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INFORMAL AEC RESEARCH & DEVELOPMENT REPORT

**HTGR FUEL REPROCESSING RECOVERY OF
URANIUM FROM SILICON CARBIDE-COATED FISSILE PARTICLES**

by

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HTGR Fuel Reprocessing - Recovery of Uranium from Silicon-Carbide-Coated Fissile Particles

INTRODUCTION

In current designs of HTGR fuel elements, the fissile and fertile fuel materials are contained in separate particles. During reprocessing, the fissile and fertile particles are separated from each other. Studies on HTGR fuel cycle costs⁽¹⁾ indicate that the lowest costs are obtained if only the bred uranium, contained in the irradiated fertile particles, is recycled to the reactor. The residual uranium in the irradiated fissile particles is not recycled. Although the residual fissile-particle uranium is not considered to be usable in HTGR's, it contains about 30 percent fissionable isotopes (U-233 and U-235) and certainly has some market value. If the anticipated long-term market value is greater than the recovery costs, processing of the fissile particles is warranted. A study on reprocessing HTGR fuels in a central, single-purpose reprocessing plant⁽²⁾ (Case III A) assumed the fissile particles are isolated, packaged, and stored for eventual recovery or disposal as a high-level waste. This report outlines the incremental processing steps required to recover the uranium in the silicon-carbide-coated (SiC-coated) fissile particles, starting with the Case III A plant, and contains estimates of the incremental recovery costs. For discussion purposes, the plant with fissile-particle processing is designated Case III A3.

SUMMARY

Conceptual flowsheets and costs have been developed in this study for the addition of fissile-particle reprocessing capability to a central HTGR fuel reprocessing plant sized to serve a 15,000 MW(e) HTGR economy (Case III A). The SiC-coated fissile particles, isolated during the screening step in the burn-leach head-end process, are routed to a grind-burn-leach auxiliary head-end process for conversion to a solvent-extraction feed solution. A two-cycle solvent-extraction system followed by a silica-gel tail-end treatment decontaminates and purifies the fissile-particle uranium. Additional equipment is needed for the grind-burn-leach and fissile uranium decontamination operations. Radioactive wastes arising from fissile uranium processing are combined with those from the main-line (fertile uranium) process for solidification and disposal.

The estimated costs associated with the HTGR fuel reprocessing plants both with and without fissile uranium recovery capability are as follows:

	<u>Case III A⁽²⁾</u>	<u>Case III A3</u>	<u>Incremental</u>
Capital cost, \$ $\times 10^6$	30.8	33.7	2.9
Annual operating cost, \$ $\times 10^6$	4.46	4.97	0.51
Reprocessing charge, \$/kg	62	69	7

The incremental cost of processing the fissile particles from irradiated fuel is an estimated \$0.50/g of fissile-particle uranium. Clearly this material, which is composed of about 30 percent fissionable isotopes, is well worth recovering even without the values associated with Np-237 and Pu-238.

STUDY ASSUMPTIONS

The process flowsheets, material balances, equipment designs, and plant layout developed in this study are based on the following assumptions and criteria:

1. The fissile-particle processing capability is incorporated into the Case III A plant described in Ref. 2.
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 the HTGR. The fissile particles initially contain the recycle U-233 and the makeup U-235. A typical fuel element makeup is shown in Table 1.
3. Where possible, the process steps, plant, and equipment designs are based on proven technology.
4. Fissile particle processing is carried out in equipment independent of the main-line (fertile particle) processing equipment.
5. The fissile uranium product is in the form of a decontaminated uranyl nitrate solution.
6. Solid residues from head-end processing are packaged and shipped to a licensed burial ground.
7. Process equipment in radioactive service with less than a 15-year life expectancy is remotely replaceable.

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		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>	
		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	
SiC	0.36	
Pyrolytic carbon	<u>2.22</u>	
		<u>3.53</u>
		129.57
Particle Diameter (μ)		
Fertile Particle		
ThO ₂ kernel		350
With buffer-carbon coating		410
With pyrolytic-carbon coating		610
Fissile Particle		
UO ₂ kernel (70% voids)		200
With buffer-carbon coating		260
With SiC intermediate coating		280
With pyrolytic-carbon coating		400
Cooling time (days)		
At reactor		90 (minimum)
At reprocessing plant		120
At start of reprocessing		210 (minimum)
Average burnup (MWD/tonne)		67,000

8. The plant equipment is to be able to process fissile particles ranging from unirradiated to fully irradiated.
9. The fuel component quantities processed are the same as those in the Case III A study⁽²⁾ and are listed in Table 2.

TABLE 2
FUEL COMPONENT QUANTITIES

Fuel blocks processed ^(a)	14,063 per year 51.3 per process day 38.5 per day (yearly avg)		
	<u>Kg/fuel block</u>	<u>Kg/year</u>	<u>Kg/process day</u>
Carbon ^(b)	115.52	1,624,500	5,928.7
Unirradiated Fuel			
Thorium	11.20	157,500	574.8
Uranium	0.573	8,055	29.4
Total	11.773	165,555	604.2
Irradiated Fuel			
Thorium	10.48	147,450	538.1
Fertile particle U (83% U-233)	0.305	4,290	15.66
Fertile-particle fission products	0.410	5,760	21.0
Fissile particle U (primarily U-234 and U-236)	0.150	2,115	7.72
Fissile-particle fission products	0.418	5,865	21.4

(a) Based on 3,750 fuel elements per 1000 MW(e) reactor and a 4-year fuel life.

(b) Does not include the buffer-carbon coating on the fissile particles.

BASIC PROCESS DESCRIPTION

The process flowsheets for the recovery of the bred U-233 are described in Ref. 2. With a few exceptions these flowsheets are unaffected by the addition of fissile-particle recovery. The exceptions are: (1) the fissile particles are routed to the grind-burn-leach processing equipment rather than to fissile-particle packaging, and (2) the quantities of the radioactive waste streams are increased. This study considers only the additional process flowsheets for processing the fissile particles and the modified waste processing flowsheet.

The SiC-coated fissile particles are isolated during the screening step of the burn-leach head-end operation. A grind-burn-leach process is used to prepare the uranium in the fissile particles for separation from the fission products by solvent extraction. Grind-burn-leach processing consists of the following steps:

1. The fissile particles along with the undersize alumina particles from the primary burners are ground in a roll crusher to fracture the SiC coatings.
2. The ground particles are burned in a small fluidized bed burner to oxidize the buffer carbon coating to carbon dioxide. Alumina is the burner bed material.
3. Leaching the burner ash with nitric acid dissolves the fissile uranium, yielding a solution suitable for feed to the solvent extraction system. The fractured SiC coatings and the alumina do not dissolve.
4. The residual solids are rinsed, dried, and screened to recover the uncrushed alumina for recycle to the burner.
5. The residue (SiC and crushed alumina) is sealed into stainless steel containers for shipment to a licensed burial ground. The water-filled basin is used for surge storage.

Figure 1 contains the block flow diagram for the grind-burn-leach processing. These process steps are based on a very limited amount of development work and are subject to considerable modification.

Separation of the fissile uranium from the fission products is achieved by solvent extraction and silica-gel treatment.

1. Two cycles of solvent extraction using 5 volume percent tributyl phosphate (TBP) in a normal paraffin hydrocarbon (NPH) diluent separate essentially all of the fission products from the fissile-particle uranium. The aqueous uranium product from the strip column of each cycle is concentrated by evaporation.
2. Aqueous wastes from the first-cycle extraction column are routed to the high-level waste system and the waste stream from the second-cycle extraction column is routed to intermediate-level waste processing.
3. Solvent raffinates from the two strip columns are processed through separate solvent-treatment systems for removal of solvent degradation products. Solvent treatment wastes are combined with the other intermediate-level wastes for disposal.

4. The concentrated uranium product from the second solvent extraction cycle is routed through a small column containing silica gel to remove residual amounts of fission product zirconium and niobium.⁽³⁾ Silica-gel column flushes and washes are combined with the intermediate-level waste system.
5. Following silica-gel treatment the fissile-particle uranium product in the form of a uranyl nitrate solution is loaded into containers for shipment.

Block flow diagrams for the solvent extraction and silica-gel treatment steps are shown in Fig. 2. Included in the study criteria is the capability of processing unirradiated fissile particles. Because of the higher uranium content, unirradiated particles were considered in establishing the solvent-extraction/silica-gel flowsheet. For the processing of irradiated fissile particles, the flow quantities would be somewhat reduced.

Process steps related to radioactive waste disposal are identical to those in the Case III A plant,⁽²⁾ but the waste quantities are increased because of the additional steps for fissile-particle processing. Figure 3 shows the modified waste-processing block flow diagram.

EQUIPMENT DESCRIPTION AND ARRANGEMENT

Grind-Burn-Leach Processing

The feed material to fissile-particle processing is one of the product streams from the screening step in the Case III A burn-leach head-end process. This feed stream contains the SiC-coated fissile particles and the degraded (undersize) alumina particles from the primary burner beds. Pyrocarbon outer coatings on the fissile particles are removed during the primary burning step. The first step necessary in the processing of the fissile particles is to expose the particle kernels. A roll crusher grinds the fissile particles and alumina, fracturing the SiC coatings. In operation, the fissile-particle fraction from the head-end screening step is periodically transferred pneumatically to a weigh hopper above the crusher. A feeder valve on the hopper discharge maintains a uniform feed rate to the crusher. Based on development work done at the Oak Ridge National Laboratory,⁽⁴⁾ reducing the particles to -140 mesh is adequate to ensure rupture of all of the fuel particle coatings. For reasons of nuclear criticality, the roller width is limited to 2 inches. ORNL studies⁽⁴⁾ indicate one roll crusher of this width should be adequate for processing the fissile particles. An inert-gas atmosphere is used to prevent uncontrolled combustion of the buffer carbon dust generated during the particle grinding step. A sintered metal filter equipped for pulse blowback removes entrained dust from the crusher

off-gas stream. The service life of a roll crusher is expected to be relatively short and an installed spare grinding system is included in the plant.

The ground fissile particles and alumina are collected in a receiver hopper below the roll crusher which provides surge storage. Nitrogen gas is used to continuously transport the crusher product from the receiver hopper into a small burner where the buffer carbon is oxidized to carbon dioxide and the UO_2 (or UC_2) fuel kernels are converted to U_3O_8 . This burner, like the main-line (primary) burners, employs a fluidized bed of alumina particles to aid in heat transfer. Since only the buffer carbon is oxidized, a burner much smaller than the primary burners is needed. The fluidized bed section of the fissile-particle burner is only 4 inches in diameter as compared to 42 inches for the two primary burners. All burners use oxygen as the burner gas.

The burner off-gas passes successively through a sintered metal filter unit equipped with pulse blowback for fines removal, a cooler, a bed of silica gel for ruthenium adsorption, and a deep-bed fiberglass filter unit for removal of residual particulates. The off-gas is then combined with reprocessing building ventilation exhaust air for final filtration by absolute filters prior to atmospheric release. Air passing through the burner jacket removes the heat of combustion. Since the amount of heat released is not large, a once-through cooling air system is used. The air is supplied by the building compressed-air system.

Burner ash, the alumina bed material, the fissile uranium in the form of U_3O_8 , and the crushed alumina are continuously discharged from the burner into an ash hopper. Periodically, the burner ash is pneumatically transported to a weigh hopper located above the fissile uranium leacher for batchwise addition to the leacher.

Fissile-uranium leaching is similar to the fertile-particle leaching operation carried out in the main-line head-end process, but there are some differences in the chemistry. Unlike the ThO_2 in the fertile particles, U_3O_8 dissolves readily in nitric acid. The acid addition to the fissile uranium leacher does not contain fluoride to catalyze the dissolution, and the quantity of nitric acid added is only the amount needed to assure dissolution of the fissile-particle kernels. Cadmium nitrate is added to the leacher acid as a criticality control measure. The SiC and the alumina are resistant to nitric acid but a small amount of alumina does dissolve. For flowsheet purposes, it is assumed that 1 percent of the alumina from the burner bed and 10 percent of the crushed alumina go into the solution as aluminum nitrate.

In design and operation, fissile-particle and main-line leachers are similar but the fissile-particle leacher is 50 percent smaller. This size

differential arises from the smaller quantity of solids and fuel material handled by the fissile-uranium leacher. After a batch of fissile particles has been leached, the product solution is transferred to a storage tank. A dilute nitric acid - cadmium nitrate solution is added to the leacher to rinse the residue (SiC hulls and alumina) and to serve as the media for transport of the residue to a drying hopper. Like its main-line counterpart, the drying hopper contains a screen that retains the leached solids but allows the rinse solution to return to the leacher. Once the major portion of the solids is removed from the leacher, the rinse solution is combined with the dissolved fissile uranium, forming the feed solution to the fissile-uranium solvent extraction system.

The residue accumulated in the drying hopper is dried by passing hot air through the hopper. Once dried, the residue is dropped at a metered rate onto a mechanical screen for separation of the larger burner bed alumina particles from the SiC hulls and the crushed alumina. For flow-sheet purposes, it is assumed that 10 percent of the bed alumina particles have been mechanically and chemically degraded and appear in the SiC fraction. The alumina particle fraction is recycled to the burner for reuse. The SiC hulls along with the crushed and degraded alumina are transferred to a weigh hopper. This waste residue contains sufficient fission products to be classified as a high-level waste but not enough to cause serious self-heating. A measured quantity of waste solids is dropped into a 12-inch-diameter by 10-foot-long stainless steel container. Once full, the container is moved by the building crane to a welding station where a plug is inserted and seal-welded. The sealed container is then moved to the monitoring tank described in Ref. 2 to check for leaks. Subsequently, the container is transferred to the water storage basin for surge storage. Periodically, the waste containers are loaded into a shipping cask and transported to a licensed burial ground for disposal. A single container holds about two days output of residue. An estimated 140 containers are filled annually.

Fissile Uranium Decontamination

A high degree of fissile uranium decontamination is achieved by two cycles of solvent extraction followed by a silica-gel tail-end step. These two solvent-extraction cycles utilize flowsheets, flow quantities, and equipment similar to those specified for the main-line second and third solvent-extraction cycles.⁽²⁾ Consequently, the solvent-extraction columns, evaporators, tanks, and auxiliaries are essentially identical to those in the main-line system (Case III A). The only important differences are the lack of a thorium evaporation and of intercycle storage tanks in the fissile-particle uranium system.

The solvent extraction flowsheet is based on the use of tributyl phosphate as the solvent. With this solvent, uranium decontamination is

limited by the fission products zirconium and niobium. These fission products, however, are readily adsorbed on silica gel.⁽³⁾ Additional decontamination from zirconium and niobium is obtained by passing the concentrated fissile-uranium product from the solvent extraction system through a column containing a fixed bed of silica gel. Such a column can process about 200 column volumes of uranyl nitrate solution before regeneration is necessary. The silica gel can be readily regenerated with a few column volumes of an oxalic acid solution. To minimize product losses and to maintain product purity, regeneration is preceded and followed by dilute nitric acid column flushes. The uranium-bearing flushes are recycled to the intercycle evaporator.

A silica-gel column 2 inches in diameter by 10 inches long is adequate for the fissile-particle uranium output. Separate tanks are used for the various flush, regeneration, and waste streams. Regeneration is done daily.

Following silica-gel treatment, the decontaminated fissile-particle uranium is loaded into containers and shipped to purchasers. The fissile-particle uranium load-out station is identical to that specified for the fertile uranium.

Waste Processing

The radioactive waste solutions arising from the fissile-particle processing operations are similar in composition to those from the main-line processing. On a volume basis, the fissile-particle wastes are less than 30 percent of the main-line wastes. Consequently, the waste processing flowsheets for the Case III A plant are utilized in the Case III A3 plant but with adjustments in equipment sizes to account for the slightly greater volumes. Although the addition of fissile-particle processing increases the concentration of the fission products in the calcined waste, the size of the high-level waste containers remains unchanged (6 inches in diameter by 10 feet long). However, the higher volumetric heat generation rates from fission product decay increase the maximum container center-line temperature during storage from 560° to 700°C. The increased salt content of the high-level wastes raises the annual output of filled waste containers from 542 to 885. In addition, the volume of intermediate-level wastes incorporated into asphalt is 14 percent higher.

Building Arrangement

The conceptual layout of the central reprocessing plant that recovers both the fissile and fertile uranium (Case III A3) is a simple modification of the Case III A plant (fertile-particle processing only). Specific building areas, with the exception of the waste storage basin, are enlarged to accommodate the additional items of equipment needed for fissile-particle processing.

The waste storage basin is decreased in size because short-term surge storage of the SiC residue containers is substituted for long-term storage of the fissile-particle containers. The criterion that the SiC waste be shipped off-site shortly after packaging requires the inclusion of a cask-loading area in the initial basin. This partially offsets the reduction in the storage-basin size. The cask-loading area will be used for the eventual shipment of the calcined waste so the cost and size of a future basin are reduced accordingly. Based on the Case III A building arrangement of Ref. 2, the changes required for the addition of fissile-particle processing capability are listed in Table 3.

TABLE 3
FISSILE-PARTICLE PROCESSING CAPABILITY CHANGES

Change	Building Area Affected	Effect
Addition of roll crushers	Crusher cell	Adds 10 ft to length
Additional burner system	Burner cell	Adds 10 ft to length
Additional leaching and screening	Leacher cell	Adds 24 ft to length
Additional solvent extraction system	Solvent extraction cell	Adds 72 ft to length
SiC residue packaging	Waste packaging cell	None (substituted for fissile-particle packaging)
Larger waste processing equipment	Waste packaging and intermediate-level waste cells	None
Waste storage and addition of cask loading area	Waste storage basin	Reduces building volume by 99,600 ft ³
Plant operation	Operating gallery	Adds 116 ft to length
Ancillary facilities	General	None (some equipment systems are slightly larger)

COSTS

The operating and capital costs developed for the Case III A plant (Ref. 2) were used as the basis in deriving the costs for the Case III A3 plant. The assumptions used in the earlier study also apply to this study.

Operating Costs

The estimated annual operating costs for both the Case III A and III A3 plants are summarized in Table 4. Case III A3 operating cost details are presented in Tables 5 through 9. For manpower and chemical costs (Tables 5 and 6) only the additional costs incurred by fissile-particle processing are presented. Since facilities related to thorium storage are not affected by fissile-particle processing, the costs remain the same. Adding fissile-particle processing capability increases the estimated annual reprocessing plant operating costs from 4.46 to 4.97 million dollars.

TABLE 4
OPERATING COST SUMMARY

Item	\$/year			Table with Case III A3 cost details
	Case III A ⁽²⁾	Incremental	Case III A3	
Manpower	2, 014, 000	332, 100	2, 346, 100	5
Chemical	902, 150	60, 600	962, 750	6
Utilities	206, 000	39, 000	245, 000	7
High-level waste disposal	972, 300	54, 400	1, 026, 700	8
Intermediate-level waste disposal	62, 500	6, 100	68, 600	9
Solid waste disposal	75, 000	15, 000	90, 000	
Thorium storage	<u>231, 900</u>	<u>---</u>	<u>231, 900</u>	
	4, 463, 850	507, 200	4, 971, 050	

TABLE 5
INCREMENTAL MANPOWER REQUIREMENTS

Position	Number	Salary \$/year	Total \$/year
Engineers	3	11, 000	33, 000
Process operators	14	7, 500	105, 000
Maintenance personnel	5	7, 800	39, 000
Chemists	1	10, 000	10, 000
Laboratory analysts	9	6, 000	54, 000
Clerks	<u>1</u>	5, 000	<u>5, 000</u>
	33		246, 000
Overhead (35%)			<u>86, 100</u>
			332, 100
Case III A annual manpower costs ⁽²⁾			<u>2, 014, 000</u>
Case III A3 annual manpower costs			<u>2, 346, 100</u>

TABLE 6
INCREMENTAL CHEMICAL REQUIREMENTS

Chemical	Annual consumption	Cost	
		\$/unit	\$/year
Nitrogen	8.85×10^5 scf	0.0025/scf	2,200
Oxygen	3.6×10^5 scf	0.005/scf	1,800
Alumina	4.8×10^4 lb	0.70/lb	33,600
Cd (NO ₃) ₂	7.0×10^3 lb	1.50/lb	10,500
Na ₂ CO ₃	4.7×10^3 lb	0.025/lb	120
Na ₂ B ₄ O ₇	1.44×10^2 lb	0.10/lb	20
NaOH (100%)	1.59×10^4 lb	0.025/lb	400
HNO ₃ (100%)	1.04×10^5 lb	0.03/lb	3,100
TBP	7.5×10^2 lb	0.40/lb	300
Diluent	1.15×10^4 lb	0.10/lb	1,150
Asphalt	5.06×10^4 lb	0.08/lb	4,050
Cation Resin	7.4 ft ³	25/ft ³	180
Anion resin	7.4 ft ³	90/ft ³	670
Miscellaneous			<u>2,500</u>
			60,600
Case III A annual chemical costs ⁽²⁾			<u>902,150</u>
Case III A3 annual chemical costs			<u>962,750</u>

TABLE 7
UTILITIES

	\$/year
Electricity ^(a)	163,000
Fuel Oil ^(b)	<u>82,000</u>
	<u>245,000</u>

(a) Based on an average power load of 1860 KW at \$0.01 per KWh.

(b) Based on an average steam demand of 18,750 lb/hr, 80% boiler efficiency, and a fuel cost of \$0.40/10⁶BTU.

TABLE 8
HIGH-LEVEL WASTE DISPOSAL

	<u>\$/year^(a)</u>
Calcined waste containers ^(b)	442, 500
SiC residue containers ^(b)	119, 700
Additional storage basins ^(c)	190, 500
Calcined waste shipping ^{(d)(e)}	70, 900
Salt mine disposal ^{(e)(f)}	73, 100
Surveillance ^{(e)(g)}	17, 000
SiC residue shipping ^(d)	<u>113, 000</u>
	1, 026, 700

(a) Assumes no byproduct recovery.

(b) Based on Refs. 5 and 6. Container unit costs: calcined waste \$500, SiC residue \$855.

(c) Based on the second and third basins built 5 to 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.

(d) Cask costs based on Refs. 7 and 8. Shipping costs based on Ref. 9 for 1000 miles.

(e) Expense incurred 15 years after processing. The listed funds are assumed to be invested for 15 years at 6% to yield the actual cost.

(f) Proportioned from Case III A (Ref. 2) salt mine disposal cost.

(g) Assume 4 process operators.

TABLE 9
INTERMEDIATE-LEVEL WASTE DISPOSAL

	<u>\$/year</u>
Cost of additional tanks ^(a)	44, 400
Surveillance ^(b, c)	2, 100
Final disposal ^(c, d)	<u>22, 100</u>
	<u>68, 600</u>

(a) Based on second and third tanks built 5 and 10 years after plant startup at a cost of \$331, 200 each. The cost of the additional tanks is normalized over the amortized plant life (15 years) at 6% interest.

(b) Assumes 0.5 man-year annually.

(c) Expenses incurred 15 years after processing. The listed funds are assumed to be invested for 15 years at 6% to yield the actual cost.

(d) Based on \$10/ft³ for retrieval, packaging, shipment, and disposal in a licensed burial ground.

Capital Costs

The incremental capital costs resulting from the inclusion of fissile-particle processing were derived from the cost breakdown developed by GGA cost engineering personnel for the Case III A plant. In this Case III A breakdown, unit costs (\$/ft³) were developed for the various areas in the reprocessing building. These unit costs were used in establishing the incremental building costs for the Case III A3 plant. Essentially all of the new equipment items needed for Case III A3 plant are the same as items in the Case III A plant or differ only in size. Where the size is the same, the estimated cost of these new items is obtained directly from the cost of the corresponding item in the Case III A plant. Where the size of an equipment item (whether new or old) is different, the estimated cost of the Case III A3 item is assumed to be equal to the cost of the Case III A item multiplied by the capacity ratio raised to the 0.6 power. The only unique additional equipment item is the roll crusher.

Direct construction costs for the Case III A3 plant are estimated to be 17.1 million dollars (Table 10). The total capital cost including indirect costs, land, and startup costs is an estimated 33.7 million dollars. For comparison, the estimated capital of the Case III A plant is 30.8 million dollars. These costs

do not include state sales or use taxes, licensing, client costs, escalation, interest charges during construction, or research and development costs.

TABLE 10
CAPITAL COST

	Cost (\$)
Case III A direct construction	15,622,000 ^(a)
Incremental direct construction	<u>1,480,500</u>
Case III A3 direct construction	17,102,500
Contractor's overhead and profit (25%)	<u>4,275,600</u>
	21,378,100
Design (15%)	<u>3,206,700</u>
	24,584,800
Contingency (25%)	<u>6,146,200</u>
	30,731,000
Land (1000 acres at \$500 per acre)	<u>500,000</u>
	31,231,000
Startup cost (50% of annual operating cost)	<u>2,485,500</u>
	33,716,500
Annual fixed charge	
$\$33,716,500 \times 0.1741^{(a)} = \$5,870,000$	

^(a)Based on Ref. 8 with 6.75% interest and a 15-year amortization period.

Reprocessing Charges

The annual reprocessing charges, including a contingency reserve fund, are an estimated 11.4 million dollars (Table 11). Based on operation of the plant at its design rate, the reprocessing charges per kg of thorium and uranium in the unirradiated HTGR fuel (Table 2) are \$69. The incremental cost for fissile uranium recovery is 1.065 million dollars per year or \$0.50 per gram of total uranium in the fissile particles.

TABLE 11
REPROCESSING CHARGES

	<u>\$/year</u>
Annual fixed charge (Table 10)	5,870,000
Operating cost (Table 4)	<u>4,971,000</u>
	10,841,000
Contingency reserve (5%)	<u>542,000</u>
	11,383,000
Thorium plus uranium = 165,555 kg/year	
Reprocessing cost, \$/kg = 69	
Mills per KWh(e) = 0.108	
Reprocessing charge for Case III A (Ref. 2), \$/year	10,318,000
Incremental charge for Case III A3 \$/year	1,065,000 (10.3%)

ALTERNATE FLOWSHEETS

An alternate method of separating the fissile-particle uranium from the fission products would be to utilize the second- and third-cycle main-line solvent extraction equipment. Both the fissile- and fertile-particle materials could be sequentially processed through this equipment. A flow-sheet based on this alternative would eliminate the need for the fissile-particle uranium solvent-extraction equipment. Several disadvantages, however, would occur. More material would be processed through the second- and third-cycle solvent-extraction systems and then throughput capacities would have to be increased accordingly. Tankage to receive and store the alternate solvent extraction feed solution would have to be provided. The fissile-particle uranium feed would not have undergone one cycle of solvent extraction like the fertile-particle material. As a result, the fission product concentrations in the dual-purpose solvent-extraction systems would be increased, and the recovered bred-uranium would require routine silica-gel treatment. Additional waste losses, increased down time, and higher waste volumes would result from turnaround between the two types of feed. Although no detailed economic comparison was made, it is likely that the alternate flowsheet would yield a lower capital cost but the flowsheet included in this study would have a lower operating cost.

HTGR FUEL VARIATIONS

The flowsheets in this study are based on HTGR fuel elements designed for a once-through fuel cycle. Here the SiC-coated fissile particles contain both the recycle U-233 and the makeup U-235. An alternate cycle - the bred-uranium fuel cycle - utilizes the fuel elements containing three particle types. These are thorium particles, thorium-recycle U-233 particles, and U-235 particles. Only the U-235 particles have SiC coatings. With a bred-uranium cycle fuel element, the uranium content of the SiC-coated particle is about 50 percent of that in a once-through cycle element. Accordingly, the quantity of uranium processed through the fissile particle reprocessing equipment is reduced by 50 percent. The process equipment described in this study has a range sufficient to allow satisfactory operation at the lower throughput rate.

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Fig. 3. Waste processing block flow diagram