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**The Distribution of Thorium During Full
Loading of Carboxylic Acid Cation
Exchange Resins with Uranium from Nitrate
Solutions at 30 and 40° C**

J. H. Shaffer
C. W. Greene

OAK RIDGE NATIONAL LABORATORY
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THE DISTRIBUTION OF THORIUM DURING FULL LOADING OF CARBOXYLIC
ACID CATION EXCHANGE RESINS WITH URANIUM FROM NITRATE SOLUTIONS
AT 30 AND 40°C

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ABSTRACT

The recycle of ^{233}U for the refabrication of fuel elements for a high-temperature gas-cooled reactor will require an assessment of chemical specifications for impurities in the uranyl nitrate product stream from the fuel reprocessing facility. The behavior of thorium, as an impurity in this simulated process stream, was investigated under equilibrium conditions during full loading of carboxylic acid cation exchange resins with uranium. Mathematical correlations of the data indicate a complex metathetical reaction for thorium distribution between the two phases. Activity coefficient ratios for thorium distribution were calculated by a simple empirical relationship with thorium concentrations in the aqueous phase over the nitrate ion concentration range of ~ 0.2 to 2.0 N . Estimates of thorium behavior and its separation from uranium can be calculated from these values and derived constants for the reaction system. In all tests, thorium was preferentially absorbed on the resin with separation factors, relative to uranium concentrations, greater than unity.

1. INTRODUCTION

The continued operation of a high-temperature gas-cooled reactor (HTGR) is based on the recycle of bred ^{233}U as the primary fissile material in replacement fuel elements. The Thorium Utilization Program has developed a method for fabricating these replacement fuel elements using fuel kernels derived from spherical cation exchange resins which have been fully loaded with uranium. This fabrication method simplifies the recycle of ^{233}U in that the ion exchange resin can be loaded directly from the uranyl nitrate product stream of a fuel reprocessing facility. Because of its origin, however, this stream will probably

contain thorium as an impurity. Thus, the behavior of thorium during resin loading with uranium and its subsequent effect on fuel performance are important considerations of the production scheme. This experimental program was conducted to determine the distribution of thorium between the resin and aqueous phases under uranyl nitrate feed conditions which would yield essentially full resin loading with uranium. The results will be directly applicable for assessing the thorium concentration in resin kernels as a function of its concentration in the aqueous phase; therefore, these results will be useful in assigning specifications for feed quality.

Resin loading, by direct contact of a weak-acid cation exchange resin (in hydrogen form) with uranyl nitrate solution, has been developed as both a batch process and a countercurrent process under conditions of chemical equilibrium.¹ Adjustment of the uranyl nitrate feed stream by partial removal of nitrate ion, with respect to uranyl ion, may be necessary in order to achieve full resin loading. This requirement has been defined by a systematic study of the exchange reaction under conditions of chemical equilibrium for both Amberlite IRC-72^{*} and Duolite C-464^{**} resins.² The study of thorium behavior as an impurity in uranyl nitrate solution during resin loading with uranium is a part of that chemical development program.

The scope of the experimental program was limited to thorium concentrations in uranyl nitrate for which analytically significant values could be obtained. Thorium concentrations in the starting solutions ranged from 1500 to 15,000 parts per million by weight with respect to uranium. Five equilibration tests were conducted at constant uranyl ion concentrations for each of five nitrate ion concentrations ranging from 0.2 to 2.0 N. Because of the primary interest of this program, uranyl ion concentrations were restricted to those which would yield essentially full resin loading under equilibrium conditions.

^{*}A trademark of the Rohm and Haas Corporation.

^{**}A trademark of the Diamond-Shamrock Company..

2. LABORATORY METHOD

The experimental procedure developed for this study was very similar to that used to determine the distribution of uranium between weak-acid cation exchange resins and uranyl nitrate solutions. Each test was conducted as a small batch loading of 15 ml of weak acid resin (sized 540 to 623 μ in diameter in the hydrogen form) by the addition of 100 ml of standard nitric acid and sufficient uranium trioxide to yield >90% loading of the resin with uranyl ion at the reaction temperature. Thorium nitrate was prepared as a standard solution in nitric acid having the same normality as that of the test. Volumetric additions from this solution (as a component of the nitric acid solution) regulated the thorium content of each test mixture. A series of five test mixtures comprised one experiment at constant nitrate and uranyl ion concentrations in which the thorium content was varied from 1500 to 15,000 ppm by weight with respect to uranium. Five experimental test series were conducted at nitrate ion concentrations of 0.2, 0.6, 1.0, 1.6, and 2.0 N. with Amberlite IRC-72 resin at 30 and 40°C. Corresponding experiments were conducted with Duolite C-464 resin at 40°C.

Each test was contained in a 250-ml Erlenmeyer flask fitted with a ground glass stopper. The flasks that comprised one test series were equilibrated simultaneously by immersion and agitation within a constant-temperature water bath of commercial design. The reaction period was terminated when the acidity of each test solution showed negligible change in pH with time. In order to preserve equilibrium conditions after conclusion of the reaction period, the flasks were removed one at a time from the bath and the contents quickly poured onto a fritted-glass filter which was connected to a vacuum source. The filtrate solution was bottled and retained for analysis. The resin was washed free of uranyl nitrate solution with distilled water and oven-dried at 110°C on the filter. The dried resin from each test was weighed and retained for analysis.

3. EXPERIMENTAL RESULTS

The data obtained for this program were derived from chemical and spectrometric analyses of filtrate and dried resin samples from each test. The General Analytical Laboratory, directed by W. R. Laing, determined nitrate and uranium values by Kjeldahl and coulometric methods, respectively. In order to avoid analytical separations of thorium from uranium, R. E. Eby of the Analytical Chemistry Division adapted an isotope dilution method for the mass spectrometric analysis of both thorium and uranium. Nanogram quantities of ^{230}Th and ^{235}U were used for these determinations. Corresponding uranium values from the two analytical methods showed consistent agreement. These results, together with calculated concentration terms, are summarized in the appendix of this report.

4. DISCUSSION

The experimental program was designed to examine distributions of thorium between the aqueous and resin phases according to the simple metathetical equilibrium,

where R denotes the anionic exchange group of the resin. By conducting each test series at constant nitrate and uranyl ion concentrations, the thermodynamic activity of uranium in each phase should remain constant. The equilibrium constant for the exchange reaction may be expressed as

$$K = \frac{K_e \gamma_{\text{U}}^2 (\text{U})_{\text{R}}}{\gamma_{\text{U}}^2 (\text{U})_{\text{aq}}} = \frac{A_{(\text{Th})_{\text{R}}}}{A_{(\text{Th})_{\text{aq}}}} \cdot \frac{[\text{UO}_2^{2+}]^2}{[\text{UO}_2\text{R}_2]^2}, \quad (2)$$

where $A_{(\text{Th})}$ is the thermodynamic activity of thorium and γ_{U} is the activity coefficient for uranium, each in the designated phase. The term K is the apparent equilibrium constant and is the product of the

true equilibrium constant, K_e , and the squared value of the activity coefficient ratio for uranium (resin/aqueous). Similarly, the expression of Eq. (1) in terms of an equilibrium quotient, K_Q , as

$$K_Q = \frac{K \gamma_{(Th)}^{aq}}{\gamma_{(Th)}^R} = \frac{[ThR_4][UO_2^{2+}]^2}{[Th^{4+}][UO_2R_2]^2}, \quad (3)$$

incorporates values for the activity coefficients for thorium, γ_{Th} , as part of the value of K_Q . Constant values for K_Q within a test series will imply that the activity coefficient ratio for thorium also remains constant. Thus, analysis of the experimental data according to Eq. (3) will permit examination of K_Q values for constancy within a test series or evaluation of K upon assignment of values for the activity coefficient ratio for thorium in the system. The concentrations of thorium and uranium in both the aqueous and resin phases were expressed as moles per unit volume. The volume of resin was its solid volume in the hydrogen form, which is six-tenths of its bulk volume.

An equivalent expression for Eq. (3) may be written as,

$$[Th/U]_R = K_Q D_U [Th/U]_{aq}, \quad (4)$$

where D_U is the distribution coefficient for uranium, defined as its concentration ratio (resin/aqueous). The term $[Th/U]$ denotes the concentration of thorium with respect to uranium in the designated phase. This concentration term may also have units of weight parts per million thorium per unit weight of uranium without alteration of the K_Q value. Its use facilitates the application of results in the engineering process and accounts for the effects of small variations in the uranium concentration within a test series. The rearrangement of Eq. (4) as

$$[Th/U]_R / [Th/U]_{aq} = K_Q D_U = (SF)_{Th} \quad (5)$$

provides direct calculation of the separation factor for thorium in the system, $(SF)_{Th}$, as the product of the uranium distribution coefficient and the equilibrium quotient. However, calculated values for $(SF)_{Th}$ (tabulated in the appendix) do show variations within an experimental test series.

The experimental data were analyzed according to the logarithmic form of the equation

$$[Th/U]_R = K_x [Th/U]_{aq}^b, \quad (6)$$

by linear regression for comparison with Eq. (4). A typical plot of the data from one test series is shown in Fig. 1. This relation does approximate a linear function over the range of thorium values for the test series and therefore yields an observed constant, K_x , from the intercept value. However, the value of the slope, b , for this relation is not unity. Similar examinations of data from all the experimental test series showed the persistence of this nonlinear relation between the relative concentration of thorium in solution and that in the resin phase. Thus, the description of thorium distribution in the cation exchange process is more complex than that inferred by Eq. (4).

Several correlations of the experimental data were examined for consistency within the limited scope of the experimental program. The best description of the exchange process was obtained by assigning an empirical expression for the calculation of activity coefficient ratios for thorium distribution between the two phases.

Since the concentration of uranium in each test series was held constant, the ratio of the thermodynamic activities of thorium in the two phases should also remain constant. Therefore, Eq. (2) should represent the chemical equilibrium of the exchange reaction under these test conditions. Rearrangement of Eq. (3) as

$$K = \frac{\gamma_{(Th)_R}}{\gamma_{(Th)_{aq}}} \cdot \frac{[Th/U]_R}{[Th/U]_{aq}} \cdot \frac{1}{D_U} \quad (7)$$

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Fig. 1. Distribution of thorium at full loading of Amberlite IRC-72 resin with uranium from nitrate solution at 40°C.

accounts for the nonideality of the reaction as the ratio of the activity coefficients for thorium, γ_{Th} , between the resin and aqueous phases. By assignment, the activity coefficient ratio for thorium was defined as an exponential function of the relative thorium concentration in the aqueous phase by the empirical expression,

$$\frac{\gamma_{(\text{Th})\text{R}}}{\gamma_{(\text{Th})\text{aq}}} = [\text{Th/U}]_{\text{aq}}^a \quad (8)$$

Substitution of Eq. (8) into Eq. (7) yields

$$\text{KD}_U = [\text{Th/U}]_{\text{R}} / [\text{Th/U}]_{\text{aq}}^b \quad (b = 1-a), \quad (9)$$

which corresponds, term by term, to Eq. (6) after setting K_x equal to KD_U . Thus, analysis of the experimental data according to Eq. (6) may be interpreted by analogy with Eq. (9). These results are included in the compilation of the experimental data in the appendix. Values for b and K_x for the various experiments are presented in Table 1. By definition of K_x and Eq. (2),

$$K_x D_U = \text{KD}_U^2 = \frac{A_{(\text{Th})\text{R}}}{A_{(\text{Th})\text{aq}}} \quad (10)$$

Values for the thorium activity ratio calculated from this equation are also listed in the table.

The effect of nitrate ion concentration on the exponential factor, b , is graphically illustrated in Fig. 2 for the Amberlite IRC-72 data at a temperature of 30°C. Similar plots for both Amberlite IRC-72 and Duolite C-464 resins at 40°C also show that the value of b approaches unity as the nitrate ion concentration is diminished. The relationship of the thorium activity ratio to uranium distribution, as defined by Eq. (10), is shown graphically in Fig. 3. These results indicate an

Table 1. Summary of results of thorium distribution during full loading of Amberlite IRC-72 and Duolite C-464 resins from nitrate solution at 30 and 40°C

Run No.	$\frac{[\text{NO}_3^-]}{(\text{N})}$	D_U	b	K_x	$A_{(\text{Th})_R} / A_{(\text{Th})_{aq}}$
<u>Amberlite IRC-72 at 30°C</u>					
3	0.92	4.46	0.71	910	4,057
4	0.60	6.46	0.81	1,097	7,084
5	1.56	2.97	0.71	245	729
6	0.22	19.33	0.90	1,350	26,100
7	1.95	2.06	0.71	117	241
<u>Amberlite IRC-72 at 40°C</u>					
8	2.0	2.17	0.88	34.0	73.9
9	1.7	2.70	0.85	52.9	142.8
10	1.0	4.49	0.84	225	1,012
11	0.6	7.21	0.83	442	3,184
12	0.23	19.90	0.91	552	10,980
<u>Duolite C-464 at 40°C</u>					
13	1.95	1.97	0.74	80.4	158
15	1.0	3.51	0.79	193	677
16	0.62	5.76	0.78	287	1,651
17	0.23	14.98	0.85	547	8,191

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Fig. 2. Exponential dependence of thorium distribution between Amberlite IRC-72 and uranyl nitrate at 30°C.

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Fig. 3. Effect of uranium activity on the thorium activity ratio at full resin loading from nitrate solution.

apparent complexity in the cation exchange system over the nitrate ion range of 0.2 to 2 N. Values for K_x also show a complex but continuous dependence on the nitrate ion concentration. Thus, description of the thorium content in the resin phase at arbitrary aqueous thorium concentrations in equilibrium with resin that is fully loaded with uranium requires selection of values for b and K_x from Table 1 for substitution into Eq. (9). Intermediate values for K_x and K may also be estimated for selected values of D_U as the product of the corresponding value for the thorium activity ratio (from Fig. 3) and $1/D_U$ of $1/D_U^2$, respectively. The relationship of uranium distribution at full resin loading to the nitrate ion concentration is shown in Fig. 4.

The assignment of the thorium activity coefficient ratio as a function of the thorium content of the aqueous phase [Eq. (8)] was arbitrarily made to facilitate interpretation of data in the engineering facility. Similar mathematical expressions would be obtained by assigning this activity coefficient ratio as a function of the resin-phase composition. However, the apparent complex relationship of the calculated thorium activity ratios and values of K or K_x to solution concentrations may reflect the interdependence of thorium activity coefficients on other system parameters. Simultaneous solution of Eqs. (6) and (7) relates the thorium activity coefficient ratio to the aqueous phase composition by the expression,

$$\frac{\gamma_{(Th)_R}}{\gamma_{(Th)_{aq}}} = \frac{KD_U}{K_x} [Th/U]_{aq}^{1-b}, \quad (11)$$

which implies a dependence on the uranium activity coefficient ratio from the definition of K by Eq. (2). The evaluation of this dependence was outside the scope of the experimental program. Therefore, Eq. (8) was used as an empirical relation to describe thorium distribution behavior under discrete process operating conditions.

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Fig. 4. Dependence of uranium distribution on nitrate ion concentration for full loading of Amberlite IRC-72 and Duolite C-464 resin with uranium at 30 and 40°C.

5. CONCLUSIONS AND RECOMMENDATIONS

The treatment of the experimental data contained in this report was directed toward correlations by which the thorium loading on a weak-acid cation exchange resin and its separation from uranium could be predicted under conditions applicable to an HTGR fuel refabrication plant. These conditions were restricted to those which would yield essentially full loading of the resin with uranium from solutions having nitrate ion concentrations in the range of 0.2 to 2.0 N.

This limited scope of the experimental program necessitated the description of the complex exchange reaction in terms of an arbitrary activity coefficient ratio for thorium distribution between the resin and aqueous phases. A more fundamental program could possibly provide analysis of the resin phase and a better definition of the exchange reaction. The inclusion of tests with partial resin loadings with uranium at each nitrate ion concentration would have provided more flexibility in the application and interpretation of the experimental results.

The results of this study have shown that thorium impurities in the uranyl nitrate feed stream to an HTGR fuel refabrication plant can be concentrated in the resin phase. In all cases, the separation factors for thorium were greater than unity. The development of operating procedures for the resin loading process should account these findings to ensure delivery of a homogeneous product and to properly assess chemical specifications for thorium as an impurity in the uranyl nitrate feed stream.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. P. A. Haas, Resin-Based Preparation of HTGR Fuels: Operation of an Engineering-Scale Uranium Loading System, ORNL-5300 (October 1977).
2. J. H. Shaffer and C. W. Greene, The Reaction of Uranyl Nitrate Solutions with Carboxylic Acid Cation Exchange Resins at 30, 40, and 50°C, ORNL/TM-6611 (in preparation).

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APPENDIX:

SUMMARY OF EXPERIMENTAL DATA

Thorium Distribution on Amberlite IRC-72 at 30°C

Thorium Distribution on Amberlite IRC-72 at 40°C

Thorium Distribution on Duolite C-464 at 40°C

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EXPERIMENT NO. 149
 RUN NO. 3
 THORIUM DISTRIBUTION ON AMBERLITE IRC-72 RESIN
 TEMPERATURE (DEG C): 30

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
46.68	1.10	10.64	122.00	12.10
46.02	1.44	10.64	118.00	18.30
46.16	2.71	10.66	121.00	42.50
45.42	2.83	10.44	126.00	51.90

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
1.464	0.877	0.513	5.22E-05	99.18
1.451	0.918	0.496	7.89E-05	155.08
1.481	0.926	0.508	1.83E-04	351.24
1.541	0.961	0.529	2.24E-04	411.90

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.319	5.61E-02	23564.7	4.523	2.376E+02
2.286	7.34E-02	31290.7	4.611	2.018E+02
2.297	1.38E-01	58708.8	4.519	1.671E+02
2.214	1.42E-01	62307.4	4.182	1.513E+02

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 4.45854

AVG [NO3-]= 0.920685

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.994128	0.169811	1.00303E-3	3.16707E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	6.81328	6.75229	6.87428
B	0.705548	0.601272	0.809824
KX=	909.853	856.017	967.075
C=	4056.61	3816.58	4311.74

EXPERIMENT NO. 149
 RUN NO. 4
 THORIUM DISTRIBUTION ON AMBERLITE IRC-72 RESIN
 TEMPERATURE (DEG C): 30

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
42.88	0.21	9.88	70.80	0.44
42.87	0.72	9.74	70.70	2.20
42.78	1.17	9.81	71.10	3.30
42.52	1.63	9.72	72.30	6.20
42.06	2.31	9.55	72.50	8.50

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
0.889	0.589	0.297	1.90E-06	6.21
0.899	0.610	0.297	9.48E-06	31.12
0.903	0.611	0.299	1.42E-05	46.41
0.906	0.597	0.304	2.67E-05	85.75
0.913	0.606	0.305	3.66E-05	117.24

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
1.978	9.94E-03	4897.4	6.649	7.880E+02
1.949	3.36E-02	16795.0	6.562	5.397E+02
1.959	5.50E-02	27349.2	6.558	5.893E+02
1.929	7.59E-02	38334.9	6.352	4.470E+02
1.875	1.06E-01	54921.5	6.156	4.684E+02

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 6.45535

AVG [NO3-]= 0.602581

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.99073	0.697713	6.52810E-3	8.07967E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	7.00034	6.88961	7.11106
B	0.813835	0.706157	0.921514
KX=	1097.	982.021	1225.45
C=	7081.53	6339.29	7910.69

EXPERIMENT NO. 149
 RUN NO. 5
 THORIUM DISTRIBUTION ON AMBERLITE IRC-72 RESIN
 TEMPERATURE (DEG C): 30

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
46.94	0.36	11.44	199.00	27.10
46.64	1.04	11.28	196.00	98.60
46.55	1.62	11.24	200.00	224.00
46.30	2.49	11.08	198.00	378.00
45.83	3.42	11.96	198.00	660.00

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
2.450	1.553	0.836	1.17E-04	136.18
2.419	1.537	0.824	4.25E-04	503.06
2.455	1.534	0.840	9.66E-04	1120.00
2.463	1.573	0.832	1.63E-03	1909.09
2.479	1.584	0.832	2.84E-03	3333.33

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.507	1.97E-02	7648.1	2.998	5.616E+01
2.456	5.60E-02	22234.1	2.982	4.420E+01
2.443	8.69E-02	34693.9	2.907	3.098E+01
2.395	1.32E-01	53671.7	2.879	2.811E+01
2.559	1.96E-01	74689.1	3.076	2.241E+01

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 2.96844

AVG [NO3-]= 1.55613

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.99265	0.625182	4.62881E-3	6.80354E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	5.50296	5.40972	5.5962
B	0.709684	0.626123	0.793245
KX=	245.417	223.57	269.4
C=	728.507	663.654	799.697

EXPERIMENT NO. 149
 RUN NO. 6
 THORIUM DISTRIBUTION ON AMBERLITE IRC-72 RESIN
 TEMPERATURE (DEG C): 30

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
47.85	0.12	11.35	29.50	0.06
47.28	0.34	11.31	29.50	0.18
47.14	0.63	11.25	31.00	0.41
46.86	0.88	11.27	30.80	0.62
46.17	1.27	11.07	31.60	0.87

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
0.353	0.210	0.124	2.59E-07	2.03
0.353	0.210	0.124	7.76E-07	6.10
0.369	0.218	0.130	1.77E-06	13.23
0.369	0.219	0.129	2.67E-06	20.13
0.376	0.221	0.133	3.75E-06	27.53

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.535	6.52E-03	2507.8	20.456	1.233E+03
2.496	1.84E-02	7191.2	20.141	1.179E+03
2.476	3.39E-02	13364.4	19.008	1.010E+03
2.466	4.75E-02	18779.3	19.052	9.329E+02
2.386	6.73E-02	27507.0	17.971	9.991E+02

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 19.3255

AVG [NO3-]= 0.215484

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.995892	0.700579	2.88962E-3	5.37552E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	7.20839	7.13473	7.28206
B	0.895838	0.817059	0.974618
KX=	1350.72	1254.79	1453.98
C=	26103.3	24249.5	28098.8

EXPERIMENT NO. 149
 RUN NO. 7
 THORIUM DISTRIBUTION ON AMBERLITE IRC-72 RESIN
 TEMPERATURE (DEG C): 30

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
45.18	0.35	10.58	256.00	112.00
43.68	1.04	10.56	253.00	383.00
44.06	1.58	10.86	255.00	734.00
44.91	1.94	11.18	269.00	1270.00
43.67	2.52	11.16	266.00	1921.00

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
3.099	1.887	1.076	4.83E-04	437.50
3.099	1.919	1.063	1.65E-03	1513.83
3.144	1.952	1.071	3.16E-03	2878.43
3.304	2.000	1.130	5.47E-03	4721.19
3.293	1.984	1.118	8.28E-03	7221.80

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.232	1.77E-02	7746.8	2.075	1.771E+01
2.153	5.26E-02	23809.5	2.026	1.573E+01
2.234	8.22E-02	35860.2	2.085	1.246E+01
2.344	1.04E-01	43197.5	2.074	9.150E+00
2.275	1.35E-01	57705.5	2.036	7.990E+00

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 2.059

AVG [NO3-]= 1.94839

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.965533	0.472936	1.68827E-2	0.129933

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	4.76161	4.58355	4.93968
B	0.706448	0.524825	0.888071
KX=	116.935	97.8614	139.725
C=	240.760	201.497	287.694

EXPERIMENT NO. 149
 RUN NO. 8
 THORIUM DISTRIBUTION ON AMBERLITE IRC-72 RESIN
 TEMPERATURE (DEG C): 40

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
47.08	0.28	11.77	273.00	104.00
47.00	0.94	11.86	276.00	332.00
46.17	1.45	11.68	277.00	650.00
45.74	2.05	11.68	274.00	939.00
44.54	2.77	11.43	277.00	1495.00

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
3.267	1.939	1.147	4.48E-04	380.95
3.315	1.969	1.160	1.43E-03	1202.90
3.360	2.019	1.164	2.80E-03	2346.57
3.367	2.065	1.151	4.05E-03	3427.01
3.403	2.047	1.164	6.44E-03	5397.11

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.587	1.58E-02	5947.3	2.255	1.561E+01
2.602	5.34E-02	20000.0	2.244	1.663E+01
2.518	8.11E-02	31405.7	2.163	1.338E+01
2.494	1.15E-01	44818.5	2.166	1.308E+01
2.377	1.52E-01	62191.3	2.042	1.152E+01

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 2.1742

AVG [NO3-]= 2.00774

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.987309	0.658379	8.46275E-3	9.19932E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	3.5276	3.40153	3.65367
B	0.880901	0.744386	1.01742
KX=	34.0421	30.01	38.616
C=	74.0143	65.2477	83.9589

EXPERIMENT NO. 149
 RUN NO. 9
 THORIUM DISTRIBUTION ON AMBERLITE IRC-72 RESIN
 TEMPERATURE (DEG C): 40

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
47.17	0.33	11.75	230.00	73.00
46.42	0.92	11.67	225.00	226.00
47.02	1.52	11.64	219.00	395.00
46.39	2.19	11.39	219.00	614.00
45.76	3.07	11.27	214.00	980.00

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
2.790	1.710	0.966	3.15E-04	317.39
2.753	1.710	0.945	9.74E-04	1004.44
2.701	1.694	0.920	1.70E-03	1803.65
2.708	1.694	0.920	2.65E-03	2803.65
2.671	1.677	0.899	4.22E-03	4579.44

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.588	1.86E-02	6996.0	2.678	2.204E+01
2.529	5.14E-02	19819.0	2.675	1.973E+01
2.555	8.47E-02	32326.7	2.777	1.792E+01
2.467	1.19E-01	47208.5	2.681	1.684E+01
2.408	1.66E-01	67089.2	2.678	1.465E+01

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 2.69759

AVG [NO3-]= 1.69677

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.997511	0.616955	1.53954E-3	3.92370E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	3.96793	3.91416	4.0217
B	0.853021	0.794655	0.911388
KX=	52.8748	50.1067	55.7957
C=	142.634	135.167	150.514

EXPERIMENT NO. 149
 RUN NO. 10
 THORIUM DISTRIBUTION ON AMBERLITE IRC-72 RESIN
 TEMPERATURE (DEG C): 40

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
45.94	0.25	11.09	130.00	6.00
45.35	0.73	10.97	119.00	18.20
44.75	1.24	10.97	120.00	35.80
44.18	1.75	10.85	122.00	56.00
43.35	2.47	10.80	114.00	87.50

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
1.626	1.066	0.546	2.59E-05	46.15
1.496	0.990	0.500	7.84E-05	152.94
1.499	0.979	0.504	1.54E-04	298.33
1.513	0.973	0.513	2.41E-04	459.02
1.434	0.947	0.479	3.77E-04	767.54

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.378	1.33E-02	5441.9	4.354	1.179E+02
2.323	3.84E-02	16097.0	4.645	1.052E+02
2.292	6.51E-02	27709.5	4.545	9.288E+01
2.238	9.09E-02	39610.7	4.366	8.629E+01
2.186	1.28E-01	56978.1	4.563	7.423E+01

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 4.49477

AVG [NO3-]= 0.990968

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.996815	0.668437	2.13588E-3	4.62156E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	5.41758	5.35424	5.48091
B	0.840288	0.775236	0.90534
KX=	225.332	211.503	240.065
C=	1012.82	950.66	1079.04

EXPERIMENT NO. 149
 RUN NO. 11
 THORIUM DISTRIBUTION ON AMBERLITE IRC-72 RESIN
 TEMPERATURE (DEG C): 40

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
47.15	0.18	11.34	76.50	1.10
46.58	0.56	11.32	79.30	4.00
46.15	0.92	11.21	81.10	8.10
45.61	1.28	11.20	81.90	11.90
45.06	1.80	11.16	81.40	20.50

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
0.926	0.566	0.321	4.74E-06	14.38
0.967	0.602	0.333	1.72E-05	50.44
0.987	0.611	0.341	3.49E-05	99.88
1.000	0.623	0.344	5.13E-05	145.30
0.990	0.610	0.342	8.84E-05	251.84

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.496	9.78E-03	3817.6	7.766	2.655E+02
2.462	3.04E-02	12022.3	7.388	2.383E+02
2.415	4.94E-02	19935.0	7.088	1.996E+02
2.385	6.87E-02	28064.0	6.930	1.931E+02
2.348	9.62E-02	39946.7	6.864	1.586E+02

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 7.20725

AVG [NO3-]= 0.602258

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.994134	0.663331	3.91390E-3	6.25612E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	6.09033	6.0046	6.17607
B	0.826247	0.739373	0.91312
KX=	441.569	405.289	481.097
C=	3182.5	2921.02	3467.38

EXPERIMENT NO. 149
 RUN NO. 12
 THORIUM DISTRIBUTION ON AMBERLITE IRC-72 RESIN
 TEMPERATURE (DEG C): 40

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
48.60	0.12	11.82	30.10	0.16
48.29	0.34	11.76	32.20	0.54
47.80	0.57	11.64	31.10	0.87
47.56	0.80	11.69	31.00	1.26
47.08	1.12	11.67	32.30	2.19

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
0.358	0.210	0.126	6.90E-07	5.32
0.392	0.242	0.135	2.33E-06	16.77
0.383	0.244	0.131	3.75E-06	27.97
0.373	0.226	0.130	5.43E-06	40.65
0.401	0.258	0.136	9.44E-06	67.80

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.682	6.79E-03	2469.1	21.205	4.645E+02
2.651	1.91E-02	7040.8	19.596	4.198E+02
2.598	3.18E-02	11924.7	19.878	4.263E+02
2.596	4.48E-02	16820.9	19.927	4.138E+02
2.565	6.26E-02	23789.3	18.900	3.509E+02

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 19.9014

AVG [NO3-]= 0.235806

EQUATION: $Y = A + B \cdot X$

$Y = \text{LOG}([TH/U]R)$

$X = \text{LOG}([TH/U]AQ)$

$A = \text{LOG}(K \cdot D(U)) = \text{LOG}(KX)$

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.994721	0.621706	3.29955E-3	5.74417E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	6.31314	6.23442	6.39186
B	0.908285	0.817702	0.998868
KX=	551.775	510.006	596.965
C=	10981.1	10149.8	11880.4

EXPERIMENT NO. 149
 RUN NO. 13
 THORIUM DISTRIBUTION ON DUOLITE C-464 RESIN
 TEMPERATURE (DEG C): 40

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
45.94	0.32	10.94	265.00	122.00
44.87	0.97	10.84	265.00	418.00
44.15	1.54	10.80	268.00	812.00
43.88	1.86	10.79	280.00	1486.00
42.99	2.56	10.68	277.00	2178.00

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
3.142	1.823	1.113	5.26E-04	460.38
3.177	1.871	1.113	1.80E-03	1577.36
3.256	1.952	1.126	3.50E-03	3029.85
3.428	2.048	1.176	6.41E-03	5307.14
3.427	2.048	1.164	9.39E-03	7862.82

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.346	1.66E-02	6900.3	2.107	1.499E+01
2.271	5.04E-02	21618.0	2.039	1.371E+01
2.226	7.97E-02	34881.1	1.977	1.151E+01
2.210	9.61E-02	42388.3	1.879	7.987E+00
2.143	1.31E-01	59548.7	1.842	7.573E+00

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 1.96881

AVG [NO3-]= 1.94839

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.968087	0.54285	1.78948E-2	0.133772

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	4.38718	4.20386	4.57051
B	0.742311	0.55882	0.925801
KX=	80.4137	66.9444	96.593
C=	158.319	131.801	190.173

EXPERIMENT NO. 149
 RUN NO. 15
 THORIUM DISTRIBUTION ON DUOLITE C-464 RESIN
 TEMPERATURE (DEG C): 40

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
45.29	0.25	10.34	130.70	9.20
44.34	0.79	10.24	141.10	43.40
43.55	1.33	10.16	142.60	82.60
42.77	1.84	10.02	139.90	119.00
41.57	2.60	9.98	146.50	241.00

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
1.551	0.905	0.549	3.97E-05	70.39
1.682	0.989	0.593	1.87E-04	307.58
1.712	1.021	0.599	3.56E-04	579.24
1.691	1.022	0.588	5.13E-04	850.61
1.774	1.069	0.616	1.04E-03	1645.05

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.186	1.22E-02	5453.7	3.981	7.748E+01
2.120	3.87E-02	17816.9	3.575	5.793E+01
2.066	6.47E-02	30539.6	3.448	5.272E+01
2.001	8.83E-02	43020.8	3.404	5.058E+01
1.937	1.24E-01	62545.1	3.147	3.802E+01

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 3.51087

AVG [NO3-]= 1.00123

EQUATION: Y = A + B*X

Y=LOG([TH/U]R

X=LOG([TH/U]AQ)

A=LOG(K*D(U))=LOG(KX)

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.994209	0.715923	4.16987E-3	6.45745E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	5.26232	5.17383	5.35082
B	0.79093	0.708305	0.873555
KX=	192.929	176.59	210.78
C=	677.349	619.984	740.022

EXPERIMENT NO. 149
 RUN NO. 16
 THORIUM DISTRIBUTION ON DUOLITE C-464 RESIN
 TEMPERATURE (DEG C): 40

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
45.15	0.23	10.40	85.30	3.50
44.67	0.61	10.32	88.50	13.30
44.17	1.00	10.33	86.70	23.00
43.33	1.47	10.13	87.70	37.00
42.51	2.04	10.14	87.50	67.10

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
1.015	0.597	0.358	1.51E-05	41.03
1.055	0.621	0.372	5.73E-05	150.28
1.038	0.618	0.364	9.91E-05	265.28
1.058	0.639	0.368	1.59E-04	421.89
1.055	0.635	0.368	2.89E-04	766.86

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.192	1.16E-02	5160.6	6.116	1.258E+02
2.152	3.02E-02	13700.5	5.788	9.116E+01
2.130	4.95E-02	22639.8	5.847	8.534E+01
2.049	7.13E-02	33925.7	5.561	8.041E+01
2.012	9.91E-02	47988.7	5.474	6.258E+01

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 5.75727

AVG [NO3-]= 0.621935

EQUATION: $Y = A + B \cdot X$

$Y = \log([TH/U]R)$

$X = \log([TH/U]AQ)$

$A = \log(K \cdot D(U)) = \log(KX)$

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.995045	0.603099	3.00333E-3	5.48026E-2

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	5.65842	5.58332	5.73352
B	0.778671	0.703443	0.853899
KX=	286.696	265.953	309.056
C=	1650.58	1531.16	1779.32

EXPERIMENT NO. 149
 RUN NO. 17
 THORIUM DISTRIBUTION ON DUOLITE C-464 RESIN
 TEMPERATURE (DEG C): 40

U-RES WT %	TH-RES WT %	R WT GRAMS	U-LIQ MG/ML	TH-LIQ MG/L
46.21	0.13	10.83	36.00	0.24
46.07	0.40	10.78	34.50	1.07
45.88	0.64	10.70	35.80	1.42
45.53	0.89	10.66	37.70	2.27
44.57	1.33	10.58	37.60	4.29

IONIC STRENGTH	[NO3] MOLAR	[UO2++] MOLAR	[TH4+] MOLAR	[TH/U]AQ PPM/U
0.415	0.224	0.151	1.03E-06	6.67
0.402	0.224	0.145	4.61E-06	31.01
0.413	0.224	0.150	6.12E-06	39.66
0.435	0.235	0.158	9.78E-06	60.21
0.439	0.245	0.158	1.85E-05	114.10

[UO2R2] MOLES/L	[THR4] MOLES/L	[TH/U]R PPM/U	U-DIST RES/LIQ	SF(TH) R/L/U
2.336	6.74E-03	2813.2	15.446	4.220E+02
2.319	2.04E-02	8595.6	15.995	2.771E+02
2.292	3.28E-02	13949.4	15.236	3.517E+02
2.266	4.54E-02	19547.6	14.304	3.246E+02
2.201	6.74E-02	29840.7	13.935	2.615E+02

K=THORIUM ACTIVITY RATIO(RES/AQ)/D(U)^2=C/D(U)^2

[TH/U]R=K*D(U)*[TH/U]AQ^B

AVG D(U)= 14.9833

AVG [NO3-]= 0.230645

EQUATION: $Y = A + B \cdot X$

$Y = \text{LOG}([TH/U]R)$

$X = \text{LOG}([TH/U]AQ)$

$A = \text{LOG}(K \cdot D(U)) = \text{LOG}(KX)$

INDEX (R^2)	EXPL VAR	UNEXPL VAR	STD ERROR
0.975194	0.642664	1.63475E-2	0.127857

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	6.30392	6.1287	6.47914
B	0.852187	0.666868	1.03751
KX=	546.71	458.84	651.408
C=	8191.5	6874.93	9760.21

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