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**REPROCESSING FLOWSHEET
AND MATERIAL BALANCE
FOR MEU SPENT FUEL**

by
L. ABRAHAM

Prepared under
Contract EY-76-C-03-0167
Project Agreement No. 53
for the San Francisco Operations Office
Department of Energy

DATE PUBLISHED: OCTOBER 1978

GENERAL ATOMIC COMPANY

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy \$5.25; Microfiche \$3.00

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ABSTRACT

In response to nonproliferation concerns, the high-temperature gas-cooled reactor (HTGR) Fuel Recycle Development Program is investigating the processing requirements for a denatured medium-enriched uranium-thorium (MEU/Th) fuel cycle. Prior work emphasized the processing requirements for a high-enriched uranium-thorium (HEU/Th) fuel cycle.

This report presents reprocessing flowsheets for an HTGR/MEU fuel recycle base case. Material balance data have been calculated for reprocessing of spent MEU and recycle fuels in the HTGR Recycle Reference Facility (HRRF). Flowsheet and mass flow effects in MEU-cycle reprocessing are discussed in comparison with prior HEU-cycle flowsheets.

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1. INTRODUCTION

The principal fuel cycle considered for commercialization of the high-temperature gas-cooled reactor (HTGR) has generally been the high-enriched uranium-thorium (HEU/Th) fuel cycle. Recent governmental policy pronouncements and heightened concerns about safeguards for minimizing the weapons proliferation potential of nuclear fuel cycles have stimulated interest in operation of the HTGR on a denatured uranium-thorium fuel cycle. Therefore, the HTGR Fuel Recycle Development Program (Ref. 1) has been redirected to address the recycle requirements for a medium-enriched uranium-thorium (MEU/Th) fuel system. The MEU cycle (approximately 20% enriched fissile uranium two-particle proliferation-resistant fuel) is the current reference fuel cycle for HTGR recycle development, while HEU (approximately 93% fissile) and LEU (low-enriched, approximately 9% fissile) are designated the first and second alternates, respectively.

The MEU HTGRs are fueled initially with fissile particles that contain about 20% U-235 in U-238, plus ThO_2 fertile particles. This reactor cycle meets the presently postulated nonproliferation criterion that the risk of surreptitious use of strategic nuclear materials from its fresh or spent fuel will be equivalent to or less than that from present LWR spent fuel.

The technology for reprocessing spent fuel for the MEU cycle is similar to that for the HEU cycle, requiring relatively minor adjustments in the reprocessing flowsheets but resulting in changed mass flows and material balances for the reprocessing system flowsheets. This report updates the reprocessing flowsheet for the HTGR MEU fuel recycle base case and summarizes the material balance for the HTGR Recycle Reference Facility (HRRF) reprocessing plant.

2. MEU FUEL RECYCLE BASE CASE

2.1. FUEL CYCLE DESCRIPTION

A reference MEU/Th cycle with nondenatured U-233 recycle in the HTGR was selected as the basis for spent fuel composition calculations for the HRRF reprocessing material balance update. The recycle of nondenatured U-233 is based on the assumption that its gamma activity in conjunction with engineered safeguards fuel cycle design features will be a sufficient deterrent against special nuclear material (SNM) diversion. The savings in U_3O_8 requirements achieved by not denaturing the recycle U-233 with U-238 are of the order of 12%. Additional savings of 6% are achieved by using continuous rather than once-through recycle (Ref. 2).

The MEU fuel recycle base case, including flexibility options to be considered during the course of later HRRF engineering feasibility studies, was approved as the FY-78 reference for HRRF studies and requirements definition (Refs. 3, 4). The flexibility options will also be evaluated in reactor optimization and nonproliferation assessment studies. Table 1 summarizes the recycle base case fuel cycle definition and desirable flexibilities as originally approved. Table 2 summarizes characteristic HTGR core parameters that evolved from subsequent iterative computer code calculations, which established equilibrium spent fuel compositions for MEU makeup fuel elements and for U-233 recycle elements (Ref. 5). An equilibrium core reload segment for a 1330-MW(e) HTGR will include 872 MEU makeup elements and 450 nondenatured U-233 recycle elements.

Core-averaged compositions of MEU makeup fuel elements (M) and of U-233 recycle elements (23R) are defined in Tables 3 and 4, respectively, and fuel particle characteristics for makeup and recycle elements are summarized in Table 5, taken from Ref. 5. The MEU/Th fuel cycle,

TABLE 1
RECYCLE BASE CASE FUEL CYCLE DEFINITION AND DESIRABLE FLEXIBILITIES

Typical Recycle Case Characteristic		Desirable Flexibility		
Power density	7.1 W/cm ³	--		
Power level	3360 MW(t)	2200		
Refueling frequency	1.0 yr	--		
Fuel lifetime	4.0 yr	--		
Annual capacity factor	80%	60 to 80		
U-233 recycle mode	Recycle of HEU-233 at reload 2	Recycle 12% to 15% MEU-233 at reload 2 or later reload		
	No denaturing	Denature in reprocessing plant with natural U or irradiated U		
		In-situ denaturing with natural U or MEU		
Makeup fissile particle disposition	No recycle; stowaway for U recovery	Stowaway for U-235 and Pu recovery		
		Recover U and blend with HEU-233 to denature U-233		
		Reenrich U and recycle all U-235 in HTGR; recycle Pu in FBR or LWR		
		Reenrich discharge U with HEU and recycle in HTGR		
		Capability for HEU-235 and HEU-233 fuel types		
C/Th ratio				
Initial core	350 ^(a)	150 → ∞ (HEU to LEU)		
Reload	850 ^(a)	150 → ∞ (HEU to LEU)		
k _{eff} end-of-cycle	1.01	1.00 to 1.01		
Fuel element (standard)				
No. of fuel holes	138	138 or 210		
Fuel pin diameter	1.17 cm (0.46 in.) ^(a)	1.0 cm to 1.6 cm		
Fuel particles				
MEU-235 fissile particle (dense UCO TRISO)		UO ₂ , UC ₂ , doped BISO		
Dimensions for MEU:		Dimensions for MEU:		
	Thickness (μm)	Radius (μm)	Thickness (μm)	Radius (μm)
Kernel	--	175 ^(a)	--	170-200
Buffer	105 ^(a)	280 ^(a)	70-120	--
IPyC	35	315	35	--
SiC	35	350	35	--
OPyC	45	395	45	--
U-233 fissile particle	Current reference HTGR HEU WAR recycle particle	Dense UCO same as MEU-235 fissile		
Thorium particle	Current reference HTGR fertile particle	Doped BISO		

^(a) Indicated typical value may change as a result of optimization for HEU-233 recycle.

TABLE 2
CHARACTERISTIC HTGR CORE PARAMETERS ^(a)

<u>Parameter</u>	<u>Value</u>
Thermal power	3360 MW(t)
Electrical power	1330 MW(e)
Fuel elements/core	5288
Fuel elements/segment	1322
M type elements/segment (at equilibrium)	872
23R type elements/segment (at equilibrium)	450
Carbon/thorium ratio (initial core)	355
Carbon/thorium ratio (reload 1)	1175
Carbon/thorium ratio (remainder of cycle)	400
Fuel rod diameter (initial core and reload 1)	11.7 mm
Fuel rod diameter (remainder of cycle)	14.0 mm
Fuel rod stack length (entire cycle)	781.6 mm
Fuel rod length (entire cycle)	65.1 mm
Fuel holes/standard element	138
Fuel holes/control element	82
Thermal power density	7.1 W/cm ³

^(a) Indicated typical values may change as a result of optimization for HEU-233 recycle.

TABLE 3
EQUILIBRIUM M FUEL ELEMENT SUMMARY
(Core-Averaged, As Charged)

<u>Component</u>	<u>Mass (kg/fuel element)</u>
Fissile particles ($\rho = 2.64 \text{ g/cm}^3$)	11.42
Outer PyC coating	2.35
SiC coating (1.85 kg Si)	2.64
Inner PyC coating	1.24
Buffer coating	1.22
Kernel (UCO_3 ; $\rho = 10.6 \text{ g/cm}^3$)	3.97
Total U (kernel)	3.55
{ 80.2% U-238 } { 19.8% U-235 } by mass	
Total C (kernel)	0.18
Total O (kernel)	0.24
Fertile particles ($\rho = 3.44 \text{ g/cm}^3$)	9.00
Outer PyC coating	2.25
Buffer coating	0.87
Kernel (ThO_2 ; $\rho = 9.9 \text{ g/cm}^3$)	5.88
Total Th (kernel)	5.16
Total O (kernel)	0.72
Graphite block (includes the plugs, dowels, matrix, and shim)	97.52
Boron	0.01
Total mass	117.95

TABLE 4
EQUILIBRIUM 23R FUEL ELEMENT SUMMARY
(Core-Averaged, As Charged)

<u>Component</u>	<u>Mass (kg/fuel element)</u>
Fissile particles ($\rho = 2.16 \text{ g/cm}^3$)	3.96
Outer PyC coating	1.00
SiC coating (0.86 kg Si)	1.23
Inner PyC coating	0.56
Buffer coating	0.38
Kernel (WAR UCO; $\rho = 3.3 \text{ g/cm}^3$)	0.79
Total U (kernel)	0.70
$\left(\begin{array}{l} 4.2\% \text{ U-236} \\ 7.9\% \text{ U-235} \\ 22.9\% \text{ U-234} \\ 65.0\% \text{ U-233} \end{array} \right)$ by mass	
Total C (kernel)	0.04
Total O (kernel)	0.05
Fertile particles ($\rho = 3.44 \text{ g/cm}^3$)	9.00
Outer PyC coating	2.25
Buffer coating	0.87
Kernel (ThO_2 ; $\rho = 9.9 \text{ g/cm}^3$)	5.88
Total Th (kernel)	5.16
Total O (kernel)	0.72
Graphite block (includes the plugs, dowels, matrix, and shim)	100.93
Boron	0.01
Total mass	113.90

TABLE 5
SUPPLEMENTAL EQUILIBRIUM FUEL CHARACTERISTICS ^(a,b)

	<u>Dimensional (μm)</u>	<u>Density (g/cm³)</u>
Makeup fissile		
Kernel (UCO)	350 diameter	10.6
Buffer	105 thickness	1.05
IPyC	35 thickness	1.9
SiC	35 thickness	3.2
OPyC	45 thickness	1.8
Total particle	790 diameter	
t/D ^(c)	0.63	
Recycle fissile		
Kernel (WAR UCO)	360 diameter	3.3
Buffer	65 thickness	1.05
IPyC	35 thickness	1.9
SiC	35 thickness	3.2
OPyC	40 thickness	1.8
Total particle	710 diameter	
t/D	0.486	
Makeup and recycle fertile		
Kernel (ThO ₂)	500 diameter	9.9
Buffer	85 thickness	1.05
PyC	75 thickness	1.90
Total particle	820 diameter	
t/D	0.195	

(a) From Ref. 5.

(b) At fuel cycle equilibrium, the fuel particle packing fractions for makeup and recycle fuel rods are assumed to be ~50% and ~25%, respectively.

(c) t/D = thickness/diameter.

applied in a recycle mode, employs a two-particle fuel system. Typically, the fissile particle may be TRISO coated dense UCO or UC_2 for makeup fuel and TRISO coated weak acid resin-derived (WAR) UC_xO_y for recycle fuel. The fertile particle is typically BISO coated ThO_2 .

2.2. FUEL ELEMENT DESCRIPTION

The standard fuel element in the HTGR is a graphite block 79.3 cm (31.4 in.) high with a hexagonal cross section 35.9 cm (14.2 in.) across the flats, as illustrated in Fig. 1. The graphite block is drilled lengthwise with two sets of holes; one allows the passage of helium coolant, and the second contains the fuel rods. Fuel rods contain selected blends of fuel and graphite shim particles in a carbonaceous matrix. Each fuel rod is 6.5 cm ($\sim$ 2.5 in.) in length and typically has a diameter of 1.40 cm (0.554 in.). The fuel particles used in the HTGR, shown schematically in Fig. 2, typically have diameters of 500 to 800 μ m.

Two particle types are used in the HTGR fuel; they are categorized by the coatings that have been applied to them (see Fig. 2). BISO particles are coated with a relatively porous buffer layer of carbon and then with a dense coating of pyrolytic carbon. TRISO coatings, in addition, have a silicon carbide coating placed between two layers of pyrolytic carbon. The SiC layer provides a means of separating these particles from the BISO particles in head-end reprocessing operations; it also enhances fission product retention in the fissile particles. BISO coatings are used for particles initially loaded only with thorium oxide, while TRISO coatings are used for particles loaded with uranium in the form of UCO or UC_2 .

2.3. REPROCESSING FLOWSHEET SCHEME

The use of discrete fissile and fertile particles in the MEU/Th fuel cycle permits separation of spent fissile fuel values (e.g., U-235 in the case of initial and makeup elements) from fertile particles which

Fig. 1. HTGR standard fuel element

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Fig. 2. HTGR coated fuel particles

contain bred U-233, thereby minimizing contamination of the high-quality bred fuel values. The separability of the fissile and fertile fuel particle types is also highly advantageous for proliferation resistance in MEU/Th fuel recycle, since plutonium bred in the MEU makeup fissile fuel may be disposed of as SiC-coated spent fissile particles without ever being separated from fission products or from spent uranium.

In the proposed MEU fuel cycle reprocessing scheme, fissile particles obtained from U-233 recycle elements are processed to recover the residual U-233 values. In contrast to spent makeup element fissile particles, the spent recycle fissile particles are not attractive as a source of fissionable plutonium, since they contain only 1.2 g of plutonium per fuel element, with approximately 85% of the plutonium being nonfissionable Pu-238 (Ref. 5). The reprocessing option selected for the MEU fuel recycle base case, therefore, involves (1) separation and disposal of initial and makeup element (I,M) fissile particles; (2) full reprocessing of recycle element (23R) fissile particles, and (3) full reprocessing of fertile particles from both I,M and 23R fuel elements.

A reprocessing flowsheet schematic for the MEU fuel recycle base case is shown in Fig. 3. Separation of fissile and fertile fuel particles from spent fuel elements is accomplished by the head-end process system, which entails primarily a crush-burn-leach sequence. The spent fuel elements are crushed in a three-stage size reduction unit to provide feed material for a fluidized-bed primary burner. Combustion in the burner removes the fuel element graphite moderator and outer carbon coating of the fuel particles by conversion to CO₂. The remaining fuel particles are separated into SiC-coated fissile and burned-back fertile particle fractions by pneumatic classification. The burned-back BISO coated fertile particle fraction is dissolved in a nitric acid solution containing a fluoride catalyst. The leachate is clarified from insolubles by centrifugation and routed to a feed adjustment step to prepare the solution for subsequent Acid Thorex solvent extraction processing. Solvent extraction removes fission products and separates U-233 from thorium.

Fig. 3. HTGR/MEU fuel recycle base case reprocessing flowsheet

The partially burned-back TRISO coated fissile particle fraction is further processed in one of two alternate ways, depending on the source spent fuel element type. Fissile particles from initial or makeup (I,M) elements are immobilized in an inert matrix and packaged for later isolation in a waste repository. Burned-back TRISO coated fissile particles from U-233 recycle (23R) elements are crushed to crack the protective SiC layer and to expose the inner carbon coating. The carbon combustion and removal process is completed in a fluidized-bed secondary burner. The fissile ash from the secondary burner is dissolved in nitric acid solution, and insolubles are removed by centrifugation. The clarified leachate is combined with U-233-containing leachate obtained from fertile particle dissolution for further processing through feed adjustment and Acid Thorex solvent extraction.

3. IMPACT OF MEU FUEL REPROCESSING FLOWSHEET ON HRRF DESIGN

3.1. HRRF-REPROCESSING DESIGN ASSUMPTIONS

The HRRF will be designed to reprocess 20,000 spent fuel elements per year. At equilibrium, the distribution of spent HTGR fuel elements to be processed is currently estimated to be 66% makeup elements (MS) which use 20% enriched U-235-containing fissile particles, and 34% recycle elements (23RS) which use nondenatured U-233-containing fissile particles. In contrast to prior HEU cycle reprocessing flowsheets, the MEU fuel recycle base case does not postulate recovery of residual U-235 fuel values; thus, the need for HRRF to reprocess U-235 recycle elements is eliminated.

As currently envisioned, spent MEU fuel originating at the Fort St. Vrain reactor will not be reprocessed but will be stored at a federal repository in spent fuel form. Spent HEU fuel originating at FSV will, however, be campaigned through HRRF reprocessing if permitted by national policy. Similarly, HRRF will provide a capability for reprocessing of very low burnup HTGR makeup fuel elements which may not have been fully irradiated owing to premature discharge from a reactor. In this case, it is intended to recover the 20%-enriched fissile material (U-235). Therefore, HRRF will include Purex solvent extraction process capability, even though the MEU cycle flowsheet indicates no need for Purex. Finally, HRRF will reprocess scrapped refabricated U-233 fuel elements on a campaign basis, after sufficient rejects have been accumulated in a dedicated scrap refabricated fuel storage area. It is important to note that HRRF will reprocess only spent initial and makeup fuel elements for approximately the first 5 years of operation, since spent recycle fuel will not be discharged from an HTGR prior to that time.

The HRRF will reprocess a number of HTGR fuel element types, e.g., standard, control, and buffer elements. Standard elements contain more fuel than do the other types. For the purpose of defining the daily throughput requirements for HRRF reprocessing, a core-averaged standard spent fuel element has been postulated and is used as the basis for material balance calculations. Daily throughput requirements for HRRF reprocessing are further defined by an interim design ground rule which assumes an overall reprocessing system availability of 80% and equipment utilization efficiency of 90%. The design ground rule also includes a 30-day-per-year allowance for customer accountability sweepdown and sampling operations in the head-end system.

On this basis, the head-end process system will have a design capacity for 86 elements per day, 233 days per year. The solvent extraction system will process the output from head-end operations in a period of 263 days per year. More specifically, the design capacity for fuel element crushing, primary burning, particle classification, and fertile particle dissolution subsystems will be based on processing 86 spent makeup elements (MS) per day; the design capacity for particle crushing, crushed particle burning, and fissile particle dissolution subsystems will be based on processing 86 spent recycle elements (23RS) per day; and, finally, the Acid Thorex solvent extraction system must have a throughput capacity sufficient to process the combined U-233 solution outputs from fertile and fissile particle dissolution.

3.2. HRRF REPROCESSING OPERATING MODE

The head-end system of HRRF reprocessing is designed to operate semicontinuously during processing of a customer's spent fuel lot, which is assumed to typically correspond to a reactor half-segment, or approximately 440 elements for a 900-MW(e) HTGR. The half-segment operating mode reduces fuel storage requirements by allowing processing to begin before spent fuel shipping for a customer is completed. Customer accountability requirements are satisfied by campaign processing of a customer's fuel

elements, daily sampling of accountability tanks, and a final sweepdown of the head-end system at the completion of each customer's spent fuel lot. An important operating mode basis is that the integrity of a customer's fuel material is maintained only through the accountability step. After that, intermixing with material from other customers' lots may occur.

The duration of batch operations during head-end processing of a customer's spent fuel lot is principally determined by the operating characteristics and cycles of key processing subsystems, such as the crushed fuel element (primary) burner, crushed fuel particle (secondary) burner, or fertile particle dissolver. Surge capacity will be provided between subsystems in the HRRF head-end process system to (1) provide a degree of flexibility, (2) provide a degree of subsystem/process decoupling, (3) make head-end system operation less sensitive to operating upsets or equipment failure, and (4) approach an essentially continuous operating mode to as high a degree as practical.

Surge storage for head-end leachate will be provided to permit continuing operation of the solvent extraction system during periods of head-end sweepdown or other downtimes. In the solvent extraction system, separate solvent extraction trains will be used to ensure a continuous processing capability and to minimize surge requirements.

The HRRF reprocessing off-gas systems will be designed to accommodate treatment of all gaseous effluents from dry and wet head-end processing. A continuous sidestream from the transport gas system will be treated in the primary burner off-gas system. Availability of the off-gas treatment systems must be assured for operation 365 days per year. Installation of parallel processing units, e.g., to permit off-stream regeneration of an adsorber bed while a like parallel unit is placed on-stream, and other appropriate design features will be used to achieve the availability goal.

4. FLOWSHEET AND MATERIAL BALANCE UPDATE

4.1. CHARACTERISTICS OF SPENT HTGR FUELS IN THE MEU CYCLE

As pointed out in the HRRF reprocessing design assumptions (Section 3.1), fuel element configurations differing somewhat from the standard element will also be reprocessed in the HRRF. However, variations in fuel element composition are considered to be a more important reprocessing parameter than is the geometric configuration of the element. In the HEU fuel cycle, fissile uranium constitutes the valuable inventory of the reprocessing plant, from the standpoint of both fuel cycle economics and regulations for safeguarding of special nuclear material (SNM). In the MEU fuel cycle, the presence of fissionable plutonium in spent makeup element fissile particles also contributes to SNM safeguards concerns. Other heavy metal and fission product content affects the operational characteristics and throughput of several processes, particularly in solvent extraction, off-gas processing, and waste treatment.

The MEU-cycle feed materials for the reprocessing plant are typified by the equilibrium spent fuel element definitions summarized in Tables 6 and 7 taken from Ref. 5). Table 6 presents the design-basis spent fuel definition for MEU-cycle makeup elements (MS), and Table 7 presents the corresponding information for MEU-cycle U-233 recycle elements (23RS). The total plutonium contents and isotopic distributions for these two types of spent fuel elements are given in Table 8. Computer printouts that fully define the detailed nuclide contents of the two design-basis spent fuel definitions are available in Ref. 5. Tentative design values that summarize radiological characteristics of MEU-cycle equilibrium spent fuels are presented in Table 9.

TABLE 6
 SPENT FUEL ELEMENT DEFINITION FOR AVERAGE HTGR
 STANDARD MAKEUP ELEMENT - MEU CYCLE
 (Core-Averaged Equilibrium Element
 at 180 Days After Discharge)

<u>Component</u>	<u>Mass</u> <u>(kg/fuel element)</u>
Fissile particles ($\rho \approx 2.64 \text{ g/cm}^3$)	10.38
Outer PyC coating	2.35
SiC coating (1.85 kg Si)	2.64
Inner PyC coating	1.24
Buffer coating	1.22
Kernel (UCO; $\rho \approx 10.6 \text{ g/cm}^3$)	2.93
Total U (kernel)	1.85
$\left\{ \begin{array}{l} 3.9\% \text{ U-235} \\ 3.5\% \text{ U-236} \\ 92.6\% \text{ U-238} \end{array} \right\}$ by mass	
Total C (kernel)	0.18
Total O (kernel)	0.24
Other fission and activation products	0.66
Fertile particles ($\rho \approx 3.44 \text{ g/cm}^3$)	7.28
Outer PyC coating	2.25
Buffer coating	0.87
Kernel (ThO ₂ ; $\rho \approx 9.9 \text{ g/cm}^3$)	4.16
Total Th (kernel)	3.22
Total U (kernel)	0.11
$\left\{ \begin{array}{l} <0.1\% \text{ U-232} \\ 83.0\% \text{ U-233} \\ 14.2\% \text{ U-234} \\ 2.5\% \text{ U-235} \\ 0.3\% \text{ U-236} \end{array} \right\}$ by mass	
Total O (kernel)	0.72
Other fission and activation products	0.11
Graphite block (includes plugs, dowels, matrix, and shim)	97.52
Boron	0.002
Total mass	115.18

TABLE 7
 SPENT FUEL ELEMENT DEFINITION FOR AVERAGE HTGR
 STANDARD U-233 RECYCLE ELEMENT - MEU CYCLE
 (Core-Averaged Equilibrium Element
 at 180 Days After Discharge)

<u>Component</u>	<u>Mass (kg/fuel element)</u>
Fissile particles ($\rho \approx 2.16 \text{ g/cm}^3$)	3.50
Outer PyC coating	1.00
SiC coating (0.86 kg Si)	1.23
Inner PyC coating	0.56
Buffer coating	0.38
Kernel (WAR UCO; $\rho \approx 3.3 \text{ g/cm}^3$)	0.33
Total U (kernel)	0.09
$\left(\begin{array}{l} <0.1\% \text{ U-232} \\ 20.2\% \text{ U-233} \\ 44.4\% \text{ U-234} \\ 19.5\% \text{ U-235} \\ 15.8\% \text{ U-236} \end{array} \right)$ by mass	
Total C (kernel)	0.04
Total O (kernel)	0.05
Other fission and activation products	0.15
Fertile particles ($\rho \approx 3.44 \text{ g/cm}^3$)	5.62
Outer PyC coating	2.25
Buffer coating	0.87
Kernel (ThO_2 ; $\rho \approx 9.9 \text{ g/cm}^3$)	2.50
Total Th (kernel)	1.66
Total U (kernel)	0.06
$\left(\begin{array}{l} <0.1\% \text{ U-232} \\ 83.0\% \text{ U-233} \\ 14.2\% \text{ U-234} \\ 2.5\% \text{ U-235} \\ 0.3\% \text{ U-236} \end{array} \right)$ by mass	
Total O (kernel)	0.72
Other fission and activation products	0.06
Graphite block (includes plugs, dowels, matrix, and shim)	100.93
Boron	0.002
Total mass	110.05

TABLE 8
PLUTONIUM CONTENT IN SPENT MEU-CYCLE FUELS
(Core-Averaged Equilibrium Elements at 180 Days After Discharge)

Nuclide [as g/FE ^(a)]	MS	MS	23RS	23RS
	Fertile <u>Particle</u>	Fissile <u>Particle</u>	Fertile <u>Particle</u>	Fissile <u>Particle</u>
Pu-236	2.3155-13	2.1553-10	1.1928-13	6.6017-11
Pu-238	3.6559-03	3.4391+00	1.8834-03	1.0342+00
Pu-239	2.5522-04	1.8083+01	1.3148-04	9.6217-02
Pu-240	6.7209-05	7.9738+00	3.4623-05	3.4617-02
Pu-241	4.1902-05	9.8282+00	2.1586-05	1.1056-02
Pu-242	5.0703-05	9.3230+00	2.6120-05	1.3224-02
Pu-243	2.8206-21	5.1864-16	1.4530-21	7.3567-19
Pu-244	6.0911-09	1.9281-04	3.1378-09	1.5086-07
Pu-245	1.3390-27	4.2387-23	6.8980-28	3.3163-26
Pu-246	2.6809-21	7.8383-17	1.3811-21	5.8905-20
Plutonium	4.0710-03	4.8647+01	2.0972-03	1.2093+00

(a) _{FE} = fuel element.

TABLE 9
RADIOLOGICAL CHARACTERISTICS OF EQUILIBRIUM SPENT FUELS

<u>Component</u>	<u>Watts/Fuel Element</u>	<u>Curies/Fuel Element</u>
23RS fertile particle	3.731×10^1	9.962×10^3
23RS fissile particle	4.945×10^1	1.197×10^4
MS fertile particle	7.242×10^1	1.934×10^4
MS fissile particle	2.081×10^2	4.737×10^4
23RS total	8.676×10^1	2.197×10^4
MS total	2.805×10^2	6.674×10^4

In addition to the design-basis spent fuels, the HRRF reprocessing plant must be capable of handling a variety of other fuel compositions. Examples include (1) low-irradiation fuel elements returned from a reactor, (2) unirradiated fuel elements that are rejected in the recycle fuel refabrication plant, (3) spent fuel elements from the first reload segment, and (4) spent special buffer zone elements with specialized fuel loadings. A number of fuel management variables may affect initial fuel loadings and, therefore, spent fuel compositions. Significant initial fuel loading variables include (1) the use of fuel rod blends to achieve desired core loadings, typically 15 or more blends per reload segment, and (2) variations within allowable ranges for both makeup and recycle fuel loading specifications.

Average spent fuel element definitions have been used as the bases for calculating the reprocessing throughput and material balances in this report. However, more reactive and possibly limiting fuel element compositions, e.g., unirradiated fuel, will be factored into later HRRF reprocessing equipment and systems design and layout studies.

4.2. FLOWSHEET UPDATE FOR MEU-CYCLE REPROCESSING

The reprocessing flowsheet scheme for the MEU fuel recycle base case is described in Section 2.3. The HRRF reprocessing flowsheets, revised for processing of spent MEU-cycle fuels rather than HEU-cycle fuels, are contained in Appendix A.

The reprocessing flowsheets for MEU-cycle fuel differ from those for HEU-cycle fuel in only a few major respects. Significant flowsheet effects brought about by a change from HEU-cycle reprocessing to MEU-cycle base-case reprocessing can be briefly summarized as follows:

1. Initial and makeup (I,M) fuel element fissile particles are separated from fertile particles by pneumatic classification. Subsequent waste system treatment of the separated fissile particles involves immobilization in an inert matrix (e.g.,

vitrification in a glass matrix) and packaging for shipment to a federal waste repository.

In the HEU flowsheet, the (I,M) fissile particles are processed through dissolution and Purex solvent extraction for recovery of residual U-235 fuel values. However, HEU fissile particles from spent 25R fuel elements, which contain recovered residual U-235 from a prior irradiation cycle, are immobilized for disposal in a manner identical to that for makeup MEU fissile particles.

2. U-233 recycle fuel (23R) fissile particles are processed through dissolution and combined with fertile solution product for Acid Thorex solvent extraction processing to recover both bred and residual U-233 fuel values.
3. Purex solvent extraction is not needed for the MEU fuel recycle base case, since U-235 residual fuel values are not recovered, nor is plutonium bred in the fissile particle separated from the residual U-235 and fission products.
4. The MEU-cycle reprocessing flowsheet makes no provision for processing of spent Fort St. Vrain/MEU fuel nor for spent U-235 recycle (25RS) fuel. Both of these spent fuel types are handled in the HEU reprocessing flowsheet.

In MEU-cycle reprocessing, control of fuel particle breakage within specified limits and limitation of fissile-fertile crossover are perhaps even more important factors than in the HEU cycle. For example, breakage of fissile particles prior to or during the primary burning step may result in carryover of denatured spent uranium into the fertile stream; contamination of fertile-bred U-233 with U-236 and U-238 is to be minimized. The flowsheet update indicates differential leaching of the fertile stream as an option for mitigating this effect of fissile-fertile crossover.

A number of miscellaneous revisions were made in the reprocessing system flowsheets, reflecting the results of recent development and engineering studies. These changes, applicable to both MEU- and HEU-cycle flowsheets, include (1) the use of a CO₂/nitrogen oxide sparge for fertile particle dissolution to promote iodine release to the off-gas system, (2) tentative changes in the sequence of burner off-gas treatment, (3) update of the Krypton Adsorption in Liquid Carbon Dioxide (KALC) off-gas processing flowsheet, (4) addition of krypton adsorption treatment for the gas stream released from C-14 fixation, and (5) inclusion of macroreticular resin treatment for a final product sidestream in the second-cycle solvent cleanup system. The resin-treated solvent is used in the second-cycle thorium solvent extraction flowsheet.

4.3. MATERIAL BALANCE UPDATE FOR MEU-CYCLE REPROCESSING

The design assumptions and proposed operating mode for HRRF reprocessing are basic factors influencing the material balance for the reprocessing system flowsheets. Both of these factors are described in Section 3. The HRRF reprocessing material balance data tables, revised for processing of spent MEU-cycle fuels rather than HEU-cycle fuels, are contained in Appendix B.

It should be noted that material balances were calculated for a throughput rate of 10,000 spent fuel elements per year, corresponding to the processing capacity of each of two parallel HRRF head-end process systems. Using a processing basis of 10,000 fuel elements per year for the MEU-cycle material balance tables has the further advantage of providing a direct comparison to prior published HEU material balance data; the HEU materials data were prepared in 1977 for the Phase I HTGR Recycle Demonstration Facility concept. This activity is described in Ref. 6.

The material balance data contained in Appendix B are based on average fuel element definitions in a recycle plant operating at equilibrium, i.e., several years after startup. The material balance for

PF-250-1, "Head-End Fuel Element Crush-Primary Burn-Classify," and PF-250-2, "Head-End Fertile Fraction Leaching," is based on 43 elements per day throughput of spent MEU makeup elements, which are defined in Table 6. This reprocessing feed was selected because it is representative of high throughput requirements for PF-250-1 and PF-250-2. The material balance for PF-250-3, "Head-End Fissile Particle Crush-Secondary Burn-Leach," is based on 43 elements per day throughput of spent U-233 recycle elements. This processing feed, defined in Table 7, had to be selected because only U-233 recycle fissile particles are reprocessed in the MEU fuel recycle base case.

Clarified dissolver solutions containing recovered residual U-233 from fissile particles, and solutions containing recovered bred U-233 from fertile particles, may be combined for accountability measurement if they originate in the same customer lot. Therefore, the combined U-233 dissolver solution was taken as the computation basis for the Thorex solvent extraction flowsheet material balances.

As shown in Section 4.2, the technology for reprocessing of spent MEU fuel does not vary significantly from that required for HEU fuel. Consequently, the flowsheet revisions for MEU-cycle reprocessing are relatively minor. However, the impact of the MEU cycle is felt more strongly in the quantification of materials flow through the reprocessing plant. Therefore, the MEU fuel cycle is expected to affect the equipment requirements and configuration for the HRRF reprocessing plant.

Differences in materials flow through reprocessing become apparent when comparing the MEU-cycle material balance data contained in Appendix B to HEU-cycle data previously reported in Ref. 6. Spent fuel definitions for makeup elements in the MEU and HEU cycles are summarized in Table 10. These spent fuel definitions highlight the difference in feed materials for MEU- and HEU-cycle reprocessing. Table 11 summarizes the spent fuel definitions for recycle fuels which will be reprocessed in MEU or HEU cycles. As shown in the table, only one type of spent recycle fuel (23R)

TABLE 10
SPENT FUEL DEFINITIONS FOR MAKEUP ELEMENTS

	<u>MEU Cycle</u>	<u>HEU Cycle</u>
Fissile particles		
Type	Dense UO ₂ or UC ₂	WAR-UC _x O _y
Kilograms/fuel element	10.38	6.45
Coating	TRISO	TRISO
Fertile particles		
Type	Dense ThO ₂	Dense ThO ₂
Kilograms/fuel element	7.28	15.86
Coating	BISO	BISO
Heavy metal content in fissile particles		
Uranium, kg	1.85	0.22
Fissile U, wt %	3.9	29.5
Non-fissile U, wt %	96.1	70.5
Plutonium, kg	0.05	0.01
Pu-239 and Pu-241, wt %	57	21
Other Pu isotopes, wt %	43	79
Pu-238, wt %	7	66
Heavy metal content in fertile particles		
Thorium, kg	3.22	7.94
Uranium, kg	0.11	0.26
U-233, wt %	83	80
U-235, wt %	<3	<4

TABLE 11
SPENT FUEL DEFINITIONS FOR RECYCLE FUELS

	<u>HEU Cycle^(a)</u>		<u>MEU Cycle</u>
	<u>23R</u>	<u>25R</u>	<u>23R</u>
Number of fuel elements/reload segment ^(a)	431 (45%)	29 (3%)	450 (34%)
Fissile particle type	WAR-UC _x O _y	WAR-UC _x O _y	WAR-UC _x O _y
Coating	TRISO	TRISO	TRISO
Kernel density, g/cm ³	3.3	3.3	3.3
Fertile particle type	ThO ₂	ThO ₂	ThO ₂
Coating	BISO	BISO	BISO
Kernel density, g/cm ³	9.9	9.9	9.9
Heavy metal content in fissile particles			
Uranium, kg	0.16	1.40	0.09
Fissile U, wt %	39.9	3.64	39.7
Nonfissile U, wt %	60.1	96.4	60.3
Plutonium, kg	0.001	0.08	0.0012
Pu-239 and Pu-241, wt %	10.8	20.8	10.5
Other Pu isotopes, wt %	89.2	79.2	89.5
Pu-238, wt %	85.2	65.8	85.1
Heavy metal content in fertile particles			
Thorium, kg	7.94	7.94	1.66
Uranium, kg	0.26	0.26	0.06
Fissile U, wt %	83.4	83.4	85.5
Nonfissile U, wt %	16.6	16.6	14.5

^(a) 3360 MW(t) HTGR (PE-type).

needs to be reprocessed in the base-case MEU cycle. In the HEU cycle, both 23R (U-233) and 25R (U-235) spent recycle fuels are to be reprocessed.

Pertinent characteristics of fresh fuel elements for the 20% enriched MEU cycle and for the 93% enriched HEU cycle are summarized and compared in Table 12.

TABLE 12
EQUILIBRIUM MAKEUP FUEL ELEMENT SUMMARY

	<u>MEU Cycle</u>	<u>HEU Cycle</u>
C/Th ratio	400-850	240
Fissile particles (TRISO coated)		
Type	Dense UCO or UC ₂	WAR-UC _x O _y
Kernel density, g/cm ³	10.6 (for UCO)	3.3
Kernel diameter, μm	350	305
Particle diameter, μm	790	650
Particle density, g/cm ³	2.64	2.2
Fertile particles (BISO coated)		
Type	Dense ThO ₂	Dense ThO ₂
Kernel density, g/cm ³	>9.5	>9.5
Kernel diameter, μm	500	500
Particle diameter, μm	820	820
Particle density, g/cm ³	3.44	3.44
Uranium loading/fuel element, kg	3.55	0.84
U-238, wt %	80.2	5.9
U-235, wt %	19.8	93.1
Thorium loading/fuel element, kg	5.16	8.55
Fuel rod diameter, cm	1.40	1.60
Makeup fuel elements/reload segment ^(a)	872 (66%)	500 (52%)

(a) 3360 MW(t) HTGR

5. SUMMARY AND CONCLUSIONS

The flowsheets for reprocessing of spent HTGR fuel elements have been revised for the MEU recycle base case, and corresponding materials balance data for HRRF reprocessing of spent MEU and recycle fuels have been calculated.

Compared to HEU fuel recycle, it was concluded that the reprocessing of spent MEU and recycle fuel elements generally uses the reprocessing technology developed for the HEU cycle. Flowsheet revisions for MEU reprocessing include:

Immobilization and packaging of I,M fissile particles, following separation from burned-back fertile particles.

Combination of 23R fissile particle product solution with fertile product solution for subsequent Thorex solvent extraction processing.

Purex solvent extraction is not needed for the MEU fuel recycle base case, since residual U-235 fuel values and bred Pu are not recovered. Nevertheless, the HRRF reprocessing plant design is expected to include a Purex capability to permit recovery of low-burnup 20%-enriched U-235 fissile values.

Reprocessing of spent MEU fuel was found to have a significant effect on materials mass flow, relative to HEU reprocessing. Therefore, the MEU fuel cycle is expected to affect the present HEU process equipment requirements and, consequently, the configuration for the HRRF reprocessing plant.

ACKNOWLEDGMENTS

The author gratefully acknowledges the valuable assistance of the technical staff of the Head-End Operations and Separation Development Branches in the preparation of material balance data.

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APPENDIX A

HRRF REPROCESSING FLOWSHEETS FOR MEU-CYCLE FUELS

9301 FLOWSHEET FOR MEU CYCLE 2/78

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9301 FLOWSHEET FOR MEU CYCLE 2/78

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2		OFF-GAS SYSTEM-BURNER OFF-GAS PROCESSING	
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APPENDIX B

HRRF REPROCESSING MATERIAL BALANCE DATA FOR MEU-CYCLE FUELS

TABLE B-1
MATERIAL BALANCE FOR HEAD-END FUEL ELEMENT CRUSH - PRIMARY BURN - CLASSIFY (PF-250-1)
(SPENT MAKEUP ELEMENTS)

	Crusher Feed	Crusher Product	Material Transport	Burner Feed	Burner Product	Material Transport	Burner Off-gas	Material Transport	Classifier Feed	Classifier Bottoms	Fertile Fraction Transport	Classifying Gas Return	Classifier Overheads	Fissile Fraction Transport	Burner Feed Gases
Stream No.	101	102	104	105	106	107	110	114	115	123	124	126	129	131	135
Type of Flow	Batch	Batch	Batch	Semi- cont.	Batch	Batch	Semi- cont.	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Semi- cont.
Avg operating h/d ^(a)	11.0	11.0	3.2	20.24	0.4	0.4	24.0	0.4	4.3	4.3	0.2	4.3	4.3	0.1	24.0
Avg solids flow, kg/d	4952.7 ^(b)	4952.7	4952.7	4952.7	516.5	516.5	TBD	516.5	516.2	179.6	179.6	TBD	336.8	336.8	--
Avg gas flow, slpd/1000		663.7	663.7			80.4	12,300	80.4	--	--	--	726.0	--	27.0	11,500
Heat load, W/kg ^(c)	2.4 ^(d)			2.44	23.4				23.4						
Activity, Ci/kg	579.0 ^(d)			579.0	5552.0				5552.0						
Bulk density, g/cm ³	1.29			1.12	2.7				2.7						
Physical Components															
Fissile particles															
Whole, kg/d	443.2	431.6	422.7 ^(e)	422.7											
Broken, kg/d	3.12	14.73	23.7	23.7	12.05	15.14		18.20	18.2				19.7	19.7	
Burned-back, kg/d					308.7	305.6		302.5	302.5	6.0	6.0		295.0	295.0	
SiC hulls, kg/d					10.86	10.86		10.9	10.9				10.9	10.9	
Fertile particles															
Whole, kg/d	311.8	309.3	308.7 ^(e)	308.7											
Broken, kg/d	1.25	3.76	4.4	4.38	2.68	2.94		3.20	3.2	0.8	0.8		2.4	2.4	
Burned-back, kg/d					176.23	176.00		175.74	175.4	172.8	172.8		2.6	2.6	
Graphite, matrix, shim, and boron, kg/d	4193.0	4193.0	4193.0	4193.0	6.2	6.2		6.2	6.2				6.2	6.2	
Chemical Components															
Burnable carbon, kg/d	4429.0	4432.0	4434.0	4434.0	6.0	7.0		8.0	8.0	{0.1	0.1}		8.0	8.0	
Bound carbon, kg/d	112.7	109.8	107.5	107.5	102.7	101.7		100.7	100.7				100.6	100.6	
Bound oxygen, kg/d	41.3	41.3	41.3	41.3	38.7	38.7		38.7	38.7	27.3	27.3		11.4	11.4	
Silicon carbide, kg/d	113.5	113.5	113.5	113.5	113.5	113.5		113.5	113.5	2.0	2.0		111.5	111.5	
Heavy metal															
U (w/U-233), kg/d ^(f)	4.73	4.73	4.73	4.73	4.73	4.73		4.73	4.73	4.6	4.6		0.13	0.13	
U (w/U-235), kg/d ^(g)	79.55	79.55	79.55	79.55	79.55	79.55		79.55	79.55	1.49	1.49		78.06	78.06	
Thorium, kg/d	138.5	138.5	138.5	138.5	138.5	138.5		138.5	138.5	135.9	135.9		2.6	2.6	
Other, kg/d	3.21	3.21	3.21	3.21	3.21	3.21		3.21	3.21				3.21	3.21	
Fission Products															
³ H, Kr, I, Xe, Rn, kg/d	4.007	4.007	4.007	4.007	3.6	3.6	0.4	3.6	3.6	2.2	2.2		1.4	1.4	
Other, kg/d	25.68	25.68	25.68	25.68	25.68	25.7	25.7	25.7	25.7	6.0	6.0		19.7	19.7	
Sulfur	0.9	0.9	0.9	0.9			0.9								
Boron	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2				0.2	0.2	
O ₂ , slpd/1000							24.6								7,676
CO ₂ , slpd/1000							10,829.0	80.4			44.2	726.0		27.0	3,824
CO, slpd/1000							1,446								

- (a) Exclusive of rework - based on 233 equivalent operating days per year.
(b) LHTGR standard makeup fuel element basis (for 10,000 fuel element/yr throughput).
(c) Decay heat only (excludes process heating and cooling effects).
(d) 180-day cooled fuel elements discharged at reload 5.
(e) Total transport breakage from crusher to burner.
(f) Total uranium in the fertile particle.
(g) Total uranium in the fissile particle.

TABLE B-2
MATERIAL BALANCE FOR HEAD-END FERTILE FRACTION LEACHING (PF-250-2)
(SPENT MAKEUP ELEMENTS)

	Fertile Leacher Feed	Thorex Acid Solu- tion	Fertile Leacher Product	Leacher Off-Gas			Centri- fuge Product Solution	Centri- fuge Product Solids	Poisoned Dilute Acid	Repulping Product	Centri- fuge Product Solution	Fertile Leach Product to SX	Centri- fuge Product Solids	Insols Products	Insols to Classify	Dryer Off- Gas	High Level Liquid Waste
Stream No.	202	203	204	205	206	207	209	210	211	212	214	218	219	220	221	225	226
Type of flow	Batch	Batch	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Batch	Batch	Semi- cont.	Semi- cont.	Batch	Batch	Batch	Batch	Semi- cont.	Semi- cont.
Avg operating h/d(a)	0.2		8-12	8-12	8-12	8-12	0.6				0.03			0.003	0.003	TBD	
Avg solids flow, kg/d	179.6		7.1				0.03 ^(b)	7.1		6.4	(b)	0.03 ^(b)	6.4	6.4	6.4		
Avg gas/vapor flow, slpd/1000(c)	44.2			408.1	407.4									0.7	0.7	TBD	
Avg liquid flow, l/d(c)		585.6	585.6			0.7	585.1	0.5	49.0	49.5	49.0	633.6	0.5				0.5
Heat load, W/l(d)			TBD				TBD	TBD		TBD	TBD	TBD	TBD	TBD	TBD		TBD
Activity, Ci/l			TBD	TBD	TBD		TBD	TBD		TBD	TBD	TBD	TBD	TBD	TBD		TBD
Fissile particles, kg/d	6.0		6.0					6.0		6.0			6.0	6.0			
Fertile particles kg/d	173.6																
Carbon, g/l			0.2				0.04	150.0		1.5		0.05	150.0	0.11	0.11		
Uranium, g/l			10.4				10.4	60.9		0.6	0.6	9.7	0.3	0.0002	0.0002		0.006
Thorium, g/l			232.0				230.9	1357.2		13.7	13.1	214.2	80.0	0.06	0.06		0.13
Fission products, g/l(e)			14.0	0.005	0.005		13.5	585.0		5.9	0.4	12.5	540.0	0.4	0.4		0.06
HNO ₃ , M		13.0	8.5				8.8		0.2	0.2	0.2	7.9	0.2				0.2
F ⁻ , M		0.05	0.05				0.05					0.05					
Al ⁺⁺⁺ , M		0.1	0.1				0.1					0.1					
Cd ⁺⁺ , M		0.075	0.075				0.075		0.075	0.075	0.075	0.075	0.075				0.075
Total NO ₃ ⁻ , M		13.4	13.4				13.4		0.3	0.3	0.3	12.4	0.3				0.3
NO _x , slpd/1000				1.2	8.15												
CO ₂ , slpd/1000																	
Air, slpd/1000				406.9	399.3											TBD	

(a) Exclusive of rework. Based on 233 equivalent operating days/year.
(b) 25% of free carbon assumed to be in final product (all shown in first centrifuge product).
(c) Operating flow rate.
(d) Decay heat only (exclusive of process heating or cooling).
(e) Includes other heavy metals.

TABLE B-3
MATERIAL BALANCE FOR HEAD-END FISSILE PARTICLE CRUSH-SECONDARY BURN-LEACH (PF-250-3)
(SPENT 23 ELEMENTS)

	Spent 23R Element Fissile Particle Transport	Fissile Crusher Feed	Fissile Crusher Product	Particle Burner Feed	Burner Feed Gases	Particle Burner Off-gas	Particle Burner Product	Burner Product Transport	Fissile Leacher Feed	Poisoned Nitric Acid Solution	Off-gas	Condensate Return	Fissile Leacher Off-gas	Fissile Leacher Product	Centrifuge Solution	Centrifuge Solids	Poisoned Dilute Acid	Repulping Product	Centrifuge Solution	Fissile Leaching Product to SX	Centrifuge Solids	Insols Dryer Product	High Level Liquid Waste	Insols Dryer Off-gas
Stream No.	301	304	307	308	309	310	311	312	313	314	315	316	317	318	320	321	322	323	325	327	328	332	334	335
Type of flow	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch
Avg operating h/d ^(a)	0.1	2.8	2.8	2.8	12.0	12.0	1.6	0.1	7.0	7.0	14.0	14.0	14.0		0.5				0.3			0.06		
Avg solids flow, kg/d	113.6	113.6	113.6	113.6	0	TBD	66.6	66.6	66.6					53.4	0.1 ^(b)	53.3		53.1		0.1	53.1	53.1	Negl.	Negl.
Avg gas/vapor flow, slpd/1000	14.0				208.3	209.7		15.0			211.4		211.3											TBD
Avg liquid flow, l/d										469.0		0.24		469.0	463.7	5.3	380.0	385.3	380.0	463.7	5.3	--	5.3	
Heat load, W/l ^(c) or W/kg	TBD	TBD	TBD	TBD		TBD	TBD	TBD	TBD		Negl.		Negl.	TBD	TBD	TBD		TBD	TBD	TBD	TBD	TBD	TBD	TBD
Activity, Ci/l or Ci/kg	TBD	TBD	TBD	TBD		TBD	TBD	TBD	TBD		Negl.		Negl.	TBD	TBD	TBD		TBD	TBD	TBD	TBD	TBD	TBD	TBD
Burned-back fissile particles, kg/d	99.9	99.9	1.0	1.0			0.9	0.9	0.9					0.9		0.9		0.9			0.9	0.9		
Broken fissile particles, kg/d	6.2	6.2	105.1	105.1			--	--	--					--		--		--			--	--		
SiC hulls, kg/d	3.7	3.7	3.7	3.7			50.0	50.0	50.0					50.0		50.0		50.0			50.0	50.0		
Burned-back fertile particles, kg/d	1.7	1.7	1.7	1.7			1.7	1.7	1.7					1.7		1.7		1.7			1.7	1.7		
U ₃ O ₈ , kg/d							4.44	4.44	4.44					0.15	--	0.15		0.1			0.1	0.1		
Other solids, kg/d ^(e)	2.0	2.0	2.0	2.0			9.6 ^(d)	9.6	9.6					0.6	0.1	0.5		0.4		0.1	0.4	0.4		
In Solution:																								
Uranium, g/l														8.0	8.0	8.0		0.2	0.2	8.0	0.2		TBD	
Thorium, g/l														Negl.	Negl.	Negl.		Negl.	Negl.	Negl.	Negl.		TBD	
Plutonium, g/l														0.4	0.4	0.4		0.01	0.01	0.4	0.01		TBD	
Other heavy metals, g/l														0.4	0.4	0.4		0.01	0.01	0.4	0.01		TBD	
Fission Products																								
³ H, Kr, I, Xe, Rn, g/l							TBD	TBD	TBD		Negl.			Negl.	Negl.	Negl.		Negl.	Negl.	Negl.	Negl.			
Other, g/l							TBD	TBD	TBD					11.7	11.7	11.7		0.3	0.3	11.7	0.3		TBD	
Boron, g/l														0.09	0.09	0.09		0.001	0.001	0.09	0.001		TBD	
HNO ₃ , M										2.5				2.0	2.0	2.0	0.2	0.2	0.2	2.0	0.2		TBD	
Cd ⁺⁺ , M										0.075				0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075		TBD	
Total NO ₃ ⁻ , M										2.5				2.5	2.5	2.5	0.3	0.3	0.3	2.5	0.3	TBD	TBD	
O ₂ , slpd/1000					94.1	29.1																		
CO ₂ , slpd/1000	14.0				114.2	171.6	TBD	15.0																TBD
CO, slpd/1000						9.0																		
NO _x , slpd/1000											0.24		0.11									TBD		
Air, slpd/1000											211.2		211.2											TBD

(a) Exclusive of rework. Based on 233 equivalent operating days per year.

(b) 25% of the insoluble carbon is assumed to go in solution (Σ from both centrifuges all shown in stream 320).

(c) Decay heat only (exclusive of process heating or cooling).

(d) All unburned carbon exterior to SiC coatings included in "other solids." All actinides and fission products associated with SiC Hulls included with hulls. B₂O₃ included in other solids.

(e) Unburned graphite, B₂O₃, and other oxygen associated with fission products and heavy metal oxides from broken fissiles from primary burn.

TABLE B-4
MATERIAL BALANCE FOR OFF-GAS SYSTEM - BURNER OFF-GAS PROCESSING (PF-650-11)

Stream No.	Primary Burner Off-gas (PBOG)	To Semivolatile FP Removal	To Iodine Removal Unit	To Sulfur Removal Unit	To CO/HT Oxidizer	To Tritium Removal Unit	To Radon Holdup Unit	To KALC Surge Tank	Secondary Burner Off-gas (SBOG)	To Semivolatile FP Removal	To Iodine Removal Unit	To CO/HT Oxidizer	To Tritium Removal Unit	To Radon Holdup Unit From SBOG	To KALC Process
	101	104	107	111	113	117	120	123	151	152	155	159	162	164	167
Type of flow	Semicont.	Semicont.	Semicont.	Semicont.	Semicont.	Semicont.	Semicont.	Semicont.	Batch	Batch	Batch	Batch	Batch	Batch	Batch
Avg operating h/d ^(a)	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
Avg gas flow, slpd/1000 ^(b)	16,311 ^(e)	16,311	16,311	16,311	16,311	16,325	16,325	16,325	416 ^(e)	416	416	416	416	416	416
Heat load, W/l ^(c)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Activity, Ci/l	>2.4 (-4)	>2.4 (-4)	>2.4 (-4)	>2.4 (-4)	>2.4 (-4)	>2.4 (-4)	>1.5 (-4)	>1.5 (-4)	>3.4 (-2)	>3.4 (-2)	>3.4 (-2)	>3.4 (-2)	>3.4 (-2)	3.4 (-2)	3.4 (-2)
O ₂ , slpd/1000	49	49	49	49	49	62.7	62.7	62.7	58	58	58	58	58	58	58
CO ₂ , slpd/1000	14,892	14,892	14,892	14,892	14,892	16,235	16,235	16,235	340	340	340	340	358	358	358
CO, slpd/1000	1,370	1,370	1,370	1,370	1,370	27.4	27.4	27.4	18	18	18	18	0.4	0.4	0.4
NO _x , slpd/1000															
Air, slpd/1000															
NH ₃ , slpd/1000															
N ₂ , slpd/1000															
Sulfur, g/l	5.6 (-5)	5.6 (-5)	5.6 (-5)	5.6 (-5)	5.6 (-7)	5.6 (-7)	5.6 (-7)	5.6 (-7)	1.1 (-5)	1.1 (-5)	1.1 (-5)	1.1 (-5)	1.1 (-5)	1.1 (-5)	1.1 (-5)
Carbon-14, g/l ^(d)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	8.3 (-7)	8.3 (-7)	8.3 (-7)	8.3 (-7)	8.3 (-7)	8.3 (-7)	8.3 (-7)
Radon, g/l	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Tritium, g/l	9.1 (-9)	9.1 (-9)	9.1 (-9)	9.1 (-9)	9.1 (-9)	9.1 (-9)	9.1 (-12)	9.1 (-12)	6.4 (-8)	6.4 (-8)	6.4 (-8)	6.4 (-8)	6.4 (-8)	6.4 (-11)	6.4 (-11)
Krypton, g/l	2.4 (-6)	2.4 (-6)	2.4 (-6)	2.4 (-6)	2.4 (-6)	2.4 (-6)	2.4 (-6)	2.4 (-6)	5.6 (-4)	5.6 (-4)	5.6 (-4)	5.6 (-4)	5.6 (-4)	5.6 (-4)	5.6 (-4)
Xenon, g/l	2.1 (-5)	2.1 (-5)	2.1 (-5)	2.1 (-5)	2.1 (-5)	2.1 (-5)	2.1 (-5)	2.1 (-5)	5.8 (-3)	5.8 (-3)	5.8 (-3)	5.8 (-3)	5.8 (-3)	5.8 (-3)	5.8 (-3)
Iodine, g/l	6.3 (-7)	6.3 (-7)	6.3 (-7)	6.3 (-10)	6.3 (-10)	6.3 (-10)	6.3 (-10)	6.3 (-10)	1.9 (-4)	1.9 (-4)	1.9 (-4)	1.9 (-7)	1.9 (-7)	1.9 (-7)	1.9 (-7)
Other FP, g/l	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Other particulates, g/l	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

(a) Exclusive of rework - based on 233 equivalent operating days per year.

(b) Exclusive of filter blowback and bed regeneration CO₂ additions. Not including impurity volumes.

(c) Decay heat only (exclusive of process heating or cooling).

(d) Carbon-14 level has increased by 80% in PBOG and 127 times in SBOG as a result of using recycle CO₂ from KALC system.

(e) Value has been adjusted to include miscellaneous gas stream inputs; e.g., transport gas bleed or coolant purge.

TABLE B-5
MATERIAL BALANCE FOR OFF-GAS SYSTEM - DISSOLVER OFF-GAS PROCESSING (PF-650-12)

	Fertile Fraction Dissolver Off-Gas	Fissile Ash Dissolver Off-Gas	Insol Dryer (Fertile Dissolution)	Insol Dryer (Fissile Dissolution)	To Dissolver Off-Gas Processing	To NO _x Converter	Ammonia Addition	To Iodine Removal	To KALC Process
Stream No.	501	502	503	504	506	512	513	519	530
Type of flow	Semi-cont.	Batch	Semi-cont.	Batch	Semi-cont.	Semi-cont.	Semi-cont.	Semi-cont.	Semi-cont.
Avg operating h/d ^(a)	14	8-12	TBD	TBD	14	14	14	14	14
Avg gas flow, slpd/1000 ^(b)	407.4	211.3	TBD	TBD	618.7	618.7	8.2	617.4	617.4
Heat load, W/l ^(c)	TBD	TBD	TBD	TBD	TBD	TBD	0	TBD	TBD
Activity, Ci/l	>2.1 (-2)	>9.0 (-4)	TBD	TBD	>1.4 (-2)	>1.4 (-2)		>1.4 (-2)	>1.4 (-2)
NO _x , slpd/1000 ^(d)	8.1	0.11			8.2	8.2	0	8.2 (-2)	8.2 (-2)
CO ₂ , slpd/1000	399.3	211.2			610.5	610.5	0	610.5	610.5
NH ₃ , slpd/1000	--	--			--	--		8.2 (-2)	8.2 (-2)
N ₂ , slpd/1000	0	0			0	0	0	6.9	6.9
Radon, g/l	TBD	TBD			TBD	TBD	--	TBD	TBD
Krypton, g/l	2.9 (-4)	1.2 (-5)			2.0 (-4)	2.0 (-4)	--	2.0 (-4)	2.0 (-4)
Xenon, g/l	1.7 (-3)	7.1 (-5)			1.1 (-3)	1.1 (-3)	--	1.1 (-3)	1.1 (-3)
Iodine, g/l	1.0 (-4)	4.9 (-6)			6.8 (-5)	6.8 (-5)	--	6.8 (-5)	6.8 (-8)

(a) Exclusive of rework - based on 233 equivalent operating days per year.

(b) Exclusive of moisture content.

(c) Decay heat only (exclusive of process heating or cooling).

(d) 2% NO_x from fertile dissolver is assumed since the fertile dissolver is sparged with NO with CO₂ (composition TBD).

TABLE B-6
MATERIAL BALANCE FOR OFF-GAS SYSTEM - KRYPTON ABSORPTION IN LIQUID CO₂ (KALC)
OFF-GAS PROCESSING (PF-650-3)

	From SBOG and DOG Off-Gas Treatment	From PBOG Off-Gas Treatment	To KALC Compressors	To Absorber/ Fractionator	To MS-CO ₂ Removal	To Krypton Storage	To Stack	To Carbon-14 Fixation
Stream No	200	201	202(a)	208(b)	218	233	237	245
Type of flow	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.
Avg operating h/d ^(c)	24	24	24	24	24	24	24	24
Avg gas flow, slpd/1000 ^(d)	<1035	16,325	17,360	17,360	357.1	0.2	5.9 (-1)	8623.9
Heat load, W/l ^(e,f)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Activity, Ci/l ^(f)	2.2 (-2)	1.5 (-4)	1.45 (-3)	1.45 (-3)	7.0 (-2)	125	TBD	2.92 (-5)
O ₂ , slpd/1000	58	62.7	120.7	120.7	3.8 (-1)	Negl	Negl	120.7
CO ₂ , slpd/1000	969	16,235	17,204	17,204	5.84	Negl	Negl	8468.3 ^(g)
CO, slpd/1000	0.4	27.4	27.8	27.8	8.8 (-2)	Negl	Negl	27.8
N ₂ , slpd/1000	6.9	0	363.3	363.3	350.1	0.1	Negl	363.3
Krypton, slpd/1000	9.45 (-2)	1.03 (-2)	1.05 (-1)	1.05 (-1)	1.04 (-1)	0.1	1.0 (-3)	1.05 (-3)
Xenon, slpd/1000	5.37 (-1)	5.86 (-2)	5.96 (-1)	5.96 (-1)	5.9 (-1)	5.0 (-3)	5.9 (-1)	5.96 (-3)
NO _x , slpd/1000	8.2 (-2)	0	8.2 (-2)	8.2 (-2)	Negl	Negl	Negl	8.2 (-2)
NH ₃ , slpd/1000	8.2 (-2)	0	8.2 (-2)	8.2 (-2)	Negl	Negl	Negl	8.2 (-2)
Sulfur, g/l ^(h)	4.4 (-6)	5.6 (-7)	7.9 (-7)	7.9 (-7)	TBD	Negl	Negl	TBD
Carbon-14, g/l	1.3 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.63 (-6)	Negl	Negl	1.6 (-6)
Radon, g/l	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Tritium, g/l	Negl	9.1 (-12)	8.6 (-12)	8.6 (-12)	TBD	Negl	Negl	TBD
Krypton, g/l	3.4 (-4)	2.4 (-6)	2.3 (-5)	2.3 (-5)	5.5 (-2)	1.90	6.4 (-3)	4.6 (-7)
Xenon, g/l	3.0 (-3)	2.1 (-5)	2.0 (-4)	2.0 (-4)	4.9 (-1)	1.5 (-1)	5.8	4.0 (-6)
Iodine, g/l	1.2 (-7)	6.3 (-10)	7.7 (-9)	7.7 (-9)	TBD	Negl	Negl	TBD
Other FP, g/l	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Other particulates or contaminants, g/l	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

(a) ">" and "<" designations have been dropped in 202 and following stream as insols; gas dryer flows are considered negligible in the large system.

(b) All terms expressed in terms of standard temperature and pressure throughout.

(c) Exclusive of rework -- based on 233 equivalent operating days.

(d) Exclusive of filter blowback and bed regeneration CO₂ additions.

(e) Decay heat only (excludes process heating and cooling).

(f) Exclusive of any activity contributed by any semivolatiles still in stream.

(g) Excluding CO₂ makeup (220).

(h) Exclusive of any SBOG sulfur content.

TABLE B-7
MATERIAL BALANCE FOR OFF-GAS SYSTEM - CARBON-14 FIXATION WITH LIME OFF-GAS PROCESSING (PF-660-1)

Stream No.	From KALC Absorber	Vent to Filters and Stack	Reactor Product	Slaked Lime Slurry	Filtrate	Moist Cake	Moisture To Vent	Dried Product	Lime To Slaker	Water To Slaker	Makeup Water	To Disposal
	501	504	505	508	509	510	511	512	513	514	515	516
Type of flow	Semi-cont.	Cont.	Cont.	Cont.	Cont.	Cont.	Cont.	Cont.	Cont.	Cont.	Cont.	Batch
Avg operating h/d ^(a)	24	24	24	24	24	24	24	24	24	24	24	24
Avg gas flow, slpd/1000 ^(b)	8623.9	482.3	Negl									
Avg slurry/solids flow, kg/d			270,994	254,531		65,490		39,607	22,744	231,787		39,607
Avg fluid flow kg/d					205,504		25,883					
Heat load, W/l or W/kg ^(c)	TBD	TBD	TBD			TBD	Negl	TBD				TBD
Activity, Ci/l or Ci/kg ^(d)	2.92 (-5)	5.27 (-4)	TBD			TBD	Negl	TBD				TBD
O ₂ , slpd/1000	120.7	120.7	Negl									
CO ₂ , slpd/1000	8468.3	84.7	Negl									
CO, slpd/1000	27.8	27.8	Negl									
N ₂ , slpd/1000	363.3	363.3	Negl									
Krypton, slpd/1000	1.05 (-3)	1.05 (-3)	Negl									
Xenon, slpd/1000	5.96 (-3)	5.96 (-3)	Negl									
NO _x , slpd/1000	8.2 (-2)	4.1 (-2)	Negl									
NH ₃ , slpd/1000	8.2 (-2)	8.2 (-2)	Negl									
Sulfur, kg/d	TBD	TBD	TBD			TBD		TBD				TBD
Carbon-14, kg/d	1.6 (-6)	1.6 (-8)	1.6 (-6)			1.6 (-6)		1.6 (-6)				1.6 (-6)
Radon, kg/d	TBD	TBD	TBD			TBD		TBD				TBD
Tritium, kg/d	TBD	TBD	TBD			TBD		TBD				TBD
Krypton, kg/d	4.6 (-7)	4.6 (-7)	Negl			Negl		Negl				Negl
Xenon, kg/d	4.0 (-6)	4.0 (-6)	Negl			Negl		Negl				Negl
Iodine, kg/d	TBD	TBD	TBD			TBD		TBD				TBD
Other FP, kg/d	TBD	TBD	TBD			TBD		TBD				TBD
Other particulates or contaminants, kg/d	TBD	TBD	682	682		682		682	682			682
CaO, kg/d									22,062			
H ₂ O, kg/d		4.8	230,037	223,305	204,114	25,923	25,883	40		230,396	26,282	40
Ca(OH) ₂ , kg/d			2,848	30,544	1,390	1,458		1,458		1,391		1,458
CaCO ₃ , kg/d			37,427		TBD	37,427		37,427				37,427

(a) Exclusive of rework. Based on 233 equivalent operating days/yr.

(b) Exclusive of filter blowback and bed regeneration CO₂ additions. Not including insol dryers air contribution.

(c) Decay heat only (excludes process heating and cooling). Excludes contribution of any "TBD" products.

(d) Excludes contribution of any "TBD" products.

ASSUMPTIONS:

1. 99% CO₂ removal.
2. 5% Ca(OH)₂ (unreacted) in the product.
3. 40% H₂O in filter cake.
4. 3% solid impurity in CaO.
5. 0.1 wt % moisture in product.

TABLE B-8
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-320-1

	From Fertile Account- ability	From Waste Recovery	H ₂ O Addition	To HLW	Formic Acid Addition	Demin. Water Addition	Denitrator Product	From Waste Rework	Cold Chem Add	1A Column Feed	Dilute Acid	1 M Acid	Waste Recovery Product	Conc. Acid	Solvent From No. 1 Treat.	Aqueous Waste	Waste Solvent	High Level Waste	1A Column Product	To Vessel Off-Gas
Stream name				1AD						1AF	1AIS	1AS	WRP	1AA	1AX	1AW		1AW	1AP	
Stream No.	100	101	103	104	105	134	106	109	110-112	114	115	116	117	118	119	120	121	122	124	133
Relative flow rate	162.5		325	411	23.6		100			100	25	125	225	33.3	1192	283.3		283.3	1417	
Avg flow, 1/d ^(a,b)	561.3	TBD	1122.6	1420	81.4	TBD	345.5	TBD	TBD	345.5	86.4	431.9	777.4	115.2	4118	979	TBD	979	4895	TBD
Oper. flow rate, 1/hr ^(b)	23.4		46.8	59.2	3.4		14.4			14.4	3.6	18.0	32.4	4.8	171.6	40.8		40.8	204	
Design flow rate, 1/hr ^(b)	47.0		94.0	118.5	6.8		29.0			29.0	7.5	36.5	65.5	9.7	344	82		82	410	
Heat load, W/1 ^(c)	TBD			TBD			TBD			TBD			TBD			TBD		TBD	TBD	TBD
Activity, Ci/1	TBD			TBD			TBD			TBD			TBD			TBD		TBD	TBD	TBD
Carbon, g/1	0.05						0.08			0.08						0.03		0.03		
Uranium, g/1	9.7						15.8			15.8			Trace			Trace		Trace	1.1	
Thorium, g/1	214.2						348.2			348.2			Trace			0.1		0.1	24.6	
Pu, g/1	0.002						0.003			0.003						Trace		Trace	Trace	
Other H.M., g/1	0.03						0.05			0.05			Trace			0.02		0.02	Trace	
Fission products, g/1	12.5			0.025			20.2			20.2			Trace			7.2		7.2	Trace	TBD
HNO ₃ , M	7.9			2.88			1.0			1.0	0.01	1.0	0.15	13.0		2.3	Trace	2.3	0.15	
F ⁻ , M	0.05			0.0006			0.075			0.075						0.03		0.03		
Al ⁺⁺⁺ , M	0.1						0.15			0.15						0.06		0.06		
Cd ⁺⁺ , M	0.075						0.12			0.12						0.04		0.04		
HCOOH, M				1.3	23.0															
TBP-NPH, V/O TBP													30		30				30	
NO _x (slpd)				1.2																
H ₂ O (slpd)																				

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.
(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.
(c) Decay heat only.

TABLE B-9
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-320-2

	1BX Feed	Dilute Acid Addition	1BX Uranium Product	1BX Thorium Product	Solvent From No. 1 Treat.	Return To 1A	1BS Thorium Product	Dilute Acid Addition	1C Uranium Product	Nitric Acid Addition	2A Feed	To Solvent Recovery	To Vessel Off-Gas
Stream name	1AP	1BX	1BU	1BXT	1BS	1BSU	1BT	1CX	1CU		1CU	1CW	
Stream No.	200	202	203	204	206	207	208	213	215	216	217	214	226
Relative flow rate	1417	850	1700	850	283.3	283.3	850	708	708	208	916	1700	
Average flow, l/d ^(a)	4895	2937	5874	2937	979	979	2937	2446	2446	720	3166	5874	TBD
Oper flow rate, l/h ^(b)	204	122.4	244.8	122.4	40.8	40.8	122.4	102	102	30	132	244.8	
Design flow rate, l/h ^(b)	410	245	492	245	82	82	245	205	205	60	265	492	
Heat load, W/ ^(c)	TBD		TBD	TBD			TBD		TBD		TBD	TBD	
Activity, Ci/l	TBD		TBD	TBD			TBD		TBD		TBD	TBD	
Uranium, g/l	1.1		0.92	0.12		0.35	0.001		2.2		1.7	0.001	
Thorium, g/l	24.6		0.002	41			41		0.005		0.004	0.002	
Pu, g/l	Trace		Trace	0.0004			0.0004		Trace		Trace	Trace	
Other H.M., g/l	Trace			Trace			Trace		Trace		Trace	Trace	
Fission products, g/l	Trace		Negl.	0.0002			0.0002		Trace		0.0002	Trace	
HNO ₃ , M	0.15	0.2	0.02	0.44		0.10	0.41	0.01	0.058	13.0	3.0	Trace	
F ⁻ , M		0.005		0.005			0.005						
TBP-NPH, % TBP	30		30		30		Trace					30	
Fe ⁺⁺ , M		0.0006		0.0006			0.0006						
N ₂ H ₄ , M		0.005		0.005			0.005						

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

TABLE B-10
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-320-3

	2A Feed	Dilute Acid Addition	Solvent From No. 2 Treat.	2A Waste	2A Uranium Product	2B Feed	Dilute Acid Addition	2B Uranium Product	To Solvent Recovery	Nitric Acid Addition	3A Feed	To Vessel Off-Gas
Stream name	2AF	2AS	2AX	2AW	2AU	2BF	2BX	2BU	2BW		2BU	
Stream No.	302	303	304	306	305	312	313	315	314	316	317	325
Relative flow rate	916	100	254	1016	254	254	170	170	254	50	220	
Average flow, 1/d ^(a)	3166	346	878	3512	878	878	587	587	878	171	758	TBD
Oper. flow rate, 1/h ^(b)	132	14.4	36.6	146.4	36.6	36.6	24.5	24.5	36.6	7.1	31.6	
Design flow rate, 1/h ^(b)	265	29	74	284	74	74	49	49	74	14.3	63.3	
Heat load, W/1 ^(c)	TBD				TBD	TBD		TBD	TBD		TBD	
Activity, Ci/1	TBD				TBD	TBD		TBD	TBD		TBD	
Uranium, g/1	1.7			0.0015	6.1	6.1		9.1	0.006		7.05	
Thorium, g/1	0.004			Trace	0.0015	0.0015		Trace	Trace		Trace	
Pu, g/1	Trace			Trace								
Other H.M., g/1	Trace											
Fission products, g/1	0.0002			Trace	Trace	Trace		Trace	Trace		Trace	
HNO ₃ , M	3.0	0.3		2.72	0.05	0.05	0.01	0.085	Trace	13.0	3.0	
F ⁻ , M												
TBP-NPH, % TBP			30		30	30			30			
Fe ⁺⁺ , M		0.005		0.0005								
N ₂ H ₄ , M		0.005		0.0005								

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

TABLE B-11
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-320-4

	3A Feed	Dilute Acid	1 M Acid	Solvent From No. 2 Treat.	To Low Level Waste	3A Uranium Product	3B Feed	Dilute Acid	To Solvent Recovery	3B Uranium Product	Solvent Addition	Wash Rework	Conc. Feed	To Vessel Off-Gas
Stream name Stream No.	3AF 402	3AIS 403	3AS 404	3AX 405	3AW 406	3AU 408	3BF 409	3BA 410	3BW 411	3BU 412	3WS 415	3WW 416	3BU 419	428
Relative flow rate	220	20	5	65	245	65	66	51	66	51	0.3	0.3	51	TBD
Average flow, l/d ^(a)	758	68.3	17.1	224	844	224	225	174	225	174	1.0	1.0	174	
Oper. flow rate, l/h ^(b)	31.6	2.85	0.7	9.3	35.2	9.3	9.4	7.25	9.4	7.25	0.04	0.04	7.25	
Design flow rate, l/h ^(b)	63.3	5.7	1.45	18.7	70.5	18.7	18.8	14.5	18.8	14.5	0.1	0.1	14.5	
Heat load W/l ^(c)	TBD				Negl	TBD	TBD		Negl	TBD			TBD	
Activity, Ci/l	TBD				TBD	TBD	TBD		TBD	TBD			TBD	
Uranium, g/l	7.05				0.005	23.8	23.7		0.024	30.6		Trace	30.6	
Thorium, g/l	Trace				Trace	Negl	Negl		Negl	Negl			Negl	
Pu, g/l														
Other H.M., g/l					Trace									
Fission product, g/l	Trace				Trace	Negl	Negl			Negl			Negl	
HNO ₃ , M	3.0	0.1	1.0		2.71	0.03	0.03	0.01	Trace	0.049		Trace	0.049	
F ⁻ , M														
TBP, %				30		30	30		30			Trace		
NPH, %				70		70	70		70		100	100		

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

TABLE B-12
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-320-5

	Conc. Feed	Conc. Over- Heads	Conc. Uranium Product	Product to Refab	To Vessel Off-Gas
Stream name	3BU		3UC	3UC	
Stream No.	500	504	503	510	517
Relative flow rate	51	46	5	5	TBD
Average flow, l/d ^(a)	174	157	17	17	
Operating flow rate, l/h ^(b)	7.25	6.5	0.7	0.7	
Design flow rate, l/h ^(b)	14.5	13.1	1.4	1.4	
Heat load, W/l ^(c)	TBD		TBD	TBD	
Activity, Ci/l	TBD		TBD	TBD	
Uranium, g/l	30.6		313	313	
Thorium, g/l	Negl		Negl	Negl	
Fission products, g/l	Negl		Negl	Negl	
HNO ₃ , M	0.049	0.02	0.32	0.32	

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

TABLE B-13
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-350-1

	IBT Conc. Feed	Conc. Over- Heads	Conc. Prod.	2D Denit. Feed	Steam Add		Formic Acid Add	To HLW	Denit. Prod.	Demin. Water	Feed Adj.	2D Feed	To Vessel Off-Gas
Stream name	1BT											2DF	
Stream No.	101	103	102	105	104	106	107	111	108	109	113-114	117	125
Relative flow rate	850	TBD	850	850	TBD	1275	29.8	2115	39.4	110.6	TBD	150	
Average flow, l/d ^(a)	2937		2937	2937		4406	102.8	7298	148.3	370.7		519	TBD
Oper. flow rate, l/h ^(b)	122.4		122.4	122.4		183.6	4.3	304	6.2	15.4		21.6	
Design flow rate, l/h ^(b)	245		245	245		367.1	8.6	608	12.4	30.9		43.3	
Heat load, W/l ^(c)	TBD		TBD	TBD				TBD	TBD	TBD		TBD	
Activity, Ci/l	TBD		TBD	TBD				TBD	TBD	TBD		TBD	
Uranium, g/l	0.002		0.002	0.002					0.04			0.01	
Thorium, g/l	41.0		41.0	41.0					812			232	
Pu, g/l	0.0004		0.0004	0.0004					0.008			0.002	
Other H.M., g/l	Trace		Trace	Trace					Trace			Trace	
Fission products, g/l	0.0002		0.0002	0.0002				Trace	0.004			0.001	
HNO ₃ , <u>M</u>	0.39		0.39	0.39					-0.35			-0.1	
F ⁻ , <u>M</u>	0.005		0.005	0.005				Trace	0.1			0.03	
HCOOH, <u>M</u>							23	0.32					
TBP-NPH, V% TBP	Trace	Trace											
Fe ⁺⁺ , <u>M</u>	0.0006		0.0006	0.0006					0.012			0.0035	
N ₂ H ₄ , <u>M</u>	0.005		0.005	0.005					0.1			0.03	

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

TABLE B-14
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-350-2

	2D Feed	Dilute Acid	5 M Acid	Solvent From No. 2 Treat.	Conc. Acid	2D Product	2D Waste	To HLW	2E Feed	2E Product	2E Waste	Dilute Acid	2ET Concen. Feed	Conc. Over- heads	2ET Product	To Th Store	To Vessel Off-Gas	2E Scrub
Stream name	2DF	2DS	2DIS	2DX	2DA	2DT	2DW		2EF	2ET	2EW	2EX	2ET		2THN	2THN		
Stream No.	200	202	201	203	236	204	205	208	210	213	212	211	216	219	218	223	235	237
Relative flow rate	150	125	25	1159	25	1159	325	325	1159	680	1301	680	680	605	75	75		142
Average flow, 1/d ^(a)	519	432.5	86.5	4010	86.5	4010	1124.5	1124.5	4010	2352	4501	2352	2352	2093	259	259	TBD	491
Oper. flow rate, 1/h ^(b)	21.6	18	3.6	167	3.6	167	46.8	46.8	167	98	187.5	98	98	87	11	11		20.5
Design flow rate, 1/h ^(b)	43.3	36	7.2	334	7.2	334	93.7	93.7	334	196	375	196	196	174	22	22		41
Heat load, W/l ^(c)	TBD					TBD	TBD	TBD	TBD	TBD	TBD		TBD		TBD	TBD		
Activity, Ci/l	TBD					TBD	TBD	TBD	TBD	TBD	TBD		TBD		TBD	TBD		
Uranium, g/l	0.01					0.001	Trace	Trace	0.001	0.001	Negl		0.002		0.015	0.015		
Thorium, g/l	232					30	0.11	0.11	30	51.1	0.027		51.1		464	464		
Pu, g/l	0.002					Negl	0.001	0.001	Negl	Negl	Negl		Negl		Negl	Negl		
Other H.M., g/l	Trace					Negl	Trace	Trace	Negl	Negl	Negl		Negl		Negl	Negl		
Fission products, g/l	0.001					Negl	0.0005	0.0005	Negl	Negl	Negl		Negl		Trace	Trace		
HNO ₃ , M	-0.1	0.01	5.0		13.0	0.05	1.16	1.16	0.05	0.10	Trace	0.01	0.10	Trace	0.5	0.5		
F ⁻ , M	0.03						0.014	0.014										
HCOOH, M																		
TBP-NPH, VZ TBP				30		30			30		30							30
Fe ⁺⁺ , M	0.0035	0.045					0.019											
N ₂ H ₄ , M	0.03						0.014											

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.