MASTER

LABORATORY AND PILOT PLANT EVALUATION
OF
STANROCK URANIUM CONCENTRATE

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AEC RESEARCH AND DEVELOPMENT REPORT

FEED MATERIALS PRODUCTION CENTER
NATIONAL LEAD COMPANY OF OHIO

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PRINTED IN U.S.A. PRICE \$1.00

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of

TECHNICAL DIVISION
NATIONAL LEAD COMPANY OF OHIO

Date of report: October 10, 1958

Date of issuance: January 26, 1959

Approved By:

Technical Director

Approved By:

Head, Chemical Department

NATIONAL LEAD COMPANY OF OHIO
Cincinnati, Ohio
Contract No. AT(30-1)-1156

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ABSTRACT

The laboratory and pilot plant evaluation of Stanrock concentrate is presented in this report. This concentrate meets all FMPC impurity tolerance limits except that for thorium content. The thorium limit can be met by the addition of phosphate as required for thorium-containing uranium concentrates. Laboratory digestion and extraction tests indicate that this material should present no problems in pulse column processing. A Pilot Plant pulse column test (a test utilizing a modified two-inch-pulse-column system) indicated that this material should present no operational problems in the National Lead Company of Ohio Refinery.

INTRODUCTION

The Stanrock Uranium Mines, Limited,¹ initiated the production of a uranium concentrate in April of 1958. The mine and mill are located in the Blind River Area, which is north of Lake Huron in Ontario, Canada. Their concentrate is a sodium precipitate of an ion exchange liquor. The present milling capacity is rated at over 1000 ore-tons per day, but it is expected that a maximum milling capacity of 3300 ore-tons per day will be reached in the fall of 1958.

The National Lead Company of Ohio has started to receive significant quantities of Stanrock concentrate to be processed in its Refinery. Thus, a complete evaluation of the concentrate is necessary to determine (1) possible refinery processing difficulties and (2) impurity concentration in reference to FMPC impurity tolerance limits (Appendix I).

Stanrock concentrate is to be processed by standard refinery procedures, which are as follows:

The uranium concentrate feed materials are digested in a nitric acid solution, producing a slurry. The uranium in the feed slurry is separated and purified by a process wherein the uranium is extracted, scrubbed, and re-extracted in pulse-type perforated-plate columns. The uranium first is extracted by a tributyl phosphate-kerosene solvent, leaving a uranium-depleted raffinate. Then the uranium-containing solvent (extract) is scrubbed to remove impurities. Finally, the uranium is re-extracted by water. The final product of the Refinery process is thus an aqueous solution of uranyl nitrate hexahydrate.

CONCLUSIONS

It can be concluded from this feed material evaluation that Stanrock concentrate should present no Refinery processing problems when handled as a thorium-containing uranium concentrate. This conclusion is based on the assumption that the material investigated is indicative of future receipts.

LABORATORY AND PILOT PLANT TESTS

The material used in the following tests was the official assayer's sample from Stanrock concentrate, Lot SR-1.

CHEMICAL ANALYSES

Samples of Stanrock concentrate, Lot SR-1, were analyzed by the National Lead Company of Ohio Analytical Department for comparison of impurity concentrations with FMPC impurity tolerance limits (Appendix I). The wet chemical analyses of the concentrate are given in Table I; the spectrochemical analyses are presented in Table II; and the rare earth analyses are listed in Table III.

TABLE I Wet Chemical Analyses of Stanrock Concentrate
(Results are in weight per cent on a uranium basis)

Constituent	Results (%)	Constituent	Results (%)
Uranium (U)	67.13*	Iron (Fe)	0.95
Ammonia (NH ₃)	0.028	Phosphate (PO ₄ ⁻³)	0.13
Calcium (Ca)	0.85	Sodium (Na)	6.4
Carbonate (CO ₃ ⁻²)	0.12	Sulfate (SO ₄ ⁻²)	2.12
Chloride (Cl ⁻)	0.09	Thorium (Th)	0.49
Fluoride (F ⁻)	0.04	Total Organic	0.009

* Per cent uranium, on an as-received basis.

TABLE II General Spectrochemical Analyses of Stanrock Concentrate
(Results are in parts per million on a uranium basis.)

Constituent	Results (ppm)	Constituent	Results (ppm)
Aluminum (Al)	<600	Magnesium (Mg)	<150
Arsenic (As)	<150	Manganese (Mn)	<60
Boron (B)	12	Molybdenum (Mo)	<15
Bismuth (Bi)	<30	Nickel (Ni)	<30
Cadmium (Cd)	<150	Silicon Dioxide (SiO ₂)	1,050
Chromium (Cr)	<150	Tin (Sn)	<15
Cobalt (Co)	<150	Vanadium (V)	<150
Copper (Cu)	<150	Zinc (Zn)	<300
Lead (Pb)	220		

NOTE: The accuracy of these results is estimated to be $\pm 50\%$.

TABLE III Spectrochemical Rare Earth Analyses of Stanrock Concentrate
(Results are in parts per million on a uranium basis.)

Constituent	Results (ppm)	Constituent	Results (ppm)
Dysprosium (Dy)	107	Samarium (Sm)	71
Erbium (Er)	48	Terbium (Tb)	22
Europium (Eu)	<6	Thulium (Tm)	9
Gadolinium (Gd)	101	Yttrium (Y)	420
Holmium (Ho)	18	Ytterbium (Yb)	31

NOTE: The accuracy of these results is estimated to be $\pm 30\%$.

TABLE IV Digestion of Stanrock Concentrate

Digestion Characteristics

Apparent Assay (wt % U)	69.1
Acid Consumption*	0.0074
Volume Change Factor**	0.980
Reactivity of HNO ₃ Dissolution	Very Mild

Slurry Characteristics

Solids (% by wt)	<0.01
Digestion Insolubles (% by wt of insolubles in Concentrate)	<0.01
Digestion Efficiency***	>99.99

* Acid consumption is reported in gram equivalents of HNO₃ consumed in digesting to 200 g U/l and 0.0N free acid per gram of concentrate.

** Volume Change Factor = Initial Volume of Dilute Acid/Final Volume of Slurry.

*** Efficiency (%) = (Soluble U/Total U) $\times$ 100

LABORATORY DIGESTION TESTS

Laboratory-scale digestions² were run on Stanrock (Lot SR-1), producing a slurry which met Refinery specifications in regard to uranium and nitric acid concentrations. Results are listed in Table IV.

LABORATORY EXTRACTION TESTS

Laboratory extraction studies³ were run on digested feed slurries of Lot SR-1 to determine the uranium distribution curve for Stanrock concentrate. The uranium distribution curve for Stanrock concentrate is compared to the uranium distribution curve for pure uranyl nitrate hexahydrate in Figure 1.

FIGURE 1 Uranium Distribution Curve for Stanrock Concentrate

PILOT PLANT TWO-INCH-COLUMN EXTRACTION TEST

A Pilot Plant two-inch-column extraction test (Appendix II) was conducted, utilizing a feed slurry prepared from Stanrock concentrate, Lot SR-1. The high thorium content of this concentrate necessitated the addition of phosphate to the feed slurry for thorium complexing.^{4,5} Therefore, the test was set up to determine extraction column performance with a feed slurry containing 10 per cent phosphate on a uranium basis. Test conditions and resulting stream analyses are listed in Tables V, VI, VII, and VIII.

TABLE V Pilot Plant Two-Inch-Column Test Conditions;
Stanrock Concentrate — Test No. 12

Feed Material

Aqueous Feed (AF): Stanrock Concentrate Slurry (Lot SR-1): 200 ± 10 g/l U; $3.0 \pm 0.2N$ HNO_3 , $100^\circ - 110^\circ F$

Organic Extractant (AX): 33.5% TBP in Kerosene, nonacidified, ambient temperature

Scrub Water (BS): Deionized water, ambient temp

Test Flowratios*

AX/AF = 1.97/1; AX/BS = 6.28/1

Test Flowrates*

AF: 6.20 gph	AR: 7.68 gph	BS: 1.95 gph	BP: 12.80 gph
AX: 12.20 gph	AP: 12.92 gph	BR: 2.08 gph	

Test Column Throughput*

A-Column = 1002 gsfh; B-Column = 713 gsfh

A-Column Flooding Throughput*

>1500 gsfh

Continuous Phase

A-Column: Organic B-Column: Aqueous

Pulse Conditions

A-Column: Frequency = 65 cpm; Amplitude = 0.75 inch

B-Column: Frequency = 35 cpm; Amplitude = 0.60 inch

Length of Test

12¾ hours

* Flowratios were held constant throughout the entire test. The flowrates and column throughputs listed are those which prevailed during sampling. A-column flooding studies were conducted after steady-state sampling had been completed.

NOTE: For identification of the various streams, see Fig. 2, Appendix II.

TABLE VI Pilot Plant Two-Inch-Column Stream Analyses;
Stanrock Concentrate – Test No. 12

	Hour of Test		
	8 ³ / ₄	9 ¹ / ₄	9 ³ / ₄
<u>A - Column Streams (1002 gsfh)</u>			
Aqueous Feed (AF)			
U (g/l)	187	189	187
HNO ₃ (N)	3.1	3.1	3.1
Th (g/l)	1.02	1.00	1.005
PO ₄ (g/l)	18.3	18.6	18.2
Organic Feed (AX)			
U (g/l)	2.6	—	2.7
HNO ₃ (N)	0.01	—	0.01
TBP (%)	34.0	—	34.0
Organic Product (AP)			
Density and Temperature	0.986 at 89°F	0.986 at 87°F	0.987 at 86°F
U (g/l)	109	111	113
HNO ₃ (N)	0.24	0.22	0.23
Th (g/l)	0.024	0.021	0.018
Aqueous Raffinate (AR)			
U (g/l)	0.19	0.19	0.16
HNO ₃ (N)	2.43	2.40	2.41
Th (g/l)	0.51	0.46	0.45
<u>B - Column Streams (713 gsfh)</u>			
Aqueous Recycle (BR)			
U (g/l)	103	104	107
HNO ₃ (N)	1.40	1.32	1.32
Th (g/l)	0.10	0.12	0.12
Scrubbed Organic Product (BP)			
Density and Temperature	0.960 at 88°F	0.960 at 87°F	0.960 at 86°F
U (g/l)	94.9	95.0	95.1
HNO ₃ (N)	0.033	0.048	0.033
Th (g/l)	0.003	0.006	0.008

TABLE VII Spectrochemical Analyses of Pilot Plant Two-Inch -Column Scrubbed Organic Product (BP)* Stanrock Concentrate - Test No. 12
(All Values are ppm, U Basis)

Element	Hour of Test		
	8½	9¼	9¾
Al	<6.0	<6.0	<6.0
Cd	<0.2	<0.2	<0.2
Cr	<10.0	<10.0	<10.0
Cu	1.0	1.0	1.0
Dy	<0.01	<0.01	<0.01
Fe	6.0	6.0	8.0
Gd	<0.01	<0.01	<0.01
Mg	<1.0	<1.0	6.0
Mn	<4.0	<4.0	<4.0
Mo	<6.0	<6.0	<6.0
Ni	<4.0	<4.0	<4.0
P	80	80	50
Pb	<1.0	<1.0	<1.0
SiO ₂	<20.0	20.0	20.0
Sn	<40.0	<40.0	<40.0
V	<40.0	<40.0	<40.0
Zn	<20.0	<20.0	<20.0

* The contamination level of the scrubbed organic product (BP) will normally be equivalent to the contamination level of a final aqueous uranyl nitrate product (CP) produced by stripping the scrubbed organic with hot deionized water.

NOTE: The accuracy of these results is estimated to be ±50%.

TABLE VIII Pilot Plant Two-Inch-Column Organic Stream Analyses;
Stanrock Concentrate – Test No. 12

Stream	Hour of Test		
	8¼	9¼	9¾
<u>Organic Feed (AX)</u>			
TBP (%)	34.0	—	34.0
Coalescence Time (sec) ⁶	165	—	—
Solids (%)	—	—	—
Aqueous (%)	—	—	—
<u>Organic Product (AP)</u>			
Solids (%)	—	<0.01	<0.01
Aqueous (%)	—	<0.01	<0.01
<u>Scrubbed Organic Product (BP)</u>			
Solids (%)	—	<0.01	<0.01
Aqueous (%)	—	<0.01	<0.01

NOTE: All percentages are volume per cent.

DISCUSSION

The chemical analyses of Stanrock concentrate reveal that this material meets all existing FMPC impurity tolerance limits with the exception of thorium content (Appendix I). The thorium concentrate is 4900 ppm, compared to the FMPC primary tolerance limit of 350 ppm. However, when handled as a thorium-containing uranium concentrate⁴ (that is, 10 per cent phosphate addition as H_3PO_4 on a uranium basis for thorium complexing), the secondary thorium tolerance limit (20,000 ppm on a uranium basis) is met.

Digestion of Stanrock concentrate to give a satisfactory feed slurry for Refinery use should present no problems. The reactivity of HNO_3 dissolution parallels that of feed materials presently used in the Refinery. The resulting slurry is very low in nitric acid insolubles and should present no slurry handling difficulties.

The uranium distribution curve for Stanrock concentrate compares favorably with the curve for standard UNH. The Stanrock curve parallels the UNH curve fairly well, indicating that the material should exhibit acceptable extraction characteristics in pulse column operation. No emulsions were encountered during this experiment.

The primary extraction column performance of a feed slurry prepared from Stanrock concentrate (with an addition of 10 per cent PO_4 on a uranium basis for thorium complexing) was satisfactory. Good operation of both columns was attained, using standard operating conditions. With normal uranium saturation of the organic product (AP), raffinate losses were within specification, while the scrubbed organic product (BP) contamination levels were well within the desired limits.

Material balance calculations (Appendix III) indicate that the column system was not at a steady-state condition with respect to thorium. This would not necessarily mean that none of the components in the system were in a steady-state condition.

There are two known possible explanations for the poor thorium balances obtained during the test (further testing being required before it can be determined which condition prevailed). Thorium may precipitate as thorium phosphate in uranium-depleted raffinate solutions which contain sizable quantities of phosphate. This may be the explanation, since all of the thorium analyses presented in this report represent soluble thorium only. The second and probably a better explanation is that thorium had not reached a steady-state condition nor had the uranium and nitric acid, reached a true steady-state condition, although the latter appeared to be at steady-state within the analytical detection range. A thorium equilibrium test⁴ indicated that thorium equilibrium is slowly attained in a column system. It is thought that the duration of this test (9 $\frac{3}{4}$ hours) may not have been sufficient to obtain thorium equilibrium.

Two-inch-pulse-column tests have indicated that the condition of the organic extractant (i.e., coalescence time measurement, Table VIII), as well as the type of feed slurry being processed, substantially affects the A-column flooding capacity. Although more work will be required for correlation of solvent condition to A-column flooding capacity, a coalescence time measurement

was made in conjunction with this extraction test and is presented in Table VIII. The A-column flooding capacity for Stanrock concentrate was >1500 gsfh.

ACKNOWLEDGMENT

The contributions of Analytical Department and Pilot Plant personnel to this project are gratefully acknowledged.

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APPENDIX I - IMPURITY TOLERANCE LIMITS FOR FMPC FEED MATERIALS

NOTE: These are figures for operable limits based on available data. A Feed Materials Evaluation Program is being conducted on all new feeds received at Fernald. These data, with those developed in various Refinery process development projects, will be used to enlarge and improve this table. In addition to data on operable limits, further data are being developed for definition of limits based on economic factors.

Constituent	Tolerance Limits	Effect of Deviation Beyond Limits
1. Uranium	30% (min) of feed materials (as received)	Reduces plant capacity
2. Sulfate	30% (max) on U basis	Reduces extractability of U from feed slurry
3. Calcium X Sulfate	$\%CA \times \%SO_4 < 40$ on U basis	Causes column scaling
4. Phosphate (see Item 16)	7% (max) on U basis	Reduces extractability of U from feed slurry
5. Phosphate plus Sulfate	$5(\%PO_4) + \%SO_4 < 35$ on U basis	Reduces extractability of U from feed slurry
6. Chlorides	0.125% on U basis	Corrosion
7. Fluorides	0.125% on U basis	Corrosion
8. Iron	40% (max) on U basis	Reduces product purity
9. Vanadium	5% (max) on U basis	Reduces product purity
10. Boron	0.7% (max) on U basis	Reduces product purity
11. Copper	4% (max) on U basis	Reduces product purity
12. Organic Material	0.12% (max) on U basis	Possible explosion hazard with HNO ₃ and reduced extractability due to addition of surfactants
13. Arsenic	Unknown (feed containing 7% As on U basis has been proc- essed satisfactorily)	Reduces product purity
14. Molybdenum	Unknown (feed containing 1.5% Mo on a U basis has been processed satisfactorily)	Reduces product purity
15. Thorium, no Phosphate	350 ppm (max) on U basis	Reduces product purity
16. Thorium, plus Phosphate	20,000 ppm (max) on U basis with 10% PO ₄ added on U basis	Reduces product purity
17. Rare Earths, Cadmium, Lead, Zinc, Chromium, Zirconium and Titanium	Data on which to base limiting conc. of these elements in feed materials are not yet available. Tolerance limits on Gd, Dy and Zr are being developed.	Reduces product purity

APPENDIX II – PILOT PLANT TWO-INCH-PULSE-COLUMN EXTRACTION TESTS

SCOPE

Two-inch-column tests, which are conducted in a system which closely duplicates the solvent-extraction pulse column system of the NLO Refinery, are made in order to determine pulse column extraction characteristics of a feed slurry prepared from the concentrate in question. Also, predictions of digestion and slurry handling behavior based on laboratory tests can be evaluated in pilot plant-scale operations.

DIGESTION PROCEDURE

A pilot plant-scale digestion of the concentrate in question is made, using previously determined digestion data. In the case of uranium concentrates which contain more than 350 ppm thorium on a uranium basis, 10 per cent PO_4 is added as H_3PO_4 for the complexing of the thorium.^{4,5} For a normal feed materials evaluation test, approximately 130 gallons of feed slurry are required. After ore addition to the proper quantity of nitric acid, each digestion batch is heated to 180° to 190°F for approximately one hour and then allowed to cool to 100° to 110°F before the extraction test begins.

EXTRACTION PROCEDURE

Pilot Plant two-inch-pulse-column extraction tests are made under the following conditions, which were chosen to parallel normal Refinery operations.

1. Streams

Aqueous Feed (AF): 200 ± 10 g/l U; $3.0 \pm 0.2N$ HNO_3 ; 100° to 110°F

Organic Extractant (AX): 33.5 per cent TBP in kerosene; non-acidified, ambient temp

Scrub Water (BS): Deionized water, ambient temp

2. AP Density 1.000 at 60°F .

3. Flowrates

AF: 6.19 gph AX: 12.27 gph BS: 1.97 gph

4. Flowratios

AX/AF = 1.99/1 AX/BS = 6.23/1 AX/AF/BS = 6.23/3.14/1

5. Total Column Throughput

A-Column: 1000 gsfh B-Column: 713 gsfh

6. Continuous Phase

A-Column: Organic B-Column: Aqueous

7. Pulse Conditions

A-Column: Frequency = 65 cpm; Amplitude = 0.75 inch

B-Column: Frequency = 35 cpm; Amplitude = 0.60 inch

8. Length of Test 10 to 12 hours

DESCRIPTION OF EQUIPMENT

The two-inch-column system (Fig. 2) consists of 2 two-inch-diameter (ID) 25-foot perforated-plate pulse columns. The columns are operated in series as a primary extraction column (A-column, in which uranium is extracted from an aqueous uranyl nitrate-nitric acid slurry by a tributyl phosphate-kerosene solvent) and a scrub column (B column, in which the uranium-containing solvent is scrubbed with small quantities of water to remove impurities and nitric acid). The aqueous recycle stream of the B-column is introduced back into the aqueous feed stream of the A-column.

DWG 184-58

FIGURE 2 The Two-Inch-Column System

The pulse columns themselves consist of ten 2.5-foot sections of 2-inch-ID Pyrex pipe, with phase disengagement sections 30 inches in length at both ends. The columns contain 150 perforated plates each, which are spaced two inches apart (15 plates to a glass section). The perforated plates are of 22-gauge, type 304 stainless steel, and have the following plate geometry:

A-Column Plates — $\frac{3}{16}$ -inch-diameter holes on $\frac{3}{8}$ -inch centers with equilateral triangular spacing to give 23 per cent free area.

B-Column Plates — $\frac{1}{8}$ -inch-diameter holes on $\frac{1}{4}$ -inch centers with equilateral triangular spacing to give 25 per cent free area.

Between each two sections of the column is a sample block $\frac{1}{2}$ -inch thick (a total of eleven intermediate sample points). In each column end section are fitted the appropriate feed and discharge lines, and a glass tee in which is installed a Moore interface indicator-controller. The columns are serviced by the equipment listed in Table IX; all of the equipment contacting the liquid streams is of stainless steel construction. Gasketing material is Teflon.

Shakedown and column performance test results have indicated that the two-inch-column system duplicates closely the Refinery's primary extraction and scrubbing system with respect to flooding capacity and uranium extraction efficiency. These results and a more detailed description of the two-inch-column system will be presented in a topical report which will be published in the near future.

TABLE IX Two-Inch-Column Equipment List

The column is serviced by the following items, among others:

Slurry Feed Pump (AF)

Clark-Cooper Simplex pump with a Master Electric motor. Capacity, 0 to 15.6 gph. The flow rate is adjusted by a calibrated piston-stroke adjustment. This flow is measured by timing the discharge of liquid from a calibrated 4-inch sight-glass.

Organic Feed Pump (AX)

Milton Roy Constametric pump with a General Electric motor. Capacity, 1.9 to 38.2 gph. The flow rate is varied by a motorspeed adjustment. This flow is measured by timing the discharge of liquid from a calibrated 4-inch sight-glass.

Aqueous Discharge Pump (AR)

Sigmamotor pump head, fitted with a U. S. Varidrive motor. Capacity, 0.2 to 80 gph. Flow is controlled manually.

Aqueous Recycle Pump (BR)

Milton Roy Constametric pump with a General Electric motor. Capacity, 0.66 to 13.2 gph. The flow rate is adjusted by a motorspeed adjustment. This flow is measured by a Brooks rotameter and/or by timing the intake of liquid into a calibrated 3-inch sight-glass.

Aqueous Product Pump (AP)

Milton Roy Constametric pump with a General Electric motor. Capacity, 1.9 to 38.2 gph. The flow rate is adjusted by a motorspeed adjustment. This flow is measured by timing the discharge of liquid from a calibrated 4-inch sight-glass.

Aqueous Pump (BS)

Milton Roy Constametric pump with a General Electric motor. Capacity, 0.66 to 13.2 gph. The flow rate is dependent upon the motor speed, which is controlled automatically by the level-controller, and is checked by timing the discharge of liquid from a calibrated 1-inch-sight-glass. Also, the flow can be controlled manually.

Primary Column Pulse Pump (A)

Lapp Pulsafeeder pump with a U. S. Varidrive motor. Frequency range, 15 to 300 cpm; amplitude range, 0 to greater than 1.5 inches, calibrated to within $\frac{1}{64}$ inch. The pulse wave approaches a sine curve.

Scrub Column Pulse Pump (B)

Modified Lapp Pulsafeeder pump with a U. S. Varidrive motor. Frequency range, 33 to 300 cpm; amplitude range, 0 to greater than 1.5 inches; calibrated to within $\frac{1}{64}$ inch. The pulse wave approaches a sine curve.

Diaphragm Valve (AR)

Research Controls $\frac{1}{4}$ -inch, 1 P.T. diaphragm valve (3 to 15 psi control pressure). This valve is connected to a Moore interface controller located in the bottom disengagement section of the A-column. This valve is used in lieu of "3" above (Aqueous Discharge Pump, AR) to control the aqueous raffinate (AR) discharge automatically while maintaining an organic to aqueous interface at the bottom of the A-column.

Digester Feed Tank (AF)

One hundred and eighty gallon stainless steel tank, equipped with cooling or heating coils, electric agitator, and a temperature gauge.

Organic Product Surge Tank (AP)

Fifty-gallon stainless steel tank equipped with a Moore liquid-level controller.

Organic Feed Tank (AX)

One hundred and eighty gallon stainless steel tank.

Aqueous Feed Tank (BS)

Fifty-gallon stainless steel tank.

Scrubbed Organic Product Hold Tank (BP)

Two hundred gallon stainless steel tank.

All of the equipment contacting the liquid streams is of 304, 316, or 18-8 stainless steel. Gasketing material is Teflon.

APPENDIX III – MATERIAL BALANCE CALCULATIONS: STANROCK CONCENTRATE – TEST NO. 12

A-COLUMN MATERIAL BALANCES*

In: (AF flowrate $\times$ AF concentration) + (AX flowrate $\times$ AX concentration) + BR flowrate $\times$ BR concentration)

Out: (AP flowrate $\times$ AP concentration) + (AR flowrate $\times$ AR concentration)

Uranium Balance

$$\begin{array}{ccc} \text{In} & & \text{Out} \\ (6.20 \times 187.6) + (12.20 \times 2.65) + (2.08 \times 104.3) & = & (12.92 \times 111) + (7.68 \times 0.18) \\ 1411.8 & = & 1435.5 \end{array}$$

$$\begin{aligned} \text{Per Cent Error} &= \frac{1435.5 - 1411.8}{1435.5} \times 100 \\ &= +1.68 \% \end{aligned}$$

HNO₃ Balance

$$\begin{array}{ccc} \text{In} & & \text{Out} \\ (6.20 \times 3.1) + (12.20 \times 0.01) + (2.08 \times 1.34) & = & (12.92 \times 0.23) + (7.68 \times 2.41) \\ 21.62 & = & 21.48 \end{array}$$

$$\begin{aligned} \text{Per Cent Error} &= \frac{21.48 - 21.62}{21.62} \times 100 \\ &= -0.65\% \end{aligned}$$

Thorium Balance

$$\begin{array}{ccc} \text{In} & & \text{Out} \\ (6.20 \times 1.008) + (12.20 \times 0) + (2.08 \times 0.113) & = & (12.92 \times 0.021) + (7.68 \times 0.473) \\ 6.48 & = & 3.90 \end{array}$$

$$\begin{aligned} \text{Per Cent Error} &= \frac{3.90 - 6.48}{6.48} \times 100 \\ &= -39.81\% \end{aligned}$$

B-COLUMN MATERIAL BALANCES*

In: (AP flowrate $\times$ AP concentration) + (BS flowrate $\times$ BS concentration)

Out: (BR flowrate $\times$ BR concentration) + (BP flowrate $\times$ BP concentration)

Uranium Balance

In

Out

$$(12.92 \times 111) + (1.94 \times 0) = (2.08 \times 104.3) + (12.80 \times 95.0)$$

$$1434.1 = 1432.4$$

$$\text{Per Cent Error} = \frac{1432.4 - 1434.1}{1434.1} \times 100$$

$$= -0.12\%$$

HNO₃ Balance

In

Out

$$(12.92 \times 0.23) + (1.94 \times 0) = (2.08 \times 1.34) + (12.80 \times 0.038)$$

$$2.97 = 3.27$$

$$\text{Per Cent Error} = \frac{3.27 - 2.97}{3.27} \times 100$$

$$= +9.17\%$$

Thorium Balance

In

Out

$$(12.92 \times 0.021) + (1.94 \times 0) = (2.08 \times 0.113) + (12.80 \times 0.0056)$$

$$0.27 = 0.30$$

$$\text{Per Cent Error} = \frac{0.30 - 0.27}{0.30} \times 100$$

$$= +10.00\%$$

SYSTEM MATERIAL BALANCES*

In: (AF flowrate $\times$ AF concentration) + (AX flowrate $\times$ AX concentration) + (BS flowrate $\times$ BS concentration.)

Out: (AR flowrate $\times$ AR concentration) + (BP flowrate $\times$ BP concentration).

Uranium Balance

$$\begin{aligned}
 &\text{In} && \text{Out} \\
 &(6.20 \times 187.6) + (12.20 \times 2.65) + (1.94 \times 0) = (7.68 \times 0.18) + (12.80 \times 95.0) \\
 &1195.4 = 1217.4 \\
 &\text{Per Cent Error} = \frac{1217.4 - 1195.4}{1217.4} \times 100 \\
 &= +1.81\%
 \end{aligned}$$

HNO₃ Balance

$$\begin{aligned}
 &\text{In} && \text{Out} \\
 &(6.20 \times 3.1) + (12.20 \times 0.01) + (1.94 \times 0) = (7.68 \times 2.41) + (12.80 \times 0.038) \\
 &19.34 = 19.00 \\
 &\text{Per Cent Error} = \frac{19.00 - 19.34}{19.34} \times 100 \\
 &= -1.76\%
 \end{aligned}$$

Thorium Balance

$$\begin{aligned}
 &\text{In} && \text{Out} \\
 &(6.20 \times 1.008) + (12.20 \times 0) + (1.94 \times 0) = (7.68 \times 0.473) + (12.80 \times 0.0056) \\
 &6.25 = 3.70 \\
 &\text{Per Cent Error} = \frac{3.70 - 6.25}{6.25} \times 100 \\
 &= -40.80\%
 \end{aligned}$$

**NOTE: All flowrates are given in gph. The units of concentrations used in these calculations are: Uranium: (g/l); Nitric Acid: (N); Thorium: (g/l).*