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SOLVENT EXTRACTION IN HTGR REPROCESSING
INTERIM DEVELOPMENT REPORT II

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

This report contains the findings of a continuing program for the testing and evaluation of both Acid-Thorex and Purex flowsheets in HTGR fuel reprocessing. The tests were conducted to extend earlier studies on the effects of solvent degradation, feed solids impact, and decontamination performance using tracer Zr-95. Experiments to date indicate that acceptable operation is attainable in the reprocessing of HTGR fuels through the use of tributyl phosphate (TBP) extractant and pulsed solvent extraction columns. A centrifugal contactor is acceptable for the extraction step of the Purex flowsheet.

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1. INTRODUCTION

This interim report contains results from the solvent extraction development work at General Atomic Company (GA) funded by the Department of Energy (DOE) HTGR Fuel Recycle Development Program. The work was performed in pilot plant equipment from January 1976 to October 1977. Prior work is described in an earlier interim report (Ref. 1). This solvent extraction development work at GA was directed toward the testing and verification of Acid-Thorex (Ref. 2) and modified Purex (Ref. 3) flowsheets for high-enrichment uranium (HEU) high-temperature gas-cooled reactor (HTGR) fuel reprocessing.

The HTGR fuel is comprised of discrete fertile and fissile particles. The fertile particles are BISO coated thorium oxide kernels and the fissile particles are TRISO coated uranium oxy-carbide material (Ref. 4). In HTGR fuel reprocessing, the fertile and fissile components are separated by pneumatic classification, and the fissile core material is converted to the oxide form during head-end operations. Dissolution of the oxide form of the fuel is accomplished in subsequent process operations in nitric acid (fissile) or Thorex (13 $\underline{M}$ nitric acid-0.1 $\underline{M}$ aluminum nitrate-0.05 $\underline{M}$ hydrofluoric acid) (fertile). A feed adjustment is performed as required on resultant dissolver product to bring the acidity and heavy metal concentration within prescribed values.

Solvent extraction is used to separate and recover bred U-233 and unburned U-235 from the fertile and fissile streams, respectively. The recovery of these fissionable isotopes is accomplished through the use of an organic extractant, i.e., 30 vol % tributyl phosphate (TBP) in normal paraffin hydrocarbon (NPH) diluent. The Acid-Thorex flowsheet is used in the solvent extraction of the fertile fuel fraction, and a modified Purex flowsheet is used in the solvent extraction of the fissile fuel fraction

The scope of the work reported herein includes:

1. A study of the applications of the Acid-Thorex process (Ref. 2) and a modified Purex process (Ref. 3) for the reprocessing of HEU-HTGR fuels.

2. The definition and evaluation of solvent extraction flowsheets for the reprocessing of HEU fuels in the HTGR recycle reference facility (HRRF).

3. Optimization of pulse column designs.

4. Performance evaluation of a Robatel® centrifugal contactor for HRRF applicability.

Previous development work at GA (Ref. 1) has dealt with the fertile kernel reprocessing. The present study extends this work, with emphasis on applicability to HEU-HRRF. In addition, recent findings on the second and third Acid-Thorex cycles and two cycles of the modified Purex process are contained in this report.

2. SUMMARY

The solvent extraction pilot plant at GA was used to test flowsheets developed for ultimate use in HRRF. The solvent extraction operations in this study were performed in pulsed columns of 5.1 to 7.6 cm (2 to 3 in.) in diameter. Thirty percent TBP/NPH was used as the solvent in these studies, and recovery of greater than 99% of the thorium and/or uranium present in feed solutions was demonstrated.

Tests conducted to evaluate the impact of dibutyl phosphate (DBP) on zirconium decontamination in the Acid-Thorex process indicate that a higher level of solvent degradation is allowable prior to the occurrence of deleterious results of a magnitude measured earlier in the Purex process (Ref. 5).

The performance of a centrifugal contactor as the primary extraction unit was evaluated in the present work. Methods for coupling the centrifugal contactor with the pilot plant pulsed column system were developed. The unit is not recommended for the initial solvent/aqueous cycle in the Acid-Thorex flowsheet; however, performance of the unit in the modified Purex flowsheet tests was satisfactory.

The effect of solids in selected feed solutions was assessed. The impact of feed solids on uranium and thorium losses in the Acid-Thorex process was found to be small. Reduced zirconium decontamination (factors of 2 to 5) were measured as a result of feed solids content.

Acceptable performance has been demonstrated in pilot plant studies of flowsheets developed for HRRF. The work performed to date indicates that the Acid-Thorex and modified Purex processes are adaptable to HTGR fuel reprocessing.

3. REQUIREMENTS

Solvent extraction will be used in HRRF to separate and recover uranium and thorium from spent HTGR fuels. The specified solvent extraction flowsheets developed for use in HRRF were designed to provide a high degree of separation of uranium and thorium from other actinides, accompanying fission products, and chemical impurities. In general, multiple solvent extraction cycles are required to yield products of sufficient purity for use in fuel refabrication with the Acid-Thorex and modified Purex processes. The tentative product specifications for uranium and thorium used in this development work are given in Appendix A in Tables A-1 and A-2, respectively.

The guidelines followed in earlier work at GA (Ref. 1) for use in the solvent extraction development studies were also used in the present work. They include:

1. A practical height limitation of 12.2 m (40 ft) for column cartridges is set.

2. Solvent extraction system operation is to be conducted under conditions which permit ready recovery from upset conditions.

3. The maximum thorium loss via the extraction column raffinate stream is to be less than 0.1% in the Acid-Thorex process.

4. The maximum uranium loss per solvent extraction cycle is to be less than 0.1% in the Acid-Thorex and Purex processes.

5. For uranium and thorium separation in the Acid-Thorex process:

    a. The partition cycle uranium product stream is to contain less than 500 parts of thorium per million parts of uranium.

    b. The partition cycle thorium product stream is to contain less than 20 parts of uranium per million parts of thorium.

6. In the Acid-Thorex process, the zirconium decontamination factor (DF) for the first cycle is to exceed 5 to prevent zirconium precipitation in the feed stream to the second thorium cycle, which is to be made acid deficient ($-[H^+]$).

7. The overall Acid-Thorex fission product DF required for the solvent extraction system as a whole is to be greater than 2×10^6 for uranium and greater than 10^3 for thorium.

8. Due to radiological considerations, the Acid-Thorex and modified Purex process flowsheets and equipment developed must be applicable to remote operation and maintenance.

4. DESCRIPTION OF EQUIPMENT AND CHEMICALS USED

The major equipment comprising the solvent extraction pilot plant at GA has been previously described in detail (Refs. 1 and 6). The columns and ancillary equipment are shown in Figs. 1 through 5.

The solvent extraction studies are generally conducted in glass columns of 5.1 to 7.6 cm (2 to 3 in.) diameter, ranging in overall heights to 9 m (28 ft). The columns are fabricated from sections of commercially available glass pipe with glass crosses at the ends as disengaging sections. The column internals, which together with the glass columns constitute the pulse column cartridges, are made from commercially available stainless steel (316) nozzle and sieve plates and spacers.

Variable pulse generators, consisting of Teflon* bellows driven by adjustable-speed motors and throw cranks, supply the prescribed pulsing conditions to the contents of a solvent extraction column during operation. Pipe [2.5 cm (1 in.)] and flexible hose connect the solution-filled bellows to the column bottoms (see Fig. 5).

Provisions are included in the pilot plant for:

1. Process, feed, and product solution transfer and storage in stainless steel (304L) equipment.
2. Intercolumn airlifts and stream flow rate control.
3. Product concentration.

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*duPont trademark.

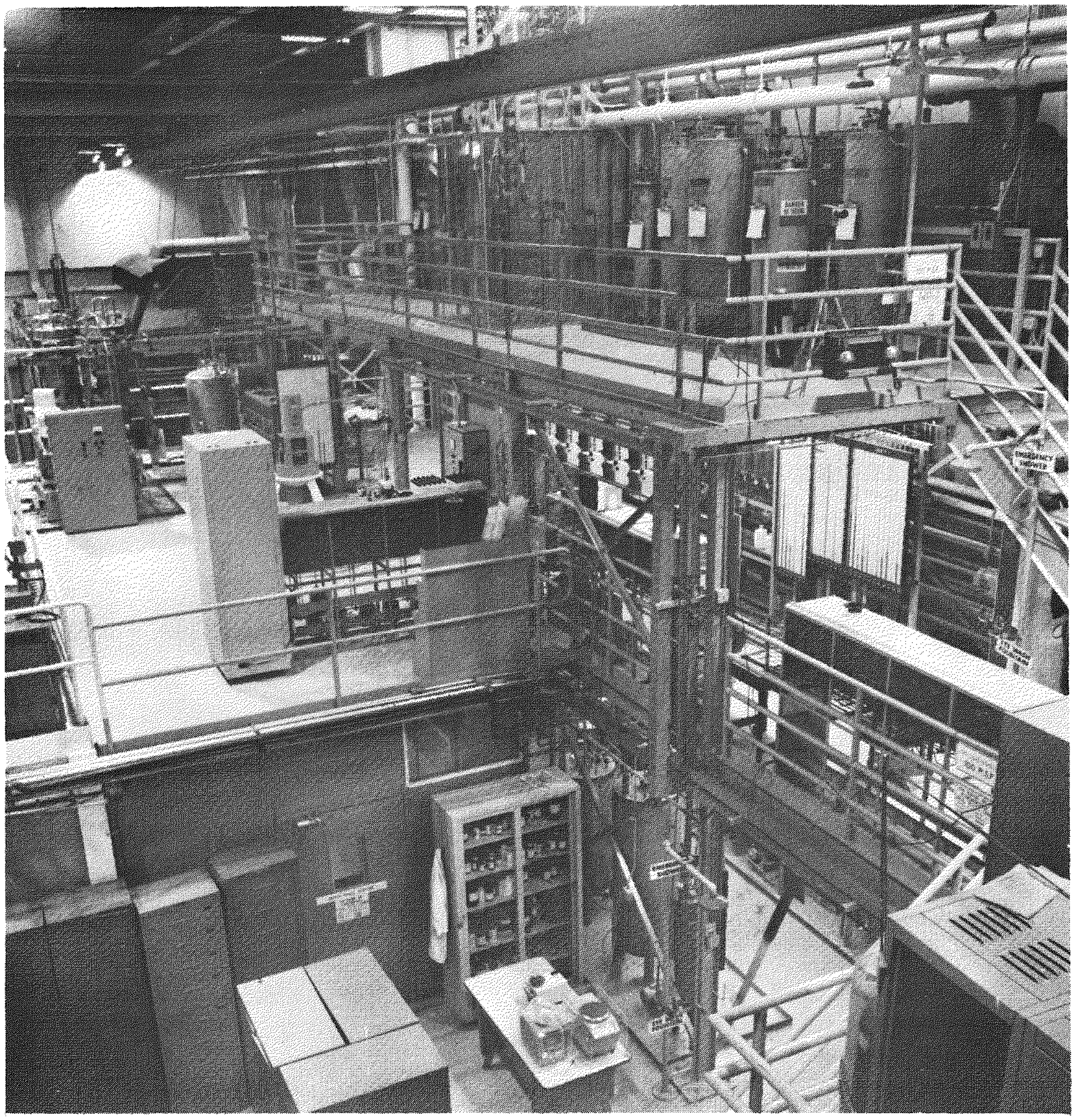

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Fig. 1. Overall view of the solvent extraction pilot plant

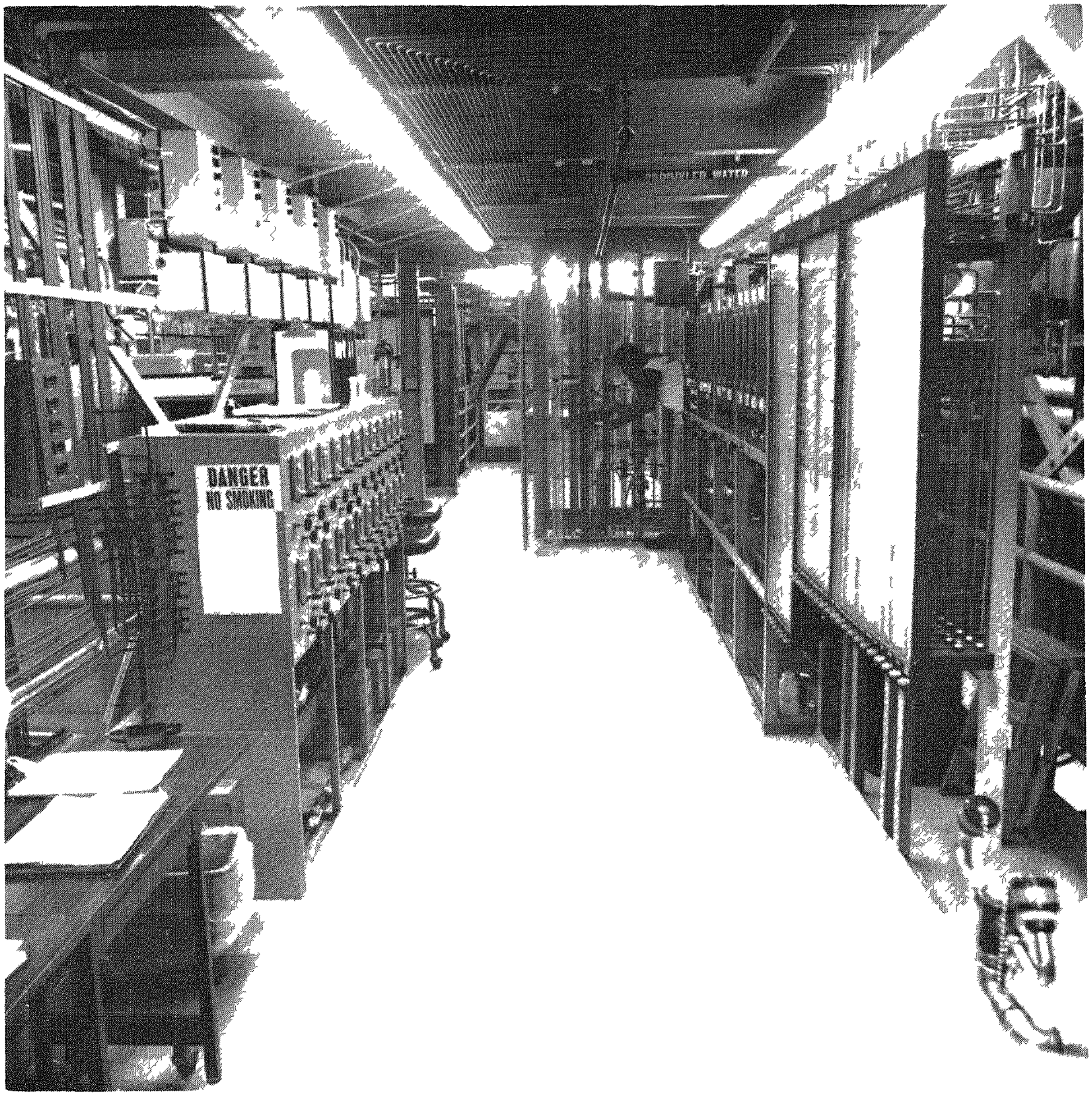

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Fig. 2. Second (control) level of the solvent extraction pilot plant

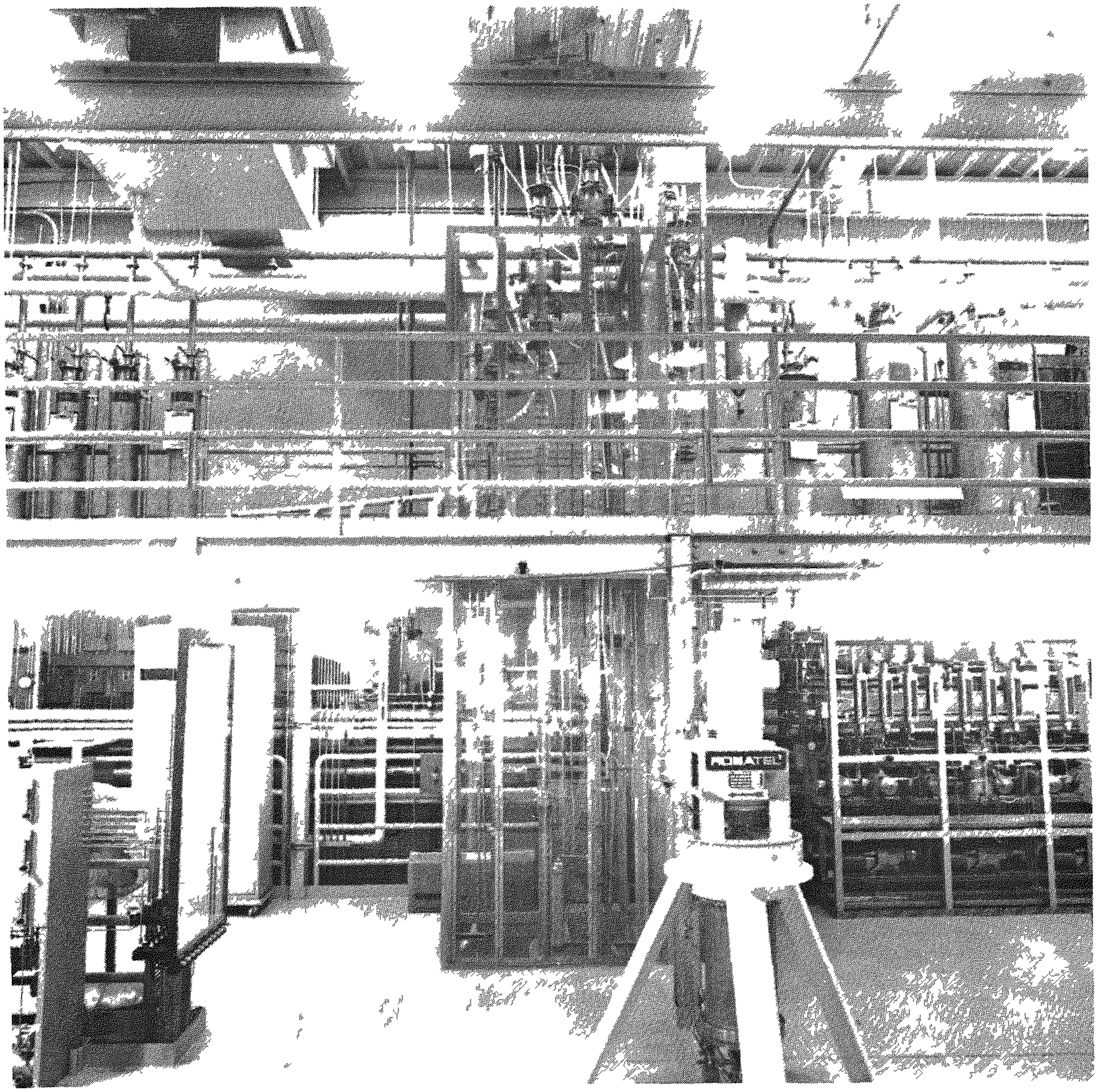

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Fig. 3. Second and third levels of the solvent extraction pilot plant showing pulsed column details

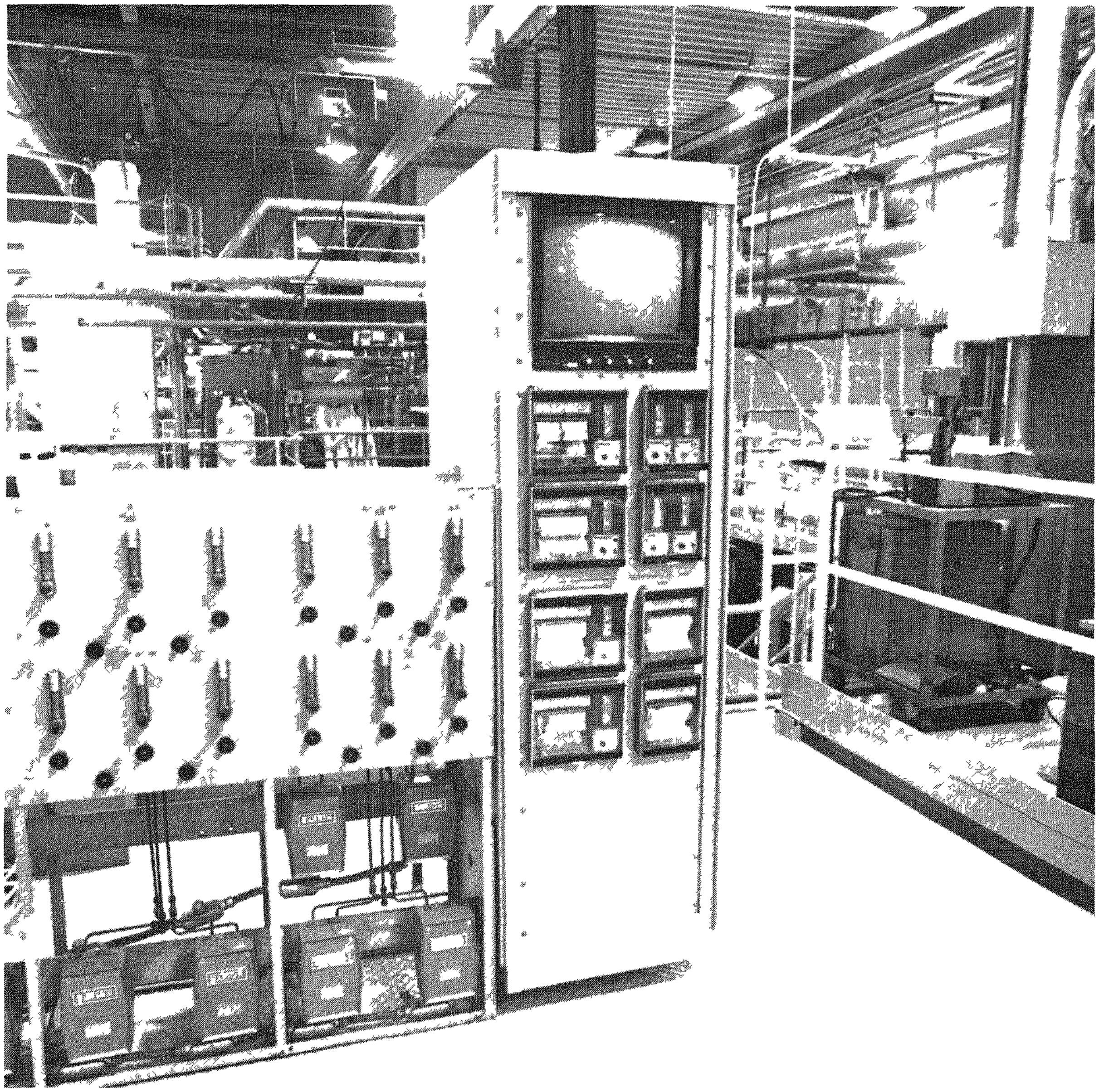

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Fig. 4. Interface control instrumentation

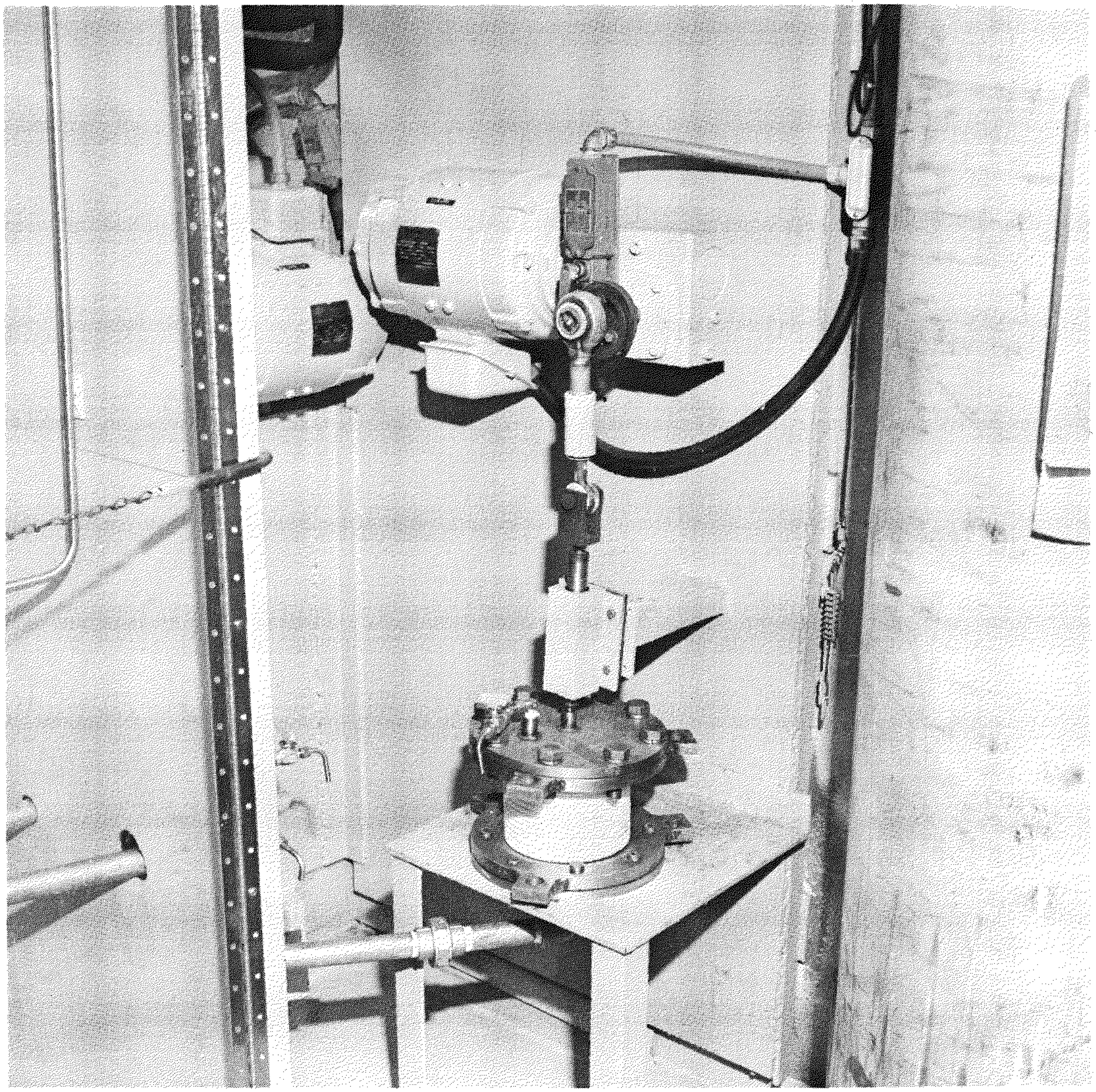

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Fig. 5. Column pulse generating mechanism

In addition to the above equipment, a centrifugal contactor* has been installed in the pilot plant facility (Fig. 6). The unit contains eight vertical centrifugal stages with a corresponding total solution volume of 3.36 liters for the stages. Power is supplied to the variable-speed dc motor through an electronic variator with 115-volt or 208-volt, 60-cycle input. The normal speed range of the unit is 1500 to 3000 rpm. Volume capacity of the unit is 60 to 180 liters per hour for a 1:1 flow ratio of aqueous to solvent phase.

The centrifugal contactor was installed and tested in the present work to permit an assessment of its potential use as the primary unit for the initial aqueous-solvent contact.

The active ingredient (extractant) of the solvent used in the pilot plant is technical grade tri-n-butyl phosphate (TBP). Normal paraffin hydrocarbon (NPH) is used to dilute the TBP concentration in the organic phase to 30% by volume. The NPH is a straight chained hydrocarbon** purchased to Atlantic Richfield Hanford Company specifications.

Figure 7 is a typical gas chromatogram obtained for the TBP/NPH solvent. The density of the purchased NPH is approximately 0.75 g/milliliter; the vendor is Southampton Oil Company, Sisbee, Texas. Concurrent work at GA has shown NPH to be more stable to nitration than diluents previously used in the Purex process (Ref. 7).

Reagent-grade uranyl nitrate hexahydrate (UNH) and thorium nitrate tetrahydrate (TNT) were used as required to prepare feed solutions of known concentration. These materials were purchased from Research Inorganic Chemicals Company, Sun Valley, California, and Tennessee Nuclear Corporation, Jonesboro, Tennessee, respectively. Technical-grade nitric acid ($\sim$14 M) was used to adjust solution acidities as required.

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*Robatel SLPI, Model LX208 NC.

**NPH consists primarily of $C_{12}H_{26}$ to $C_{14}H_{30}$ normal saturated hydrocarbons with an aromatic content of <0.2%.

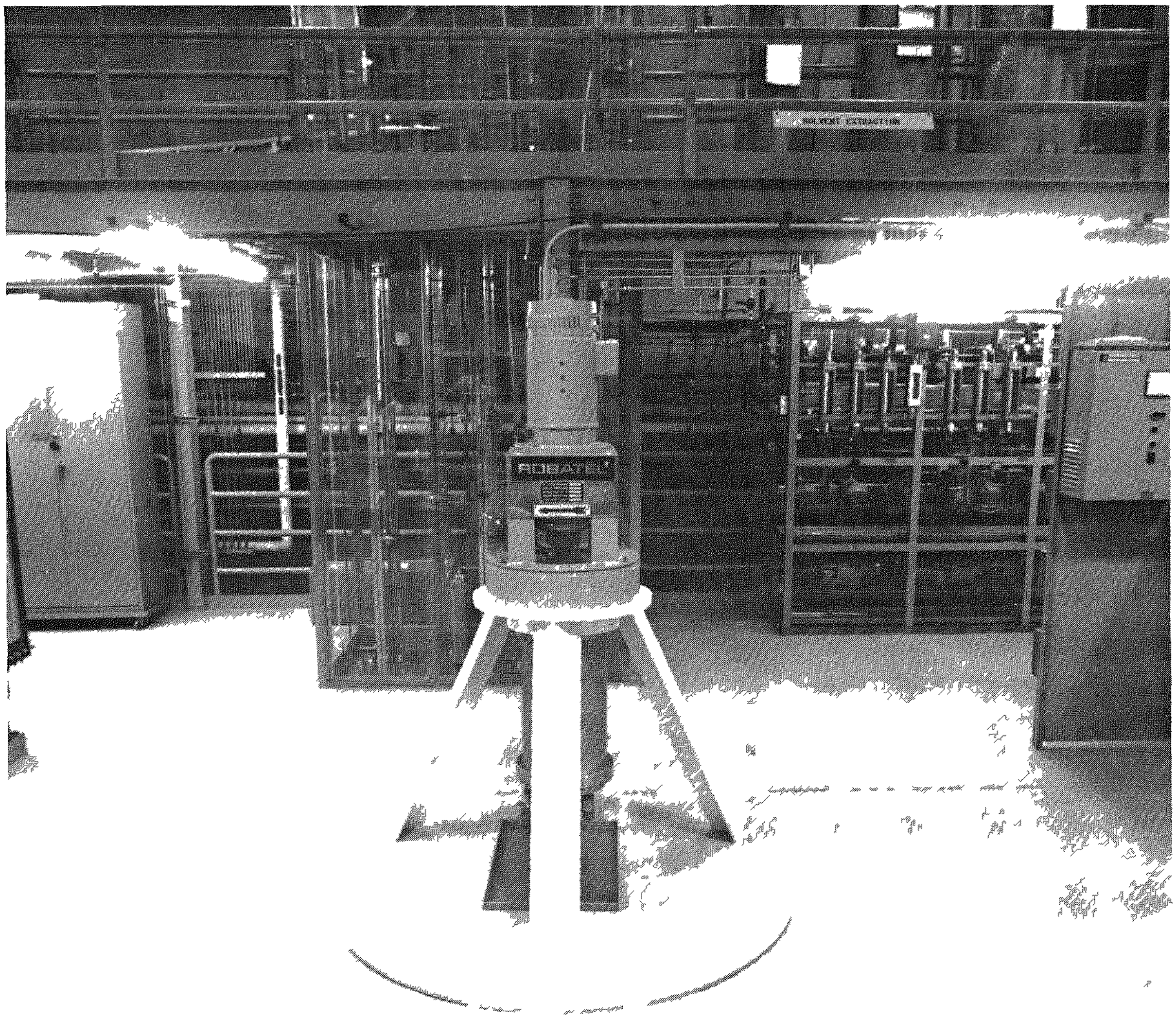

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Fig. 6. Centrifugal contactor unit

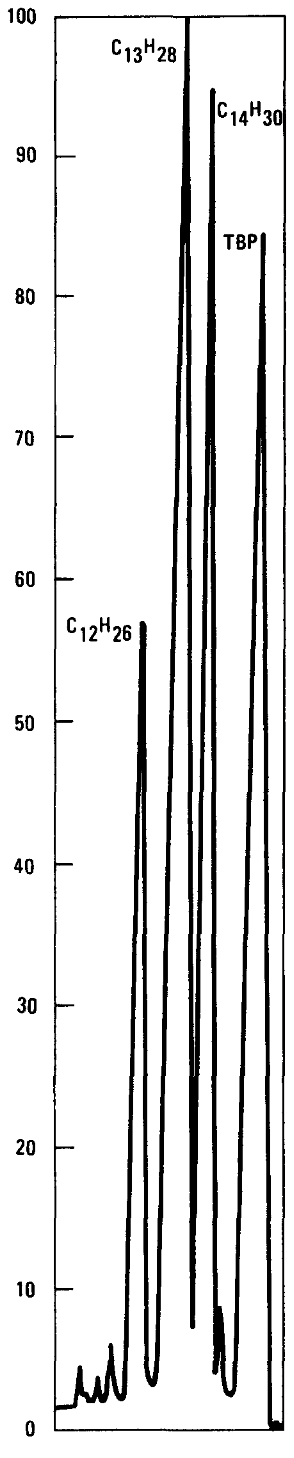


Fig. 7. Gas chromatogram of 30% TBP/NPH solvent. Conditions: 5-microliter sample, column OV101, 30.5 cm x 0.32 cm, 150°C - 1 min, 40°C rise/min to 225°C final temperature, helium carrier gas

5. FLOWSHEET DEVELOPMENT

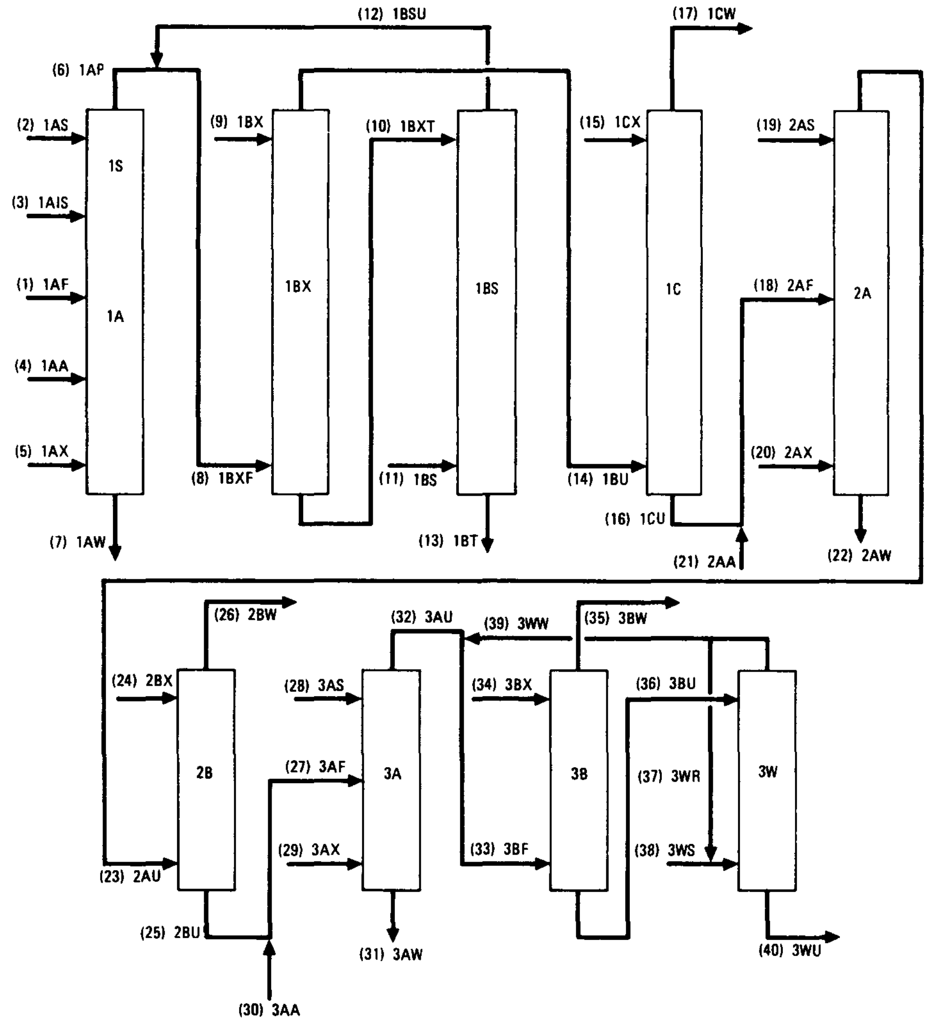
The flowsheets developed in the present study are based on previous work (Refs. 2 and 3). Some changes from earlier flowsheets were necessitated by the characteristics of HTGR fuel. Dissolver solutions for solvent extraction processing prepared from HTGR fuels generally contain high levels of fission products and solid materials, e.g., finely divided silicon carbide and unburned graphite.

Earlier flowsheet development work at GA was directed toward design of solvent extraction systems for the Idaho National Engineering Laboratory (INEL) pilot plant (Ref. 8) and the HTGR Recycle Demonstration Facility (HRDF) (Ref. 9). Changes in the workscope of the HTGR Fuel Recycle Development Program at GA required development of the flowsheets contained herein for ultimate use in HRRF.

5.1. ACID-THOREX FLOWSHEET

Figure 8 contains the nominal Acid-Thorex process flowsheet tested and proposed for use in HEU-HRRF. The Acid-Thorex flowsheet developed provides a method for the recovery of uranium (U-233) and thorium from the HTGR fertile process stream. Stream and relative flow rate data for the first uranium-thorium cycle and the second and third uranium cycles are presented in Fig. 8. No work was conducted in this interim study on the second thorium cycle.

In the proposed partition flowsheet (Fig. 8), uranium and thorium in the 1AF feed stream (Stream 1) are extracted into 30% TBP/NPH. Fission products and chemical impurities remain in the aqueous phase and are removed via the 1AW aqueous waste stream (Stream 7). The top section of the 1A column (above the 1AF feed point) is the scrub section; i.e., the 1A column is operated in a compound extraction-scrub mode. The purpose



			COMPOSITION		
STREAM	STREAM NO	RELATIVE FLOW RATE	U (G/L)	Th (G/L)	HNO_3 (M)
1AF	1	100	35	348	1 0
1AS	2	104			0 01
1AIS	3	26			5 0
1AA	4	32			13 0
1AX	5	1000		[30% TBP]	
1AP	6	1000	3 5	35	
1AW	7	262		FISSION PRODUCTS	
1BXF	8	1180			
1BX	9	600		(Fe^{+2} = 0 01 M)	0 2
1BXT	10	600			
1BS	11	180		[30% TBP]	
1BSU	12	180			
1BT	13	600	TRACE	102	
1BU	14	1180	2 98		
1CX	15	593			0 01
1CU	16	593	5 93		
1CW	17	1180		[30% TBP]	
2AF	18	771	6		3 0
2AS	19	85		(Fe^{+2} = 0 005 M)	0 3
2AX	20	215		[30% TBP]	
2AA	21	178			13 0
2AW	22	856			
2AU	23	215			
2BX	24	192			0 01
2BU	25	192			
2BW	26	215		[30% TBP]	
3AF	27	250			
3AS	28	23			0 3
3AX	29	100		[30% TBP]	
3AA	30	58			13 0
3AW	31	273			
3AU	32	100			
3BF	33	100			
3BX	34	108			0 01
3BW	35	100		[30% TBP]	
3BU	36	108			
3WR	37	3		[NPH]	
3WS	38	0 3		[NPH]	
3WW	39	0 3		[NPH]	
3WU	40	108			

Fig. 8. HEU-HRRF Acid-Thorex flowsheet: first uranium-thorium cycle, second and third uranium cycles

of the scrub section is to remove fission products from the loaded organic phase and return them to the 1AW waste stream (Stream 7).

In the 1BX (partition) and 1BS (partition-scrub) columns, uranium and thorium are separated from each other. This separation is accomplished by adjusting phase flow ratios and nitric acid concentrations to favor uranium distribution in the organic phase with a resultant transfer of thorium to the aqueous phase. The thorium exits the 1BS column via the 1BT stream (Stream 13). The 1BT stream is used to prepare feed for the second thorium cycle following denitration and concentration. The uranium remains in the organic phase and overflows the 1BX column in the 1BU stream (Stream 14).

The uranium is stripped by a dilute nitric acid stream from the organic phase in the 1C column and exits the 1C column in the 1CU stream (Stream 16). The 1CW organic stream (Stream 17) overflows the 1C column and is treated in a solvent washing system (Ref. 1) which utilizes sodium carbonate solution to remove chemical impurities, fission products, and solvent degradation products prior to reuse.

The HEU-HRRF flowsheet differs from an earlier flowsheet developed for the proposed INEL pilot plant in that uranium product from the first Acid-Thorex cycle will be fed directly to the second and third uranium cycles without concentration. These second and third cycles are required to produce a uranium product of sufficient purity for use in fuel refabrication. The second and third cycles consist of two extraction-scrub and stripping operations. The incoming 2AF feed stream (Stream 18) is processed through these cycles for additional thorium separation and fission product decontamination.

Plutonium will not be partitioned in separate columns in the HRRF flowsheet of the first Acid-Thorex cycle due to operability problems with successive plutonium and thorium partition columns. The work conducted to test a flowsheet in which plutonium partitioning would be accomplished in separate columns in the first Acid-Thorex cycle* is discussed in Section 5.3.

As presently planned, plutonium will be chemically reduced with hydrazine-stabilized ferrous nitrate in the 1BX column and allowed to follow the thorium product stream (Stream 13). A separation of thorium and plutonium would be required in the second thorium cycle prior to reuse of the thorium source material.

A provision is incorporated in the second uranium cycle of the Acid-Thorex process for the separation of residual plutonium from uranium. The plutonium separation is accomplished through the addition of hydrazine-stabilized ferrous nitrate in the 2A extraction-scrub column. The ferrous nitrate chemically reduces the Pu^{+4} to Pu^{+3}, which is inextractable in the organic phase. Plutonium reduced to valence +3 exits the 2A column with the fission product waste stream (Stream 22). Final uranium product leaves the 3B stripping column via the 3BU stream (Stream 36) and is subjected to an NPH wash prior to concentration.

Hydroxylamine nitrate could possibly be substituted for ferrous nitrate as a plutonium reductant but some developmental verification work is needed.

5.2. PUREX FLOWSHEET

Figure 9 contains two cycles of the modified Purex process flowsheet tested and proposed for use in HEU-HRRF. The developed flowsheet will enable a recovery of uranium from the fissile stream during HTGR fuel reprocessing. Stream and relative flow rate data for two cycles of the process are presented in Fig. 9. A third cycle will be used in HRRF to achieve final uranium product specification (see Appendix, Table A-1).

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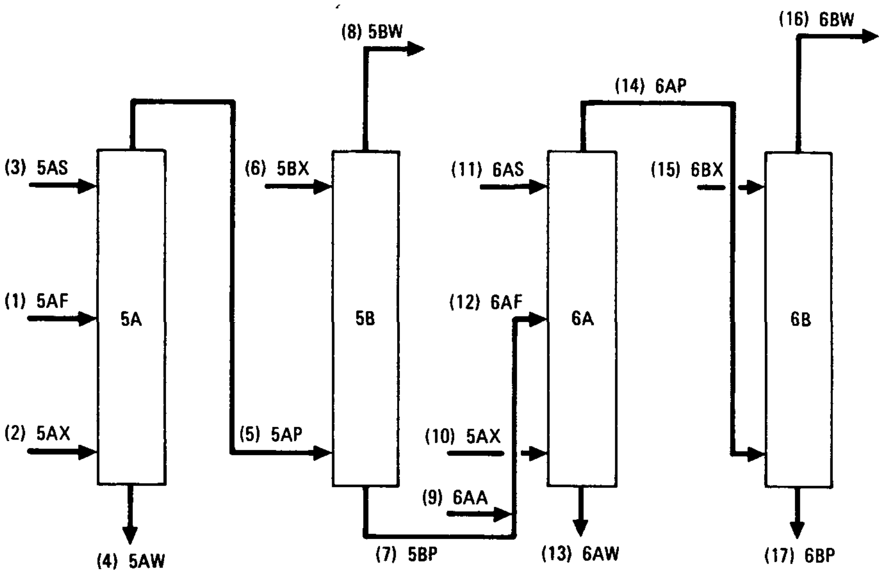
*No plutonium was used in pilot plant studies; however, chemical additions necessary to reduce plutonium were made to simulate operation with plutonium present.



STREAM	STREAM NO	RELATIVE FLOW RATE	COMPOSITION U (G/L)	COMPOSITION HNO$_3$ (M)
5AF	1	100	12	2.0
5AX	2	64	[30% TBP]	
5AS	3	25		1.0
5AW	4	25	FISSION PRODUCTS	
5AP	5	64		
5BX	6	67		0.01
5BP	7	67		
5BW	8	64	[30% TBP]	
6AA	9	2		13.0
6AX	10	46	[30% TBP]	
6AS	11	20	[Fe^{+2} = 0.05 M]	2.5
6AF	12	69		
6AW	13	20		
6AP	14	46		
6BX	15	39		0.01
6BW	16	46	[30% TBP]	
6BP	17	39	29	

Fig. 9. HEU-HRRF Purex flowsheet: two uranium cycles

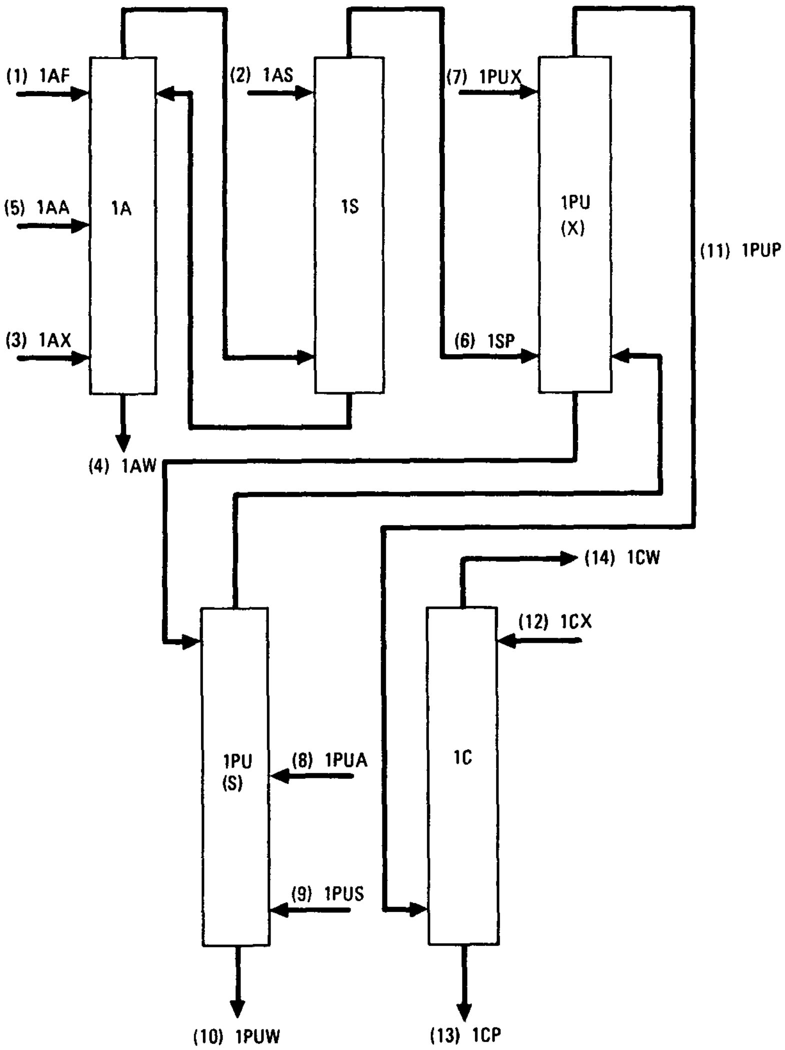
Ultimate use of the recovered uranium in fuel manufacturing is contingent on the amount of U-236 present in the U-235 product. Uranium-235 is a neutron poison and, therefore, its level limits the use of recovered uranium product. As presently planned, the recovered uranium from the fissile stream will be recycled once for use in fuel refabrication. The fissile fuel will then be retired without reprocessing. Future improvements in isotopic separation methods may allow reuse of the retired fuel at a later time.

The column configuration for two cycles of the modified Purex flowsheet is identical to that used in the second and third uranium cycles of the above-described Acid-Thorex flowsheet. In the proposed flowsheet, uranium-bearing (U-235) feed solution prepared from secondary fissile burner ash is fed to a compound extraction-scrub (5A) column. The uranium is extracted into the 30% TBP/NPH organic phase and overflows the 5A column in the 5AP stream (Stream 5). The fission products and chemical impurities are removed from the 5A column via the 5AW aqueous waste stream (Stream 4).

Uranium product from the 5A column is introduced into the bottom of the 5B column for stripping of uranium to the aqueous phase. The uranium-depleted 5BW organic stream (Stream 8) overflows the 5B column and is treated in a sodium carbonate washing system (Ref. 1) prior to reuse. The uranium product leaves the 5B column via the 5BP stream (Stream 7) and, following acidity adjustment, becomes the 6AF feed solution for the second cycle (Stream 12). The second cycle is identical in process operation to the first cycle described above.

5.3. PLUTONIUM PARTITION FLOWSHEET

Figure 10 contains the plutonium partitioning flowsheet evaluated for potential use in the first cycle Acid-Thorex process for HRRF. Successful operation of the flowsheet would allow for a separation of the small amounts of plutonium isotopes during HTGR fuel reprocessing. This



			COMPOSITION		
STREAM	STREAM NO	RELATIVE FLOW RATE	U (G/L)	Th (G/L)	HNO_3 (M)
1AF	1	100	14	348	<1 0
1AS	2	190			1 0
1AX	3	1200		[30% TBP]	
1AW	4	320			
1AA	5	30			13 0
1SP	6	1200	1 2	29	
1PUX	7	125		(Fe^{+2} = 0 05 M)	1 0
1PUA	8	9			13 0
1PUS	9	120		[30% TBP]	
1PUW	10	135			
1PUP	11	1320	1 1	26	
1CX	12	1200			0 01
1CP	13	1200	1 2	29	
1CW	14		[30% TBP]		

Fig. 10. HEU-HRRF Acid-Thorex flowsheet: first uranium-thorium cycle, plutonium partition

plutonium (when using highly enriched uranium fissile particles) is mostly Pu-238. Stream and relative flow rate data for the flowsheet are given in Fig. 10. This flowsheet was operated in the cold pilot plant without plutonium but with all chemicals added to simulate plutonium partitioning.

In the plutonium partition operation, the incoming 1SP feed stream (Stream 6) is treated with nitric acid (Stream 7) containing hydrazine-stabilized ferrous nitrate. Valence +3 plutonium exits the bottom of the 1PU(X) column with the aqueous phase, which is subsequently scrubbed in the 1PU(S) column. The separated plutonium exits the bottom of the 1PU(S) column in the 1PUW stream (Stream 10). Uranium and thorium in the partition flowsheet overflow the 1PU(X) and 1PU(S) columns, and these overflow streams are combined to constitute the 1PUP stream (Stream 11).

Pilot plant operation of the plutonium partition flowsheet was found to be troublesome due to marginal stability. The interfaces for the 1PU(X) and 1PU(S) columns were difficult to control because of the low aqueous flow rates required to minimize thorium stripping into the aqueous stream (Stream 10). High thorium losses (>20 g/liter in some runs) to the plutonium partition stream (Stream 10) were common. In addition, recovery from flood conditions was time consuming.

As noted above, the use of two additional columns [1PU(S) and 1PU(X)] for plutnoium partitioning in the first Acid-Thorex cycle is not currently being considered for HRRF.

6. EXPERIMENTAL

Data collected during pilot plant runs were used herein to evaluate run performance. Typical run data include measurements of:

1. Feed and process stream flow rates.
2. Stream temperatures.
3. Pulse amplitudes and frequencies for each column.

In addition, visual observations were recorded during each run, e.g., uranium colorline position and the occurrence of column flooding. Samples of end streams and intermediate locations were taken and retained for analysis during each solvent extraction run following attainment of steady-state operation at the nominal flow rates. The resultant analytical data were used to construct a profile of solvent extraction performance for a given run.

Flooding studies were made in several of the runs reported herein. Flooding is initiated in a column by increasing the pulse frequency to a point where the aqueous and organic phases cannot pass countercurrently through the column at a preset pulse amplitude [generally 2.5 cm (1 in.)]. Stable column operation, i.e., absence of flooding, was usually attained during column operation at 70 to 80% of the observed flooding frequency for a given column. Cyclic (regional) flooding sometimes occurs under column operation greater than approximately 90% of flooding frequency.

The cartridge (plate spacing and type) for each column was selected based on capacity and efficiency data. The cartridges that were tested were derived from previous studies (Ref. 1).

Normal and tracer zirconium were added to selected feed solutions in the present work to simulate the presence of this limiting fission product.

The total quantity of zirconium added was equivalent to the amount of zirconium expected in equilibrium-spent HTGR fuels. The tracer used was Zr-95 and additions of ∿10 mCi were made to the respective feed solutions. Use of Zr-95 allowed calculation of zirconium distribution in stream samples from subsequent gamma spectrometric analysis. Decontamination factors (DFs) were calculated from zirconium distribution data. The Zr-95 tracer was utilized in the present work because chemical measurement of zirconium in samples containing heavy metals is difficult and subject to error.

Dibutyl phosphate (DBP) was added in selected feeds to simulate solvent degradation. The dibutyl phosphate added was isolated from a purchased mixture of ∿1:1 DBP-monobutyl phosphate (MBP) by chemical treatment prior to use. The addition of DBP permitted a study of the effects of solvent degradation in HTGR fuel reprocessing.

The feeds used in two solvent extraction runs conducted in the present study were prepared from solutions generated in pilot plant dissolution experiments. These feeds were selected because they contained solids typically present in HTGR fuel process solutions, e.g., graphite and/or silicon carbide. Solids generally follow the aqueous stream in the extraction column. Earlier work has shown that a feed solids carbon content in excess of 0.5% causes a deleterious effect in solvent extraction performance (Ref. 1).

7. DISCUSSION AND RECOMMENDATIONS

7.1. COLUMN RECOMMENDATIONS - HRRF FLOWSHEET

As noted in Section 3, a maximum column height limit of 12.2 m (40 ft) was assumed due to anticipated building height limitations. The column heights recommended herein are based on pilot plant experience. Columns recommended are capable of remote operation and maintenance. The column heights for the HRRF Acid-Thorex process are given in Table 1. Table 2 contains recommended heights for the three cycles of the HEU-HRRF modified Purex process.

No column heights are suggested for a separate plutonium-partitioning operation in the proposed HEU-HRRF flowsheet. However, the column heights used in the pilot plant evaluation of a separate plutonium partition flowsheet are given in Table 3.

7.2. COLUMN EFFICIENCY

Pilot plant operation of equipment at selected volume throughput rates and pulse frequencies is required to generate data suitable for determining the relative column diameters, plate types, plate hole sizes, and plate spacings for a given flowsheet. Tables A-3 through A-21 in the Appendix contain the data from pilot plant operations (Refs. 10 through 17).

The efficiency of each column tested in the flowsheets developed for HRRF has been satisfactory. The efficiency findings for the columns in the first cycle of the HRRF Acid-Thorex flowsheet are similar to those reported in earlier work at GA (Ref. 1). A discussion of the efficiency of other columns in HRRF flowsheet studies follows.

TABLE 1
RECOMMENDED COLUMN INTERNALS DESCRIPTION OF HEU-HRRF ACID-THOREX PROCESS[a]

Column	Height of Cartridge [m (ft)]	Column i.d. [cm (in.)]	Nozzle Plates (Stainless Steel)				Operating Temperature (°C)
			Nozzle[b] Direction	Hole Size [mm (in.)]	Free Area (%)	Plate Spacing [cm (in.)]	
1A	4.6 (15)	20.6 (8.1)	Down	3 (1/8)	23	5.1 (2)	20-25
1S	6.4 (21)	20.6 (8.1)	Down	3 (1/8)	23	5.1 (2)	20-25
1BX	9.8 (32)	31.0 (12.2)	Up	5 (3/16)	23	Graded[c]	20-25
1BS	8.5 (28)	15.5 (6.1)	Up	5 (3/16)	23	5.1 (2)	20-25
1C	7.0 (23)	31.0 (12.2)	Up	5 (3/16)	23	Graded[c]	50
2A	4.6 (15)	15.5 (6.1)	Down	3 (1/8)	23	5.1 (2)	20-25
2S	6.4 (21)	15.5 (6.1)	Down	3 (1/8)	23	5.1 (2)	20-25
2B	8.5 (28)	15.5 (6.1)	Up	5 (3/16)	23	5.1 (2)	50
3A	4.6 (15)	7.6 (3.0)	Down	3 (1/8)	23	5.1 (2)	20-25
3S	6.4 (21)	7.6 (3.0)	Down	3 (1/8)	23	5.1 (2)	20-25
3B	8.5 (28)	7.6 (3.0)	Up	5 (3/16)	23	5.1 (2)	50

(a) For pulse amplitudes of 2.5 cm (1 in.) for each column.

(b) Nozzle depths are 0.89 mm to 1.27 mm (0.035 to 0.050 in.) below plane of plate.

(c) Variable plate spacing from 10.2 cm (4 in.) at bottom of column to 5.1 cm (2 in.) at the top.

TABLE 2
RECOMMENDED COLUMN INTERNALS DESCRIPTION OF HEU-HRRF MODIFIED PUREX PROCESS[a]

Column	Height of Cartridge [m (ft)]	Nozzle Plates (Stainless Steel)			Operating Temperature (°C)
		Nozzle[b] Direction	Hole Size [mm (in.)]	Free Area (%)	
5A	4.6 (15)	Down	3 (1/8)	23	20-25
5S	6.4 (21)	Down	3 (1/8)	23	20-25
5B	8.5 (28)	Up	5 (3/16)	23	50
6A	4.6 (15)	Down	3 (1/8)	23	20-25
6S	6.4 (21)	Down	3 (1/8)	23	20-25
6B	8.5 (28)	Up	5 (3/16)	23	50
7A	4.6 (15)	Down	3 (1/8)	23	20-25
7S	6.4 (21)	Down	3 (1/8)	23	20-25
7B	8.5 (28)	Up	5 (3/16)	23	50

Note: Plate spacing is 5.1 cm (2 in.).

[a] For pulse amplitudes of 2.5 cm (1 in.) for each column.

[b] Nozzle depths are 0.89 mm and 1.27 mm (0.035 to 0.050 in.) below plane of plate.

TABLE 3
PILOT PLANT COLUMN INTERNALS DESCRIPTION OF PLUTONIUM PARTITION(a)

Column(b)	Height of Cartridge [m (ft)]	Nozzle Plates (Stainless Steel)			
		Nozzle(c) Direction	Hole Size [mm (in.)]	Free Area (%)	Plate Spacing [cm (in.)]
1PU(X)	5.8 (19)	Up	5 (3/16)	23	Graded(d)
1PU(S)	5.2 (17)	Up	5 (3/16)	23	2 (5.1)

(a) For pulse amplitudes of 2.5 cm (1 in.) for each column.

(b) Column diameters: 1PU(X) = 7.6 cm (3.0 in.), 1PU(S) = 5.1 cm (2.0 in.); operating temperatures: 1PU(X) = ambient, 1PU(S) = 45°C.

(c) Nozzle depths are 0.89 mm to 1.27 mm (0.035 to 0.050 in.) below plane of plate.

(d) Variable plate spacing from 10.2 cm (4 in.) at bottom of column to 5.1 cm (2 in.) at top.

7.2.1. 2A and 3A Extraction-Scrub Efficiency - Acid-Thorex Process

The A column operations consist of extraction of uranium into 30% TBP/NPH solvent from an aqueous feed stream. The bulk of fission product decontamination occurs in the A columns. In pilot plant operations, recovery of greater than 99.9% of uranium was demonstrated in the A columns. Zirconium decontamination factors ranged from 250 to 2800 for the 2A column to 7×10^4 across the entire second and third uranium cycles.* Attempts to improve uranium recovery generally resulted in an increase in fission product extraction and, consequently, a reduction in fission product decontamination. Use of longer scrub sections (extension of A column lengths above the feed point) increased the zirconium DFs without reducing uranium recovery below 99.9%.

7.2.2. 2B and 3B Column Stripping Efficiency - Acid-Thorex Process

The recovery of greater than 99.9% of feed uranium was demonstrated in the B column stripping operations.

7.2.3. 5A and 6A Extraction-Scrub Efficiency - Purex Process

Uranium recoveries in A column of greater than 99.9% were demonstrated in the pilot plant operations. Zirconium DFs on a uranium basis ranged from 450 to 750 for the 5A column and 10 to 25 for the 6A column.

7.2.4. 5B and 6B Column Stripping Efficiency - Purex Process

B column uranium losses were generally less than 0.05% under steady-state operation. Uranium losses increased to 1.0% in the 5B column in the presence of 0.3 g/liter DBP in the 5BW stream. Zirconium DFs calculated for the 5B and 6B stripping columns were 1.2 in each case.

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*Measured thorium-to-uranium DFs across the entire second and third cycles ranged from 2 to 30.

7.3. CONTINUOUS PHASE RECOMMENDATIONS - HRRF FLOWSHEET

Three factors are predominant in the selection of the continuous phase for each column in the HRRF flowsheet. These three factors are: (1) column efficiency in performing the desired separation, (2) column control or operability, and (3) column interface position; i.e., the column interface is to be kept away from the product end to allow interfacial materials to exit with the column waste.

7.3.1. Acid-Thorex Process

Recommendations for the continuous phase in each column of the first Acid-Thorex cycle for the processing of HTGR fuel were made in earlier work at GA (Ref. 1). These recommendations were followed in the present study. Column continuous-phase recommendations for the second and third uranium cycles of the HRRF Acid-Thorex process are given in Table 4. Operation of the second and third cycle A columns in an organic continuous mode permits a physical isolation of any interfacial crud (and attendant fission product activity) from the product ends of the columns. This result is achieved because interfacial crud tends to follow the effluent stream. The above-listed advantages for organic continuous-phase operation of the A columns offset the potential operational disadvantage of a more difficult recovery from flooding.

7.3.2. Modified Purex Process

Column continuous-phase recommendations for two cycles of the HRRF Purex process are given in Table 5. Pilot plant experience with the suggested operational modes was satisfactory.

7.3.3. Plutonium Partitioning

No continuous-phase recommendations are made for potential separate plutonium partitioning in the HRRF. The continuous phases used in the pilot plant studies simulating plutonium partitioning are given in Table 6.

TABLE 4
HRRF ACID-THOREX FLOWSHEET - SECOND AND THIRD URANIUM CYCLES RECOMMENDED CONTINUOUS PHASE FOR THE SOLVENT EXTRACTION COLUMNS

Column	Continuous Phase
2A	Organic
2B	Aqueous
3A	Organic
3B	Aqueous

TABLE 5
HEU-HRRF PUREX FLOWSHEET - TWO CYCLES RECOMMENDED CONTINUOUS PHASE FOR THE SOLVENT EXTRACTION COLUMNS

Column	Continuous Phase
5A	Organic
5B	Aqueous
6A	Organic
6B	Aqueous

TABLE 6
HRRF ACID-THOREX FLOWSHEET - PLUTONIUM PARTITION CONTINUOUS PHASE USED FOR THE SOLVENT EXTRACTION COLUMNS

Column	Continuous Phase
1PU(X)	Aqueous
1PU(S)	Aqueous

7.4. CARTRIDGE RECOMMENDATIONS

The cartridge recommendation for each column in the HRRF flowsheet is based on column efficiency and capacity. The cartridge descriptions are given in Tables 1, 2, and 3 (see Section 7.1). The nozzle plates used in all cases are stainless steel with 23% free area. The hole diameters for aqueous and organic continuous operations are generally 4.8 mm (3/16 in.) and 8.2 mm (1/8 in.), respectively. Recent studies conducted in the pilot plant indicate that a slight capacity advantage is realized in the 1BX column with 4.8 mm (3/16 in.) diameter holes. Therefore, 4.8 mm (3/16 in.) diameter holes are recommended for the 1BX column based on throughput considerations.

As noted in earlier work at GA (Ref. 1), operation of the 1A-1S system (extraction-scrub) as a single compound column is preferred. This mode of operation eliminates control problems in the HRRF Acid-Thorex flowsheet, particularly in the presence of a thorium-rich (second organic) phase. The formation of a second organic phase occurs when thorium concentration in the solvent exceeds 30 to 35 g/liter. This second organic phase causes operational difficulties at the column interface in a split organic continuous scrub section when apparent density difference is used to sense the interface position.

7.5. FLOWSHEET RECOMMENDATIONS - HRRF

The recommended flowsheets for use in HRRF are shown in Figs. 8 and 9 (see Sections 5.1 and 5.2). As presently planned, plutonium will not be partitioned in separate columns from the 1AP stream in the first cycle of the Acid-Thorex process. Rather, it is recommended that plutonium be allowed to follow the thorium in the process and exit the first cycle with the 1BT thorium product. The plutonium would subsequently be partitioned more effectively during the second thorium cycle in the 2D column.

In addition, it is recommended that plutonium be allowed to follow the uranium through the first cycle of the modified Purex process. The plutonium would be partitioned in the second cycle in the 6A column and made to follow the 6AW waste stream.

7.6. ZIRCONIUM DECONTAMINATION

Zirconium was added to selected feed solutions in the HEU-HRRF flowsheet tests to allow calculation of arithmetic DFs.* Zirconium was chosen for study to represent the fission product elemental group because it is difficult to remove in solvent extraction processes using TBP.

Normal zirconium was added to feed solutions to approximate the anticipated concentration for a given feed solution. Zirconium-95 tracer was also added (∿10 to 20 mCi per 40 liters of feed solution) to permit a rapid determination of zirconium distribution in process stream samples by gamma spectrometric analysis. A GeLi detector was used in the gamma spectrometric procedure to isolate the gamma radiation at the 756-keV energy level (due to Zr-95) from the gamma radiation at the 766-keV energy level (due to daughter Nb-95). In addition, all Zr-95 measurements were normalized to the date and time of a given solvent extraction run.

Complete uranium and thorium recovery is the primary goal of flowsheets developed for HTGR fuel reprocessing. In general, the flowsheets tested herein demonstrated a high degree of zirconium decontamination with greater than 99.9% uranium and thorium recovery.

Tests with the first cycle Acid-Thorex process indicate that zirconium DFs as high as 75 (thorium basis) and 36 (uranium basis) are achievable in the 1A column. Additional decontamination can be obtained in the scrub section if phase ratios and acidities are optimized. In the pilot plant, the DFs across the scrub section (1S) ranged from 1.5 to 40.

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*Arithmetic zirconium DF is the ratio of zirconium to heavy metal in the feed divided by the ratio of zirconium to heavy metal in the product.

Zirconium typically follows the aqueous phase in the 1BX and 1BS columns and, therefore, accompanies the thorium. As a consequence, zirconium-uranium decontamination is enhanced in the partitioning operation. In the present study, 1BX zirconium-uranium decontamination factors ranged from 3.5 to 140.

Some zirconium-uranium decontamination occurs in the IC column (DFs to 2.6) due probably to the association of zirconium with unstrippable organic degradation products in the process solvent.

The second and third uranium cycles of the proposed HEU-HRRF flowsheet were also tested for zirconium decontamination. Overall zirconium-uranium DFs attained in these cycles were very high and ranged from 1.6×10^3 to 7.2×10^4, even with shortened scrub sections used in these tests because of pilot plant height limitations (see Tables 1, 2, 3, and A-3 through A-21).

Overall zirconium-uranium DFs for tests performed with two cycles of the modified Purex process ranged from 8.4×10^3 to 1.9×10^4. Most of the decontamination was accomplished in the extraction columns (5A and 6A); however, some additional DF was obtained in the stripping columns (5B and 6B).

There is some evidence that the system using the centrifugal contactor (see Section 7.8) gives ∿50% higher zirconium DFs than the all-pulse column system. This DF improvement could be due to less extraction of zirconium in the high acid end of the centrifugal contactor as a result of lower residence time.

7.7. SIMULATED SOLVENT DEGRADATION - EFFECTS OF DIBUTYL PHOSPHATE

Tributyl phosphate (TBP) is subject to degradation due to radiolysis and acid hydrolysis. The primary degradation product is dibutyl phosphate (DBP), although monobutyl phosphate (MBP) is formed to a lesser extent.

The presence of TBP degradation products in solvent extraction operations results in deleterious process effects. In the Acid-Thorex process, these effects include:

1. Reduction in partitioning efficiency due to the formation of an acid unstrippable thorium-DBP complex.

2. Loss of fission product decontamination due to the formation of solvent-soluble DBP-fission product complexes, particularly zirconium, which reduce scrubbing effectiveness.

3. Changes in phase dispersion characteristics in the uranium stripping column (1C) due to precipitation of thorium-DBP at lower stripping acidities.

4. Precipitation of thorium hydroxide in the solvent wash column on contact with the basic (sodium carbonate) wash solution.

Earlier work at GA (Ref. 1) has demonstrated the utility of fluoride ion in reducing the adverse effects of DBP in the Acid-Thorex process. Selective stripping of thorium results on contact of a solvent phase containing thorium-DBP complex with fluoride ion in an aqueous medium. Therefore, the addition of fluoride ion to the 1BX and 1CX streams in concentrations of 0.005 M and 0.001 M, respectively, is recommended.

The radiation effects observed by Richardson (Ref. 5) on the Purex system show a greater loss in zirconium decontamination per unit of radiation damage (watt-hr/liter or g/liter DBP) than does the Acid-Thorex system (Fig. 11, solid line). The reason for this observed difference is that thorium ion forms a stronger DBP complex than does uranyl ion and, therefore, the amount of uncomplexed DBP available for raising the equilibrium distribution coefficient for zirconium is less in the Acid-Thorex process. In the present study, the zirconium decontamination losses measured during the addition of the HRRF projected amount of DBP to the

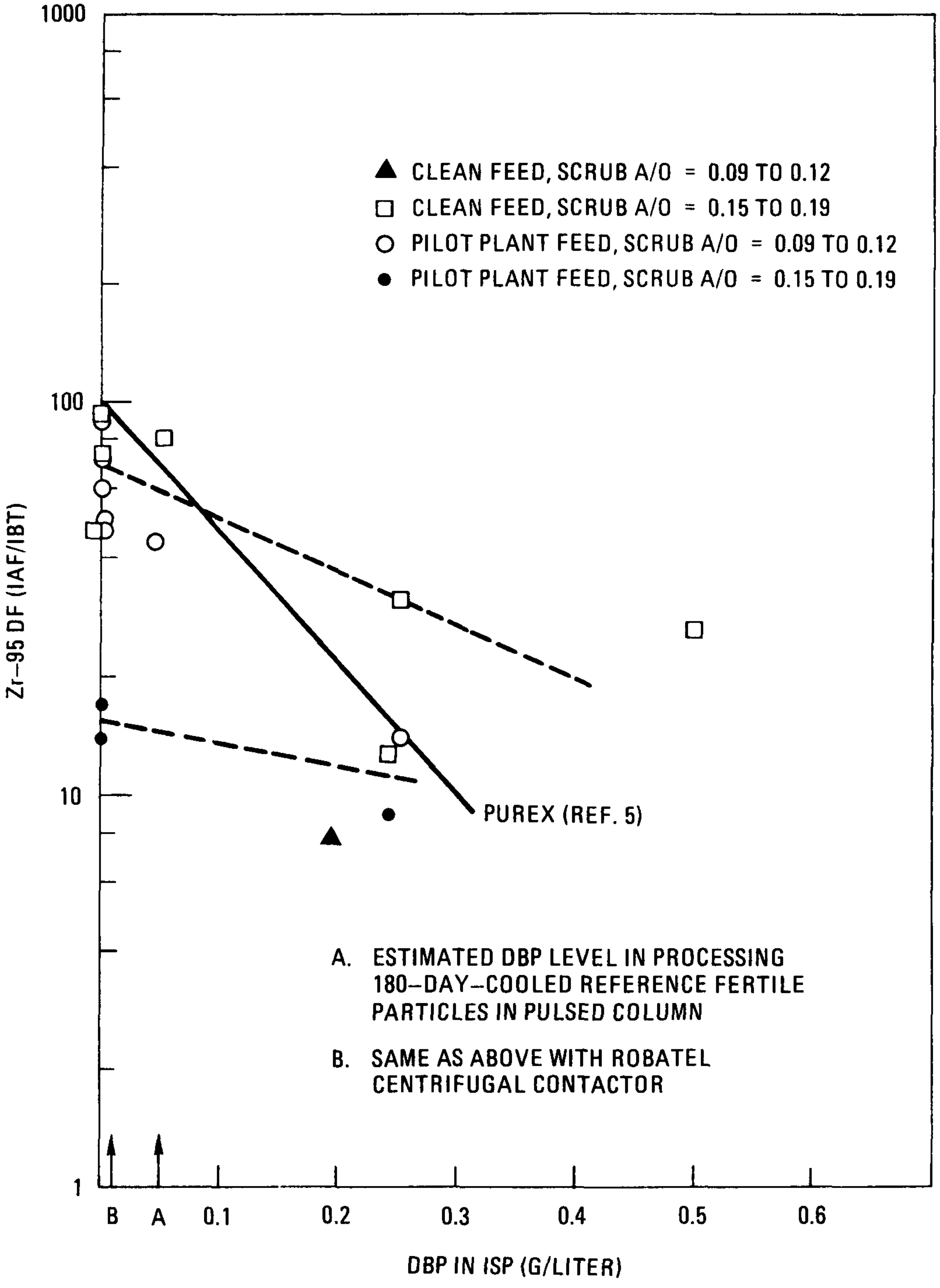


Fig. 11. Measured Zr-95 decontamination factors

extraction column were so small as to be indistinguishable from the normal experimental variations in the absence of DBP.

The data displayed in Fig. 11 indicate that the scrub section flow rate is a more important variable in Zr-95-thorium separation than the DBP content of the scrub section organic phase. In addition, from these data it is apparent that pilot plant feed (with attendant solids) does not appreciably lower Zr-95-thorium decontamination in the Acid-Thorex process.

In tests of the HEU-HRRF modified Purex flowsheet, the principal manifestation of DBP presence was a marked loss of stripping efficiency in the 5B column. Uranium losses via the 5BW stream increased to about 1% in the presence of DBP. The calculated height equivalent to a theoretical stage (HETS) value for the 5B stripping column also increased following DBP additions. The above results were due to the formation of a DBP-uranium complex that is difficult to strip, and they occurred in the presence of a greater-than-anticipated amount of DBP in the HRRF Purex flowsheet.

7.8. CENTRIFUGAL CONTACTOR STUDIES

A Robatel® centrifugal contactor was used to perform the extraction functions in several HRRF flowsheet tests. The unit evaluated was a Model LX208NSC (see Section 4). The potential advantages of a centrifugal contactor in extraction operations include:

1. Shorter feed-solvent contact time and, therefore, a reduction in solvent degradation due to acid hydrolysis and radiolysis.

2. Small liquid holdup inventory.

3. Decreased startup and shutdown times.

4. Minimal height requirements.

5. Improved DFs for some fission products due to shorter contact times.

The potential disadvantages associated with centrifugal contactors include:

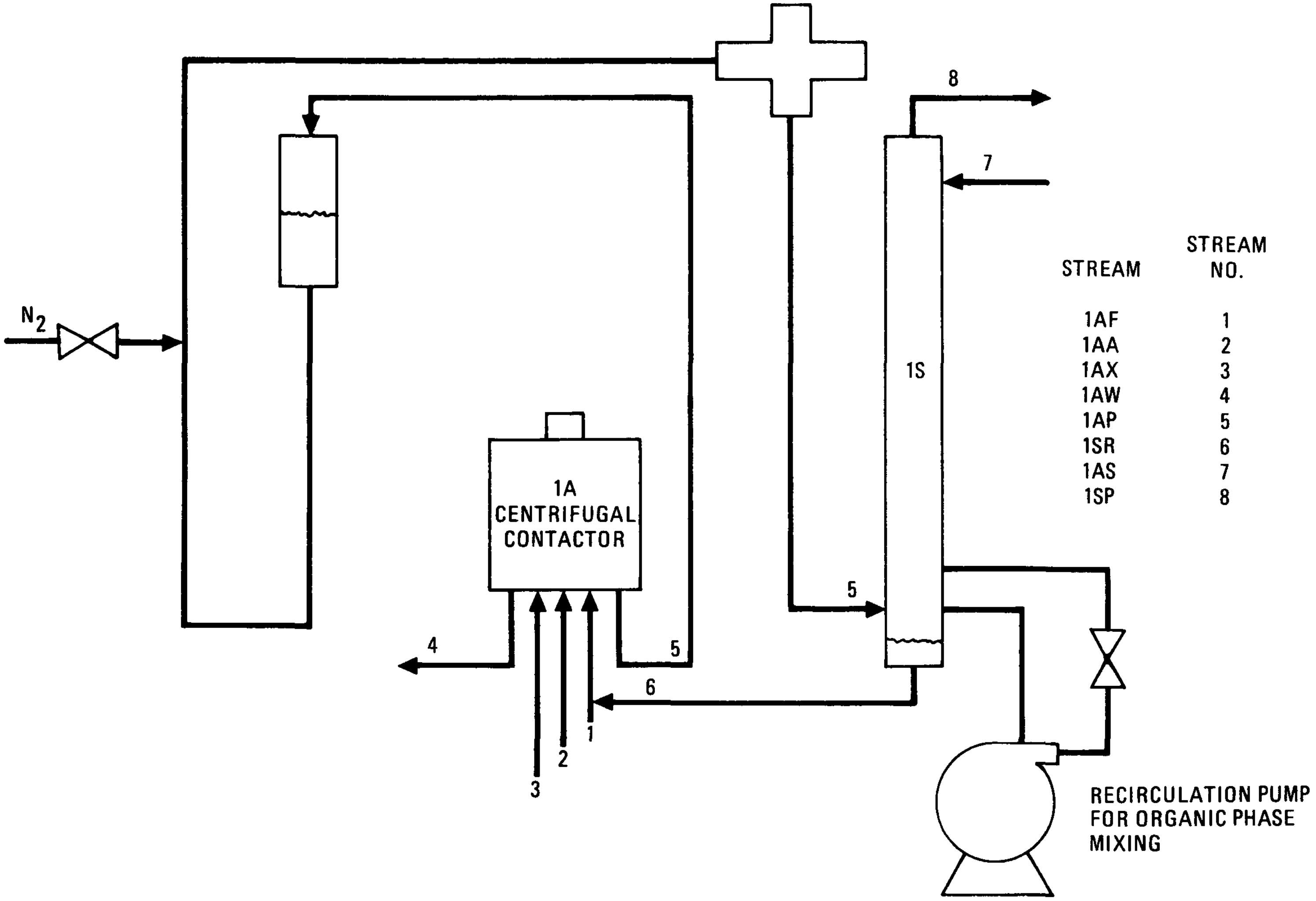
1. Inability to handle solids, e.g., silicon carbide.

2. Inability to handle the third phase formation characteristic of the 30% TBP-thorium system at higher solvent thorium loadings (>30 to 35 g/liter).

3. The need for a separate scrub column.

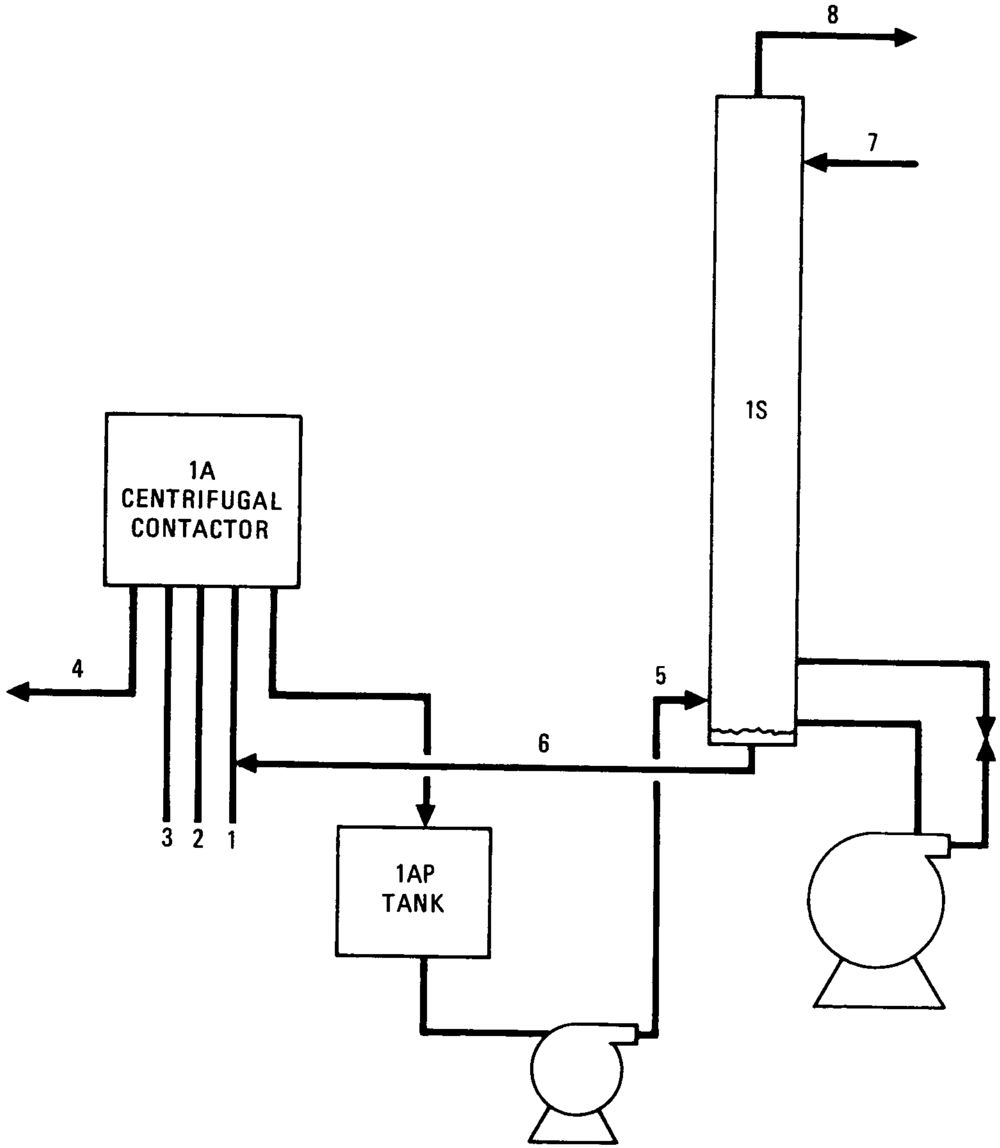
Initial attempts to couple the centrifugal contactor with the pilot plant pulse columns through the use of an airlift resulted in flow control difficulties (see Fig. 12). In addition, the presence of a third phase in the contactor product (1AP) made interface control in the scrub column (1S) difficult. A successful coupling was, however, attained with a contactor product storage tank and a transfer pump (in lieu of the air lift). Third-phase difficulties in the scrub column lower disengaging section were solved through the use of a recirculating pump for phase mixing. A schematic drawing for the operation of the contactor in conjunction with the 1S column is given in Fig. 13. Pilot plant operation of the centrifugal contactor in the configuration shown in Fig. 13 is recommended if the contactor is to be used as the primary extraction device. The successful operation of the contactor depends on satisfaction of the following requirements:

1. No restriction in the contactor organic phase outflow--uranium and thorium losses to the aqueous raffinate were observed with 1AP flow restrictions.



STREAM	STREAM NO.
1AF	1
1AA	2
1AX	3
1AW	4
1AP	5
1SR	6
1AS	7
1SP	8

Fig. 12. Centrifugal contactor 1A and column 1S with airlift transfer



STREAM	STREAM NO.
1AF	1
1AA	2
1AX	3
1AW	4
1AP	5
1SR	6
1AS	7
1SP	8

Fig. 13. Centrifugal contactor 1A and column 1S with 1AP pump system

2. Use of a mixing device such as an auxiliary circulating pump to insure mechanical mixing of the organic phase above the scrub column (1S) interface to prevent separation of the third phase (second organic phase).

During operation of the centrifugal contactor, anticipated solids blockage of the aqueous raffinate stream (1AW) was a frequent occurrence.* Blockage of the aqueous transfer ports in the contactor generally resulted in both the aqueous waste stream (1AW) and the product stream (1AP) exiting the contactor via the normal product stream route. In all cases of contactor blockage, the plug was successfully removed by flushing with 13 M nitric acid and increasing the contactor rotating speed.

Extraction efficiency studies for uranium and thorium-30% TBP/NPH systems were conducted in the pilot plant with the centrifugal contactor. To determine the efficiency of the contactor, the flow rates of the aqueous feed and solvent were adjusted to increase the uranium or thorium loading in the solvent to give measurable losses in the aqueous waste stream. Figures 14 and 15 contain the flowsheet schematic drawings for the thorium and uranium contactor efficiency studies, respectively. The stream flow rate and analytical data for each system are given in the Appendix, Tables A-22 and A-23. The calculated losses and related data for the contactor efficiency studies are presented in the Appendix, Tables A-24 and A-25. Table 7 contains data on the centrifugal contactor and pulse columns used in the efficiency studies.

The SEPHIS computer code (Ref. 18) was used to calculate theoretical values for the effluent streams in the efficiency tests. These values were compared with analytical values obtained from pilot plant samples. Data from these comparisons are presented in the Appendix, Tables A-26 and A-27.

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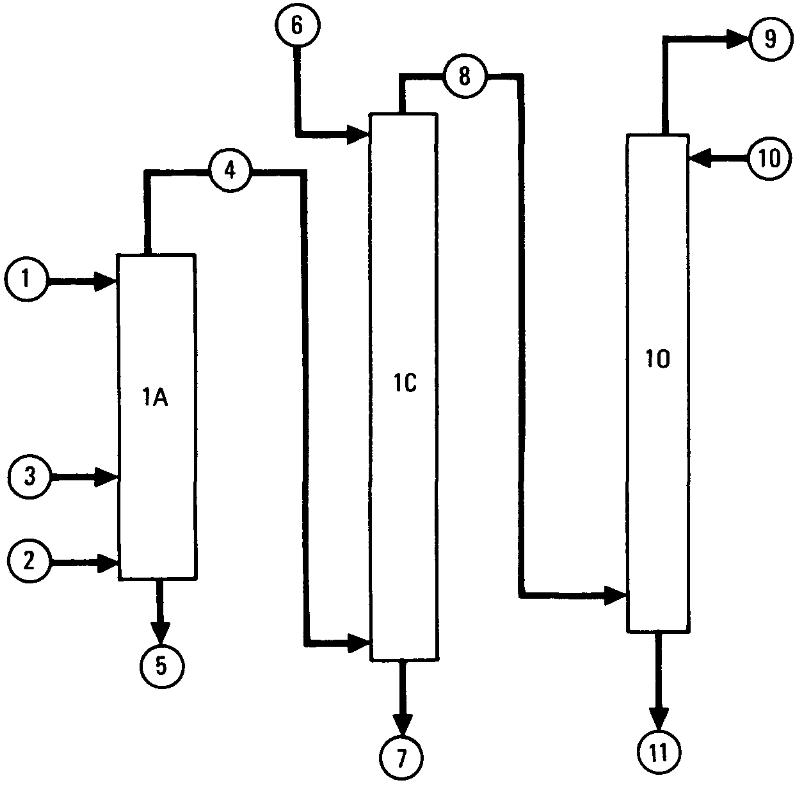
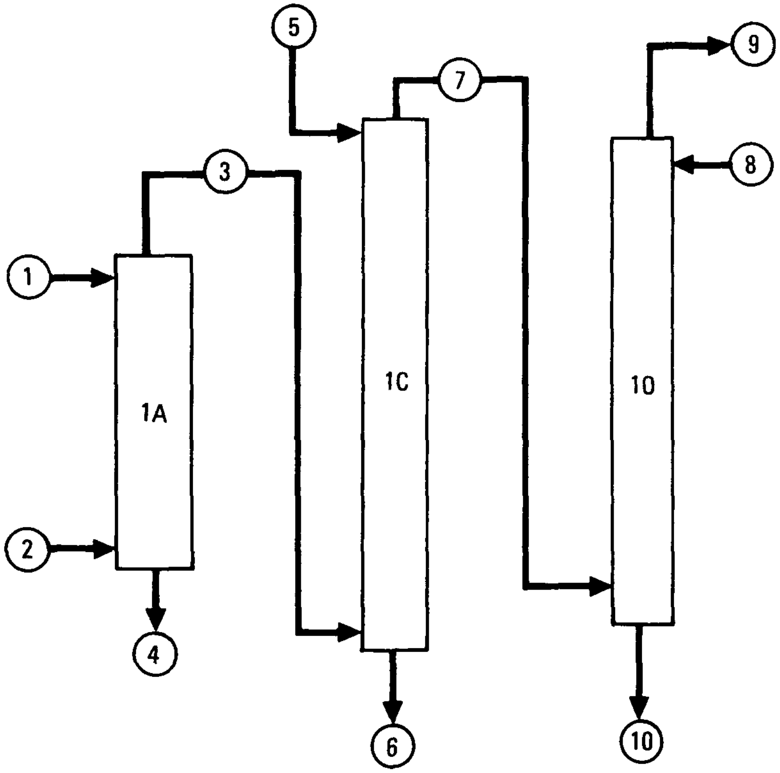
*A Consler Model SPCP-1 in-line filter equipped with a 5-micron filter cartridge was used to remove bulk feed solids prior to centrifugal contactor processing. The unit is available from Consler Mfg. Co., Honeoye Falls, NY



		COMPOSITION	
STREAM	STREAM NO.	Th (G/LITER)	HNO_3 ($\underline{M}$)
1AF	1	80 - 175	1.35
1AX	2	-	[30% TBP]
1AA	3	-	13.0
1AP	4	-	-
1AW	5	-	-
1CX	6	-	0.01
1CP	7	30 - 50	-
1CW	8	-	[30% TBP]
1OO	9	-	[30% TBP]
1OS	10	-	[0.2% $\underline{M}$ Na_2CO_3]
1OW	11	-	WASTE

Fig. 14. Centrifugal contactor efficiency study flowsheet: thorium - 30% TBP system



STREAM	STREAM NO.	COMPOSITION U (G/LITER)	HNO$_3$ ($\underline{M}$)
1AF	1	10-180	2.0
1AX	2	-	[30% TBP]
1AP	3	-	-
1AW	4	-	-
1CX	5	-	0.01
1CU	6	10-100	-
1CW	7	-	[30% TBP]
1OS	8	-	[0.2 $\underline{M}$ Na_2CO_3]
1OO	9	-	[30% TBP]
1OW	10	-	WASTE

Fig. 15. Centrifugal contactor efficiency study flowsheet: uranium - 30% TBP system

TABLE 7
CENTRIFUGAL CONTACTOR AND COLUMN CARTRIDGE DESCRIPTION

Unit	Purpose	Diameter (mm)	Total Height of Mixing Area (m)	Other			
1A contactor	Extraction	180	0.32	8 stages with 0.4 liters total holdup per stage			
				Plates			
				Nozzle Direction	Hole Size (mm)	Free Area (%)	Plate Spacing (mm)
1C column	U-strip	76	4.6	Up	4.8	23	Graded(a)
10 column	Solvent wash	51	5.5	Down	3.2	23	51

(a) Graded cartridge is, from the bottom, 2.6 m with 100 mm spacing, 0.5 m with 76 mm spacing, and the remainder with 51 mm spacing.

The operating efficiency of the contactor for the uranium-30% TBP/NPH system was found to approach 100%. Typical uranium losses measured were less than predicted by the SEPHIS code. The absolute determination of the centrifugal contactor uranium efficiency is not possible due to known inaccuracy (±5%) in the analysis of TBP content in the solvent uncertainties in the SEPHIS code under conditions of high uranium solvent loading, and the uncertainty in the operating temperature within the contactor.

The agreement between the results from the SEPHIS code calculation and the analyses of the end stream samples from the thorium-30% TBP/NPH runs was not good. One reason for the differences is the uncertainties of the code. The development of the code used correlations which are applicable at conditions of lower solvent loading than used in these tests. In addition, the code does not take into account the three phases which are present at higher thorium concentrations.

Under conditions of near-saturation of the solvent, very erratic thorium values were obtained for the contactor product (1AP). These variations are due to the cyclical nature in which the third phase was built up in the contactor and then released. Part of the release of the third phase may have occurred via the aqueous raffinate (1AW) stream, which would account for the high and erratic analytical 1AW values. More likely, the fluctuation in end stream thorium concentrations was caused by intermittent recycle of the heavy solvent phase through the aqueous routing from stage to stage within the centrifugal contactor.

In the first cycle of the Thorex flowsheet, an operation with the thorium loading of the solvent in the third phase region is desirable to permit significant fission product decontamination. In a pulsed column, this desired solvent loading can be achieved without any adverse or uncontrolled losses of thorium. In the centrifugal contactor, however, these same conditions produce unpredictable and significant losses of thorium. Therefore, a centrifugal contactor is not recommended for thorium TBP/NPH extraction because of the uneven operation in the presence of a second organic phase (third phase). A compound pulse column with the scrub section attached to the top of the extraction section is recommended for the Acid-Thorex process.

Based on (1) the high efficiency measured for the centrifugal contactor with the uranium-30% TBP/NPH system and (2) the satisfactory pilot plant performance observed with the contactor in HEU-HRRF modified Purex flowsheets, use of the unit is a feasible alternative to pulsed columns for the initial aqueous-solvent contact in this flowsheet provided a highly efficient feed clarification step is used.

7.9. EFFECT OF FEED SOLIDS

Some solid material, e.g., graphite and silicon carbide in quantities of <0.5 wt %, are expected to carry through to solvent extraction from head-end operations. Therefore, four runs were conducted in the present study to assess the impact of feed solids on the proposed HEU-HRRF Acid-Thorex flowsheet.

The experiments confirm earlier findings (Ref. 1) of a reduction in measured zirconium decontamination. In HRRF Acid-Thorex studies, lower Zr-95 DFs (factors of 2 to 5) were observed across the flowsheet for runs in which feed solutions were prepared from HTGR head-end operations product material.

The impact of feed solids on uranium and thorium losses was found to be small. The extraction column developed flooding at lower relative column throughput rates when solids were present. However, the efficiency of thorium and uranium extraction remained within acceptable limits. The maximum thorium and uranium losses encountered in runs using pilot-plant-prepared feed solutions were 0.51% and 0.05%, respectively. Runs conducted in the absence of feed solids (feeds prepared from purchased materials) gave thorium and uranium losses of 0.04% and 0.08%, respectively.

7.10. ANALYSIS OF STREAM SAMPLES

Difficult challenges are encountered in the analyses of some stream samples from the HRRF Acid-Thorex process. The 1BT thorium partition product and the 1CU uranium product are samples that are particularly troublesome from an analytical standpoint. The difficulty is attributable to the extreme ratios present in these samples. The ratio of thorium to uranium in typical 1BT samples is $\sim 2.0 \times 10^4$ to 1. A typical ratio of uranium to thorium in 1CU samples is $\sim 1.5 \times 10^4$ to 1.

Procedures were developed in the current study to permit accurate and rapid measurement of the trace level component in 1BT and 1CU samples. These procedures are described in detail in Ref. 14.

7.11. OTHER FUEL CYCLE APPLICABILITY

Work described in the present report addresses the solvent extraction processing of high-enriched uranium (HEU) fuels. The HTGRs developed in the United States have emphasized the use of the Th-U-233 cycle. This cycle uses thorium and 93% enriched U-235 in the initial and the makeup fuel.

The current uncertainty in regulations affecting nuclear safeguards has resulted in commercialization options for closing the HTGR fuel cycle based on the introduction of early HTGRs on alternate cycles, such as a denatured Th-U-233 stowaway for MEU recycle fuel cycle. This work is generally applicable to these alternate cycles; however, for U/Th ratios that are greatly different than those reported herein, verification is needed.

If MEU fissile particles are processed, the feed to the modified Purex process would have a higher uranium concentration than HEU-derived feed. This increased concentration would be possible because the relative fission product level is less for MEU fuels. In addition, the increased quantity of plutonium present in MEU fissile streams may require isolation of the element as a pure product.

7.12. FUTURE WORK

Future solvent extraction development should include:

1. Additional testing of the second and third uranium cycles for the HRRF Acid-Thorex flowsheet. Further testing is required to optimize A column scrub section lengths in order to attain greater uranium fission product DFs.

2. A pilot plant study for the development of a second thorium-cycle solvent extraction flowsheet for HRRF and evaluation thereof to produce thorium products with less than 10 parts of uranium per million parts of thorium. Included in this study would be an assessment of methods for a separation of plutonium from thorium in the first-cycle thorium partition product (1BT).

3. Optimization of solvent washing and solvent cleanup methods initiated in earlier work at GA (Ref. 1).

4. A study of the effectiveness of ruthenium and zirconium decontamination using the HRRF flowsheets developed. These elements are of concern due to the difficulty of their separation from uranium and thorium.

5. Studies to test the effect of different thorium-to-uranium ratios in the feed solutions for MEU-HRRF flowsheets and the different product requirements of some fuel cycle options.

6. Testing of new pulse column plate designs developed by GA under the Alternate Fuel Cycle Technologies (AFCT) Program.

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*Presently employed by Rockwell Hanford Operations, Richland, Washington.

APPENDIX
PILOT PLANT OPERATIONAL DATA

The appendix contains data from pilot plant operations. The total height of each column cartridge is given. Throughput rates are reported as both volume velocity and superficial velocity. Volume velocity is the sum of the phase volumes per unit time per cross-sectional area of the column. The superficial velocity is the linear velocity ($\overline{V}_a$ is the aqueous phase, $\overline{V}_o$ is the organic phase) of each phase based on total cross section of the column.

The flooding frequency is given for each volume velocity. The other data in each table were obtained at the percent of flooding frequency as given for each operation.

Fuel product specification data are presented in Tables A-1 and A-2, pilot plant operational data are given in Tables A-3 through A-21, and data relative to operation of the centrifugal contactor appear in Tables A-22 through A-27.

TABLE A-1
TENTATIVE URANIUM PRODUCT SPECIFICATION (U-233, U-235)[a]

Element	Maximum Concentration Limit (μg/g U)
Aluminum	75
Calcium plus magnesium	150
Chlorine plus fluorine	50
Chromium	150
Cobalt	75
Copper	200
Iron plus chromium	200
Lead	200
Manganese	200
Molybdenum	200
Nickel	150
Phosphorus	200
Silicon	200
Sulfur	30
Tantalum	200
Thorium	600
Tin	200
Titanium	200
Tungsten	200
Vanadium	200
Zinc	200
Uranium	$1.0 \pm 0.5\ \underline{M}\ UO_2(NO_3)_2$
NO_3^-/heavy metal ratio	$2 < NO_3^-$/heavy metal < 2.5
Boron equivalent	≤ 20 μg/g U burnable ≤ 2 μg/g U nonburnable

[a] Data from Ref. 19.

TABLE A-2
TENTATIVE THORIUM PRODUCT SPECIFICATION FOR STORAGE(a)

Thorium	2.1 ± 0.1 M $Th(NO_3)_4$
NO_3^-/Th	$4 < NO_3^-/Th < 4.5$
Uranium	<25 μg/g Th
Plutonium	<10 μg/g Th

(a) Data from Ref. 20.

TABLE A-3
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 1A (EXTRACTION) IN 1A-1S TWO-COLUMN SYSTEM

Volume Velocity[(a)] (gal/hr/ft^2)	Superficial Velocity[(a)]		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding					
	$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous Organic Flow Ratio[(b)]	Percent of Flooding Frequency	Percent Loss U	Percent Loss Th	1AW HNO$_3$ (M)	1AP Th (g/ℓ)
933	0.245	0.810	91	0.302	80	0.08	0.04	1.2	39.5
949	0.245	0.840	90	0.291	81	0.08	0.03	1.9	39.1
		0.840	90	0.305	81		0.03	1.9	33.3
942	0.257	0.808	91	0.318	90	0.05	0.51	1.9	53.2
946	0.259	0.811	90	0.317	91	0.02	0.21	1.5	76.5
952	0.264	0.813	89	0.319	92	0.01	0.08	1.5	55.7
871	0.24	0.74	97	0.330	82	0.002	0.52	1.6	55.5
991	0.23	0.89	87	0.264	92	0.001	0.40	1.2	109
917	0.24	0.80	93	0.295	86	0.001	0.64	1.6	49.7
936	0.26	0.80	91	0.322	90	0.17	0.04	2.0	45.2
904	0.26	0.76	94	0.399	87	0.15	0.04	2.1	51.3
996	0.24	0.89	86	0.271	95	0.14	0.03	1.8	52.5
925	0.24	0.80	92	0.303	86	0.15	0.05	1.5	40.0
861	0.19	0.78	97	0.244	81	0.10	0.03	1.8	49.1
881	0.18	0.82	96	0.216	82	0.12	0.03	1.6	46.8

Notes: Operating temperature: ambient.

Column data: total cartridge height = 6.7 m (22 ft); extraction height = 4.0 m (13 ft); scrub height = 2.8 m (9 ft); column diameter = 5.1 cm (2 in.).

Pulse amplitude: 2.5 cm (1 in.)

[(a)] $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

[(b)] Ratio of $\frac{1AF + 1AS + 1AA}{1AX}$.

TABLE A-4
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 1S (SCRUB) IN 1A-1S TWO-COLUMN SYSTEM

Volume Velocity[(a)] (gal/hr/ft^2)	Superficial Velocity[(a)]		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding					
	$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous Organic Flow Ratio[(b)]	Percent of Flooding Frequency	Percent Recycle to Column 1A		1SR HNO_3 (M)	1SP Th (g/ℓ)
						U	Th		
841	0.14	0.81	100	0.178	82	2.72	34.9	1.20	22.97
885	0.16	0.84	96	0.186	85	3.17	41.3	1.30	35.27
850	0.14	0.82	96	0.190	85	2.57	44.0	1.39	25.99
841	0.14	0.81	100	0.176	85	3.31	37.8	1.08	27.38
850	0.15	0.81	99	0.182	86	4.68	34.9	0.90	31.33
858	0.16	0.81	98	0.188	87	4.05	49.4	0.88	33.18
781	0.14	0.74	105	0.191	77	3.43	37.2	0.98	31.79
894	0.12	0.89	95	0.140	85	2.77	16.2	1.00	38.29
829	0.14	0.80	101	0.170	80	2.59	44.1	1.01	30.40
833	0.14	0.80	100	0.177	84	3.00	37.3	1.23	29.93
800	0.14	0.76	103	0.185	82	3.65	46.6	1.13	29.70
881	0.11	0.89	95	0.123	88	3.59	53.4	1.16	42.70
838	0.14	0.80	100	0.180	83	2.49	32.7	1.21	23.67
769	0.09	0.78	107	0.110	78	2.11	24.4	1.21	23.90
786	0.09	0.80	105	0.109	79	1.85	23.8	1.45	32.02

Notes: Operating temperature: ambient.

Column data: total cartridge height = 5.5 m (18 ft); column diameter = 5.1 cm (2 in.).

Pulse amplitude: 2.5 cm (1 in.).

(a) $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

(b) Ratio of $\frac{1AS}{1AX}$.

TABLE A-5
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 1A-1S SINGLE-COLUMN SYSTEM (EXTRACTION-SCRUB)(SEE FIG. 8)

Volume Velocity(a) (gal/hr/ft^2)	Superficial Velocity(a)		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding					
	$\overline{V}a$ (cm/s)	$\overline{V}o$ (cm/s)		Aqueous Organic Flow Ratio(b)	Percent of Flooding Frequency	Percent Loss		1AW HNO$_3$ ($\underline{M}$)	1SP Th (g/ℓ)
						U	Th		
915	0.25	0.78	136	0.325	51	0.01	1.80	2.21	53.37
965	0.29	0.80	134	0.360	52	0.01	2.24	2.50	39.45

Notes: Operating temperature: ambient.

Column data: total cartridge height = 6.7 m (22 ft); extraction height = 4.6 m (15 ft); scrub height = 2.1 m (7 ft); column diameter = 5.1 cm (2 in.).

Pulse amplitude: 2.5 cm (1 in.).

(a) $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

(b) Ratio of $\frac{1AF + 1AS + 1AA}{1AX}$.

TABLE A-6
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 1BX (PARTITION) (SEE FIG. 8)

Total Cartridge Height(a) [m (ft)]	Volume Velocity(b) (gal/hr/ft^2)	Superficial Velocity(b)		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding			
		$\bar{V}_a$ (cm/s)	$\bar{V}_o$ (cm/s)		Aqueous/ Organic Flow Ratio(c)	Percent of Flooding Frequency	HETS Thorium Basis [m (ft)]	Arithmetic Decontamination Factor for Uranium(d)
4.6 (15)	605	0.26	0.43	82	0.595	82	1.15 (3.36)	7.5
4.6 (15)(e)	601	0.25	0.42	82	0.603	85	0.97 (3.19)	9.5
4.6 (15)(e)	614	0.26	0.44	81	0.579	85	1.08 (3.53)	21.3
4.6 (15)	606	0.25	0.43	82	0.580	79	1.01 (3.33)	9.4
4.6 (15)(e)	608	0.26	0.43	82	0.590	67	0.95 (3.12)	12.4
4.6 (15)(e)	599	0.25	0.43	83	0.589	66	1.01 (3.33)	7.7
4.6 (15)	585	0.25	0.41	82	0.617	60	1.86 (6.1)	5.3
4.6 (15)(e)	641	0.25	0.47	81	0.534	60		10.0
4.6 (15)(e)	595	0.25	0.42	81	0.582	60		6.7
5.8 (19)	618	0.25	0.45	81	0.560	73	1.22 (4.0)	6.5
5.8 (19)(e)	597	0.25	0.43	81	0.599	73		8.6
5.8 (19)(e)	663	0.26	0.49	80	0.543	74		7.6
5.8 (19)	617	0.26	0.44	82	0.587	71	1.34 (4.4)	5.4
5.8 (19)(e)	607	0.26	0.42	81	0.619	72		7.9
5.8 (19)(e)	608	0.27	0.41	81	0.661	72		8.4
5.8 (19)	572	0.25	0.40	84	0.628	67		16.2
5.8 (19)	589	0.26	0.41	83	0.637	80		2.4
5.8 (19)	577	0.26	0.40	84	0.644	67		6.8
5.8 (19)	590	0.25	0.42	83	0.609	67		6.3
5.8 (19)	591	0.25	0.42	83	0.591	67		7.1
5.8 (19)	610	0.27	0.43	82	0.625	72		7.8
5.8 (19)	608	0.26	0.43	82	0.618	72		
5.8 (19)	609	0.26	0.43	82	0.618	72		8.8
5.8 (19)	612	0.27	0.43	82	0.626	73		4.9
5.8 (19)(e)	629	0.26	0.46	81	0.558	74		6.9
5.8 (19)(e)	621	0.26	0.44	82	0.596	73		7.3
5.8 (19)	608	0.26	0.43	82	0.603	72		6.6
5.8 (19)	616	0.26	0.44	82	0.601	72		8.1
5.8 (19)	629	0.27	0.44	81	0.606	73		7.2
5.8 (19)	597	0.25	0.42	82	0.603	77	1.28 (4.2)	3.9
5.8 (19)	611	0.26	0.43	82	0.597	77	1.28 (4.2)	7.1

Notes: Operating temperature: ambient.

Pulse amplitude: 2.5 cm (1 in.).

(a) Column diameter = 76 mm (3 in.).

(b) $\bar{V}_a + \bar{V}_o = \bar{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\bar{V}_t$).

(c) Ratio of $\frac{1BX}{1AX + 1BS}$.

(d) Arithmetic DF is the ratio of uranium to thorium in the feed divided by the ratio of uranium to thorium in the product.

(e) DBP added to 1A column during pilot plant run.

TABLE A-7
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 1BS (PARTITION-SCRUB)(SEE FIG. 8)

Volume Velocity[a] (gal/hr/ft^2)	Superficial Velocity[a]		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding			
	$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous/ Organic Flow Ratio[b]	Percent of Flooding Frequency	HETS Uranium Basis [m (ft)]	Arithmetic Decontamination Factor for Uranium[c]
644	0.57	0.15	74	3.71	76	0.58 (1.89)	222
610	0.57	0.11	75	5.04	75	0.41 (1.36)	40
652	0.58	0.17	73	3.46	77	0.55 (1.79)	148
649	0.57	0.17	74	3.38	68	0.55 (1.79)	1001
651	0.58	0.16	74	3.71	68	0.50 (1.65)	393
630	0.56	0.15	74	3.84	68	0.61 (2.00)	519
659	0.57	0.18	82	3.18	66		681
659	0.57	0.18	82	3.21	66		2499
631	0.56	0.15	85	3.57	64		2002
682	0.56	0.21	72	2.72	76	1.30 (4.25)	36
674	0.57	0.19	72	3.00	76		45
714	0.60	0.21	71	2.82	77		30
680	0.58	0.19	72	3.10	74	10.88 (2.90)	104
674	0.59	0.17	72	3.46	74		81
658	0.62	0.13	73	4.76	73		73
649	0.56	0.17	88	3.25	57		1656
643	0.58	0.14	74	4.08	62		102
620	0.58	0.13	86	4.58	70		55
625	0.57	0.14	85	4.09	71		37
630	0.56	0.15	85	3.63	71		71
684	0.60	0.18	83	3.38	63		24
678	0.59	0.18	83	3.38	63		
675	0.59	0.17	83	3.45	63		14
608	0.56	0.12	86	4.50	63		112
647	0.57	0.16	84	3.64	64		298
713	0.59	0.22	81	2.72	67		208
668	0.58	0.17	84	3.36	63		169
675	0.59	0.17	83	3.38	64		407
707	0.60	0.20	82	3.08	65		469
653	0.57	0.17	84	3.42	69	<0.61 (<2.0)	1979
665	0.58	0.17	84	3.40	69	<0.61 (<2.0)	2121

Notes: Operating temperature: ambient.

Column data: total cartridge height = 5.2 m (17 ft); column diameter = 5.1 cm (2 in.)

Pulse amplitude: 2.5 cm (1 in.)

[a] $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

[b] Ratio of $\frac{1BX}{1BS}$.

[c] Arithmetic DF is ratio of uranium to thorium in the feed divided by the ratio of uranium to thorium in the product.

TABLE A-8
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 1C (U-STRIP) (SEE FIG. 8)

Total Cartridge Height(a) [m (ft)]	Volume Velocity(b) (gal/hr/ft^2)	Superficial Velocity(b)		Flooding Frequency (cycles/min)	*Data at Indicated Percent of Flooding*				
		$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous/ Organic Flow Ratio(c)	Percent of Flooding Frequency	HETS(d) Uranium Basis [m (ft)]	Percent Uranium Loss	Temp. (°C)
4.6 (15)	566	0.21	0.43	85	0.493	85	0.80 (2.63)	0.01	50
4.6 (15)(e)	565	0.22	0.42	85	0.507	85	0.85 (2.80)	0.02	50
4.6 (15)(e)	578	0.21	0.44	84	0.488	86	1.17 (3.85)	0.28	50
4.6 (15)	576	0.19	0.43	85	0.478	50	0.82 (2.68)	0.01	46
4.6 (15)(e)	575	0.20	0.43	85	0.513	50	0.82 (2.68)	0.01	46
4.6 (15)(e)	569	0.20	0.43	85	0.509	50			
4.6 (15)	553	0.22	0.41	97	0.530	77		0.001	52
4.6 (15)(e)	601	0.21	0.47	94	0.437	80		0.087	52
4.6 (15)(e)	570	0.22	0.42	96	0.515	78		0.14	52
4.6 (15)	591	0.22	0.47	94	0.493	73		0.002	51
4.6 (15)(e)	565	0.21	0.43	96	0.508	72		0.002	51
4.6 (15)(e)	635	0.23	0.49	92	0.473	75		0.002	51
4.6 (15)	576	0.21	0.44	95	0.483	75		0.06	47
4.6 (15)(e)	564	0.21	0.42	97	0.505	73		0.27	47
4.6 (15)(e)	545	0.20	0.41	97	0.490	73		0.28	47
4.6 (15)	537	0.21	0.40	98	0.527	67		0.03	
4.6 (15)	553	0.22	0.41	97	0.536	71		0.03	46
4.6 (15)	586	0.35	0.31	95	1.13	74		0.03	47
4.6 (15)	593	0.35	0.32	95	1.10	74		0.03	47
4.6 (15)	673	0.41	0.35	90	1.18	78		0.03	47
4.6 (15)	541	0.22	0.40	98	0.541	66		0.06	53
4.6 (15)	554	0.21	0.41	97	0.512	67		0.02	53
4.6 (15)	567	0.21	0.43	96	0.527	68		0.02	53
4.6 (15)	564	0.21	0.43	86	0.501	81		0.49	53
4.6 (15)	564	0.21	0.43	86	0.500	81			53
4.6 (15)	563	0.21	0.43	86	0.495	81		0.08	53
4.6 (15)	532	0.20	0.40	98	0.507	72		1.22	49
4.6 (15)(e)	591	0.21	0.46	94	0.463	76		10.29	49
4.6 (15)(e)	557	0.19	0.44	96	0.433	74		6.29	49
4.6 (15)	571	0.22	0.43	95	0.504	69		1.22	52
4.6 (15)	575	0.22	0.44	95	0.495	69		2.01	52
4.6 (15)	588	0.22	0.44	94	0.502	70		1.39	52
4.6 (15)	842	0.48	0.47	79	1.02	89		0.03	46
4.6 (15)	778	0.43	0.45	83	0.953	89		0.02	46
4.6 (15)	780	0.44	0.44	83	0.994	84		0.02	42
4.6 (15)	825	0.42	0.51	80	0.831	88			42
4.6 (15)	860	0.47	0.50	78	0.929	90		0.05	42
4.6 (15)	799	0.44	0.46	82	0.969	78		0.03	47
4.6 (15)	821	0.44	0.48	80	0.916	80		0.02	47
4.6 (15)	558	0.21	0.42	96	0.499	75	0.91 (3.0)	0.01	47
4.6 (15)	570	0.21	0.43	95	0.491	76	0.91 (3.0)	0.01	47

Note: Pulse amplitude: 2.5 cm (1 in.).

(a) Column diameter = 76 mm (3 in.).

(b) $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

(c) Ratio of $\frac{1CX}{1AX + 1BS}$.

(d) In cases where no HETS value is given, column functioned in service capacity only.

(e) DBP added to 1A column during pilot plant run.

TABLE A-9
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR CENTRIFUGAL CONTACTOR 1A (EXTRACTION) (SEE FIG. 13)

Aqueous/ Organic Flow Ratio[(a)]	Percent Loss		Operating Speed (rpm)
	U	Th	
0.342	0.04	0.01	1850
0.309	0.13	0.05	2070
0.337	0.01	0.005	1200
0.335	0.01	0.005	1200
0.305	0.02	0.005	2300
0.330	0.11	0.02	1200
0.305	0.12	0.02	1200
0.310	0.09	0.02	1200
0.319	0.30	0.17	1200
0.325	0.31	0.43	1200
0.332	0.28	0.41	1200
0.286	0.01	0.01	1200
0.285	0.01	0.56	1200
0.304	0.02	0.14	2200
0.319	0.02	0.76	1200
0.305	0.02	0.27	1200
0.254	0.01	0.10	1200
0.248	0.01	0.01	1200
0.256	0.01	0.01	1200
0.268	0.01	0.01	1200
0.257	0.02	0.01	1200
0.274	0.02	0.01	1200
0.276	0.02	0.02	1200
0.297	0.02	0.02	1200

Notes: Flooding speed for the contactor = <500 rpm.

Number of contactor stages = 8.

(a) Ratio of $\frac{1AF + 1AA + 1AS}{1AX}$.

TABLE A-10
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 1S IN CENTRIFUGAL CONTACTOR (1A) - 1S SYSTEM (SEE FIG. 13)

Volume Velocity[a] (gal/hr/ft^2)	Superficial Velocity[a]		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding					
	$\bar{V}a$ (cm/s)	$\bar{V}o$ (cm/s)		Aqueous/ Organic Flow Ratio[b]	Percent of Flooding Frequency	Percent Recycle to 1A		1SR HNO_3 (M)	1SP Th (g/ℓ)
						U	Th		
767	0.15	0.72	105	0.202	76	2.40	31.9	1.49	13.92
810	0.14	0.77	101	0.186	80	3.53	36.7	1.08	16.24
748	0.15	0.70	109	0.208	62	3.28	38.1	1.37	23.21
765	0.15	0.72	106	0.205	64	4.54	64.9	1.44	34.81
818	0.14	0.79	102	0.178	59	3.66	41.1	1.71	23.21
810	0.15	0.77	101	0.193	79	6.80	66.7	1.74	25.53
829	0.14	0.79	100	0.181	72	6.43	65.9	1.74	27.85
826	0.14	0.79	101	0.181	71	7.49	82.9	1.74	27.85
820	0.15	0.78	101	0.191	79	3.98	35.2	1.82	23.21
820	0.15	0.78	101	0.188	79				
824	0.15	0.79	101	0.186	72	2.89	33.5	1.86	30.17
805	0.14	0.76	102	0.286	81	1.92	22.6	1.63	25.53
899	0.15	0.87	94	0.285	88	1.79	21.2	1.65	23.21
811	0.14	0.77	102	0.304	81	4.53	73.8	1.72	27.85
828	0.14	0.79	101	0.183	83	2.73	28.5	1.58	27.85
841	0.15	0.80	99	0.182	72	4.00	37.8	1.76	30.17
788	0.09	0.80	105	0.113	68	1.93	24.0	2.04	34.81
1008	0.15	0.90	86	0.148	93	4.47	17.3	2.23	23.21
968	0.15	0.94	89	0.157	90	1.65	10.1	2.46	27.85
935	0.15	0.91	91	0.166	90	5.96	10.2	1.79	25.53
1064	0.15	1.05	82	0.146		3.14	27.9	1.64	164.7
1036	0.15	1.01	84	0.159		2.37	13.3	1.64	32.49
974	0.16	0.93	90	0.17	77	2.35	32.9	2.16	27.85
1015	0.16	0.99	86	0.16	55	2.23	29.1	1.78	30.17

Notes: Column data: total cartridge height = 6.7 m (22 ft); column diameter = 5.1 cm (2 in.)

Operating temperature: ambient.

Pulse amplitude: 2.5 cm (1 in.).

[a] $\bar{V}_a + \bar{V}_o = \bar{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\bar{V}_t$).

[b] Ratio of $\frac{1AS}{1AX}$.

TABLE A-11
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 2A (EXTRACTION)(SEE FIG. 8)

Volume Velocity[(a)] (gal/hr/ft^2)	Superficial Velocity[(a)]		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding			
	$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous/ Organic Flow Ratio[(b)]	Percent Uranium Loss	Percent of Flooding Frequency	HETS [m (ft)]
939	0.996	0.066	101	4.17	0.68	77	1.44 (4.71)
			101				1.40 (4.59)
950	0.849	0.225	101	3.77	0.025	79	1.34 (4.41)
947	0.852	0.219	101	3.89	0.009		1.12 (3.66)
934	0.841	0.215	101	3.91	0.035	65	1.05 (3.43)
			101		0.043		1.06 (3.49)
950	0.857	0.217	101	3.95	0.040	81	1.04 (3.41)
			101		0.048		1.33 (4.36)
948	0.882	0.220	101	4.01	0.027	79	0.87 (2.86)
					0.007		0.79 (2.60)

Notes: Operating temperature: ambient.

Column data: total cartridge height = 6.7 m (22 ft); extraction height = 4.0 m (13 ft); scrub height = 2.7 m (9 ft); column diameter = 5.1 cm (2 in.).

Pulse amplitude: 2.5 cm (1 in.)

(a) $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

(b) Ratio of $\frac{2AF + 2AS}{2AX}$.

TABLE A-12
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 2B (STRIP) (SEE FIG. 8)

Volume Velocity(a) (gal/hr/ft^2)	Superficial Velocity(a)		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding					
	$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous Organic Flow Ratio(b)	Percent Uranium Loss	Thorium DF Uranium Basis(c)	Percent Flooding Frequency	HETS [m (ft)]	Temp. (°C)
296	0.129	0.206	89	0.63	0.973	588	72		50
460	0.296	0.225	98	1.31	0.019	2.61	88	1.56 (5.12)	50
461	0.303	0.219	98	1.39	0.004	2.13	88	1.53 (5.02)	50
396	0.233	0.215	98	1.00	0.002		82	1.31 (4.31)	50
					0.002		82	1.31 (4.31)	50
378	0.210	0.217	108	0.97	0.006	13.0	80	1.14 (3.76)	50
					0.006	14.8	80	1.14 (3.76)	50
384	0.214	0.220	122	0.97	0.004	24.7	79	1.15 (3.77)	50
					0.002	18.5	79	1.14 (3.76)	50

Notes: Column data: total cartridge height = 4.6 m (15 ft); column diameter = 5.1 cm (2 in.).

Pulse amplitude: 2.5 cm (1 in.) with exception of data corresponding to a volume velocity of 296 gal/hr/ft^2, which was 3.8 cm (1.5 in.) amplitude.

(a) $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

(b) Ratio of $\frac{2BX}{2AX}$.

(c) Arithmetic DF is ratio of thorium to uranium in the feed divided by the ratio of thorium to uranium in the product (2AF/2BU).

TABLE A-13
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR
COLUMN 3A (EXTRACTION)(SEE FIG. 8)

Volume Velocity[(a)] (gal/hr/ft^2)	Superficial Velocity[(a)]		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding				
	$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous/ Organic Flow Ratio[(b)]	Percent Uranium Loss	Thorium DF Uranium Basis[(c)]	Percent Flooding Frequency	HETS [m (ft)]
257	0.197	0.094	134	2.10	0.142	24	78	2.00 (6.57)
			134					0.87 (2.84)
499	0.368	0.114	134	3.22	0.056	20.6	73	0.81 (2.66)
456	0.372	0.143	134	2.60	0.311	11.9	73	1.01 (3.31)
403	0.350	0.105	92	3.33	0.020	6.0	85	1.20 (3.94)
						2.4	85	1.16 (3.81)
362	0.313	0.096	92	3.26	0.026	27.7	92	1.15 (3.77)
					0.017	25.5	92	1.09 (3.58)
395	0.345	0.102	92	3.38	0.031	24.0	92	1.12 (3.69)
					0.022	18.2	92	1.07 (3.51)

Notes: Column data: total cartridge height = 5.2 cm (17 ft); extraction height = 4.0 m (13 ft); scrub height = 1.2 m (4 ft); column diameter = 5.2 cm (2 in.).

Operating temperature: ambient

Pulse amplitude: 2.5 cm (1 in.).

(a) $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

(b) Ratio of $\frac{3AF + 3AS}{3AX}$.

(c) Arithmetic DF is ratio of thorium to uranium in the feed divided by the ratio of thorium to uranium in the product (2AF/3BU).

TABLE A-14
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 3B (STRIP)(SEE FIG. 8)

Volume Velocity[a] (gal/hr/ft^2)	Superficial Velocity[a]		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding					
	$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous/ Organic Flow Ratio[b]	Percent Uranium Loss	Thorium DF Uranium Basis[c]	Percent of Flooding Frequency	HETS [m (ft)]	Temp. (°C)
145	0.070	0.093	65	0.75	16.3	1.0	77	1.11 (3.64)	50
170	0.077	0.114	120	0.54	2.1×10^{-5}		82	0.65 (2.13)	50
195	0.078	0.143	120	0.68	1.9×10^{-5}	6.4	82	0.65 (2.13)	50
248	0.099	0.105	120	0.94	1.8×10^{-3}		67	0.87 (2.85)	50
					1.2×10^{-3}		67	0.87 (2.85)	50
182	0.109	0.096	120	1.14	2.8×10^{-3}	2.1	67	1.07 (3.51)	50
					9.1×10^{-4}	1.7	67	1.07 (3.51)	50
185	0.107	0.102	120	1.05	1.8×10^{-3}	1.1	89	1.05 (3.43)	50
					9.2×10^{-4}	0.9	89	1.05 (3.43)	50

Notes: Column data: total cartridge height = 5.2 m (17 ft).

Pulse amplitude: 2.5 cm (1 in.).

(a) $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

(b) Ratio of $\frac{3BX}{3AX}$.

(c) Arithmetic DF is ratio of thorium to uranium in the feed divided by the ratio of thorium to uranium in the product (3AF/3BU).

TABLE A-15
HRRF MODIFIED PUREX PROCESS: OPERATING DATA FOR COLUMN 5A (EXTRACTION-SCRUB)(SEE FIG. 9)

Volume Velocity(a) (gal/hr/ft^2)	Superficial Velocity(a)		Flooding Frequency (cycles/min)	Data at Indicated Percent of Flooding			
	$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous/ Organic Flow Ratio(b)	Percent of Flooding Frequency	Percent Uranium Loss	5AW HNO_3 ($\underline{M}$)
992	0.70	0.42	131	1.675	67	0.02	2.13
998	0.74	0.38	131	1.929	61	0.01	1.79
995	0.76	0.37	131	2.047	61	0.01	1.81
974	0.72	0.38	131	1.870	67	0.02	1.84

Notes: Operating temperature: ambient.

Column data = total cartridge height = 6.7 m (22 ft); extraction height = 4.0 m (13 ft); scrub height = 2.8 m (9 ft); column diameter = 5.1 cm (2 in.).

Pulse amplitude: 2.5 cm (1 in.).

(a) $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

(b) Ratio of $\frac{5AS + 5AF}{5AX}$.

TABLE A-16
HRRF MODIFIED PUREX PROCESS: OPERATING DATA FOR COLUMN 5B (STRIP)(SEE FIG. 9)

Total Cartridge Height[a] [m (ft)]	Volume Velocity[b] (gal/hr/ft^2)	Superficial Velocity[b]		Frequency (cycles/min)	Data at Indicated Percent of Flooding				
		$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous/ Organic Flow Ratio[c]	Percent of Flooding Frequency	HETS [m (ft)]	Percent Uranium Loss	Temp. (°C)
4.6 (15)	316	0.198	0.159	73[d]	1.24				50
4.6 (15)	258	0.116	0.176	73[d]	0.66				50
4.6 (15)	302	0.132	0.209	73[d]	0.63				50
4.6 (15)	283	0.151	0.170	70[d]	0.89				51
4.6 (15)[e]	280	0.135	0.181	70[d]	0.74				52
4.6 (15)[e]	324	0.184	0.182	70[d]	1.01			0.01	52
4.6 (15)	292	0.144	0.186	119[f]	0.77	72		0.04	49
4.6 (15)	272	0.138	0.170	119[f]	0.81	84		0.04	50
4.6 (15)	261	0.131	0.164	120[f]	0.80	83	1.26 (4.13)	0.002	50
4.6 (15)[e,g]	748	0.464	0.383	119[f]	1.21	72	1.63 (5.36)	1.05	50

[a] Column diameter = 7.6 cm (3.0 in.).

[b] $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

[c] Ratio of $\frac{5BX}{5AX}$.

[d] Operating pulse frequency.

[e] DBP added to 1A extraction unit during pilot plant run.

[f] Flooding frequency.

[g] Column diameter = 5.1 cm (2.0 in.) this run only.

TABLE A-17
HRRF MODIFIED PUREX PROCESS: OPERATING DATA FOR COLUMN 6A (EXTRACTION-SCRUB)(SEE FIG. 9)

Volume Velocity(a) (gal/hr/ft^2)	Superficial Velocity(a)		Frequency (cycles/min)	Data at Indicated Percent of Flooding			
	$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous/ Organic Flow Ratio(b)	Percent of Flooding Frequency	Percent Uranium Loss	6AW HNO_3 ($\underline{M}$)
734	0.584	0.245	80(c)	2.38		0.21	1.36
543	0.366	0.248	80(c)	1.48		0.05	0.91
582	0.399	0.259	80(c)	1.54		0.11	0.93
667	0.479	0.275	80(c)	1.74		0.01	1.03
621	0.448	0.264	80(c)	1.70		0.01	1.02
733	0.557	0.271	80(c)	2.05		0.02	1.03
563	0.411	0.227	103(d)	1.82	83	1.5	1.34
579	0.438	0.217	103(d)	2.02	77	0.04	1.18
512	0.426	0.153	104(d)	2.78	77	0.14	1.21
793	0.620	0.277	103(d)	2.24	83	0.26	0.92

Notes: Operating temperature: ambient.

Column data: total cartridge height = 6.7 m (22 ft); extraction height = 4.0 m (13 ft); scrub height = 2.8 m (9 ft); column diameter = 5.1 cm (2 in.).

Pulse amplitude: 2.5 cm (1 in.).

(a) $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

(b) Ratio of $\frac{6AS + 6AF}{6AX}$.

(c) Operating pulse frequency.

(d) Flooding frequency.

TABLE A-18
HRRF MODIFIED PUREX PROCESS: OPERATING DATA FOR COLUMN 6B (STRIP)(SEE FIG. 9)

Total Cartridge Height[a] [m (ft)]	Volume Velocity[b] (gal/hr/ft^2)	Superficial Velocity[b]		Frequency (cycles/min)	Data at Indicated Percent of Flooding			
		$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)		Aqueous/ Organic Flow Ratio[c]	Percent of Flooding Frequency	Percent Uranium Loss	Temp. (°C)
5.2 (17)	479	0.295	0.246	73[d]	1.20			45
5.2 (17)	494	0.311	0.247	73[d]	1.26			45
5.2 (17)	485	0.290	0.258	73[d]	1.12			45
5.2 (17)	446	0.229	0.275	68[d]	0.83			45
5.2 (17)[e]	434	0.231	0.259	68[d]	0.83			45
5.2 (17)[e]	448	0.236	0.270	68[d]	0.87			45
5.2 (17)	403	0.230	0.226	77[f]	1.02	94	0.01	38
5.2 (17)	382	0.215	0.217	77[f]	0.99	88	0.01	38
5.2 (17)	332	0.223	0.153	79[f]	1.45	86	0.01	38
5.2 (17)[e]	465	0.249	0.277	77[f]	0.90	94	0.01	50
5.2 (17)[e]	465	0.249	0.277	77[f]	0.90	94	0.02	50

[a] Column diameter = 5.1 cm (2 in.).

[b] $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

[c] Ratio of $\frac{6BX}{6AX}$.

[d] Operating pulse frequency.

[e] DBP added to 1A extraction unit during pilot plant run.

[f] Flooding frequency.

TABLE A-19
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 1PUX (EXTRACTION)(SEE FIG. 10)

Volume Velocity[a] (gal/hr/ft^2)	Superficial Velocity[a]		Flooding Frequency (cycles/min)	Aqueous/ Organic Flow Ratio[b]	Percent Flooding Frequency
	$\overline{V}_a$ (cm/s)	$\overline{V}_o$ (cm/s)			
461	0.049	0.47	93	0.105	80
447	0.055	0.45	93	0.122	80
429	0.042	0.44	95	0.096	63
492	0.047	0.51	90	0.092	76
494	0.054	0.50	90	0.107	76
446	0.051	0.50	93	0.995	75
474	0.051	0.48	93	0.106	75

Notes: Operating temperature: ambient.

Column data: total cartridge height = 5.8 m (19 ft); column diameter = 7.6 cm (3.0 in.).

Pulse amplitude = 2.5 cm (1 in.).

[a] $\overline{V}_a + \overline{V}_o = \overline{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\overline{V}_t$).

[b] Ratio of $\frac{1PU(X)}{1PUS + 1AX}$.

TABLE A-20
HRRF ACID-THOREX PROCESS: OPERATING DATA FOR COLUMN 1 PUS(SCRUB)(SEE FIG. 10)

Volume Velocity[a] (gal/hr/ft^2)	Superficial Velocity[a]		Flooding Frequency (cycles/min)	Aqueous/Organic Flow Ratio[b]	Percent Thorium Loss	Percent Flooding Frequency	Temp. (°C)
	$\bar{V}_a$ (cm/s)	$\bar{V}_o$ (cm/s)					
165	0.118	0.068	103	1.74	7.83	75	46
176	0.141	0.072	103	1.95	8.78	75	46
175	0.110	0.088	100	1.25	2.3	76	42
191	0.110	0.096	97	1.25	6.8	78	42
231	0.138	0.123	90	1.12	9.6	84	42
180	0.102	0.101	97	1.02	1.79	77	47
190	0.115	0.100	97	1.15	1.44	77	47

Notes: Column data: total cartridge height = 5.2 m (17 ft); column diameter = 5.2 cm (2 in.).

Pulse amplitude = 2.5 cm (1 in.).

[a] $\bar{V}_a + \bar{V}_o = \bar{V}_t$; volume velocity (in gal/hr/ft^2) = 885 ($\bar{V}_t$).

[b] Ratio of $\frac{\text{1PU(X) + 1PUA}}{\text{1PUS}}$.

TABLE A-21
HRRF MODIFIED PUREX PROCESS: OPERATING DATA FOR CENTRIFUGAL CONTACTOR 5A (EXTRACTION)

Aqueous/ Organic Flow Ratio[(a)]	Percent Uranium Loss	Operating Speed (rpm)
1.98	$<10^{-2}$	1200
1.87	$<10^{-2}$	1200
1.54	$<10^{-2}$	1200
1.95	10^{-2}	1200
1.81	10^{-2}	1200
1.90	10^{-2}	1200

Notes: Flooding speed of contactor < 500 rpm; number of contactor stages = 8.

Operating temperature: ambient.

(a) Ratio of $\frac{5AF + 5AS}{5AX}$.

TABLE A-22
CENTRIFUGAL CONTACTOR EFFICIENCY STUDY: STREAM AND SAMPLE DATA FOR THORIUM-30% TBP SYSTEM

1AF (Stream 1)[a]			1AX (Stream 2)	1AA (Stream 3)	1AP (Stream 4)	1AW (Stream 5)	
Flow (mℓ/min)	Th (g/ℓ)	HNO_3 (M)	Flow (30% TBP) (mℓ/min)	Flow (13 M HNO) (mℓ/min)	Th (g/ℓ)	Th (g/ℓ)	HNO_3 (M)
331	78.39	1.34	878	31	9.84	0.093	1.71
502	78.39	1.34	1143	30	14.8	0.066	1.34
502	78.39	1.34	955	25	20.4	0.038	1.34
321	78.39	1.34	528	25	36.8	5.45	1.78
319	78.39	1.34	689	25	30.4	0.066	1.42
271	166.71	1.35	830	21	38.4	0.027	1.70
249	166.71	1.35	574	30	16.58	31.81	2.61
285	166.71	1.35	710	26	120.6	0.482	2.28
267	166.71	1.35	603	24	29.8	2.92	2.37
317	166.71	1.35	618	23	36.8	20.60	2.20

(a) See Fig. 14; 1AF stream enters stage 1; 1AA stream enters stage 6; 1AX stream enters stage 8.

TABLE A-23
CENTRIFUGAL CONTACTOR EFFICIENCY STUDY: STREAM AND SAMPLE DATA FOR URANIUM-30% TBP SYSTEM

1AF (Stream 1)(a)			1AX (Stream 2)	1AP (Stream 3)		1AW (Stream 4)	
Flow (mℓ/min)	U (g/ℓ)	HNO_3 (M)	Flow (30% TBP) (mℓ/min)	U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
372	10.81	1.71	328	11.25	0.231	$<10^{-3}$	1.46
327			314	10.07	0.36	$<10^{-3}$	1.35
320			273	12.04	0.36	$<10^{-3}$	1.42
422			282	14.26	0.23	$<10^{-3}$	1.48
386			207	20.04	0.27	$<10^{-3}$	1.59
376			153	28.12	0.20	$<10^{-3}$	1.60
433			87	37.45	0.20	$<10^{-3}$	1.63
466			99	46.10	0.16	$<10^{-3}$	1.66
397	85.39	2.2	366	81.76	0.13	$<10^{-3}$	1.953
518	85.39	2.2	401	96.73	0.13	$<10^{-3}$	2.134
549	85.39	2.2	488	108.25	0.13	$<10^{-3}$	2.152
604	85.39	2.2	384	104.12	0.11	13.3	2.152
495	180.71	2.1	933	90.26	0.11	$<10^{-3}$	1.85
496	180.71	2.1	732	109.45	0.09	$<10^{-3}$	1.65
473	180.71	2.1	706	108.89	0.05	$<10^{-3}$	2.19
485	180.71	2.1	419	131.70	0.09	59.22	2.10
504	180.71	2.1	732	115.68	0.07	8.67	2.08
∿504	180.71	2.1	785	--	--	2.89	2.01

(a) See Fig. 15; 1AF stream enters stage 1; 1AA stream enters stage 6; 1AX stream enters stage 8.

TABLE A-24
CENTRIFUGAL CONTACTOR EFFICIENCY STUDY: CALCULATED THORIUM LOSS AND FLOW RATE DATA FOR 30% TBP/NPH SYSTEM[a]

Total Flow (ℓ/min)	Contactor Operating Rate (rpm)	Aqueous to Organic Ratio	Percent Thorium Loss	Temp.[b] (°C)
1.240	1200	0.412	0.12	24.7
1.675	1200	0.465	0.08	25.6
1.482	2000	0.552	0.05	26.0
0.874	1200	0.655	6.95	26.7
1.033	1200	0.499	0.08	26.7
1.122	1200	0.352	0.02	25.0
0.853	1200	0.486	19.08	25.6
1.021	1200	0.438	0.29	26.0
0.894	1200	0.483	1.75	27.2
0.958	2000	0.550	12.36	29.4

(a) Contactor used for initial extraction.

(b) Average of 1AW and 1AP temperatures.

TABLE A-25
CENTRIFUGAL CONTACTOR EFFICIENCY STUDY: CALCULATED URANIUM LOSS AND FLOW RATE DATA FOR 30% TBP/NPH SYSTEM[a]

Total Flow (ℓ/min)	Aqueous to Organic Ratio	Percent Uranium Loss	Temp.[b] (°C)
0.700	1.134	$<10^{-2}$	26
0.641	1.041	$<10^{-2}$	27
0.593	1.172	$<10^{-2}$	28
0.704	1.496	$<10^{-2}$	29
0.593	1.865	$<10^{-2}$	29
0.529	2.458	$<10^{-2}$	29
0.520	4.977	$<10^{-2}$	29
0.565	4.707	$<10^{-2}$	29
0.763	1.085	$<10^{-2}$	22
0.919	1.292	$<10^{-2}$	24
1.037	1.125	$<10^{-2}$	24
0.988	1.573	15.6	24
1.428	0.531	$<10^{-2}$	25
1.228	0.678	$<10^{-2}$	26
1.179	0.670	$<10^{-2}$	26
0.904	1.158	32.7	26
1.236	0.689	4.80	27
1.289	0.642	1.60	27

(a) Contactor used for initial extraction; contactor operating rpm = 1200, flooding frequency = <500 rpm.

(b) Average of 1AW and 1AP temperatures.

TABLE A-26
CENTRIFUGAL CONTACTOR EFFICIENCY STUDY: DATA COMPARISON FOR THORIUM-30% TBP SYSTEM

Corresponding Input Flow Rate[a] (mℓ/min)	Output Stream	Pilot Plant Results		SEPHIS Eight-Stage Calculation	
		Th (g/ℓ)	HNO_3 (<u>M</u>)	Th (g/ℓ)	HNO_3 (<u>M</u>)
1. 878 (1AX)	1AP	9.84	--	29.52	0.26
362 (1AF + 1AA)	1AW	0.093	1.71	0.01	1.72
2. 1143	1AP	14.8	--	34.43	0.22
532	1AW	0.066	1.34	0.01	1.52
3. 955	1AP	20.4	--	40.93	0.19
527	1AW	0.038	1.34	0.12	1.56
4. 528	1AP	36.8	--	43.67	0.18
346	1AW	5.45	1.78	5.39	1.92
5. 689	1AP	30.4	--	36.26	0.21
344	1AW	0.066	1.42	0.01	1.76
6. 830	1AP	38.4	--	54.44	0.21
292	1AW	0.027	1.70	0.01	1.60
7. 574	1AP	16.58	--	68.55	0.12
279	1AW	31.81	2.61	6.26	2.36
8. 710	1AP	120.6	--	66.57	0.14
311	1AW	0.482	2.28	0.03	2.01
9. 603	1AP	29.8	--	68.56	0.12
291	1AW	2.92	2.37	9.21	2.07
10. 618	1AP	36.8	--	68.76	0.12
340	1AW	20.60	2.20	30.32	1.92

(a) See Table A-22 for composition of each stream.

TABLE A-27
CENTRIFUGAL CONTACTOR EFFICIENCY STUDY: DATA COMPARISON FOR URANIUM-30% TBP SYSTEM

Corresponding Input Stream Flow Rate[a] (mℓ/min)	Output Stream	Pilot Plant Results		SEPHIS Eight-Stage Calculation	
		U (g/ℓ)	HNO_3 (M)	U (g/ℓ)	HNO_3 (M)
1. 401 (1AX)	1AP	96.7	0.13	105.8	0.09
518 (1AF)	1AW	$<10^{-3}$	2.13	$<10^{-3}$	2.18
2. 488	1AP	108.3	0.13	92.4	0.16
549	1AW	$<10^{-3}$	2.15	$<10^{-3}$	2.11
3. 384	1AP	104.1	0.11	107.3	0.08
604	1AW	13.3	2.15	14.6	2.19
4. 933	1AP	90.3	0.11	92.2	0.19
495	1AW	$<10^{-3}$	1.85	$<10^{-3}$	1.84
5. 732	1AP	109.5	0.09	115.1	0.05
496	1AW	$<10^{-3}$	1.65	1.90	2.14
6. 706	1AP	108.9	0.05	114.9	0.05
473	1AW	$<10^{-3}$	2.19	$<10^{-3}$	2.14
7. 419	1AP	131.7	0.09	115.1	0.05
485	1AW	59.2	2.10	79.3	2.12
8. 732	1AP	115.2	0.07	115.1	0.05
504	1AW	8.67	2.08	4.9	2.14

(a) See Table A-23 for concentration of uranium and nitric acid in each input stream.

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