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INFORMAL AEC RESEARCH  
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HTGR FUEL REPROCESSING  
EFFECTS OF INCLUDING A SILICON  
CARBIDE COATING ON FERTILE FUEL PARTICLES

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## INTRODUCTION

Advanced designs of HTGR fuel elements include a silicon carbide barrier coating on both the fertile and fissile fuel particles. Previous studies (Refs. 1,2) on the reprocessing of spent HTGR fuel elements are based on element designs in which only the fissile particles have a silicon carbide coating. In the basic study (Ref. 1), Case IIIA, the fissile particles are not processed and the reprocessing method used does not penetrate the silicon carbide coating on these fissile particles. The Case IIIA3 study (Ref. 2) considers processing the silicon carbide-coated fissile particles and discusses the additional process steps needed to penetrate this barrier coating preparatory to forming a solvent extraction feed solution. The inclusion of a silicon carbide coating on the fertile particles also requires additional process steps, similar to some of those outlined in Ref. 2. This report discusses the additional process steps required in a plant processing only fertile particles (Case IIIB) and in a plant processing both fissile and fertile particles (Case IIIB1).

## SUMMARY

Conceptual flow sheets and reprocessing costs have been developed for the recovery of thorium and uranium from HTGR fuel elements containing silicon carbide-coated fissile and fertile particles. Two cases were considered. In Case IIIB the fertile particles are processed, and the fissile particles are isolated, packaged, and stored for eventual disposal or future processing. In Case IIIB1, both types of particles are processed to recover the contained uranium. The flow sheets and costs were derived from those contained in an earlier study (Ref. 1) where only the fissile particles had a silicon carbide coating. A modified burn-leach head-end process is used to prepare the fuel components for separation and decontamination by solvent extraction.

The estimated costs associated with the two cases are listed below. The Case IIIA costs are included for reference.

	Case IIIA	Case IIIB	Case IIIB1
Capital cost, millions of dollars	30.8	32.2	34.7
Annual operating cost, millions of dollars	4.5	5.0	5.4
Reprocessing charge, dollars per kg (Th + U)	62	67	73

The reprocessing charges given above assume plant operation at its design capacity. No credit is included for the recovered thorium or fissile particle uranium. The incremental cost of recovery of the fissile particle uranium is \$0.45/g.

## STUDY BASES

The process flow sheets, material balances, equipment designs, and plant arrangements used in this study are based on the following assumptions and criteria.

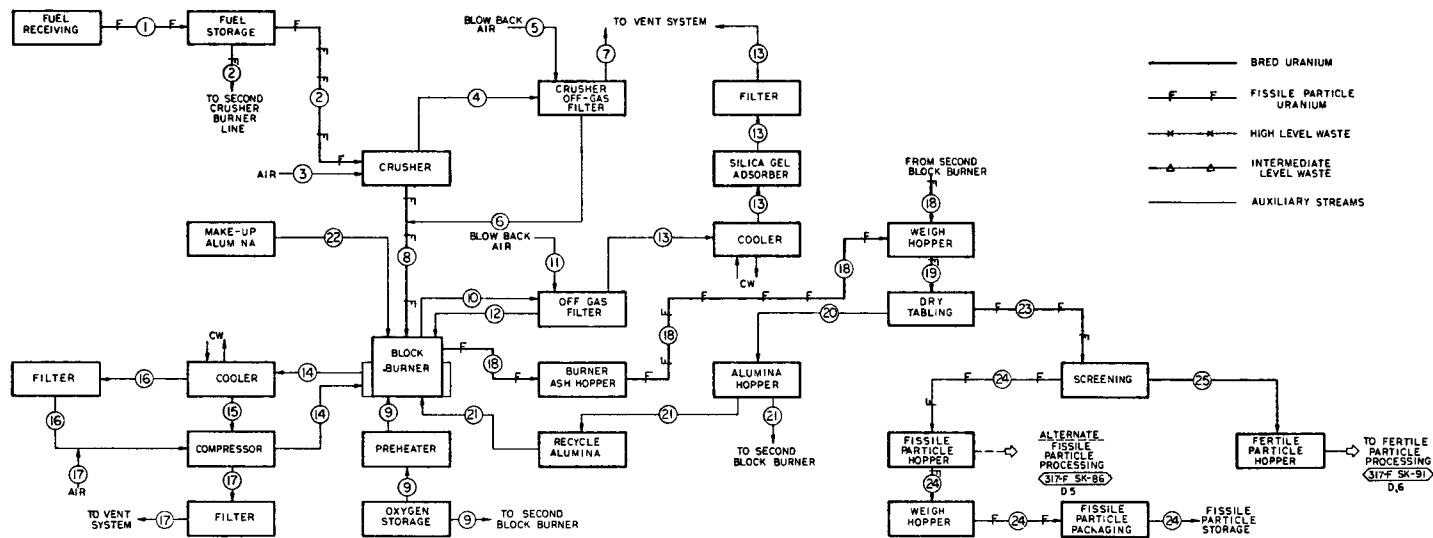
1. The capability of processing silicon carbide-coated fertile and fissile particles is incorporated into the basic plant (Case IIIA) described in Ref. 1.
2. A once-through, two-particle HTGR fuel cycle is used, i.e., the residual uranium in the spent fissile particles is not recycled to HTGRs. The fissile particles initially contain the recycle  $U^{233}$  from the spent fertile particles and the makeup  $U^{235}$ . A typical fuel element composition is shown in Table 1. Fuel elements designed to operate on the HTGR bred uranium cycle are discussed under HTGR FUEL VARIATIONS.
3. Where it is possible, the process steps, plant, and equipment designs are based on proven technology.
4. The plant has the capacity to serve a 15,000 Mw(e) HTGR economy.
5. Process equipment in radioactive service with less than a 15-year life expectancy is designed for remote replacement.
6. Silicon carbide residues from head-end processing are packaged and shipped to a licensed burial ground.
7. Fissile particle processing (Case IIIB1) is carried out in equipment independent of the main line (fertile particle) processing equipment.

## PROCESS DESCRIPTION

The basic process steps used to prepare silicon carbide-coated fertile particles for solvent extraction are a combination of those described in Refs. 1 and 2. Spent HTGR fuel elements are crushed and then fed to a large burner where the graphite block, the carbon binder, and the outer pyrocarbon fuel particle coatings are oxidized to  $CO_2$ . The ash from the block burner contains the silicon carbide-coated particles, both fissile and fertile, and the fused aluminum oxide (alumina) burner bed material. The burner ash then undergoes a two-stage mechanical separation to divide it into its three components. First a dry tabling step separates the particles according to shape. This divides the ash into two fractions, one containing the spherical fuel particles and the other the irregularly shaped alumina particles. An estimated 5% crossmixing occurs because dry tabling does not give a complete separation. The alumina fraction and the unseparated fuel particles are recycled to the block burner so that eventually all of the fuel particles exit with the fuel particle fraction. From the dry tabling step, the fuel particle fraction is fed to a mechanical screener which separates the two particle types according to size difference. The alumina in the screen feed divides between the fissile and fertile particle fractions. For flowsheet purposes, the alumina is assumed to divide evenly between these two screen products. The block flow diagram and material balance for the above crushing, block burning, and mechanical separation steps are shown in Fig. 1. With the exception of the dry

Table 1  
FUEL ELEMENT CHARACTERISTICS

Shape .....	hexagonal block
Width, in. ....	14.17 across flats
Length, in. ....	31.22
Weight at discharge, kg/element:	
Graphite fuel block .....	97.46
Carbon binder .....	6.93
Fertile particles:	
Thorium .....	10.48
Uranium (primarily U <sup>233</sup> ) .....	0.30
Fission products .....	0.41
Oxygen (oxides) .....	1.55
Pyrocarbon .....	5.09
Silicon carbide .....	1.86
Buffer carbon .....	1.40
Fissile particles:	
Uranium (primarily U <sup>234</sup> and U <sup>236</sup> ) .....	0.15
Fission products .....	0.42
Oxygen (oxides) .....	0.08
Pyrocarbon .....	2.22
Silicon carbide .....	0.36
Buffer carbon .....	0.30
	129.01
Particle diameter, $\mu\text{m}$ :	
Fertile particle:	
ThO <sub>2</sub> kernel .....	400±100
With buffer carbon coat .....	500
With silicon carbide coat .....	535
With pyrocarbon coat .....	655
Fissile particle:	
UO <sub>2</sub> kernel (70% voids) .....	200±50
With buffer carbon coat .....	260
With silicon carbide coat .....	280
With pyrocarbon coat .....	400
Average burnup, Mwd/tonne .....	67,000



LINE NUMBERS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
LINE NAMES	FUEL RECEIVING	FUEL STORAGE	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER	CRUSHER
C (t)	4700	2865						2865		2		2													
T.H.	404	749						769																	
FERTILE U	11.7	7.85						2.85																	
FERTILE SP <sub>2</sub>	15.8	10.5						10.5																	
FERTILE SiC	71.5	47.7						50.1																	
FERTILE BUFFER	53.8	35.9						35.9																	
FERTILE PARTICLES	615	410						410																	
FERTILE PARTICLES	50.6	33.9						33.9																	
AIR			5	5	1		6				10														
O <sub>2</sub>									147		11														
N <sub>2</sub>																									
CO <sub>2</sub>																									
CO																									
NO+NO <sub>2</sub> +HNO <sub>2</sub>																									
WATER VAPOR																									
MOLECULARITY																									
ENERGY																									

(2) EXCLUDED BUFFER CARBON COATINGS  
 NOTES - (1) INCLUDED KERNELS, BUFFER CARBON COATINGS, AND SiC COATINGS

Fig. 1--Block flow diagram - block burning and particle separation

tabling separator, the process equipment for the operations discussed above are the same as those used in the Case IIIA study. The dry tabling equipment is about the same size as the screener.

In Case IIIB, the fissile particle fraction is packaged as in the Case IIIA study (Ref. 1). The packaged particles are placed in a water-filled basin for interim storage and are eventually shipped to a repository for disposal. Retrieval for processing is possible at any time prior to final disposal. Case IIIB fissile particle disposal facilities differ slightly from those described in Ref. 1. In the Case IIIB process, the quantity of alumina associated with the fissile particles is reduced by a factor of 2.5. This reduction arises because Case IIIB uses a two-stage mechanical separation process and avoids passing the block burner bed through the leacher, which contributes to alumina degradation. Consequently, the volume of the fissile particle fraction to be packaged is about 60% of the Case IIIA volume. Because of the lower alumina content, the volumetric heat generation rate from the fission-product decay is increased and the required container size is reduced in diameter from 8 in. to 6 in. This results in about the same number of fissile particle containers per year for both Case IIIA and IIIB. Since Case IIIB containers are smaller, the waste storage basin space allocated to fissile particle storage is reduced.

In Case IIIB1, the fissile particles are immediately processed for recovery of the residual uranium. The flow diagrams, material balances, and equipment for processing these particles are, in essence, identical to those described in Ref. 2.

The process steps to prepare the separated silicon carbide-coated fertile particles for solvent extraction are similar to those used for the fissile particles. However, there are some differences in the leaching and feed preparation steps. The particle grinding and burning steps are the same for the two particle types but because of the difference in particle quantities, the fertile particle processing equipment pieces are somewhat larger. For leaching the fertile particle burner ash, a solution containing 13 M  $\text{HNO}_3$  and 0.04 M HF is used to dissolve the thorium oxide. In a final solvent extraction feed preparation step, the leacher solution is made acid-deficient by evaporation and steam sparging. This final step is not needed in preparing fissile particles (uranium oxide) for solvent extraction. The fertile particle leacher, stripper, and auxiliary equipment pieces are the same as those described in Ref. 1. Figure 2 shows the block flow diagram and the material balance for the grind-burn-leach processing of the fertile particles.

The flow sheets, material balances, and equipment for the solvent extraction processing of the fertile particles are essentially identical to those described in Ref. 1. For waste processing, the flow sheets, material balances, and equipment described in either Refs. 1 or 2 is used depending on the disposition of the fissile particles.

In Case IIIB, an additional packaging and welding station is needed for the disposal of the fertile particle silicon carbide residues. Also, the waste storage basin is modified to include a surge storage area and a cask loading area for the residue containers. This cask loading area will eventually be used for loading and shipping the calcined waste and fissile particles.



### BUILDING ARRANGEMENT

The conceptual plant layouts for both the Case IIIB and Base IIIB1 plants are adaptations of the Case IIIA plant as described in Ref. 1. Several specific reprocessing building areas, with the exception of the waste storage basin, are enlarged to accommodate the additional equipment items needed to penetrate the silicon carbide coatings. The Case IIIB1 modifications to the plant layout are more extensive than those required in Case IIIB, as more equipment is needed.

In both cases, the required size of the waste storage basin is smaller than in Case IIIA because less material requires prolonged storage. Since Case IIIB1 does not require fissile particle storage, the reduction in basin size is greater than in Case IIIB. In both cases, the inclusion of a surge storage area and a cask loading area for the silicon carbide residues partially offsets the reduction in basin size. Also, in Case IIIB1, the volume of calcined waste is increased by the same amount as in Case IIIA3.

Based on the building arrangement described in Ref. 1, the cases considered in this study require the following changes:

#### CASE IIIB

Change	Building Area Affected	Effect
1. Addition of roll crushers	Crusher cell	Adds 10 ft to length
2. Addition of mechanical separation step and particle burner	Burner cell	Adds 23 ft to length
3. Addition of silicon carbide residue packaging operation	Waste cell	Adds 10 ft to length
4. Plant operation	Operating gallery	Adds 24,250 ft <sup>3</sup> to building volume
5. Waste storage and addition of cask loading area	Waste storage basin	Reduces building volume by 62,800 ft <sup>3</sup>

## CASE IIIB1

Change	Building Area Affected	Effect
1. Addition of roll crushers	Crusher cell	Adds 20 ft to length
2. Addition of a mechanical separation step and two particle burners	Burner cell	Adds 33 ft to length
3. Silicon carbide residue packaging operation	Waste cell	None (substituted for fissile particle packaging)
4. Fissile particle leaching and screening	Leacher cell	Adds 24 ft to length
5. Fissile particle solvent extraction	Solvent extraction cell	Adds 72 ft to length
6. Plant operation	Operating gallery	Adds 129 ft to length
7. Waste storage and addition of cask loading area	Waste storage basin	Reduces building volume by 99,600 ft <sup>3</sup>

The auxiliary facilities and buildings are the same as those for Case IIIA.

### COSTS

The operating and capital costs developed for the Case IIIA plant were used to derive the costs for cases contained in this study. The assumptions made in developing costs cited in Ref. 1 also apply.

#### Operating Costs

The estimated annual reprocessing plant operating costs are summarized in Tables 2 and 3 for both Case IIIB and Case IIIB1. Cost breakdowns are presented in Tables 4 through 9. For manpower and chemical costs, only the costs over and above those required for the Case IIIA plant are shown.

#### Capital Costs

The capital costs for the two cases considered in this report were developed by estimating the incremental direct construction costs for the plant and equipment additions, and adding these to the Case IIIA cost. The total capital cost was then determined by adding the indirect costs, land costs, and startup costs. Table 10 summarizes these costs. The incremental reprocessing building costs were estimated from (1) unit costs (dollars/ft<sup>3</sup>) developed by Gulf General Atomic for the various reprocessing plant building

Table 2  
CASE IIIB OPERATING COST SUMMARY

	Dollars per Year		
	Case IIIA <sup>a</sup>	Incremental	Case IIIB
Manpower	2,014,000	190,200	2,204,200 <sup>b</sup>
Chemicals	902,200	90,600	992,800 <sup>c</sup>
Utilities	206,000	20,000	226,000
High-level waste disposal	972,300	189,200	1,161,500 <sup>d</sup>
Intermediate-level waste disposal	62,500	---	62,500
Solid waste disposal	75,000	5,000	80,000
Thorium storage	231,900	---	231,900
	4,463,900	495,000	4,958,900

<sup>a</sup> See Ref. 1.  
<sup>b</sup> See Table 4.  
<sup>c</sup> See Table 5.  
<sup>d</sup> See Table 6.

Table 3  
CASE IIIB1 OPERATING COST SUMMARY

	Dollars per Year		
	Case IIIA <sup>a</sup>	Incremental	Case IIIB1
Manpower	2,014,000	471,900	2,485,900 <sup>b</sup>
Chemicals	902,200	151,200	1,053,400 <sup>c</sup>
Utilities	206,000	47,000	253,000
High-level waste disposal	972,300	264,500	1,236,800 <sup>d</sup>
Intermediate-level waste disposal	62,500	6,100	68,600 <sup>e</sup>
Solid waste disposal	75,000	20,000	95,000
Thorium storage	231,900	---	231,900
	4,463,900	960,700	5,424,600

<sup>a</sup> See Ref. 1.  
<sup>b</sup> See Table 7.  
<sup>c</sup> See Table 8.  
<sup>d</sup> See Table 9.  
<sup>e</sup> See Ref. 2.

Table 4  
CASE IIIB INCREMENTAL MANPOWER COSTS

	Number	Salary (\$/yr)	Total (\$/yr)
Engineers	1	11,000	11,000
Process operators	9	7,500	67,500
Maintenance personnel	3	7,800	23,400
Chemists	1	10,000	10,000
Laboratory analysts	4	6,000	24,000
Clerks	1	5,000	<u>5,000</u>
			140,900
Overhead (35%)			<u>49,300</u>
			190,200

Table 5  
CASE IIIB INCREMENTAL CHEMICAL COSTS

Chemical	Annual Consumption	Unit Cost	Annual Cost (\$)
Nitrogen	$1.94 \times 10^6$ scf	\$0.0025/scf	4,800
Oxygen	$1.65 \times 10^6$ scf	\$0.005/scf	8,300
Alumina	$1.06 \times 10^5$ lb	\$0.70/lb	74,500
Miscellaneous			<u>3,000</u>
			\$90,600

Table 6

## CASE IIIB HIGH-LEVEL WASTE DISPOSAL COSTS

	<u>(\$/yr)<sup>a</sup></u>
Containers <sup>b</sup>	
Calcined waste .....	298,000
Fissile particle .....	196,000
Silicon carbide residue .....	<u>171,000</u>
	665,000
Additional storage basins <sup>c</sup>	
First .....	123,800
Second .....	<u>92,500</u>
	216,300
Shipping <sup>d, e</sup>	
Calcined waste .....	49,700
Fissile particle .....	35,200
Silicon carbide residue .....	<u>97,600</u>
	182,500
Salt mine disposal	
Calcined waste <sup>e, f</sup> .....	44,800
Fissile particle <sup>e, g</sup> .....	<u>35,900</u>
	80,700
Surveillance <sup>e, h</sup> .....	<u>17,000</u>
	1,161,500

<sup>a</sup> Assumes no by-product recovery.

<sup>b</sup> Based on Refs. 3 and 4. Container unit costs: calcined waste and fissile particle \$500, silicon carbide residue \$855.

<sup>c</sup> Based on additional basins built 5 and 10 years after plant startup at a cost of \$1,610,000 each. The costs of the additional basins are normalized over the amortized plant life (15 years) at 6% interest.

<sup>d</sup> Cask costs are based on Refs. 5 and 6. Freight costs are based on Ref. 7 for a 1000-mile distance.

<sup>e</sup> Expenses incurred 15 years after processing. The listed funds are assumed to be invested for 15 years at 6% interest to yield the actual cost.

<sup>f</sup> Proportioned from the Case IIIA salt mine disposal cost.

<sup>g</sup> Same as the Case IIIA salt mine disposal cost.

<sup>h</sup> Assumes four process operators.

Table 7  
CASE IIIB1 INCREMENTAL MANPOWER COSTS

Position	Number	Salary (\$/yr)	Total (\$/yr)
Engineers	4	11,000	44,000
Process operators	22	7,500	165,000
Maintenance personnel	7	7,800	54,600
Chemists	1	10,000	10,000
Laboratory analysts	11	6,000	66,000
Clerks	2	5,000	<u>10,000</u>
Overhead (35%)			349,600
			<u>122,300</u>
			471,900

Table 8  
CASE IIIB1 INCREMENTAL CHEMICAL COSTS

Chemical	Annual Consumption	Unit Cost	Annual Cost (\$)
Nitrogen	$2.83 \times 10^6$ scf	\$0.0025/scf	7,100
Oxygen	$2.0 \times 10^6$ scf	\$0.005/scf	10,000
Alumina	$1.54 \times 10^5$ lb	\$0.70/lb	108,000
$\text{Cd}(\text{NO}_3)_2$	$7.0 \times 10^3$ lb	\$1.50/lb	10,500
$\text{Na}_2\text{CO}_3$	$4.7 \times 10^3$ lb	\$0.025/lb	120
$\text{Na}_2\text{B}_4\text{O}_7$	$1.4 \times 10^2$ lb	\$0.10/lb	20
NaOH (100%)	$1.59 \times 10^4$ lb	\$0.025/lb	400
$\text{HNO}_3$ (100%)	$1.04 \times 10^5$ lb	\$0.03/lb	3,100
TBP	$7.5 \times 10^2$ lb	\$0.40/lb	300
Diluent	$1.15 \times 10^4$ lb	\$0.10/lb	1,200
Asphalt	$5.06 \times 10^4$ lb	\$0.08/lb	4,100
Cation resin	$7.4 \text{ ft}^3$	25/ $\text{ft}^3$	180
Anion resin	$7.4 \text{ ft}^3$	90/ $\text{ft}^3$	670
Miscellaneous			<u>5,500</u>
			151,200

Table 9

## CASE III B1 HIGH-LEVEL WASTE DISPOSAL COSTS

	(\$/yr) <sup>a</sup>
Containers <sup>b</sup>	
Calcined waste .....	442,500
Silicon carbide residue .....	<u>290,700</u>
	733,200
Additional storage basins <sup>c</sup>	
First .....	109,000
Second .....	<u>81,500</u>
	190,500
Shipping <sup>d, e</sup>	
Calcined waste .....	70,900
Residue .....	<u>152,100</u>
	223,000
Salt mine disposal <sup>e, f</sup> .....	73,100
Surveillance <sup>e, g</sup> .....	<u>17,000</u>
	1,236,800

<sup>a</sup> Assumes no by-product recovery.

<sup>b</sup> Based on Refs. 3 and 4. Container unit cost: calcined waste \$500, silicon carbide residue \$855.

<sup>c</sup> Based on additional basins built 5 and 10 years after plant startup at a cost of \$1,418,000 each. The costs of the additional basins are normalized over the amortized plant life (15 years) at 6% interest.

<sup>d</sup> Shipping cask costs are based on Refs. 5 and 6. Freight costs are based on Ref. 7 for a 1000-mile shipping distance.

<sup>e</sup> Expenses incurred 15 years after processing. The listed funds are assumed to be invested for 15 years at 6% interest to yield the actual costs.

<sup>f</sup> Proportioned from the Case IIIA salt mine disposal costs.

<sup>g</sup> Assumes four process operators.

areas in the Case IIIA plant, (2) the reprocessing building layout shown in Ref. 1, and (3) the required changes in building area sizes contained in this report.

Nearly all of the new equipment items needed are the same as those in the Case IIIA plant or differ only in size. Where the sizes are the same, the equipment piece cost is taken directly from the Case IIIA cost breakdown. Where the sizes differ, the equipment piece cost is assumed to be equal to the cost of the Case IIIA equipment piece cost multiplied by the capacity ratio raised to the 0.6 power. The incremental direct construction cost of the plant equipment is listed in Table 10.

Excluded from the capital costs are state sales or use taxes, licensing, client costs, escalation, interest charges during construction, and research and development expenses.

#### Reprocessing Charges

The annual reprocessing charges, including a contingency reserve fund, are estimated to be \$11.1 and \$12.0 million for Cases IIIB and IIIB1, respectively (see Table 11). Assuming that the plants operate at design capacities, the corresponding reprocessing charges per kilogram of uranium and thorium in the unirradiated HTGR fuel are \$67 and \$73. These charges do not include credits for recovered thorium or fissile particle uranium. The inclusion of a silicon carbide coating on the fertile particle increases the estimated reprocessing cost by \$5/kg (the difference between Cases IIIA and IIIB). The incremental cost of processing the fissile particles (the Case IIIB and Case IIIB1 differential) corresponds to \$0.45/g of fissile particle uranium in the spent fuel.

#### ALTERNATE FLOWSHEETS

The processing methods for both the fertile and fissile particles are basically similar. An alternate method of operation would be to sequentially process the two particle types through the same equipment, thereby eliminating the need for separate processing lines. However, differences in the throughput capacities of the two particle types at various points in the process limit the extent to which common equipment can be used. For example, the quantity of material processed through the particle grinding and burning step is much larger for the fertile particles but in the solvent extraction system, after the thorium has been separated, the flow quantities for the two particle types are about the same. It does not appear feasible to design equipment with sufficient flexibility to handle both particle types sequentially throughout the plant. Only partial common usage is feasible.

Because of equipment design configurations imposed by criticality considerations, throughput rangeability of individual equipment pieces, and the relative costs of the particle head-end and solvent extraction systems, only the use of a common solvent extraction system warrants serious consideration. As discussed in Ref. 2, the use of a single solvent extraction system would require (1) a somewhat larger solvent extraction system, (2) additional

Table 10  
CAPITAL COST

	Case IIIB	Case IIIB1
Case IIIA direct construction cost <sup>a</sup>	\$15,622,000	\$15,622,000
Incremental direct construction cost		
Reprocessing building	151,300	655,900
Equipment	499,500	1,263,900
Total direct construction cost	16,272,800	17,541,800
Contractors overhead and profit (25%)	4,068,200	4,385,500
	20,341,000	21,927,300
Design (15%)	3,051,000	3,289,100
	23,392,000	25,216,400
Contingency (25%)	5,848,000	6,304,100
	29,240,000	31,520,500
Land (1000 acres at \$500/acre)	500,000	500,000
	29,740,000	32,020,500
Startup cost (50% of annual operating cost)	2,479,000	2,712,300
Total capital cost	32,219,000	34,732,800
Annual fixed charge <sup>b</sup>	5,609,000	6,047,000

<sup>a</sup>  
From Ref. 1.

<sup>b</sup>  
17.41% of total capital cost. Based on Ref. 6 with 6.75% interest and a 15-year amortization period.

Table 11  
REPROCESSING CHARGES

	Case IIIB (\$/year)	Case IIIB1 (\$/year)
Annual fixed charge (Table 10) .....	5,609,000	6,047,000
Operating cost (Tables 2 and 3).....	4,958,900	5,424,600
	10,567,900	11,471,600
Contingency reserve (5%) .....	528,400	573,600
	11,096,300	12,045,200
Thorium plus uranium .....	165,555 kg/year	
Cost per kg (Th+U):		
Case IIIB .....	\$67	
Case IIIB1 .....	\$73	
Case IIIA .....	\$62 (Ref. 1)	

tankage to receive and store the alternate feed solution, (3) routine silica gel tail-end treatment of the bred uranium, and (4) turnaround between the two feed types. With turnaround, both the waste losses and waste volumes would increase. Although no detailed comparison has been made, it appears that a plant with a single solvent extraction system would have a lower capital cost but a higher operating cost than the plant considered here.

#### HTGR FUEL VARIATIONS

The flow sheets included in this study are based on HTGR fuel elements designed for a once-through fuel cycle, with both the recycle  $U^{233}$  and the makeup  $U^{235}$  combined in the fissile particles. In HTGR fuel elements designed for a bred-uranium fuel cycle, the recycle  $U^{233}$  is combined with part of the thorium in particles similar in design to the fertile particles. With this fuel, the quantity of fissile particle uranium ( $U^{235}$  only) processed is reduced, but the quantity of fertile particle uranium is increased. As discussed in Ref. 1, it is not anticipated that the cost of reprocessing bred uranium fuels will differ significantly from once-through fuels.

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