particles and silicon-carbide coated fissile particles. Flowsheets are based on a burn-leach head-end process, which prepares the HTGR fuel elements for subsequent decontamination and separation of the bred uranium.

The estimated capital, operating, and reprocessing costs for the three plants, based on present day costs, are given in Table 1.

TABLE 1
ESTIMATED CAPITAL, OPERATING, AND REPROCESSING COSTS

	Case IIIA1	Case IIIA	Case IIIA2
HTGR economy size, MW(e)	5,000	15,000	45,000
Capital cost, millions of dollars	20.7	30.8	58.8
Operating cost, millions of dollars per year	2.77	4.46	9.25
Reprocessing cost, millions of dollars per year	6.69	10.32	20.46
Reprocessing cost, dollars per kg of Th + U	121	62	41
Cost ratio (compared to Case IIIA)	0.648	----	1.98

The cost ratio for the IIIA2 plant is higher than that for the IIIA1 plant. Both the capital and operating cost contribute to the disproportionately high cost of the Case IIIA2 plant. Equipment size limitations require multiple process lines in the head-end processing steps in the Case IIIA2 plant. This requirement results in not only more equipment pieces, but also a substantially larger building than that needed for the smaller capacity plants. Major factors in plant operating costs are manpower, chemicals, and high-level waste disposal. Manpower costs do not vary greatly with plant capacity, but chemical and high-level waste disposal costs are essentially directly proportional to plant throughput. Manpower is the primary operating cost item in small plants. In the large plant, chemical and high-level waste disposal costs are of prime importance despite the manpower costs being somewhat higher than those in a small plant.

The reprocessing cost per unit of production decreases with increasing plant size. The percentage decrease, however, decreases with increasing plant capacity.

STUDY ASSUMPTIONS

The flowsheets and the equipment and plant designs used for this study are based on those used in the base-case (IIIA) study.⁽²⁾ The assumptions and criteria used are:

1. The plants are self-sufficient; i. e., all of the ancillary facilities required for sustained operation are incorporated into the plant sites.
2. Reprocessing capability is limited to HTGR fuel elements.
3. A "once-through" two-particle HTGR fuel cycle is used; i. e., the irradiated fissile particles that initially contain the fissile U^{233} and the U^{235} are not reprocessed. The composition of a typical fuel element is shown in Table 2.
4. When possible, the process steps and the plant and equipment designs are based on proven technology.
5. The plants operate at their design capacities 274 days/yr (75% on-line operating efficiency).
6. Plant products are thorium and bred U^{233} in the form of nitrate solutions. The U^{233} is shipped as required to an HTGR fuel refabrication plant and has a chemical purity adequate for fuel refabrication. Thorium is available for fuel refabrication after 10 to 15 yr of storage.
7. The plants have the capability of reworking U^{233} nitrate solutions from the refabrication plant.
8. A 15-yr amortization period is used.
9. The plants are located in the United States and meet U. S. Atomic Energy Commission licensing requirements.
10. HTGR fuels are shipped by rail in large standardized casks (capacity of about 40 elements).
11. The Case IIIA1 and Case IIIA2 plants have the capability of storing fuel elements for 90 and 60 days, respectively, when operating at their design rate.
12. Process equipment in radioactive service with less than 15-yr service life expectancy can be replaced remotely.
13. High-level radioactive wastes are solidified and shipped to repositories for ultimate disposal.
14. Reactor reflector blocks are not shipped to the reprocessing plants for disposal.
15. The Case IIIA1 and Case IIIA2 plants have the same basic plant layouts and equipment designs as the Case IIIA plant.

The fuel quantities processed for the three plants are listed in Table 3.

TABLE 2
FUEL ELEMENT CHARACTERISTICS

Shape	Hexagonal block
Width (across flats), in.	14.17
Length, in.	31.22
Weight at discharge from reactor, kg/element	
Graphite fuel block	97.46
Carbon binder	4.94
Fertile particle components	
Thorium	10.48
Uranium (primarily U ²³³)	0.30
Fission products	0.41
Oxygen (oxides)	1.55
Pyrolytic carbon and buffer carbon coatings	<u>10.90</u>
Subtotal	23.64
Fissile particle components	
Uranium (primarily U ²³⁴ and U ²³⁶)	0.15
Fission products	0.42
Oxygen (oxides)	0.08
Buffer carbon	0.30
Silicon carbide	0.36
Pyrolytic carbon	<u>2.22</u>
Subtotal	<u>3.53</u>
Total	129.57
Particle diameter, μ	
Fertile particle	
ThO ₂ kernel	350
With buffer carbon coating	410
With pyrolytic carbon coating	610
Fissile particles	
UO ₂ kernel (70% voids)	200
With buffer carbon coating	260
With silicon carbide intermediate coating	280
With pyrolytic carbon coating	400
Average burnup, MWD/tonne of actinides	67,000

TABLE 3
FUEL COMPONENT QUANTITIES

		Case IIIA		Case IIIA1		Case IIIA2	
		14, 063		4, 688		42, 188	
		51.3		17.1		154	
Fuel elements processed	Kg per Fuel Element	Kg per Year	Kg per Process Day	Kg per Year	Kg per Process Day	Kg per Year	Kg per Process Day
Per year							
Per process day							
Per day (yearly average)							
Carbon ^(a)	115. 52	1, 624, 500	5929	541, 600	1975	4, 873, 500	17, 790
Unirradiated fuel							
Thorium	11. 20	157, 500	574. 8	52, 500	191. 5	472, 500	1, 724 8
Uranium	0. 573	8, 055	29. 4	2, 685	9. 8	24, 165	88 2
Total	11. 793	165, 555	604. 2	55, 185	201. 3	496, 665	1, 813 0
Irradiated fuel							
Thorium	10. 48	147, 450	538. 1	49, 130	179. 2	442, 130	1, 614
Fertile particle U (83% U ²³³)	0 305	4, 290	15. 66	1, 430	5. 21	12, 870	47 0
Fertile particle fission products	0. 410	5, 760	21. 0	1, 920	7. 0	17, 300	63 1
Fissile particle U (primarily U ²³⁴ and U ²³⁶)	0. 150	2, 115	7. 72	703	2. 56	6, 330	23 1
Fissile particle fission products	0. 418	5, 865	21. 4	1, 960	7. 15	17, 630	64 4

(a) Does not include the buffer carbon coating on the fissile particles

In estimating the construction costs, the following assumptions, used in the Case IIIA study, (2) apply:

1. Labor costs are the same as those in Denver, Colorado, which are close to the national average.
2. A single general contractor acts as prime contractor and is responsible for site preparation, procurement, expediting, and testing.
3. Costs are those of September 1967.
4. No allowance is made for costs for unusual travel, subsistence or isolation pay, or severe weather conditions.
5. The site is free of obstructions.
6. No rock blasting is necessary.

The capital cost does not include state sales or use taxes, AEC licensing costs, client costs, escalation, or interest charges during construction or research and development.

DISCUSSION

The costs for Cases IIIA1 and IIIA2 were derived from the flowsheet, material balances, equipment designs, plant arrangements, and cost breakdowns developed for the Case IIIA plant. (2) With this approach, reasonably accurate cost estimates can be obtained with a minimum expenditure of time and effort. Deriving costs in this manner, however, requires that the derived cases have essentially the same flowsheet, equipment designs, and plant arrangements as those used in the base case.

FLOWSHEET AND EQUIPMENT DESIGNS

Although the same basic flowsheet is used in all three cases, process and size limitations on specific equipment items require a different number of equipment pieces to carry out given process steps for the different cases. In other process steps, the equipment items differ in size but not in number. For example, the required number of waste storage containers is directly related to the plant throughput rate, but an evaporator need differ only in size.

With the exception of multiple containers for fuel and waste storage and product shipment, Case IIIA requires duplicate process equipment items in the fuel-crushing and fuel-burning steps. Two burners are needed, primarily because of equipment size limitations. Material flow problems indicate that each burner should have an attendant crusher. It is likely that the burners will have a shorter service life than the other equipment

items. The use of multiple burners then provides greater assurance of operational continuity, although the plant processing rate may be reduced at times. With the lower processing rate of Case IIIA1 (one-third that of Case IIIA), it is possible to use just one burner. Two burners, however, are specified for reasons of assured operational continuity. Thus, except for equipment size, the main processing line for Case IIIA1 is identical to that used for Case IIIA. A simplified block flow diagram for Cases IIIA and IIIA1 is shown in Fig. 1.

The high processing rates of Case IIIA2 (three times that of Case IIIA) necessitate parallel process equipment items not only for the crushing and burning steps but also for the leaching, screening, waste-calcination, and waste-packaging steps. The Case IIIA burners are judged to be about the maximum size that can be used in a reprocessing plant. As a result, six burners and attendant crushers are required in the Case IIIA2 plant. For purposes of operational control and accountability, it is judged necessary to maintain the output from each burner as a separate batch. It is also desirable to minimize the lag time between burner discharge and leaching, thus reducing the in-process inventory and the surge storage requirements between the two process steps. On this basis, three leachers, each the size of the Case IIIA leacher, are specified. Separate receiver tanks, screening equipment, and hoppers are associated with each leacher because of material flow considerations. Beyond the leacher, the process steps in which only liquids are handled use single equipment items with throughput ratings three times those of Case IIIA. In the waste-calcination step, heat transfer considerations indicate the need for two Case IIIA2 fluidized bed calciners, each 50% larger than the Case IIIA calciner. Figure 2 shows a simplified block flow diagram for Case IIIA2.

PROCESS BUILDING

A central reprocessing plant must have the capability to receive and unload fuel elements from shipping casks and should provide storage for a supply of fuel elements. In Case IIIA, the plant has a fuel storage area with a capacity equivalent to 90 days of processing. This capability minimizes the dependency of plant operational continuity on fuel shipment and permits part of the required preprocessing decay storage to take place at the reprocessing plant. A similar storage capacity in terms of process days is specified for the Case IIIA1 plant. In terms of fuel element storage capacity, Case IIIA1 is one-third that of Case IIIA. Although the space occupied by the Case IIIA1 fuel storage racks is one-third that of Case IIIA, the building space needed for fuel receiving and fuel movement is essentially the same. As a result, the building volume of the Case IIIA1 fuel receiving and storage area (external dimensions) is only 40% less than the corresponding Case IIIA building volume.

Fig. 1. Block flow diagram for central HTGR fuel reprocessing plant, Cases IIIA and IIIA1

Fig. 2. Block flow diagram for central HTGR fuel reprocessing plant, Case IIIA2

Because of the high throughput rate of the Case IIIA2 plant, a simple scaleup of the Case IIIA fuel receiving and storage area configuration cannot be used. The number of fuel elements received per day at the Case IIIA plant is judged to be about the maximum that can be handled by a single receiving area. Thus, the Case IIIA2 plant needs multiple receiving areas. In addition, the time required for handling fuel storage containers indicates the need for two crusher cells in the Case IIIA2 plant. On the basis of the above, the Case IIIA2 plant has two separate storage areas with four receiving areas (two per storage area). With the inherently large HTGR economy associated with a Case IIIA2 plant, many shipping casks will be available for transporting the spent fuels from a large number of reactors. This factor should then allow significant flexibility in the scheduling of fuel shipments and reduce the reprocessing plant storage requirements in terms of the number of process days. The capacity of the Case IIIA2 storage areas is equivalent to 60 days of operation, as compared with 90 days for the Case IIIA and Case IIIA1 plants. Although the number of fuel elements stored in one of the Case IIIA2 storage areas is the same as that for Case IIIA, the Case IIIA2 building volume is 12% larger because of the additional receiving area.

Based on a process equipment arrangement similar to that used in the Case IIIA plant, the sizes of the various process cells were estimated for the Case IIIA1 and IIIA2 plants. The estimated overall external dimensions of the process cells are given in Table 4.

TABLE 4
OVERALL ESTIMATED EXTERNAL DIMENSIONS OF
PROCESS CELLS

	Width (ft)	Height (ft)	Length (ft)
Case IIIA	25	62	360
Case IIIA1	23	62	332
Case IIIA2	25	62	621

The building height requirements are established by the heights of the burners and the solvent-extraction columns. Since the heights of these equipment pieces are essentially independent of throughput capacity, equally tall buildings are required in all three cases. The smaller diameters of the Case IIIA1 equipment pieces permit a slight reduction in both the building width and length. The larger number of equipment pieces needed in the Case IIIA2 plants accounts for the significantly greater building length in comparison with the other two cases.

The size of the crusher cells is a function of the number of crushers. Because the Case IIIA and Case IIIA1 plants each require two crushers, the crusher cells are identical. The Case IIIA2 plant requires six crushers. As discussed previously, time-cycle considerations indicate the need of at least two independent crusher cells. Thus, the six crushers are equally divided between two cells. With three crushers per cell, the cell volume per crusher is somewhat less than that needed in a two-crusher cell. The volume of the Case IIIA2 crusher cells is 2.66 times that needed in Case IIIA.

The thorium and waste-storage requirements are directly related to the plant throughput capability. For thorium, the same number (six) of storage tanks is used in all three cases; however, the tank sizes vary from case to case. With intermediate-level waste, the fission product decay heat imposes some limit on the storage tank volume. For estimating purposes, the intermediate-level waste tank specified for the Case IIIA plant is taken as the maximum allowable size. In order to accommodate a 5-yr output of intermediate-level waste, Case IIIA1 has a tank one-third the size of the Case IIIA tank, and Case IIIA2 has three separate tanks. In all three cases, the packaged calcined high-level waste and fissile particles are stored in a single storage area. Since the size of the individual storage containers is the same in all cases, the required floor space for the containers is directly proportional to the plant throughput capability. The volume of the waste-storage building, however, is somewhat less than proportional to plant size because of the space allocated to personnel access and waste-container transfer.

In estimating the building volumes associated with the operating and maintenance galleries for the derived cases, the gallery heights and widths of the Case IIIA plant were used. Gallery lengths are established by the respective building lengths. The building volume assigned to the analytical facilities is the same for all three cases because the types of analyses required are essentially independent of the plant processing rate. Because of the multiple head-end process lines required in the Case IIIA2 plant, more samples will be taken and the number of analytical personnel is increased.

Identical administration buildings are specified for Cases IIIA and IIIA1. A slightly larger administration building is used in Case IIIA2 because of the greater personnel requirements. Other major structures, i. e., the warehouse, the shops and utilities building, and the plant stack, vary in size with the plant capacity.

COST DEVELOPMENT

In order to evaluate the reprocessing costs for the various size plants, both the capital and operating costs must be estimated. The capital costs for the Case IIIA1 and Case IIIA2 plants were derived from the cost breakdowns used in developing the costs for the base-case (IIIA) plant. In this cost breakdown the direct construction costs were divided into four main categories: (1) the reprocessing building, (2) miscellaneous structures, (3) process equipment, and (4) auxiliary equipment (piping, electrical, and instrumentation).

When the construction cost breakdown for the Case IIIA reprocessing building was developed, the costs associated with each of the various building areas were estimated. The building volume for each of the areas was determined from the plant arrangement drawings developed for this case. Based on a comparison of the number and size of the equipment pieces contained in each area, the building volumes of the corresponding areas in the derived cases were estimated. The construction cost of the various building areas was then determined by assuming that the construction costs are proportional to the building volume. These reprocessing building area costs are contained in Table 5.

The estimated construction costs for the various miscellaneous structures are listed in Table 6. The vaults for the thorium storage tanks and the intermediate-level waste tanks constitute the major cost items in this category. As discussed above, the capacities of these storage facilities are proportional to the plant throughput capabilities. All three plants utilize one thorium storage vault but their sizes vary. The costs of the Case IIIA1 and Case IIIA2 thorium storage vaults were derived from the estimated cost of the Case IIIA vault by applying the so-called "six-tenths" factor. This factor assumes that the cost of a unit differing only in size from a unit whose cost is known is proportional to the 0.6 power of the size ratio. For example, the Case IIIA1 vault equals the cost of the IIIA vault times (capacity of the Case IIIA1 vault/capacity of the Case IIIA vault)^{0.6} or \$522,000 (0.33/1)^{0.6} = \$271,000. The power of the size ratio is also known as the scaling factor. The cost of the Case IIIA1 intermediate-level waste storage tank was also estimated by applying the "six-tenths" factor. As discussed previously, the Case IIIA2 intermediate-level waste storage facility contains three tanks of the same design as the Case IIIA tank. The construction cost of the Case IIIA2 storage tanks is then taken as three times the Case IIIA cost.

The estimated cost of the process equipment for the derived cases was obtained from the itemized equipment cost breakdown developed for Case IIIA. As discussed above, both the number and size of the equipment

TABLE 5
COST OF REPROCESSING BUILDING

Building Area	Case IIIA(a)		Case IIIA1		Case IIIA2	
	Building Volume (ft ³)	Cost (\$)	Building Volume (ft ³)(b)	Cost (\$)(c)	Building Volume (ft ³)(b)	Cost (\$)(c)
Fuel receiving and storage	285,460	805,000	167,800	474,000	637,720	1,800,000
Crusher cell	70,743	199,000	70,743	199,000	188,600	530,000
High-level waste cell	91,904	258,000	73,888	210,000	114,030	324,000
Burner cell	87,296	246,000	67,000	189,000	266,000	750,000
Leacher cell	62,304	176,000	50,900	144,000	152,700	431,000
Solvent extraction cell	117,930	334,000	105,000	298,000	163,000	462,000
Intermediate-level waste cell	74,400	210,000	59,900	169,000	89,900	254,000
Uranium purification	60,500	170,000	55,600	156,000	71,300	200,000
Air lock	51,100	146,000	47,000	134,000	60,500	173,000
Analytical laboratory	136,290	383,000	136,290	383,000	136,290	383,000
Waste storage basin	379,710	980,000	155,150	401,000	961,370	2,480,000
Miscellaneous areas	384,147	733,300	357,886	681,000	709,856	1,352,000
Total		4,640,300		3,438,000		9,139,000

(a) From cost engineering estimate

(b) Estimated on basis of plant arrangement in Ref. 2

(c) Based on cost per cubic foot for corresponding Case IIIA area

TABLE 6
COST OF MISCELLANEOUS STRUCTURES

Structure	Cost (dollars)		
	Case IIIA ^(a)	Case IIIA1 ^(b)	Case IIIA2 ^(b)
Warehouse	32, 000	20, 000	60, 000
Shops and utilities	172, 000	150, 000	250, 000
Administration building	90, 000	90, 000	110, 000
Miscellaneous buildings	44, 700	40, 000	65, 000
Thorium storage vault	522, 000	271, 000	1, 010, 000
Intermediate-level waste storage tank	170, 000	88, 000	510, 000
Stack	<u>89, 000</u>	<u>70, 000</u>	<u>150, 000</u>
	1, 119, 700	729, 000	2, 155, 000

(a) From cost engineering estimate

(b) Estimated from costs for Case IIIA. A scaling factor of 0.6 was used for the thorium storage vault costs and the Case IIIA1 intermediate-level waste tank cost. In Case IIIA2, three intermediate-level waste tanks identical to the Case IIIA tank are used; therefore, the cost is given as three times the Case IIIA cost.

pieces differ from case to case. Where only the number of a particular equipment piece varied, the same unit price was applied in all three cases. Where only the size varied, a 0.6 scaling factor was used. The estimated costs of the process equipment for the various processing areas are summarized in Table 7.

The cost of auxiliary equipment (piping, electrical equipment, and instrumentation) is presented in Table 8. The base-case (IIIA) study did not detail the process and service piping, electrical work, and instrumentation. Costing was done by analyzing the published cost breakdowns of existing fuel reprocessing plants to determine the cost of these various auxiliary items as a percentage of the process equipment cost. These percentages were applied to the HTGR fuel reprocessing plants. The costs of pumps and yard piping for the derived cases were obtained by applying a 0.6 scaling factor to the Case IIIA costs. A constant cost (1.0 scaling factor) was used for the concrete encased piping because the major cost is associated with the encasements, the cost of which is essentially independent of the contained pipe size.

The overall capital costs for the three cases are summarized in Table 9, together with the calculated overall scaling factors. With the Case IIIA plant capital cost as reference, the scaling factor for the Case IIIA2 plant cost (0.59) is significantly higher than the scaling factor for the Case IIIA1 plant cost (0.36). This difference results from the greater number of head-end process equipment pieces and the much larger reprocessing building required for the high-capacity plant. Table 9 also lists the annual fixed charges on the capital investment. This charge includes return on the capital investment, depreciation, taxes, and equipment replacement.

A plot of the capital cost of the three cases as a function of plant capacity is shown in Fig. 3, along with the capital costs developed in other central reprocessing plant studies. In comparing the results of this study with the results of the other studies, it should be kept in mind that the other studies were based on natural or slightly enriched uranium fuels and were made 5 to 10 yr ago. A similarity in the scaling factors (slopes of the curves), however, is evident.

The operating costs for the various size HTGR plants are summarized in Table 10; the cost developments of the various categories are contained in Tables 11 through 14. Items that account for most of the operating costs are manpower, chemicals, and high-level waste disposal. Manpower costs are relatively insensitive to plant throughput capacity, but chemical and high-level waste disposal are essentially directly proportional to the plant production rate. Manpower cost, then, is the major factor in the Case IIIA1

TABLE 7
COST OF PROCESS EQUIPMENT

Area	Cost (dollars)		
	Case IIIA ^(a)	Case IIIA1 ^(b)	Case IIIA2 ^(b)
Fuel receiving and storage	1, 107, 000	427, 500	2, 337, 400
Crusher cell	156, 900	148, 600	421, 000
High-level waste cell	251, 900	217, 300	419, 300
Burner cell	475, 200	246, 300	1, 408, 100
Leacher cell	186, 600	96, 700	465, 100
Solvent extraction cell	195, 700	103, 400	398, 600
Intermediate-level waste cell	176, 400	91, 000	339, 700
Uranium purification cell	118, 400	61, 300	269, 800
Waste storage basin	112, 100	68, 100	198, 300
Analytical laboratory	987, 200	987, 200	987, 200
Thorium storage	429, 000	222, 000	829, 000
Auxiliary facilities	<u>580, 600</u>	<u>348, 300</u>	<u>978, 500</u>
Total	4, 777, 000	3, 017, 700	9, 052, 000

(a) From cost engineering estimate

(b) Based on: (1) same process as Case IIIA, (2) number of parallel process steps as shown in Figs. 1 and 2, (3) itemized cost breakdown for Case IIIA using a scaling factor of 0.6 for equipment pieces that differ in size from Case IIIA.

TABLE 8
COST OF PIPING, ELECTRICAL EQUIPMENT, AND
INSTRUMENTATION

Item	Cost (dollars)		
	Case IIIA ^(a)	Case IIIA1	Case IIIA2
Process piping (48.6% of equipment cost)	2,320,000	1,465,000	4,400,000
Service piping (28% of equipment cost)	1,340,000	845,000	2,540,000
Pumps	67,000	35,000 ^(b)	130,000 ^(b)
Encased yard piping	122,000	122,000	122,000
Other yard piping	56,000	29,000 ^(b)	108,000 ^(b)
Electrical equipment (9.7% of equipment cost)	464,000	293,000	880,000
Instrumentation (13.9% of equipment cost)	<u>662,000</u>	<u>418,000</u>	<u>1,253,000</u>
	5,031,000	3,207,000	9,433,000

(a) From cost engineering estimate

(b) Derived from Case IIIA cost using a scaling factor of 0.6.

TABLE 9
CAPITAL COST SUMMARY

	Cost (dollars)		
	Case IIIA	Case IIIA1	Case A2
Reprocessing building (Table 5)	4,640,300	3,438,000	9,139,000
Miscellaneous structures (Table 6)	1,119,700	729,000	2,155,000
Equipment (Table 7)	4,777,000	3,017,700	9,052,000
Piping, electrical equipment, and instrumentation (Table 8)	5,031,000	3,207,000	9,433,000
Yard improvements	54,000 ^(a)	54,000 ^(b)	70,000 ^(b)
Direct construction cost	15,622,000	10,445,700	29,849,000
Contractors overhead and profit (25%)	3,906,000	2,611,400	7,462,500
	19,528,000	13,057,100	37,311,500
Design (15%)	2,929,000	1,958,600	5,596,700
	22,457,000	15,015,700	42,908,200
Contingency (25%)	5,614,000	3,754,000	10,727,000
	28,071,000	18,769,700	53,635,200
Land	500,000	500,000	500,000
	28,571,000	19,270,000	54,135,000
Startup cost ^(c)	2,232,000	1,386,000	4,626,000
Capital cost	30,803,000	20,656,000	58,761,000
Cost ratio (compared to Case IIIA)		0.670	1.90
Scaling factor ^(d) based on Case IIIA		0.36	0.59
Annual fixed charge (17.41% of capital cost) ^(e)	5,362,800	3,596,200	10,229,300

(a) From cost engineering estimate

(b) Derived from Case IIIA cost breakdown.

(c) Taken as 50% of annual operating cost (Table 10).

(d) Defined by $(\text{Size A}/\text{Size B})^S = \text{Cost A}/\text{Cost B}$, where S is the scaling factor.

(e) Based on Ref. 3 with a 15-yr plant life.

Fig. 3. Reprocessing plant capital cost versus plant capacity

TABLE 10
OPERATING COST SUMMARY

	Cost (\$/yr)		
	Case IIIA	Case IIIA1	Case IIIA2
Manpower (Table 11)	2, 014, 000	1, 789, 500	2, 650, 700
Chemicals	902, 200 ^(a)	300, 700 ^(b)	2, 706, 500 ^(c)
Utilities	206, 000 ^(a)	103, 000 ^(d)	412, 000 ^(e)
High-level waste disposal (Table 12)	972, 300	373, 700	2, 701, 600
Intermediate-level waste disposal (Table 13)	62, 500	33, 400	185, 400
Solid waste disposal	75, 000	50, 000	150, 000
Thorium storage (Table 14)	<u>231, 900</u>	<u>121, 000</u>	<u>446, 100</u>
	4, 463, 900	2, 771, 300	9, 252, 300

(a) From Ref. 2.

(b) One-third Case IIIA.

(c) Three times Case IIIA.

(d) One-half Case IIIA.

(e) Twice Case IIIA.

TABLE 11
MANPOWER REQUIREMENTS AND COST

Position	Case IIIA			Case IIIA1			Case IIIA2		
	No.	Dollars/Year		No.	Dollars/Year		No.	Dollars/Year	
		Salary	Total		Salary	Total		Salary	Total
Plant manager	1	20,000	20,000	1	20,000	20,000	1	22,000	22,000
Assistant plant manager	1	17,500	17,500	1	17,500	17,500	1	18,500	18,500
Production manager	1	15,000	15,000	1	15,000	15,000	1	16,000	16,000
Engineering manager	1	15,000	15,000	1	15,000	15,000	1	15,000	15,000
Employee relations manager	1	12,000	12,000	1	12,000	12,000	1	12,000	12,000
Personnel manager	1	12,000	12,000	1	12,000	12,000	1	12,000	12,000
Laboratory manager	1	12,000	12,000	1	12,000	12,000	1	12,000	12,000
Maintenance manager	1	11,000	11,000	1	11,000	11,000	1	12,000	12,000
Materials manager	1	11,000	11,000	1	11,000	11,000	1	12,000	12,000
Accounting manager	1	14,000	14,000	1	14,000	14,000	1	14,000	14,000
Assistant accounting manager	1	10,000	10,000	1	10,000	10,000	1	10,000	10,000
Accountability manager	1	12,000	12,000	1	12,000	12,000	1	13,000	13,000
Health physics manager	1	11,000	11,000	1	11,000	11,000	1	11,500	11,500
Shift supervisors	5	12,000	60,000	5	12,000	60,000	5	12,500	62,500
Assistant shift supervisors	5	10,000	50,000	5	10,000	50,000	5	10,500	52,500
Engineers	15	11,000	165,000	13	11,000	143,000	17	11,000	187,000
Power operators	10	8,000	80,000	10	8,000	80,000	12	8,000	96,000
Process operators	50	7,500	375,000	42	7,500	315,000	80	7,500	600,000
Maintenance personnel	25	7,800	195,000	20	7,800	156,000	35	7,800	273,000
Health physicists	10	7,500	75,000	6	7,500	45,000	15	7,500	112,500
Chemists	5	10,000	50,000	5	10,000	50,000	5	11,000	55,000
Laboratory analysts	21	6,000	126,000	21	6,000	126,000	30	6,000	180,000
Secretaries	7	5,500	38,500	6	5,500	33,000	8	5,500	44,000
Clerks	8	5,000	40,000	6	5,000	30,000	10	5,000	50,000
Guards	7	6,000	42,000	7	6,000	42,000	7	6,000	42,000
Nurses	2	6,000	12,000	2	6,000	12,000	3	6,000	18,000
Janitors	2	5,500	11,000	2	5,500	11,000	2	5,500	11,000
	185		1,492,000	163		1,325,500	247		1,963,500
Overhead (35%)			522,000			464,000			687,200
			2,014,000			1,789,500			2,650,700

TABLE 12
COSTS FOR HIGH-LEVEL WASTE DISPOSAL

Cost of second basin, ^(a) dollars Cost of third basin, ^(b) dollars	Case IIIA		Case IIIA1		Case IIIA2	
	1, 962, 000		842, 800		4, 812, 600	
	2, 232, 000		1, 112, 100		5, 082, 100	
	Cost (\$/yr)					
	Fissile Particles	Calcined Waste	Fissile Particles	Calcined Waste	Fissile Particles	Calcined Waste
Containers ^(c)	226, 800	271, 000	75, 600	90, 400	680, 400	813, 000
Second basin (built 5 yr after plant startup) ^(d)	75, 500	75, 500	32, 400	32, 400	185, 100	185, 100
Third basin (built 10 yr after plant startup) ^(d)	64, 000	64, 000	32, 000	32, 000	146, 100	146, 100
Shipping ^(e)	55, 900	46, 000	19, 800	16, 500	168, 000	131, 000
Salt mine disposal ^(f, g)	35, 900	40, 700	12, 000	13, 600	107, 700	122, 100
Surveillance ^(g, h)	8, 500	8, 500	8, 500	8, 500	8, 500	8, 500
	466, 600	505, 700	180, 300	193, 400	1, 295, 800	1, 405, 800
	972, 300		373, 700		2, 701, 600	

^(a) Building cost (Table 5) plus equipment cost (Table 7) plus indirect costs

^(b) \$150, 000 is added to direct construction cost of second basin. Cost difference reflects indirect costs

^(c) Unit costs: \$600 per fissile particle container and \$500 per calcined waste container

^(d) Basin costs are normalized over the plant life (15 yr) at 6% interest and divided equally between fissile particle and calcined waste storage.

^(e) Shipping cask costs based on Refs. 3 and 4. Shipping costs based on Ref. 5 for 1000-mile distance

^(f) Expenses incurred 15 yr after processing. The listed costs are invested for 15 yr at 6% interest to yield actual cost.

^(g) Based on Refs. 4 and 6

^(h) Based on 4 man years annually and costs divided equally between fissile particles and calcined wastes

TABLE 13

COSTS FOR INTERMEDIATE-LEVEL WASTE DISPOSAL

	Case IIIA	Case IIIA1	Case IIIA2
Cost of tank(s), dollars	305,500 ^(a)	158,000 ^(b)	916,000 ^(c)
	Cost (\$/yr)		
First tank(s) ^(d)	0	0	0
Second tank(s) (built 5 yr after plant startup) ^(e)	23,500	12,200	70,500
Third tank(s) (built 10 yr after plant startup) ^(e)	17,600	9,100	52,800
Surveillance	2,100 ^(f, g)	2,100 ^(f, g)	4,200 ^(g, h)
Final disposal	<u>19,300^(g, i)</u>	<u>10,000^(g, i)</u>	<u>57,900^(g, i)</u>
	62,500	33,400	185,400

(a) From Ref. 2

(b) Tank is one-third the size of that in Case IIIA. Cost taken as $(1/3)^{0.6}$ times that of Case IIIA.

(c) Three tanks the size of that in Case IIIA are used. Cost taken as three times that of Case IIIA.

(d) Included in plant capital cost.

(e) Costs normalized over plant operating life (15 yr) at 6% interest.

(f) For one-half man year annually

(g) Expenses incurred 15 yr later. Listed costs are assumed to be invested for 15 yr at 6% interest to yield actual cost.

(h) For one man year annually

(i) Based on \$10/ft³ of waste for retrieval packaging, shipment, and disposal to a licensed burial ground.

TABLE 14
COSTS FOR THORIUM STORAGE

	Case IIIA	Case IIIA1	Case IIIA2
Cost per vault, dollars	1,709,000 ^(a)	885,000 ^(b)	3,303,500 ^(c)
	Cost (\$/yr)		
First vault ^(d)	0	0	0
Second vault (built 5 years after plant startup) ^(e)	131,500	68,000	254,000
Third vault (built 10 years after plant startup) ^(e)	98,300	50,900	190,000
Surveillance ^(f)	<u>2,100</u>	<u>2,100</u>	<u>2,100</u>
	231,900	121,000	446,100

(a) From Ref. 2

(b) Vault and tanks are one-third the size of those in Case IIIA. Cost taken as $(1/3)^{0.6}$ times that of Case IIIA.

(c) Vault and tanks are three times the size of those in Case IIIA. Cost taken as $3^{0.6}$ times that of Case IIIA.

(d) Included in plant capital cost

(e) Vault cost normalized over plant operating life (15 yr) at 6% interest

(f) Assumes one-half man year annually for 15 yr. Listed costs are invested for 15 yr at 6% interest to yield actual cost.

operating cost; however, in Case IIIA2, chemical and high-level waste disposal costs are equally important.

Table 15 presents the estimated reprocessing charges in terms of both the annual cost and the cost per kilogram of thorium plus uranium processed. The cost per kilogram for the Case IIIA1 and Case IIIA2 plants are 200 and 67%, respectively, of the Case IIIA plant. Thus, although the reprocessing charges decrease with increasing plant capacity, the degree of reduction decreases. A plot of the reprocessing charges as a function of plant capacity is shown in Fig. 4. This plot also contains the results of earlier studies on uranium fuel reprocessing plants. Again, the trends indicated by this study are in line with the other studies. In determining the reprocessing charges, not only for the HTGR fuel reprocessing plants but also for the other reprocessing plants referred to in Fig. 4, it is assumed that the plants operate at their design capacities. Because of the high annual fixed charges inherent to fuel reprocessing plants, operation at rates less than the design rate would significantly increase the reprocessing cost per unit of fuel processed. Reprocessing costs in a plant operating at 50% of design capacity would be a factor of almost two higher than the costs for a plant operating at capacity.

TABLE 15
REPROCESSING CHARGES

	Cost (\$/yr)		
	Case IIIA	Case IIIA1	Case IIIA2
Fixed charge (Table 9)	5,362,800	3,596,200	10,229,300
Operating cost (Table 10)	4,463,900	2,771,300	9,252,300
	<u>9,826,700</u>	<u>6,367,500</u>	<u>19,481,600</u>
Contingency reserve (5%)	<u>491,300</u>	<u>318,400</u>	<u>974,100</u>
	10,318,000	6,685,900	20,455,700
Cost ratio (compared to Case IIIA)		0.648	1.98
Scaling factor		0.40	0.62
Thorium plus uranium, kg/year ^(a)	165,555	55,185	496,665
Dollars per kg	62	121	41

(a) Based on content in unirradiated fuel

Fig. 4. Reprocessing cost versus plant capacity

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