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**The Reaction of Uranyl Nitrate Solutions
with Amberlite IRC-72 Cation
Exchange Resin at 30° C:
A Kinetic Investigation for the
HTGR Fuel Recycle Plant**

J. H. Shaffer
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HTGR FUEL RECYCLE PROGRAM
FUEL REFABRICATION — TASK 500

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Deceased.

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ABSTRACT

A kinetic investigation of the reaction of uranyl nitrate solution with Amberlite IRC-72 cation exchange resin was conducted at 30°C under conditions similar to those anticipated for a High-Temperature Gas-Cooled Reactor fuel refabrication facility. A simplified mass transfer analogue expression was developed to evaluate the effects of process parameters on the resin loading rate. Correlation of the experimental data with the integrated rate expression depended only on the determination of the reaction velocity constant and the limiting distribution coefficient for uranium in the system.

1. INTRODUCTION

One mode of refabrication of High-Temperature Gas-Cooled Reactor (HTGR) fuels, as developed by the Thorium Utilization Program, will utilize direct loading of ^{233}U on spherical cation exchange resins from the uranyl nitrate product stream of the fuel reprocessing facility. In successive thermal processes, these fully loaded resin particles will be dried, carbonized, and partially converted to uranium carbide microspheres. Following this operation, the individual particles will be coated with carbon and then with silicon carbide to improve their chemical stability and fission-product retention properties. In the fabrication of HTGR fuel elements, these fuel kernels will be compacted in a carbon matrix as cylindrical sticks and inserted and bonded in channels of machined graphite blocks.

*Deceased.

This report is associated with the chemical and engineering development of the resin loading process and describes laboratory results of a kinetic investigation of the reaction of uranyl nitrate solution with a weak-acid cation exchange resin.

Weak-acid cation exchange resins (carboxylic acid exchange groups) have been preferred for this process because of their relatively high loading capacity for uranyl ions, based on both volume and weight, and because of their stability upon irradiation as coated fuel kernels.¹ The strong acid resins (i.e., sulfonic acid exchange groups) tested for this program did not have sufficient particle loading capacity and also retained significant quantities of sulfur after carbonization. Commercially available macroreticular resins of the polyacrylic type are of general interest in this program. However, the systematic development and evaluation of the resin loading process has been conducted with two resins, Amberlite IRC-72* and Duolite C-464,** which have been sized in the sodium form between 630- and 785- μ screen openings. This study was conducted with Amberlite IRC-72 resin at 30°C.

Early development tests with Amberlite IRC-72 resin demonstrated that acid deficient solutions of uranyl nitrate are required to attain full loading of the resin.² Acid deficiency was introduced by adding UO_3 to the uranyl nitrate solution for exchange with the resin in a batch process. The solubility of UO_3 in this system is sufficient to yield a clear supernatant in equilibrium with the fully loaded resin.³ Under these conditions, the final liquor has a composition nearly equivalent to the hypothetical compound $\text{UO}_2(\text{OH})_{0.5}(\text{NO}_3)_{1.5}$. Thermodynamic reversibility was also demonstrated for resin loading by this process.³ Engineering development tests have utilized an immiscible amine extractant for partial removal of nitrate ion in order to achieve requirements for acid deficiency in the uranyl nitrate feed stream.⁴ This development avoids additional process steps for producing UO_3 and associated solid-materials handling equipment.

* Trademark of Rohm and Haas Corporation.

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For the actual refabrication of HTGR fuel elements from recycle ^{233}U , the resin loading process must be located within a hot-cell enclosure because of the energetic gamma rays associated with decay products of the ^{232}U impurity (~ 1000 ppm) in the $^{233}\text{UO}_2(\text{NO}_3)_2$ feed solution. Quality control of the resin loading process will be aggravated by the remote control procedures necessary for plant operation. Consequently, this experimental program was conducted with natural uranium and with conventional laboratory apparatus and control procedures.

2. EXPERIMENTAL PROCEDURE

The full-scale resin loading facility for the HTGR Fuel Refabrication Pilot Plant has been planned as a batch process with a production rate of about 4 kg of uranium per day. The approximate 10-liter resin requirement for this production level will probably be contained in a 5-in. (12.7-cm)-diam column to simplify nuclear criticality control procedures. Uranyl nitrate feed solution will be introduced at the base of this column at an initial flow rate of about 1.6 liters/min and will be increased to about 4.8 liters/min as the density of the resin particles increases. Process control of this parameter will probably be based on resin-bed expansion to approximately 18 liters to either fluidized- or spouting-bed conditions. The effluent stream will be returned to the feed tank. Feed quality will be maintained by processing sidestream loops from the feed tank. Excess water will be removed by evaporation and excess nitrate ion will be extracted with an immiscible amine.

In the experimental assembly, resin loading was conducted in a small jacketed column constructed from a 250-ml glass burette (3.0 cm diam) that was fitted with a porous glass plate for retention of the resin. The column was loaded with selected volumes of sized Amberlite IRC-72 resin in its hydrogen form. For experimental expedience, the tests in this program were conducted with downflow of uranyl nitrate feed solution (fixed resin bed) without recycle; this was in place of upflow conditions (expanded resin bed) proposed for the pilot-plant process. Isothermal conditions were maintained at 30°C for the exchange

reaction by recirculating water from a thermostatic bath through the outer annulus of the column and through a heat exchanger on the feed stream. Preliminary measurements of temperatures in the system showed that a temperature gradient of less than 1°C could be maintained through the resin bed at feed flow rates anticipated for this test series.

Operating parameters of the experimental tests are summarized in Table 1. Uranyl nitrate stock solutions were prepared at three concentration levels by control of the nitrate ion content and by saturation of the solutions with UO_3 at room temperature. The feed solution for each test was filtered just prior to use and was sampled for chemical analyses. The feed concentrations listed in Table 1 were calculated from these analytical values. Resin volumes of 50, 75, and 125 ml were arbitrarily chosen to evaluate the effect on the observed resin loading rate. The length-to-diameter ratio in the experimental resin bed varied from about 2.2 to 5.6 as compared to values of about 6 to 12 in the engineering facility.

Uranyl nitrate solution was fed into the resin loading column at a constant rate by means of a small finger pump. To obtain initial conditions, the column was filled with water to the top of the resin bed, and the water level was maintained by closing a valve in the column effluent line. With the top of the column vented to the atmosphere, feed solution was pumped into the column until a shallow layer of feed solution was established over the resin bed. The column was then sealed from the atmosphere, and the valve in the column effluent was opened. This procedure regulated the column effluent flow rate to that of the feed inlet rate. Clock time started when the valve in the column effluent line was opened. The progress of the exchange reaction was related to clock time by periodic withdrawal of small samples of the effluent. These samples approximated instantaneous conditions rather than averages over the time interval. The total column effluent was collected and measured volumetrically as a verification of the feed flow rate.

The data from this experimental program were derived from chemical analyses of uranium concentrations in the influent and effluent streams,

Table 1. Summary of controlled experimental parameters

Run No.	Feed concentration		Feed flow rate (liters/min)	Resin bed	
	[UO ₂ ²⁺] (moles/liter)	[NO ₃ ⁻] (moles/liter)		Volume (liters)	Configuration (length/diam)
1	0.349	0.566	0.020	0.125	5.6
1A	0.402	0.584	0.040	0.125	5.6
2	0.694	1.161	0.010	0.125	5.6
2A	0.794	1.145	0.020	0.125	5.6
3	1.068	1.790	0.007	0.125	5.6
3A	1.223	1.774	0.020	0.125	5.6
4	0.368	0.568	0.010	0.075	3.4
5	0.714	1.129	0.005	0.075	3.4
6	1.113	1.798	0.003	0.075	3.4
18	0.381	0.600	0.020	0.075	3.4
19	0.635	0.987	0.020	0.075	3.4
20	1.101	1.732	0.020	0.075	3.4
7A	0.441	0.681	0.020	0.050	2.2
8	0.895	1.319	0.015	0.050	2.2
9	1.370	2.113	0.015	0.050	2.2

from feed flow rates, and from measurements of the effluent stream acidity. Although effluent acidity values were not used in the analysis of the data, they provided operator control on sampling frequency and were measured continuously from a Corning semimicro-combination electrode that had been mounted in the effluent line. These values were read from a Beckman pHAsar-I digital pH meter with the electrode standardized at a pH of 2 with certified KCl-HCl buffer solution. The resin-bed capacity for each loading was determined in situ by the exchange of sodium from a standard caustic solution and by its elutriation with a standard nitric acid solution.

The established time = 0 condition assumed slug flow of feed solution above the resin bed and minimal mixing or reaction at the liquid-resin interface in the column. Under the flow conditions and bed configuration of the experiments, axial concentration gradients in the loading fluid surrounding the resin particles could not be measured. Consequently, effluent concentration values were assumed as averages for that of the fluid within the shallow resin bed. Measurement of the resin packing fraction showed a value of 0.6 of the total bed volume. Concentrations of uranium in the resin were calculated for solid resin volumes. The volume of solution in the reaction zone was 0.4 of the bed volume plus a measured volume of 17 cm^3 for solution between the resin bed and the discharge spout.

3. THE REACTION RATE MODEL

The primary objective of this experimental program was to evaluate the effects of process parameters with respect to time required to fully load Amberlite IRC-72 cation exchange resin with uranyl ion from nitrate solution. Under the imposed experimental conditions, direct analysis of the resin beads for uranium content was not feasible. Thus, a mathematical model to describe this reaction in terms of process control parameters will infer the rate of resin loading by material balance on the system. The mass flow of uranium into the system is the product of the feed concentration, C_0 , and the feed flow rate, Q . The mass flow of uranium from the system is the product of the effluent

concentration, C_1 , at time, t , and the flow rate. The rate at which uranium is retained by the resin may be expressed as the product of the bed surface area, A , and the flux, J , at the liquid-resin bead interface. The material balance for uranium in the system may thus be expressed as

$$V_1 \frac{dC_1}{dt} = Q(C_o - C_1) - AJ, \quad (1)$$

where V_1 is the volume of solution in the reaction zone; it is defined as

$$V_1 \text{ (liters)} = (0.4) \text{ (resin-bed volume)} + 0.017.$$

The term 0.017 liters is the holdup volume between the base of the resin bed and the effluent discharge spout as discussed earlier. Therefore, the mathematical description of the resin loading process depends on the definition of the AJ term of Eq. (1) and the simultaneous solution of two or more differential equations.

Although some early investigators have assigned reaction velocity in ion exchange processes as a chemical rate mechanism,^{5,6} subsequent research has favored diffusional processes.⁷ Diffusion mechanisms have been assigned for both the retention of trace quantities of cations on ion exchange resins⁸ and for the self-diffusion of cations in equilibrium systems.⁹ Relatively simple criteria have also been proposed for predicting film diffusion and/or particle diffusion as the rate controlling step on the basis of a dimensionless modulus.¹⁰

3.1 Reaction at Constant Potential

In order to assess the influence of diffusion in the solid phase on the resin loading process, a preliminary set of ad hoc experiments were performed to examine the relative rates at which the resin would exchange with uranyl ion under constant potential conditions in the surrounding liquid. For this test, small samples of hydrogen-form Amberlite IRC-72 resin were immersed in an excess of acid-deficient uranyl nitrate solution under well-stirred conditions. At discrete reaction time intervals, the resin particles were quickly separated from the uranyl nitrate solution

by filtration, washed with distilled water, and freeze-dried with liquid nitrogen to arrest further penetration of uranyl ion into the resin beads.

The conditions of these tests and the analytical values for uranium retained on the resin are summarized in Table 2. Representative particles from each test were submitted for microprobe examination of the uranium concentration profile across the resin bead diameters at the midplane of the particles. Figure 1 shows typical results obtained from these examinations.¹¹ When normalized, the results show a pronounced effect of diffusion resistance within the resin particle. The depressed concentration of uranium in the surface layer of the beads may be attributed to leaching during the water wash step or to macroporosity in the beads. This deficiency is equivalent to about 10 to 15% of the total uranium content of a fully loaded resin bead.

Both Fig. 1 and Table 2 show that uranium rapidly diffused into the outer shell of the resin particles and that the shell loading represented a major fraction of the resin capacity. This rapid diffusion rate may partially be attributed to the diffusivity of uranyl ions in the loading solution. A relatively large value ($1.05 \times 10^{-5} \text{ cm}^2/\text{sec}$) for the diffusivity of uranyl ions in nitric acid solution at 30°C was obtained by extrapolation of previously reported data.¹² In consideration of this rapid exchange rate and in the absence of direct analysis of the resin particles for uranium content, interpretation of the data in terms of a bulk diffusion model was not pursued. Instead, a rather complete

Table 2. Uranium loading of Amberlite IRC-72 resin from excess uranyl nitrate solution at 30°C

Solution concentration: $0.3 \text{ M } \text{UO}_2^{2+}$, $0.45 \text{ N } \text{NO}_3^-$

Sample No.	Reaction time (min)	Uranium (wt %)	% Loading
DR-1	∞	48.5	100
DR-7	5	26.5	54.6
DR-8	15	36.4	75.1
DR-9	30	40.2	82.9

Fig. 1. Electron microprobe analyses for uranium in loaded and dried Amberlite IRC-72 resin at bead midplane.

but simplified mass-transfer analogue was developed. This approximation of a bulk diffusion model provided consistent correlation of the experimental data and direct evaluation of the effects of process control parameters on the rate of resin loading. In retrospect, a description of the distribution of uranium within the resin particle, which could be inferred by a bulk diffusion model, would have little impact on a process dedicated to full resin loading.

3.2 The Analogue Reaction Rate Expression

The mass-transfer analogue for bulk diffusion considered the effects of film diffusion and chemical reaction resistances, both individually and in combination, as the rate controlling step in the resin loading process. However, correlations of the experimental data for film resistance generated coefficients that were almost entirely unrelated to a real film when compared with coefficients derived from theoretical film mechanisms for mass transfer in liquid-solid systems.^{13,14} Consequently, the mass-transfer analogue could be further simplified and was, in fact, derived for a conventional first-order reversible process. Reaction rates of higher order required numerical analytical techniques for solution. These were not pursued since reasonable and consistent correlations were obtained with the first-order rate expression.

In its elementary form, a reversible first-order reaction rate is given by:

$$\frac{dc_{\tau}}{dt} = k_1 C_1 - k_2 C_{\tau}, \quad (2)$$

where C_{τ} is the molar concentration in the solid resin, and the constants, k_1 and k_2 , are the reaction velocity constants for the forward and reverse reactions, respectively. In a true first-order reaction, these may be defined in terms of an equilibrium constant, K , as

$$K = \frac{k_1}{k_2} = \frac{C_{\tau}}{C_1}. \quad (3)$$

Substitution of Eq. (3) into Eq. (2) yields:

$$\frac{dC_{\tau}}{dt} = k_1(C_1 - C_{\tau}/K), \quad (4)$$

which expresses the rate in terms of a single reaction velocity constant and the equilibrium constant.

The resin loading reaction occurs by the replacement of hydrogen from the weak-acid resin by uranyl ion in solution and can be expressed by the thermodynamically reversible reaction,

where R represents the anionic resin group. The equilibrium quotient, K_Q , for this reaction can be calculated from the equation,

$$K_Q = \frac{[UO_2R_2][H^+]^2}{[UO_2^{2+}][HR]^2}, \quad (6)$$

where concentrations in both the aqueous and resin phases are expressed as moles per unit volume.

Although ion exchange resins have finite loading capacities, the actual concentration of uranyl ion that can be transferred to the solid resin phase depends on the chemical equilibria with the liquid phase, as expressed by Eq. (6). In the application of a first-order rate expression for the resin loading reaction, the terms C_{τ} and C_1 in Eq. (3) must be analogous to the terms $[UO_2R_2]$ and $[UO_2^{2+}]$ in Eq. (5). Furthermore, Eq. (3) also requires that the ratio of these concentrations remains constant. This condition is met when the effluent concentration, C_1 , approaches that of the feed solution, C_o , as a limit. Thus, K represents the limiting distribution of uranium in the system and can be further defined as

$$K = \frac{C_{\tau}^*}{C_o}, \quad (7)$$

where C_T^* is the molar concentration of uranium in the solid resin phase that will be in equilibrium with uranium in the feed solution. Substitution of Eq. (7) into Eq. (4) provides for the empirical relation,

$$\frac{dC_T}{dt} = k_1 \left(C_1 - C_o C_T / C_T^* \right), \quad (8)$$

for expressing the resin loading reaction as a first-order reaction rate. The term $C_o C_T / C_T^*$ expresses the reaction resistance as a fraction of the limiting chemical potential of the feed, C_o . The rate of resin loading is proportional to the difference in the chemical potential of the solution, C_1 , and that of the resin expressed as a fraction of the feed potential. As C_1 approaches C_o with time, $\frac{dC_T}{dt}$ will approach zero.

The mass balance for uranium in the system, as stated in Eq. (1) has units of moles of uranium per unit time. Therefore, the term AJ of that equation is defined as $V_2 \frac{dC_T}{dt}$ for application of a chemical resistance model, where V_2 is the volume of the solid resin bed ($V_2 = 0.6 \times$ resin-bed volume). Thus, the overall mass balance for uranium in the system becomes

$$V_1 \frac{dC_1}{dt} = Q \left(C_o - C_1 \right) - V_2 \frac{dC_T}{dt}. \quad (9)$$

For a flowing system, Eq. (4) can be expressed as a molar reaction rate by

$$V_2 \frac{dC_T}{dt} = k_1 Q \left(C_1 - KC_T \right), \quad (10)$$

since the term KC_T has been shown to be a function of the aqueous feed concentration, C_o . The integrated rate expression can then be obtained by putting Eq. (10) into Eq. (9). Its solution is that of a quadratic equation and may be expressed in terms of the concentration of uranium in the effluent at time, t , as

$$C_1(t) = C_o + \alpha_1 e^{S_1 t} + \alpha_2 e^{S_2 t}. \quad (11)$$

The roots S_1 and S_2 can be calculated from the equations,

$$S_1 = \frac{-(\beta_1 + \beta_2 + \beta_3) + \left[(\beta_1 + \beta_2 + \beta_3)^2 - 4\beta_1\beta_2 \right]^{1/2}}{2}, \text{ and}$$

$$S_2 = \frac{-(\beta_1 + \beta_2 + \beta_3) - \left[(\beta_1 + \beta_2 + \beta_3)^2 - 4\beta_1\beta_2 \right]^{1/2}}{2}.$$

The values for the coefficients, α_1 and α_2 , are

$$\alpha_1 = \frac{\beta_1 C_o}{S_1 - S_2} \left(1 + \frac{\beta_2}{S_1} \right), \text{ and}$$

$$\alpha_2 = \frac{\beta_1 C_o}{S_2 - S_1} \left(1 + \frac{\beta_2}{S_2} \right).$$

The beta terms were introduced in the general solution as a convenient method for calculating the effects of changes in process parameters. They are defined as follows:

$$\beta_1 = Q/V_1,$$

$$\beta_2 = k_1 Q/V_2 K,$$

$$\beta_3 = k_1 Q/V_1.$$

It is of interest to note that the values for β_1 for a pilot plant producing 4 kg of uranium per day are well within the range of those calculated from the experimental data. The inferred values for C_T at time, t , may be developed through substitution of Eq. (11) into Eq. (10) and integration over the time interval, 0 to t .

4. EXPERIMENTAL RESULTS

4.1 Correlation of Analogue Terms

The mathematical derivation of the integrated rate expression for the two simultaneous first-order processes in which feed mixing was combined with an apparent chemical reaction resistance yielded the general solution of Eq. (11). Correlation of the experimental data with this derived expression depended on the selection of two arbitrary constants and the evaluation of the three analogue terms defined by β_1 . Since the constant K , which represents the limiting distribution of uranium in the system at $t = \infty$, is a function of the feed concentration, that value was estimated for each run from a planimeter trace of a plot of $C_1(t)/C_0$ vs t . The second arbitrary constant was chosen as the value for β_2 . In this manner, β_3 was calculated as a proportional quantity of β_2 ; the value for β_1 was fixed by the feed flow rate and the liquid volume of each experiment. The value for k_1 would therefore be available from a plot of β_3 vs β_1 for all experiments.

In order to normalize the experimental results, Eq. (11) was divided by C_0 to obtain the expression

$$\frac{C_1(t)}{C_0} = 1 + \frac{\alpha_1}{C_0} e^{S_1 t} + \frac{\alpha_2}{C_0} e^{S_2 t}. \quad (12)$$

The analytical method for fitting the experimental data to Eq. (12) consisted of the comparison of the experimental values for $C_1(t)/C_0$ with those obtained by trial calculations over the complete experimental time interval using discrete values for β_2 and K . Point-by-point correlation was made by linear regression analysis of the equation

$$\left[C_1(t)/C_0 \right]_{\text{exp}} = A + B \left[C_1(t)/C_0 \right]_{\text{calc}}. \quad (13)$$

Values for β_2 and K were adjusted until reasonable correlation of the data was obtained and the slope and intercept values of Eq. (13)

approximated one and zero, respectively. It became apparent that minor adjustments for $t = 0$ were necessary (≤ 5 min) to compensate for uncertainties introduced by the start-up procedure. Since values for resin loading, $C_T(t)$, and hydrogen ion production by the resin, $C_H(t)$, could be calculated directly, these values are included in the compilation of data in the Appendix.

4.2 The Reaction Velocity Constant

Using the reduced time parameter $\beta_1 t$, typical results are shown graphically in Fig. 2 for four of the experimental runs. As illustrated in Fig. 3, values for β_3 show a linear correlation with β_1 . Thus, the reaction velocity constant, k_1 , has a single value over the range of parameters represented by this test program. Values obtained for K and the three analogue terms are given in Table 3, which also shows that the mean value of k_1 is 0.56 min^{-1} with a standard deviation of about 0.07 min^{-1} .

4.3 The Uranium Distribution Coefficient

As developed independently in this study, values for K listed in Table 3 should correspond to the limiting distribution coefficient, C^*/C_0 , when the loaded resin is in equilibrium with the feed solution. As noted by Eq. (6), this condition is defined by an equilibrium quotient, K_Q , which equates the uranium distribution coefficient to the squared power of the hydrogen ion distribution coefficient by the simple relationship,

$$D_U = K_Q D_H^2, \quad (14)$$

where

$$D_U = \frac{[UO_2 R_2]}{[UO_2^{2+}]}, \text{ and}$$

$$D_H = \frac{[HR]}{[H^+]}.$$

Fig. 2. Typical correlation of experimental data and calculated results.

Fig. 3. Correlation of β_1 and β_3 terms used in analytical solution of simplified analogue equation.

Thus, the analogy that $D_U = K = \frac{C^*_T}{C_O}$ may be tested by comparison of values obtained for K with those calculated from Eq. (14).

Table 3. Analytical solutions for a simplified analogue equation

Experiment No.	Equilibrium coefficient, K	Analogue terms			
		β_1	β_2	β_3	β_3/β_1
1	6.7	0.299	0.022	0.165	0.552
1A	6.1	0.597	0.050	0.341	0.571
2	3.3	0.149	0.022	0.081	0.544
2A	3.4	0.299	0.040	0.152	0.508
3	2.1	0.104	0.024	0.056	0.538
3A	2.2	0.299	0.067	0.165	0.552
4	6.5	0.213	0.020	0.125	0.587
5	3.4	0.106	0.025	0.081	0.764
6	2.1	0.064	0.018	0.036	0.563
18	6.3	0.426	0.040	0.241	0.566
19	3.9	0.426	0.063	0.235	0.552
20	2.2	0.426	0.110	0.232	0.545
7A	5.3	0.541	0.069	0.297	0.549
8	2.5	0.405	0.100	0.203	0.501
9	1.5	0.405	0.150	0.182	0.449

Mean value of $\beta_3/\beta_1 = 0.556$

Standard deviation = 0.067

Equilibrium quotients defined by Eq. (6) were obtained in a related experimental program.¹⁵ Those values for K_Q that are applicable to this program are listed in Table 4. The dependence of K_Q on the nitrate ion concentration reflects the hydrolysis of uranyl ion and its buffering effect on the hydrogen ion concentration in the aqueous phase.¹⁶ Comparison of calculated values for hydrogen ion production by the resin, $C_H(t)$ with those obtained by pH measurements (see Appendix) also illustrates this hydrolytic effect. A similar dependence of experimental values of K on the nitrate ion concentration is shown in Fig. 4.

Table 4. Equilibrium quotients calculated for the uranium loading of Amberlite IRC-72 resin from uranyl nitrate solution at 30°C

Nitrate ion (N)	K_Q^a	Limits on K_Q (95% confidence)	
		+	-
0.2	3.0×10^{-4}	5.0×10^{-4}	1.8×10^{-4}
0.6	4.3×10^{-4}	5.3×10^{-4}	3.3×10^{-4}
1.0	6.7×10^{-4}	8.3×10^{-4}	5.3×10^{-4}
1.6	2.3×10^{-3}	3.0×10^{-3}	1.7×10^{-3}
2.0	4.8×10^{-3}	7.7×10^{-3}	3.0×10^{-3}

^a K_Q is based on concentration in solid resin volume, V_2 .

The selection of uranyl nitrate feed solutions was influenced by a prior knowledge of the equilibrium quotient values; feed conditions of concentration and acidity were chosen to yield essentially complete resin loading (i.e., >95%) in each kinetic experiment. Because of possible variations in the packing fraction of the resin, the value for the resin loading capacity, $[\text{HR}]_0$, was determined in situ on each resin batch by titrations with standard caustic and acid solutions. An average value of 3.1 equiv of replaceable hydrogen per bulk liter of resin was determined for resin sized between 500 to 623- μ -diam screen openings. The advertised exchange capacity of this resin is 3.4 equiv/liter for particles sized between -20 to +50-mesh screens (U.S. Sieve Series). Adjustment of the experimental value for the measured 40% void fraction yields a capacity of 5.17 equiv per liter of solid resin.

The experimental values for K were related to those obtained from the independent evaluation of K_Q by their use in calculations of $[\text{HR}]$, the unloaded resin concentration, in equilibrium with each experimental feed solution at its measured acidity, and determination of the resin loading fraction, $1 - [\text{HR}]/[\text{HR}]_0$, which they represent. Values for $K_{\text{max}} = 0.5[\text{HR}]_0/C_0$ were also calculated for comparison with K and

Fig. 4. Effect of nitrate ion concentration on the distribution of uranium between Amberlite IRC-72 resin and uranyl nitrate solution at 30°C.

demonstrate the feed quality of C_O in each experiment. These values are summarized in Table 5 to illustrate the coincidence of the experimental values for $K = C_T^*/C_O$ with the limiting value for D_U from Eq. (14).

5. CONCLUSION

This report has summarized the results of a study of the rate at which Amberlite IRC-72 cation exchange resin can be loaded with uranium from nitrate solution at 30°C. Within the precision of the experimental measurements and within the process control capabilities of an HTGR fuel refabrication plant, the resin loading rate can be accurately described by a simple mass-transfer analogue expression. This development depicts the simulated process as two simultaneous first-order rate processes in which the effects of feed mixing are combined with that of a chemical reaction resistance. The generalized application of the integrated rate expression depends on the value $0.56 \pm 0.07 \text{ min}^{-1}$ as the reaction velocity constant and the determination of the limiting distribution coefficient for uranium in the system. This is obtained from the knowledge of feed parameters and the equilibrium quotient for the reaction. Values for the equilibrium quotient for the range 0.2 to 2.0 N nitrate ion at 30°C were obtained from a separate study¹⁵ and are tabulated in this report.

Table 5. Calculated maximum resin loading fraction from experimental uranium distribution coefficients

Run No.	Feed conc. C_o (moles/liter)	Feed acidity (pH units)	K_Q	Uranium distribution coefficient		Calculated maximum resin loading from $K_{exp}^{a,b}$ (% of loading capacity)
				K_{exp}	K_{max}	
1	0.349	2.8	4.2×10^{-4}	6.7	7.4	96.1
1A	0.402	2.94	4.3×10^{-4}	6.1	6.4	97.4
2	0.694	2.5	8.8×10^{-4}	3.3	3.7	96.3
2A	0.794	2.7	8.7×10^{-4}	3.4	3.3	97.6
3	1.068	2.3	3.3×10^{-3}	2.1	2.4	97.6
3A	1.223	2.5	2.9×10^{-3}	2.2	2.1	98.3
4	0.368	2.9	4.2×10^{-4}	6.5	7.0	97.0
5	0.714	2.5	8.3×10^{-4}	3.4	3.6	96.1
6	1.113	2.3	3.3×10^{-3}	2.1	2.3	97.6
18	0.303	2.9	4.3×10^{-4}	6.3	6.8	97.1
19	0.635	2.75	6.8×10^{-4}	3.9	4.1	97.4
20	1.101	2.4	2.8×10^{-3}	2.2	2.4	97.8
7A	0.441	2.9	4.8×10^{-4}	5.3	5.9	97.4
8	0.895	2.66	1.2×10^{-3}	2.5	2.9	98.1
9	1.370	2.25	7.3×10^{-3}	1.5	1.9	98.4

$$^a [HR]^2 = [K_{exp}][H^+]^2 / K_Q.$$

$$^b \% \text{ load} = 100 (1 - [HR]/5.17).$$

6. NOMENCLATURE

A	surface area of resin bed, cm^2
A	intercept value for Eq. (13)
B	slope value for Eq. (13)
C_o	feed concentration, moles of uranium per liter
C_1 or $C_1(t)$	effluent concentration at time, t, moles of uranium per liter
$C_H(t)$	concentration of hydrogen atoms released from resin at time, t, equiv/liter
C_T	uranium concentration in solid resin phase, moles of uranium per liter
C_T^*	uranium concentration in resin, C_T , in equilibrium with C_o , moles of uranium per liter
d	diameter of resin bed, cm
D_H	distribution coefficient for hydrogen defined on p. 15
D_U	distribution coefficient for uranium defined on p. 15
$[H^+]$	hydrogen ion concentration in aqueous phase calculated from pH measurements, equiv/liter
$[HR]$	concentration of exchangeable hydrogen in resin phase, equiv/liter solid resin
$[HR]_o$	resin capacity in hydrogen form, equiv/liter solid resin
J	mass transfer flux, moles of uranium $\text{cm}^{-2} \text{min}^{-1}$
k_1	forward reaction velocity constant defined by Eq. (2), min^{-1}
k_2	constant defined by Eq. (2), liters resin/liter solution per min
K	apparent equilibrium coefficient, C_T^*/C_o
K_Q	equilibrium quotient defined by Eq. (6)
l	length of resin bed, cm
l/d	length to diameter ratio of resin bed, dimensionless
Q	feed flow rate, liters/min
S_n	roots of rate equation defined on p. 13
t	time, min

$\left[\text{UO}_2^{2+} \right]$ uranyl ion concentration in aqueous phase, moles/liter

$\left[\text{UO}_2\text{R}_2 \right]$ uranyl ion concentration in solid resin phase, moles/liter

V_b bulk resin bed volume, liters

V_1 loading solution volume, $0.5 V_b + 0.017$, liters

V_2 solid resin volume, $0.6 V_b$, liters

α_n coefficients of rate equation defined on p. 13

β_n constant coefficients of root equation defined on p. 13

7. REFERENCES

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APPENDIX
TABULATION OF EXPERIMENTAL DATA AND CALCULATED RESULTS

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EXPERIMENT NO. 147
 RUN NO. 1
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 0.3487
 FEED FLOW RATE (LITERS/MINUTE)= 0.02
 RESIN VOLUME (LITERS) 0.125

$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$
 $C'(TAU) = K \cdot C + A'1 \cdot \exp(S_1 \cdot T) + A'2 \cdot \exp(S_2 \cdot T)$
 $CH(T) = A''1 \cdot \exp(S_1 \cdot T) + A''2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$

K= 6.7 BETA 1= 0.2985 BETA 2= 0.0220 BETA 3= 0.1650

$S_1 = -1.39258E-2$ $S_2 = -0.471582$
 $A_1 = -0.13187$ $A_2 = -0.21683$
 $A'1 = -2.40738$ $A'2 = 0.07109$
 $A''1 = 0.26374$ $A''2 = 0.43366$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C ₁ (T)/C	C'(T)/C*	CH(T)
1.	0.1176	0.1259	0.2390	0.0028	0.0133
6.	0.5495	0.1995	0.6154	0.0540	0.1519
11.	0.7038	0.1585	0.6721	0.1161	0.2026
16.	0.7459	0.1413	0.6970	0.1754	0.2054
21.	0.7542	0.1259	0.7177	0.2309	0.1956
26.	0.7580	0.1122	0.7367	0.2826	0.1833
36.	0.7783	0.0891	0.7709	0.3758	0.1597
46.	0.7978	0.0708	0.8007	0.4570	0.1390
56.	0.8219	0.0501	0.8266	0.5276	0.1209
66.	0.8434	0.0200	0.8492	0.5890	0.1052
76.	0.8712	0.0063	0.8688	0.6424	0.0915
86.	0.8927	0.0040	0.8858	0.6889	0.0796
96.	0.9122	0.0032	0.9007	0.7293	0.0693

EXPERIMENT NO. 147
 RUN NO. 1A
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 0.4017
 FEED FLOW RATE (LITERS/MINUTE)= 0.04
 RESIN VOLUME (LITERS) 0.125

$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$
 $C'(TAU) = K \cdot C + A'_1 \cdot \exp(S_1 \cdot T) + A'_2 \cdot \exp(S_2 \cdot T)$
 $CH(T) = A''_1 \cdot \exp(S_1 \cdot T) + A''_2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$

K= 6.1 BETA 1= 0.5970 BETA 2= 0.0500 BETA 3= 0.3414

$S_1 = -3.11839E-2$ $S_2 = -0.957249$
 $A_1 = -0.156259$ $A_2 = -0.245441$
 $A'_1 = -2.53288$ $A'_2 = 8.25126E-2$
 $A''_1 = 0.312518$ $A''_2 = 0.490882$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	$C(T)/C$	$CH(T)$	$C_1(T)/C$	$C'(T)/C$	$CH(T)$
3.	0.6286	0.1413	0.6112	0.0605	0.1784
8.	0.7197	0.0417	0.6966	0.1946	0.2370
13.	0.7573	0.0076	0.7406	0.3108	0.2080
18.	0.8170	0.0040	0.7781	0.4103	0.1783
23.	0.8389	0.0031	0.8101	0.4955	0.1525
28.	0.9081	0.0028	0.8375	0.5683	0.1305
33.	0.8922	0.0025	0.8610	0.6306	0.1117
38.	0.9111	0.0023	0.8811	0.6840	0.0956
43.	0.9174	0.0022	0.8982	0.7296	0.0818
48.	0.9363	0.0021	0.9129	0.7686	0.0700

EXPERIMENT NO. 147
 RUN NO. 2
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 0.6941
 FEED FLOW RATE (LITERS/MINUTE)= 0.01
 RESIN VOLUME (LITERS) 0.125

$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$
 $C'(TAU) = K \cdot C + A'_1 \cdot \exp(S_1 \cdot T) + A'_2 \cdot \exp(S_2 \cdot T)$
 $CH(T) = A''_1 \cdot \exp(S_1 \cdot T) + A''_2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$

K= 3.3 BETA 1= 0.1493 BETA 2= 0.0220 BETA 3= 0.0813

$S_1 = -1.37521E-2$ $S_2 = -0.23877$
 $A_1 = -0.276126$ $A_2 = -0.417974$
 $A'_1 = -2.43052$ $A'_2 = 0.139986$
 $A''_1 = 0.552253$ $A''_2 = 0.835947$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C ₁ (T)/C	C'(T)/C*	CH(T)
1.	0.1017	0.0794	0.1333	0.0015	0.0074
6.	0.4031	0.2512	0.4900	0.0375	0.1411
11.	0.6199	0.3981	0.6145	0.0923	0.2664
16.	0.7101	0.3981	0.6676	0.1498	0.3341
21.	0.7518	0.3548	0.6980	0.2055	0.3589
26.	0.7621	0.3162	0.7206	0.2580	0.3593
36.	0.7731	0.2818	0.7574	0.3532	0.3303
46.	0.7814	0.2512	0.7887	0.4363	0.2919
56.	0.7918	0.1995	0.8158	0.5087	0.2553
76.	0.8147	0.1259	0.8601	0.6269	0.1942
96.	0.8529	0.0251	0.8937	0.7166	0.1475
116.	0.9092	0.0079	0.9193	0.7847	0.1120
136.	0.9450	0.0050	0.9387	0.8365	0.0851
156.	0.9576	0.0045	0.9534	0.8758	0.0646
176.	1.0019	0.0040	0.9646	0.9057	0.0491

EXPERIMENT NO. 147
 RUN NO. 2A
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 0.7941
 FEED FLOW RATE (LITERS/MINUTE)= 0.02
 RESIN VOLUME (LITERS) 0.125

$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$
 $C'(\tau) = K \cdot C + A'1 \cdot \exp(S_1 \cdot T) + A'2 \cdot \exp(S_2 \cdot T)$
 $CH(T) = A''1 \cdot \exp(S_1 \cdot T) + A''2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$

K= 3.4 BETA 1= 0.2985 BETA 2= 0.0400 BETA 3= 0.1522

$S_1 = -2.56741E-2$ $S_2 = -0.465072$
 $A_1 = -0.301023$ $A_2 = -0.493077$
 $A'1 = -2.8577$ $A'2 = 0.157758$
 $A''1 = 0.602047$ $A''2 = 0.986153$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	$C(T)/C$	$CH(T)$	$C_1(T)/C$	$C'(T)/C*$	$CH(T)$
5.	0.6085	0.3311	0.6059	0.0748	0.2689
10.	0.6720	0.2630	0.7008	0.1818	0.3949
15.	0.7196	0.1318	0.7415	0.2799	0.3925
20.	0.7513	0.0219	0.7731	0.3666	0.3563
25.	0.8096	0.0076	0.8005	0.4429	0.3160
35.	0.8784	0.0049	0.8457	0.5691	0.2451
45.	0.8995	0.0041	0.8806	0.6666	0.1896
55.	0.8995	0.0037	0.9076	0.7421	0.1467
65.	0.9207	0.0035	0.9286	0.8005	0.1135
75.	0.9365	0.0033	0.9447	0.8457	0.0878
85.	0.9418	0.0032	0.9572	0.8806	0.0679
95.	0.9312	0.0032	0.9669	0.9077	0.0525
105.	0.9524	0.0031	0.9744	0.9286	0.0406

EXPERIMENT NO. 147
 RUN NO. 3
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 1.0685
 FEED FLOW RATE (LITERS/MINUTE)= 0.007
 RESIN VOLUME (LITERS) 0.125

$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$
 $C'(TAU) = K \cdot C + A'1 \cdot \exp(S_1 \cdot T) + A'2 \cdot \exp(S_2 \cdot T)$
 $CH(T) = A''1 \cdot \exp(S_1 \cdot T) + A''2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$

K= 2.1 BETA 1= 0.1045 BETA 2= 0.0240 BETA 3= 0.0564

$S_1 = -1.47359E-2$ $S_2 = -0.17016$
 $A_1 = -0.451548$ $A_2 = -0.616952$
 $A'1 = -2.45659$ $A'2 = 0.212743$
 $A''1 = 0.903095$ $A''2 = 1.2339$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C ₁ (T)/C	C'(T)/C*	CH(T)
1.	0.0727	0.0794	0.0965	0.0012	0.0057
6.	0.2477	0.2512	0.4052	0.0320	0.1295
11.	0.4876	0.3981	0.5518	0.0836	0.2806
16.	0.6032	0.4467	0.6282	0.1414	0.3929
21.	0.6591	0.4467	0.6737	0.1992	0.4592
26.	0.7149	0.4467	0.7050	0.2548	0.4892
36.	0.7664	0.4467	0.7501	0.3561	0.4843
46.	0.8348	0.4467	0.7852	0.4442	0.4415
56.	0.8223	0.3981	0.8148	0.5203	0.3896
66.	0.8325	0.3162	0.8402	0.5860	0.3393
76.	0.8553	0.2239	0.8621	0.6428	0.2939
86.	0.8883	0.0501	0.8810	0.6917	0.2540
106.	0.8864	0.0158	0.9114	0.7704	0.1894
126.	0.9630	0.0100	0.9340	0.8290	0.1410
146.	1.0082	0.0079	0.9508	0.8727	0.1050
166.	1.0000	0.0071	0.9634	0.9052	0.0782

EXPERIMENT NO. 147
 RUN NO. 3^A
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 1.2227
 FEED FLOW RATE (LITERS/MINUTE)= 0.02
 RESIN VOLUME (LITERS) 0.125

$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$
 $C'(TAU) = K \cdot C + A'1 \cdot \exp(S_1 \cdot T) + A'2 \cdot \exp(S_2 \cdot T)$
 $CH(T) = A''1 \cdot \exp(S_1 \cdot T) + A''2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$

K= 2.2 BETA 1= 0.2985 BETA 2= 0.0670 BETA 3= 0.1650

$S_1 = -4.08444E-2$ $S_2 = -0.489663$
 $A_1 = -0.520758$ $A_2 = -0.701942$
 $A'1 = -2.93474$ $A'2 = 0.244796$
 $A''1 = 1.04152$ $A''2 = 1.40338$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	$C(T)/C$	$CH(T)$	$C_1(T)/C$	$C'(T)/C*$	$CH(T)$
8.	0.6151	0.3802	0.6814	0.2149	0.5546
13.	0.7389	0.1047	0.7486	0.3586	0.5644
18.	0.8144	0.0115	0.7957	0.4770	0.4832
23.	0.8625	0.0079	0.8335	0.5736	0.4045
28.	0.8625	0.0069	0.8643	0.6523	0.3313
38.	0.8488	0.0060	0.9098	0.7689	0.2206
48.	0.9140	0.0058	0.9400	0.8464	0.1466
58.	0.9037	0.0035	0.9601	0.8979	0.0975
68.	0.9450	0.0054	0.9735	0.9321	0.0648
78.	0.9519	0.0052	0.9824	0.9549	0.0431
88.	0.9656	0.0051	0.9883	0.9700	0.0286
98.	0.9210	0.0051	0.9922	0.9801	0.0190
108.	0.9279	0.0050	0.9948	0.9868	0.0126

EXPERIMENT NO. 147
 RUN NO. 4
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 0.3681
 FEED FLOW RATE (LITERS/MINUTE)= 0.01
 RESIN VOLUME (LITERS) 0.075

$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$
 $C'(TAU) = K \cdot C + A'1 \cdot \exp(S_1 \cdot T) + A'2 \cdot \exp(S_2 \cdot T)$
 $CH(T) = A''1 \cdot \exp(S_1 \cdot T) + A''2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$

K= 6.5 BETA 1= 0.2128 BETA 2= 0.0200 BETA 3= 0.1245

$S_1 = -1.23380E-2$ $S_2 = -0.344896$
 $A_1 = -0.146251$ $A_2 = -0.221849$
 $A'1 = -2.48142$ $A'2 = 8.87678E-2$
 $A''1 = 0.292503$ $A''2 = 0.443697$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C ₁ (T)/C	C'(T)/C*	CH(T)
1.	0.1940	0.1000	0.1807	0.0019	0.0081
6.	0.4749	0.1585	0.5549	0.0416	0.1223
11.	0.6289	0.1778	0.6395	0.0954	0.1945
16.	0.6724	0.1585	0.6714	0.1488	0.2174
21.	0.7020	0.1413	0.6929	0.1996	0.2176
26.	0.7156	0.1259	0.7116	0.2475	0.2094
36.	0.7305	0.1000	0.7452	0.3348	0.1873
46.	0.7430	0.0794	0.7748	0.4121	0.1658
56.	0.7683	0.0631	0.8009	0.4803	0.1466
76.	0.7979	0.0316	0.8444	0.5939	0.1145
96.	0.8560	0.0040	0.8785	0.6827	0.0895
116.	0.9144	0.0020	0.9050	0.7521	0.0699
136.	0.9315	0.0016	0.9258	0.8063	0.0546

EXPERIMENT NO. 147

RUN NO. 5

AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 0.7143

FEED FLOW RATE (LITERS/MINUTE)= 0.005

RESIN VOLUME (LITERS) 0.075

$$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$$

$$C'(T) = K \cdot C + A'_1 \cdot \exp(S_1 \cdot T) + A'_2 \cdot \exp(S_2 \cdot T)$$

$$CH(T) = A''_1 \cdot \exp(S_1 \cdot T) + A''_2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$$

K= 3.4 BETA 1= 0.1064 BETA 2= 0.0250 BETA 3= 0.0814

$$S_1 = -1.33359E-2$$

$$S_2 = -0.19943$$

$$A_1 = -0.35715$$

$$A_2 = -0.35715$$

$$A'_1 = -2.60266$$

$$A'_2 = 0.17404$$

$$A''_1 = 0.7143$$

$$A''_2 = 0.7143$$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C ₁ (T)/C	C'(T)/C*	CH(T)
1.	0.1470	0.0794	0.0970	0.0012	0.0056
6.	0.2789	0.1259	0.3873	0.0324	0.1207
11.	0.3653	0.1585	0.5125	0.0825	0.2532
16.	0.4689	0.1778	0.5755	0.1372	0.3460
21.	0.5717	0.1905	0.6145	0.1912	0.3977
26.	0.5941	0.1995	0.6437	0.2427	0.4191
36.	0.7059	0.1778	0.6903	0.3370	0.4115
46.	0.7529	0.1585	0.7292	0.4197	0.3761
56.	0.7529	0.1413	0.7631	0.4922	0.3348
76.	0.8117	0.0631	0.8185	0.6111	0.2588
96.	0.8470	0.0141	0.8610	0.7021	0.1985
116.	0.8705	0.0071	0.8936	0.7718	0.1521
136.	0.9118	0.0050	0.9185	0.8253	0.1165
156.	0.9353	0.0040	0.9376	0.8662	0.0892

EXPERIMENT NO. 147

RUN NO. 6

AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 1.1134

FEED FLOW RATE (LITERS/MINUTE)= 0.003

RESIN VOLUME (LITERS) 0.075

$$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$$

$$C'(TAU) = K \cdot C + A'1 \cdot \exp(S_1 \cdot T) + A'2 \cdot \exp(S_2 \cdot T)$$

$$CH(T) = A''1 \cdot \exp(S_1 \cdot T) + A''2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$$

K= 2.1 BETA 1= 0.0638 BETA 2= 0.0180 BETA 3= 0.0362

$$S_1 = -1.07062E-2$$

$$S_2 = -0.107315$$

$$A_1 = -0.50116$$

$$A_2 = -0.61224$$

$$A'1 = -2.59725$$

$$A'2 = 0.259113$$

$$A''1 = 1.00232$$

$$A''2 = 1.22448$$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C ₁ (T)/C	C'(T)/C*	CH(T)
1.	0.1124	0.1000	0.0607	0.0006	0.0024
6.	0.2211	0.1585	0.2891	0.0165	0.0648
11.	0.2959	0.1905	0.4310	0.0466	0.1636
16.	0.3672	0.1995	0.5220	0.0840	0.2625
21.	0.4453	0.2239	0.5828	0.1245	0.3463
26.	0.5132	0.2512	0.6255	0.1659	0.4104
36.	0.5774	0.2692	0.6823	0.2468	0.4837
46.	0.6981	0.2818	0.7210	0.3220	0.5031
56.	0.7132	0.2512	0.7515	0.3904	0.4909
76.	0.7434	0.1995	0.8003	0.5077	0.4272
96.	0.7736	0.0251	0.8389	0.6026	0.3538
116.	0.8604	0.0126	0.8700	0.6792	0.2881
136.	0.8793	0.0100	0.8951	0.7410	0.2333
156.	0.8755	0.0079	0.9153	0.7909	0.1885
176.	0.8755	0.0063	0.9316	0.8312	0.1523

EXPERIMENT NO. 147

RUN NO. 7A

AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 0.4412

FEED FLOW RATE (LITERS/MINUTE)= 0.02

RESIN VOLUME (LITERS) 0.05

$$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$$

$$C'(T) = K \cdot C + A'1 \cdot \exp(S_1 \cdot T) + A'2 \cdot \exp(S_2 \cdot T)$$

$$CH(T) = A''1 \cdot \exp(S_1 \cdot T) + A''2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$$

K= 5.3 BETA 1= 0.5405 BETA 2= 0.0690 BETA 3= 0.2965

$$S_1 = -4.32268E-2$$

$$S_2 = -0.862827$$

$$A_1 = -0.173491$$

$$A_2 = -0.267709$$

$$A'1 = -2.46169$$

$$A'2 = 0.123328$$

$$A''1 = 0.346981$$

$$A''2 = 0.535419$$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C ₁ (T)/C	C'(T)/C*	CH(T)
3.	0.6095	0.0891	0.6090	0.0793	0.1707
8.	0.6951	0.0275	0.7211	0.2551	0.2344
13.	0.8162	0.0036	0.7758	0.3998	0.1970
18.	0.8819	0.0024	0.8194	0.5165	0.1593
23.	0.8989	0.0020	0.8545	0.6105	0.1284
28.	0.9295	0.0018	0.8828	0.6862	0.1034
33.	0.9485	0.0016	0.9239	0.7963	0.0671
48.	0.9714	0.0015	0.9506	0.8678	0.0436
58.	0.9810	0.0014	0.9680	0.9142	0.0283
78.	0.9905	0.0013	0.9865	0.9639	0.0119
98.	1.0000	0.0013	0.9943	0.9848	0.0050

% UNDERFLOW IN EXP IN LINE 453

118. 1.0000 0.0013 0.9976 0.9936 0.0021

EXPERIMENT NO. 147

RUN NO. 8

AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 0.895

FEED FLOW RATE (LITERS/MINUTE)= 0.015

RESIN VOLUME (LITERS) 0.05

$$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$$

$$C'(TAU) = K \cdot C + A'1 \cdot \exp(S1 \cdot T) + A'2 \cdot \exp(S2 \cdot T)$$

$$CH(T) = A''1 \cdot \exp(S1 \cdot T) + A''2 \cdot \exp(S2 \cdot T) - 2 \cdot C \cdot \exp(-B1 \cdot T)$$

$$K = 2.5 \quad BETA \ 1 = 0.4054 \quad BETA \ 2 = 0.1000 \quad BETA \ 3 = 0.2027$$

$$S1 = -6.28261E-2$$

$$S2 = -0.645282$$

$$A1 = -0.368594$$

$$A2 = -0.526406$$

$$A'1 = -2.47885$$

$$A'2 = 0.241346$$

$$A''1 = 0.737187$$

$$A''2 = 1.05281$$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C1(T)/C	C'(T)/C*	CH(T)
2.	0.4836	0.0871	0.4750	0.0526	0.1441
7.	0.7746	0.0052	0.7283	0.2875	0.3816
12.	0.8638	0.0033	0.8060	0.4788	0.3335
17.	0.9154	0.0029	0.8584	0.6193	0.2516
22.	0.9436	0.0027	0.8966	0.7219	0.1848
27.	0.9530	0.0025	0.9245	0.7969	0.1351
37.	0.9765	0.0023	0.9597	0.8916	0.0721
47.	0.9812	0.0022	0.9785	0.9422	0.0385
57.	0.9906	0.0022	0.9885	0.9692	0.0205

EXPERIMENT NO. 147
 RUN NO. 9
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 1.3697
 FEED FLOW RATE (LITERS/MINUTE)= 0.015
 RESIN VOLUME (LITERS) 0.05

$$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$$

$$C'(TAU) = K \cdot C + A'1 \cdot \exp(S_1 \cdot T) + A'2 \cdot \exp(S_2 \cdot T)$$

$$CH(T) = A''1 \cdot \exp(S_1 \cdot T) + A''2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$$

K= 1.5 BETA 1= 0.4054 BETA 2= 0.1500 BETA 3= 0.1824

S1=-9.45280E-2 S2=-0.64331
 A1=-0.593784 A2=-0.775916
 A'1=-2.40845 A'2= 0.353898
 A''1= 1.18757 A''2= 1.55183

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C1(T)/C	C'(T)/C*	CH(T)
4.	0.6012	0.1122	0.6598	0.2100	0.3908
9.	0.8804	0.0105	0.8131	0.4999	0.4407
14.	0.9356	0.0076	0.8845	0.6879	0.3070
19.	0.9571	0.0069	0.9281	0.8055	0.1959
24.	0.9663	0.0066	0.9552	0.8787	0.1227
29.	0.9693	0.0063	0.9720	0.9244	0.0766
39.	0.9877	0.0060	0.9891	0.9706	0.0298
49.	0.9969	0.0058	0.9958	0.9886	0.0116
59.	0.9969	0.0056	0.9984	0.9956	0.0045

EXPERIMENT NO. 147
 RUN NO. 18
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 0.3807
 FEED FLOW RATE (LITERS/MINUTE)= 0.02
 RESIN VOLUME (LITERS) 0.075

$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$
 $C'(TAU) = K \cdot C + A'1 \cdot \exp(S_1 \cdot T) + A'2 \cdot \exp(S_2 \cdot T)$
 $CH(T) = A''1 \cdot \exp(S_1 \cdot T) + A''2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$

K= 6.3 BETA 1= 0.4255 BETA 2= 0.0400 BETA 3= 0.2413

$S_1 = -2.49636E-2$ $S_2 = -0.681845$
 $A_1 = -0.148548$ $A_2 = -0.232152$
 $A'1 = -2.48956$ $A'2 = 9.11471E-2$
 $A''1 = 0.297096$ $A''2 = 0.464304$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C ₁ (T)/C	C'(T)/C*	CH(T)
2.	0.4944	0.0912	0.4729	0.0223	0.0763
7.	0.6753	0.0871	0.6672	0.1287	0.2147
12.	0.7197	0.0603	0.7106	0.2307	0.2157
17.	0.7528	0.0275	0.7447	0.3210	0.1938
22.	0.7836	0.0074	0.7747	0.4006	0.1715
27.	0.8122	0.0044	0.8011	0.4710	0.1514
37.	0.8718	0.0022	0.8451	0.5878	0.1180
47.	0.9028	0.0017	0.8793	0.6789	0.0919
57.	0.9228	0.0015	0.9060	0.7498	0.0716
77.	0.9469	0.0014	0.9429	0.8482	0.0435
97.	0.9824	0.0013	0.9654	0.9078	0.0264

EXPERIMENT NO. 147
 RUN NO. 19
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 0.6345
 FEED FLOW RATE (LITERS/MINUTE)= 0.02
 RESIN VOLUME (LITERS) 0.075

$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$
 $C'(TAU) = K \cdot C + A'1 \cdot \exp(S1 \cdot T) + A'2 \cdot \exp(S2 \cdot T)$
 $CH(T) = A''1 \cdot \exp(S1 \cdot T) + A''2 \cdot \exp(S2 \cdot T) - 2 \cdot C \cdot \exp(-B1 \cdot T)$

K= 3.9 BETA 1= 0.4255 BETA 2= 0.0630 BETA 3= 0.2352

$S1 = -3.91583E-2$ $S2 = -0.684618$
 $A1 = -0.254687$ $A2 = -0.379813$
 $A'1 = -2.62467$ $A'2 = 0.150124$
 $A''1 = 0.509374$ $A''2 = 0.759626$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C1(T)/C	C'(T)/C*	CH(T)
2.	0.4966	0.1122	0.4766	0.0347	0.1224
7.	0.7086	0.0871	0.6899	0.1941	0.3290
12.	0.7682	0.0126	0.7489	0.3370	0.3109
17.	0.8211	0.0048	0.7937	0.4549	0.2609
22.	0.8741	0.0032	0.8304	0.5518	0.2151
27.	0.9006	0.0028	0.8606	0.6315	0.1769
37.	0.9270	0.0023	0.9057	0.7509	0.1196
47.	0.9535	0.0021	0.9363	0.8316	0.0809
57.	0.9601	0.0020	0.9569	0.8862	0.0547
77.	0.9868	0.0019	0.9803	0.9480	0.0250
97.	0.9868	0.0018	0.9910	0.9762	0.0114

EXPERIMENT NO. 147
 RUN NO. 20
 AT 30 DEG C

KINETICS OF THE RESIN LOADING PROCESS

FEED CONCENTRATION (MOLES U/LITER)= 1.1008
 FEED FLOW RATE (LITERS/MINUTE)= 0.02
 RESIN VOLUME (LITERS) 0.075

$C_1(T) = C + A_1 \cdot \exp(M_1 \cdot T) + A_2 \cdot \exp(M_2 \cdot T)$
 $C'(TAU) = K \cdot C + A'1 \cdot \exp(S_1 \cdot T) + A'2 \cdot \exp(S_2 \cdot T)$
 $CH(T) = A''1 \cdot \exp(S_1 \cdot T) + A''2 \cdot \exp(S_2 \cdot T) - 2 \cdot C \cdot \exp(-B_1 \cdot T)$

K= 2.2 BETA 1= 0.4255 BETA 2= 0.1100 BETA 3= 0.2317

$S_1 = -6.68308E-2$ $S_2 = -0.700403$
 $A_1 = -0.477575$ $A_2 = -0.623225$
 $A'1 = -2.67721$ $A'2 = 0.255453$
 $A''1 = 0.95515$ $A''2 = 1.24645$

TIME (MIN)	EXPERIMENTAL DATA		CALCULATED DATA		
	C(T)/C	CH(T)	C ₁ (T)/C	C'(T)/C*	CH(T)
3.	0.5420	0.1413	0.5757	0.1083	0.3199
8.	0.7978	0.0100	0.7437	0.3527	0.4910
13.	0.8932	0.0060	0.8180	0.5363	0.3921
18.	0.9313	0.0051	0.8697	0.6680	0.2858
23.	0.9428	0.0047	0.9067	0.7623	0.2052
28.	0.9466	0.0045	0.9332	0.8298	0.1470
38.	0.9695	0.0043	0.9658	0.9128	0.0754
48.	0.9809	0.0041	0.9825	0.9553	0.0386
58.	0.9847	0.0040	0.9910	0.9771	0.0198

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