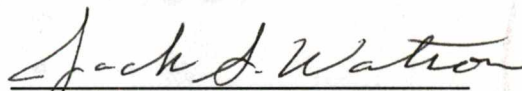


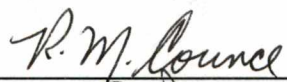
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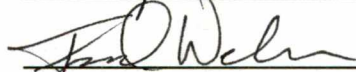
I am submitting herewith a thesis written by Reggie Hall entitled "Pilot-Scale Demonstration of Strontium Removal from Low-Level Radioactively Contaminated Process Wastewater Using Continuous Countercurrent Ion Exchange (CCIX)." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemical Engineering.



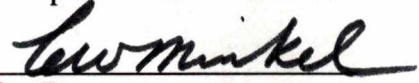
Jack S. Watson, Major Professor

We have read this thesis
and recommend its acceptance:





Accepted for the Council:



Vice Provost
and Dean of The Graduate School

**PILOT-SCALE DEMONSTRATION OF STRONTIUM REMOVAL FROM LOW-LEVEL
RADIOACTIVELY CONTAMINATED PROCESS WASTEWATER USING
CONTINUOUS COUNTERCURRENT ION EXCHANGE (CCIX)**

A Thesis

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Degree

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Reggie Hall

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ABSTRACT

A mobile pilot-scale Continuous Countercurrent Ion-exchange (CCIX) system was operated at the Oak Ridge National Laboratory (ORNL) for the treatment of wastewaters that contain predominantly calcium, sodium, and magnesium bicarbonates and are slightly contaminated with ^{90}Sr and ^{137}Cs radioisotopes. A demonstration study was conducted to evaluate the near-steady-state performance and feasibility of a pilot-scale continuous countercurrent ion-exchange column for the selective removal of strontium from the wastewater. Test results show that the process removes 99% of the strontium from the water while significantly reducing the volume of secondary waste generation. The technique entails recycling of the resin regeneration streams to minimize secondary waste.

This study discusses (a) mathematical modeling of multicomponent equilibria using an iterative nonlinear parameter estimation technique (Levenberg-Marquardt) to determine equilibrium constants for predicting distribution coefficients, (b) applications of the Thomas model for predicting breakthrough curves, scale-up, and ion-exchange column behavior, and (c) a method predicting breakthrough behavior in a CCIX column using an extension of the Thomas model.

Experimental results show that the breakthrough distribution for a multicomponent feed system can be reduced to a binary system and predicted (within 10%) using multicomponent equilibrium constants. Furthermore, the effect of changing feed concentrations on column performance are predicted using the Thomas model. Although the CCIX column effectively removes strontium from the wastewater, the height of a transfer unit was significantly greater than that observed in fixed-bed experiments, probably because of the simple fluid inlet distribution used and mixing during resin movement.

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NOMENCLATURE

a	coefficient for Eq. 50.
A	concentration of cation reacting, g-mol/cm ³
B	concentration of cation reacting, g-mol/cm ³
b	estimates of Δ
C	concentration of solute in fluid, g-mol/cm ³
C_o	concentration of solute in feed, g-mol/cm ³
C_s	average concentration of solute A solid phase, meq/g-resin
d	particle diameter, cm
D	diffusion coefficient, cm ² /s
D_A	effective axial diffusion coefficient of solute A, cm ² /s
f	superficial flow rate through column, cm ³ /s
k_a	mass-transfer adsorption coefficient, cm ³ /g-mol-s
k_{de}	mass-transfer desorption coefficient, 1/s
K_a	overall mass-transfer coefficient for system, cm ³ /g-mol-s
K_d	distribution coefficient, mL solution/mL resin, or mL solution/g-dry resin
K'	equilibrium constant, L/meq
K'_d	distribution coefficient, cm ³ /g resin when $X = 1$
N	number of mass-transfer units, dimensionless
q	concentration of solute in solid, g-mol/g
q^*	concentration of solute in solid at equilibrium, g-mol/g
q_s^*	asymptotic maximum solid phase concentration for component i, meq solute/g resin
q_v	concentration of solute per unit volume of sorbent bed, g-mol/g
Q'	asymptotic maximum solid phase concentration, meq solute/g resin
r^*	variable separation factor, dimensionless
R	constant separation factor, dimensionless
$SS(\theta)$	sum of squares of linearized model

T	throughput parameter, dimensionless
U_z	average interstitial velocity through the column, cm/s
V	effluent volume, cm ³
v	sorbent bed volume, cm ³
X	concentration of solute in fluid phase divided by concentration solute in feed, dimensionless
Y	concentration of solute in solid phase divided by maximum solid phase concentration, dimensionless
Y^E	observed dependent variable
Z	length of ion exchange bed, cm
Z	$\partial f(\eta, \theta) / \partial \theta$

Greek Letters

δ	fractional change in parameter value
δ_S	fractional change in sum of squares
Δ	change in parameter estimates
ϵ	residuals in nonlinear model, or void volume in ion exchange bed
η_k	independent variable
ρ	particle density, g/cm ³
ρ_b	bulk density of sorbent, g/cm ³
θ_p	parameter estimates
Ω_a	constant given in Eq. 32

1. INTRODUCTION

Alternative methods for treatment of wastewaters slightly contaminated with radioactivity are being developed at the Oak Ridge National Laboratory (ORNL). Studies indicate that calcium and magnesium compete with strontium and other radionuclides for sites on cation exchange resin making the efficient removal of strontium from multicomponent mixtures of ions in wastewater extremely difficult. Ion-exchange resins can be selected which will separate strontium from magnesium and monovalent ions found in wastewaters using a fixed-bed ion-exchange system. However, currently used fixed-bed ion-exchange systems can not efficiently separate strontium from calcium since the separation factor is low. Therefore, large quantities of calcium are often found in waste streams that are only slightly contaminated with trace quantities of strontium. ORNL currently removes ^{90}Sr by chemical precipitation and ion-exchange unit operations operated in series. Calcium, strontium, and a portion of the cesium are precipitated by addition of sodium hydroxide. The final precipitate sludge is packaged and ultimately disposed. The remaining cations in solution are removed by ion exchange. The ion-exchange resin is regenerated using nitric acid. The regenerate solution from the ion-exchange column (primarily calcium salts) is concentrated in an evaporator forming a concentrated radioactive liquid waste solution. Waste disposal costs for contaminated solids and liquids are generally based on total volume. Finding a treatment process that will efficiently separate ^{90}Sr from Ca would be desirable to reduce the volume of secondary waste generated and simplify the process flowsheet.

A pilot-scale Continuous Countercurrent Ion-exchange (CCIX) system marketed by the CSA Company in Oak Ridge, Tennessee, was purchased as a potentially economical

alternative flowsheet for treatment of slightly contaminated wastewaters. The CCIX system has the potential for efficiently removing strontium from the wastewater while simultaneously minimizing secondary waste generation by (1) loading strontium and calcium on an ion-exchange resin, (2) separating strontium from calcium and other multicomponent ions slightly loaded on the resin using a 1 M NaCl solution, (3) separating strontium (and any other ions) from the loaded resin using a 5 M NaCl recyclable solution, and (4) precipitating strontium from the 5 M NaCl waste stream followed by subsequent disposal of strontium-rich solid precipitates. One paramount feature of the CCIX process is the ability to selectively remove a preferred component, strontium, from other multicomponent ions, calcium, magnesium etc., even at conditions where ion-exchange separation factors are near unity.¹ To maximize production efficiency and produce low volumes of secondary waste under conditions of low distribution coefficients, poor separation factors, and high production rates, a CCIX system is often preferred over a fixed-bed ion-exchange system. The countercurrent operation is more efficient in utilizing the resin exchange capacity. Resin in a CCIX system is continuously reacted and regenerated, thus minimizing the amount of resin required for a given amount of liquid processed.²

This report summarizes the results of a pilot-scale demonstration of the CSA CCIX system for treatment of process wastewaters generated from the multi-purpose research facilities at ORNL. Since the ORNL process wastewater is essentially tap water and groundwater that is slightly contaminated with ⁹⁰Sr and ¹³⁷Cs, the data and results discussed in this paper should be widely applicable to other systems with similar characteristics.

2. LITERATURE REVIEW

2.1 MATHEMATICAL MODELS FOR FIXED-BED ION-EXCHANGE SYSTEMS

Multicomponent ion-exchange systems are often encountered in industrial operations. Treatment of wastewaters containing multiple ions (Ca^{2+} , Mg^{2+} , Na^+ , $^{90}\text{Sr}^{2+}$ and $^{137}\text{Cs}^+$, etc.) competing for exchange sites requires use of multicomponent equilibrium relations in an attempt to understand the interactions among species. The design of fixed-bed ion-exchange systems (adsorbers) generally requires information regarding the effluent component concentration profile as a function of volume processed. These profiles are typically known as breakthrough curves which are a function of equilibrium conditions and mass transfer kinetics, which are affected by column configuration, feed composition, flow rates, etc.

Mathematical models have not been developed to predict multicomponent ion-exchange breakthrough curves from theoretical data. Therefore, modeling of multicomponent fixed-bed ion-exchange columns have been restricted to semi-empirical methods. Data for these models are obtained experimentally from laboratory and pilot tests. Equilibrium data are used to evaluate a resin, and experimental breakthrough curves are used to obtain rate data and evaluate the equipment. Mathematical models are often utilized for optimization and prediction of column performance at different operating conditions and this reduces the time and expense required for exploring operating conditions experimentally.

The first step in determining a system's ability to perform a separation effectively is to determine the equilibrium behavior. In predicting the behavior of an ion-exchange system, the shape of the equilibrium curve given in Fig. 1 is often used to determine if the equilibrium is "favorable" or "unfavorable." Favorable equilibrium is noted when the curvature for the equilibrium curve is negative; unfavorable equilibrium is noted when the

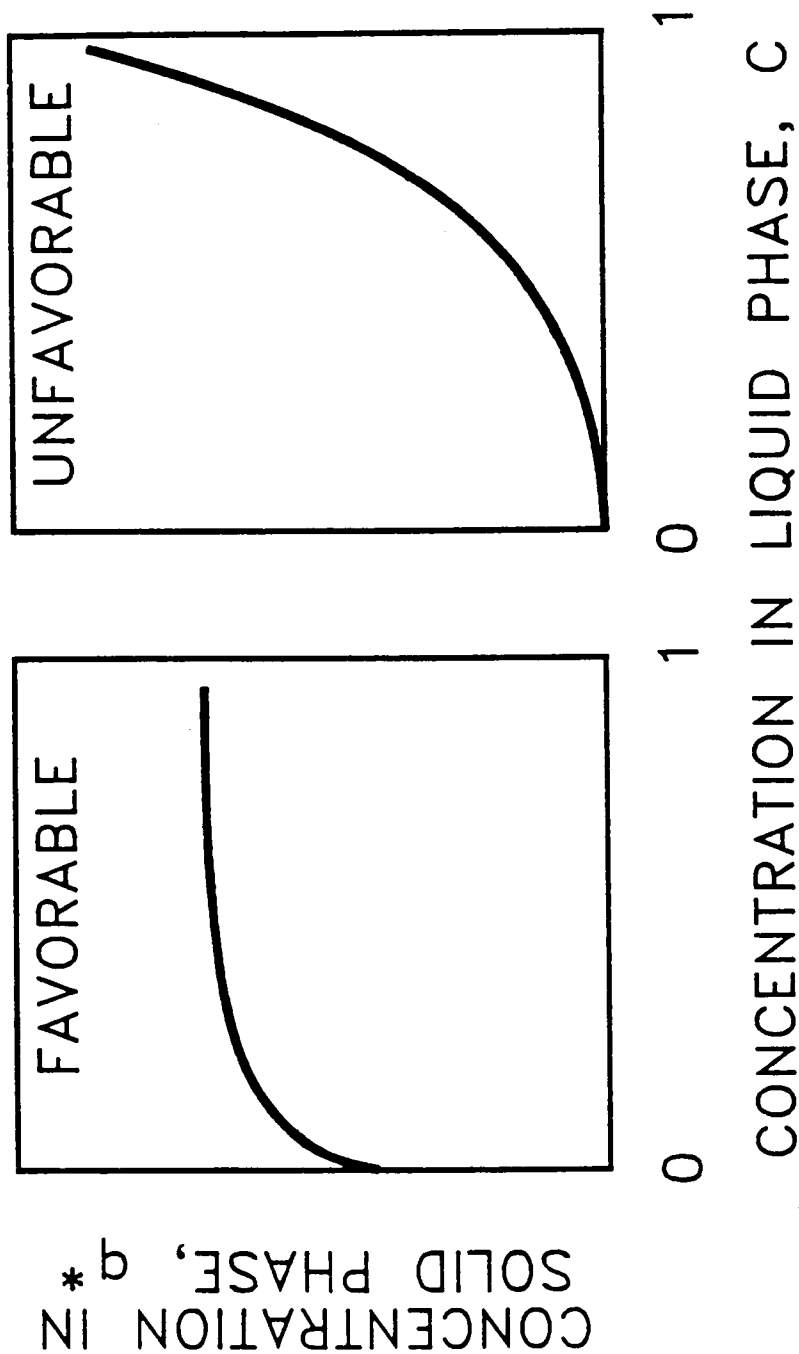


Fig. 1. Shapes of equilibrium isotherm curves for favorable and unfavorable equilibrium.

curvature is positive.³ There are a limited number of simple equilibrium models available for adsorption from liquids. Some very simple models such as the Langmuir, Volmer, and BET isotherms for adsorption systems have been developed for single component systems, and modified versions have been extended for multicomponents.⁴ Modeling of equilibrium relations for multicomponent systems is complicated by competition or interactions among species and competition among multiple ions in wastewaters (Ca^{2+} , Mg^{2+} , Na^+ , $^{90}\text{Sr}^{2+}$ and $^{137}\text{Cs}^+$, etc.), requires multicomponent equilibrium relations to be measured to understand the interactions.

A review of the literature reveals that there are very few examples of predictive modeling of fixed-bed multicomponent liquid systems. Most mathematical models for liquid multicomponent ion-exchange systems have dealt only with the treatment of binary fixed-bed systems.⁵ There are some models in the literature for extracting data from binary systems and predicting multicomponent ion-exchange equilibria for ternary systems.^{6,7} For water treatment applications of dilute solutions, a good alternative for the prediction of multicomponent equilibria data is cited by Digiano.⁸ This model is based upon fundamental thermodynamic principles which could be extended to any number of competing components.

A general analytical solution, however, to fixed-bed ion-exchange systems developed by Thomas is usually used for the basis for design of ion-exchange columns.⁹ The Thomas model assumes a Langmuir isotherm and that ion-exchange mass transfer can be approximated by a second-order kinetic equation (Langmuir-like kinetics) using the following three parameters: (1) T, a throughput parameter; (2) N, column height as transfer units; and (3) R, the separation factor. For dilute solutions, such as those used in this study, R and T are unity. The value of N is determined from experimental breakthrough curves. Parameters

obtained from the Thomas model are used to predict breakthrough curves from laboratory-scaled systems and scale-up parameters for pilot-scale and industrial-scale systems.^{10,11}

2.2 BACKGROUND INFORMATION

2.2.1 ORNL Process Wastewater Composition

The process waste system at ORNL is used to collect liquid wastes that have the potential to be radioactively contaminated and liquid wastes that are slightly contaminated with radioactivity. These include process wastewater from research laboratories, groundwater, and condensate from evaporation of liquid low-level radioactive wastes (LLLW). Approximately 50 volume percent of the process waste is surface and ground water which is slightly contaminated with radioactivity. The process wastewater at ORNL contains a number of trace radionuclides, shown in Table 1, and relatively large amounts of competing ions (representative of city water and local groundwater in Oak Ridge, Tennessee) as shown in Table 2.¹² The major chemical constituents are calcium, sodium, and magnesium bicarbonates which are introduced by local river water and shallow drainage wells. The major radionuclides are ^{90}Sr and ^{137}Cs . The ^{90}Sr is the more hazardous contaminant because of its potential for introduction into the human and animal food chain. Discharge limits into the environment, as defined by the Code of Federal Regulations, Chapter 10, Part 20 (10CFR20), are 11 Bq/L for ^{90}Sr and 740 Bq/L for ^{137}Cs .

The concentration of ^{90}Sr and ^{137}Cs in the feed to the process waste treatment system average 1000 Bq/L and 110 Bq/L, respectively. Concentration spikes have occurred occasionally due to drainages from construction sites, leaks in underground piping, etc. Feed compositions may vary between 500 and 8000 Bq/L ^{90}Sr and 200 and 1000 Bq/L ^{137}Cs .

Table 1. Radiochemical composition of process wastewater at ORNL.

Radionuclide	Concentration Bq/L ^a
Gross alpha	5
Gross beta	6000
⁶⁰ Co	25
⁹⁰ Sr	4000
⁹⁵ ZrNb	50
¹⁰⁶ Ru	10
¹³⁷ Cs	400

^a 1 Bq = 1 disintegration per second = 2.7×10^{-11} Curies

Table 2. Chemical composition of ORNL process wastewater.
(pH = 7.7)

Cation	Concentration (mg/L)	Concentration Anion	(mg/L)
Ca	40	HCO ₃	60
Mg	10	SO ₄	18
Na	20	Cl	6
Si	2	NO ₃	4
K	2	F	1
Sr	0.2	PO ₄	0.2
Al	0.1		
Fe	0.05		
Zr	0.05		
Cu	0.02		
Ni	<0.02		
Cr	<0.02		
U	<0.001		

2.2.2 Removal of ^{90}Sr And ^{137}Cs From ORNL Wastewater - Current Approach

Process wastewater that is slightly contaminated with ^{90}Sr and ^{137}Cs radioisotopes has been routinely treated at the ORNL Process Waste Treatment Plant (PWTP) using chemical precipitation and filtration followed by fixed bed ion-exchange columns containing strong acid cation resin.¹³ The objective of treatment is to decontaminate the process wastewater sufficiently for release to the environment while concentrating the radioactive materials (^{90}Sr and ^{137}Cs) into a solid waste form that can be safely stored with minimum surveillance.

New federal regulations on discharge limits for ^{90}Sr and ^{137}Cs along with higher costs for disposal of the concentrated secondary liquid low-level radioactive wastes (LLLW) produced during resin regeneration have prompted efforts to improve the efficiency of the PWTP. Therefore, extensive research, development, and analyses of alternatives are being conducted to support PWTP upgrades and improvements.¹⁴ Based on previous experience, the removal of ^{137}Cs from the process water can be achieved by using an inorganic zeolite.¹⁵ However, zeolites have a low capacity for ^{90}Sr for the case of unsoftened process water. Most zeolites have high ^{137}Cs distribution coefficients (up to 23,000), but distribution coefficients of only 2000 to 3000 for ^{90}Sr were obtained at ORNL when column residence times of 10 minutes were used. The present plan for upgrading the PWTP is to install zeolite columns which will remove both strontium and cesium. However, finding an ion-exchanger that will efficiently separate ^{90}Sr from Ca mixed with multicomponent ions (^{137}Cs , Na, Mg, etc.) would be desirable to reduce the volume of secondary waste disposal and improve the overall performance of the decontamination process.

2.2.3 CSA Continuous Countercurrent Ion-exchange System (CCIX)

The CSA CCIX system has been demonstrated for the removal of ^{90}Sr from milk at the Beltsville Laboratory in Beltsville, Maryland.¹⁶ Other applications of CCIX have been reported in the literature for recovery of trace quantities of uranium from mine ores.^{17,18} Also, the removal of nonradioactive strontium from Oak Ridge tap water was demonstrated using a CCIX system.¹⁹ In this demonstration, the feed composition to the CCIX system was constant. However, a pilot-scale demonstration was needed to determine if the CCIX process could maintain steady-state operation and continually produce low waste volumes under conditions where feed compositions and flow rates were variables.

A review of literature on cleanup of contaminated waste streams indicates that one of the largest expense items associated with contaminated or hazardous processes was waste disposal. The CSA Continuous Countercurrent Ion-exchange (CCIX) system has the potential for significantly minimizing secondary waste generation by separating strontium from calcium and recycling strip streams used for regeneration of resin in the removal process. As a result, only one low volume secondary waste stream is generated for subsequent disposal.²⁰ The CCIX system shown in Fig. 2 has been proposed for removal of strontium from wastewaters typical of the ORNL process wastewater. The discharge stream concentrations and flow rates given in Fig. 2 are estimates by the CSA Company in Oak Ridge, Tennessee. A zeolite column is proposed for removal of ^{137}Cs coupled with the CCIX process for ^{90}Sr removal, which could potentially reduce the cost of secondary waste disposal.

3. EXPERIMENTAL

A general understanding of the ion-exchange process where counter ions in the resin phase are displaced in stoichiometric proportions by counter ions initially in the liquid phase was needed to develop mathematical models to predict column performance at various operating conditions. Four factors needed to predict the ion-exchange column performance were (1) the equilibrium relation for the multicomponent system, (2) the bulk flow rate of feed solution through the column, (3) a representation of the ion-exchange kinetics and mass transfer mechanism controlling the diffusion of counter ions between the liquid and solid phases, and (4) column length and geometry. These parameters provide information needed to describe the breakthrough curves.

Equilibrium isotherms were obtained from bench-scale batch tests for (a) a binary system consisting of strontium and calcium, and (b) the multicomponent process wastewater feed (Sr, Ca, Mg, and Na). Separation factors and distribution coefficients were determined from the equilibrium relations for each system, respectively. The multicomponent batch equilibrium data were needed to develop a mathematical model describing the fundamental equilibrium relation for the multicomponent process wastewater feed. These data were fitted to a nonlinear multicomponent Langmuir model (given in Section 4 of this report).

The feed flow rate parameter and the mass transfer relation that describes the diffusion controlled rate determining step in the overall ion-exchange process are contained in the column breakthrough curve expressions. Breakthrough curves for the multicomponent process wastewater feed solution were obtained from continuous sampling of the effluent from the loading of process wastewater feed on a Dowex HGR-W2 cation resin in a bench-scale column. Likewise, the elution curves were obtained by displacing the feed solution counter ions from the loaded resin using sodium chloride solutions.

Experimental tests were also conducted to establish steady-state operating parameters and overall operating performance of the pilot-scale CCIX system for removal of strontium from the process wastewater under conditions where the feed compositions and operating parameters often vary.

3.1 BATCH EQUILIBRIUM TESTS

The purpose of the bench-scale batch ion-exchange tests was to determine the equilibrium isotherm for (a) a strontium and calcium binary system, and (b) the multicomponent process wastewater feed system consisting of strontium, calcium, magnesium, and sodium. Distribution coefficients and separation factors were determined from the batch equilibrium tests.

3.1.1 Binary (Sr-Ca) Equilibrium Data

Batch equilibrium tests were conducted at 23 ° C using approximately 50 mL of reagent grade strontium chloride feed solutions (13.0 mg/L Sr, 11 mg/L Cl) mixed for 24 hours with various quantities of Dowex HGR-W2 cation resin in the calcium form using a Burrell Model 75 wrist action shaker (setting = 6). The Dowex resin, originally in the sodium form, was converted to calcium form after washing with copious volumes of ~10 mg/L CaCl₂ solutions. The calcium form resin was thoroughly rinsed with water and allowed to dry in an oven at 100 ° C for one hour prior to mixing with the SrCl₂ feed solution. The binary data are given in Table 3. Distribution coefficients, the ratio of solute ion concentration on the resin (solid phase) divided by the solute ion concentration in solution (liquid phase) were calculated from a material balance obtained by analysis of the feed and supernate liquid concentrations.

Table 3. Binary (Sr-Ca) equilibrium data for strontium chloride solution and Dowex HGR-W2 Ca resin at 23 C.
(Shake Time = 24 hrs)

Part I. Feed concentrations			
		<u>mg/L</u>	<u>meg/L</u>
Strontium		13.6	0.309
Cl		10.9	0.309

Part II. Strontium equilibrium data				
Batch volume mL	Resin weight g	Liquid phase meg/L	Solid phase meg/ g resin	Distribution coefficient Kd mL/g-resin
50	0.1265	0.0309	0.1098	3557
50	0.0212	0.0871	0.5229	6005
50	0.0452	0.0586	0.2768	4723
50	0.0345	0.0640	0.3548	5545

Part III. Calcium equilibrium data					
Batch volume mL	Resin weight g	Liquid phase meg/L	Solid phase meg/ g resin	Kd Ca mL/g-resin	Alphas Kd(Sr)/Kd(Ca)
50	0.1265	1.15	3.54	3369	1.06
50	0.0212	0.6519	2.46	5334	1.13
50	0.0452	0.9438	2.96	3945	1.20
50	0.0345	0.6968	2.99	5231	1.06
Average Alpha =					1.11

Separation factors (α_s) are ratios of distribution coefficients for strontium and calcium respectively.

3.1.2 Multicomponent (Sr-Ca-Mg-Na) Equilibrium Data

The multicomponent batch equilibrium tests were conducted using simulated ORNL process wastewater feed with the major cations found in the wastewater (Sr^{+2} , Ca^{+2} , Mg^{+2} , and Na^{+}) and Dowex HGR-W2 resin. Feed solutions were equilibrated with the resin originally in the sodium form. All initial equilibration solutions contained 107 mg/L Sr, 71 mg/L Ca, 41 mg/L Mg, and 47 mg/L Na. Approximately 100 mL batches were allowed to mix for 24 hours with various quantities of resin at ambient temperature (23 ° C) using a Burrell Model 75 wrist action automatic shaker (setting equal 6). Samples of the feed and supernate liquid were analyzed to measure the equilibrium concentrations for strontium, calcium, magnesium, and sodium in the solution and the quantities of these cations that had been transformed to or from the resin. Concentrations in the solid resin phase were determined by changes in the solution concentrations. The multicomponent equilibrium data for both liquid and solid phases are given in Table 4. The separation factor (α) is the ratio of the distribution coefficient (K_d) for each component using calcium distribution as the reference.

Differences in distribution coefficients obtained in the binary (Sr-Ca) and multicomponent (Sr-Ca-Mg-Na) equilibrium tests are attributed to the multicomponent interactions between Ca and Mg. The resin prefers Sr over Ca, Mg, and Na, respectively. Since the resin has a finite capacity, Mg competition for sites on the resin and partial loading decreases the Ca concentration on the resin. By material balance, reduction in Ca ^ Table

Table 4. Multicomponent equilibria data for simulated ORNL process wastewater

Resin Wt. g	Liquid phase Conc. (meq/L)	Solid phase Conc. (meq/ g resin)	K_d (mL/g-resin)	α $K_d / K_d(Ca)$
Strontium equilibrium data				
0.2958	0.0106	0.817	7.70e+04	1.96
0.1875	0.318	1.13	3.54e+05	1.62
0.1574	0.572	1.18	2.06e+03	1.51
0.0564	1.47	1.69	1.15e+03	1.45
0.6728	0.0006 ^a	0.361	6.12e+05	4.99 ^b
0.3433	0.0065	0.705	1.09e+05	1.62
0.2529	0.0301	0.948	3.15e+04	1.87
0.3145	0.0100	0.769	7.67e+04	1.99
Average $\alpha = 1.72 \pm 0.22$				
Calcium equilibrium data				
0.2958	0.0305	1.19	3.92e+04	1
0.1875	0.701	1.53	2.18e+03	1
0.1574	1.13	1.55	1.36e+03	1
0.0564	2.47	1.95	7.90e+02	1
0.6728	0.0043	0.529	1.23e+05	1
0.3433	0.0154	1.03	6.70e+04	1
0.2529	0.0815	1.38	1.69e+04	1
0.3145	0.0292	1.12	3.86e+04	1

^a Concentration may be too low for accurate measurement.

^b Value not used in average.

Table 4. (continued)

Resin Wt. g	Liquid phase Conc. (meq/L)	Solid phase Conc. (meq/ g resin)	K_d (mL/g-resin)	α $K_d / K_d(Ca)$
Magnesium equilibrium data				
0.2958	0.0926	1.12	1.21e+04	0.309
0.1875	1.56	0.988	6.33e+02	0.291
0.1574	1.64	1.126	6.87e+02	0.504
0.0564	2.92	0.865	2.96e+02	0.375
0.6728	0.0119	0.505	4.24e+04	0.345
0.3433	3.28	0.0389 ^a	1.19e+01	1.78e-04 ^b
0.2529	0.0729	1.32	1.81e+04	1.07 ^b
0.3145	0.0771	1.06	1.38e+04	0.357
			Average $\alpha = 0.364 \pm 0.075$	
Sodium equilibrium data				
0.2958	10.7	1.08	273	0.007
0.1875	7.44	1.12	387	0.177
0.1574	8.36	0.0001 ^a	480	0.352 ^b
0.0564	4.45	0.0065	960	1.215 ^b
0.6728	11.7	2.56	123	0.001
0.3433	8.82	2.02	224	0.003
0.2529	10.8	0.557	320	0.019
0.3145	11.4	1.02	261	0.007
			Average $\alpha = 0.036 \pm 0.07$	

^a Concentration may be too low for accurate measurement.^b Value not used in average.

concentration on the resin increases the Ca concentration in the liquid phase. The net result is a decrease in the Ca distribution coefficient, (i.e., concentration ratio of Ca on resin to Ca concentration in liquid phase), for the multicomponent feed system. Strontium distribution coefficient on the resin is only decreased slightly when Mg is added. The average separation factors between Sr and Ca from the binary and multicomponent (Sr-Ca-Mg-Na) measurements were 1.1 and 1.7, respectively (see Table 3 and Table 4).

Batch tests were repeated at various shake times to determine that equilibrium was attained after 6 hours of continuous shaking. Table 5 gives strontium concentration in the supernate liquid that was essentially in equilibrium with the Dowex cation resin after various mixing times. The concentration of strontium in the supernate liquid remained essentially constant for shake times ≥ 6 hours.

3.2 BENCH-SCALE COLUMN TESTS

Bench-scale column tests were performed to measure experimental breakthrough curves and distribution coefficients at approximately the 50% breakthrough point for strontium, calcium, and magnesium in the process wastewater feed. Elution curves were measured to determine the efficiency of removing strontium and calcium ions from the loaded resin using dilute and strong salt (NaCl) solutions.

Table 5. Batch tests to determine time required to reach equilibrium

Sample ID	Strontium		Solid phase concentration meq/g resin	Shake time, hours	Equilibrium ^a % attained
	Liquid phase concentration				
	mg/L	meq/L			
FEED #2	3.50	0.0796	0	0	0.0
LS1	1.45	0.0329	1.22	1	64.9
LS2	0.75	0.0170	1.63	2	86.9
LS3	0.53	0.0121	1.76	4	93.7
LS4	0.33	0.0076	1.88	6	100.0
LS5	0.33	0.0076	1.88	24	100.0
Resin wt. g		0.0384			

^aEquilibrium is noted when the change in Strontium feed concentration divided by Strontium liquid concentration is constant.

3.2.1 Experimental Breakthrough Curves

Experimental breakthrough curves were obtained using ORNL process wastewater feed and a Dowex HGR-W2 cation-exchange resin originally in the sodium form. A fixed-bed ion-exchange column (7 mm id, 76 mm length) was packed with glass wool (to distribute flow over the column cross section) and then loaded with 3 mL (1.5 g) of Dowex HGR-W2 sodium form resin [20-50 mesh (0.84 - 0.30 mm), resin capacity equals 2.2 meq/mL wet resin].²¹ ORNL process wastewater feed at composition of 10.5 mg/L Sr, 53 mg/L Ca, 10 mg/L Mg, and 10.5 mg/L Na was fed to the top of the ion-exchange column at a flow rate of 3 mL/min (1 bed volume per minute). Effluent samples were collected at the bottom of the ion-exchange column and analyzed at intervals to produce concentration profiles (breakthrough curves) for calcium, strontium, and magnesium. These experimental breakthrough curves, shown in Fig. 3, were obtained by plotting the mean throughput versus fractional breakthrough (ie., effluent concentration divided by feed concentration). The distribution coefficient, K_d , is a volume-based (mL solution per mL resin) distribution approximately equal to the number of bed volumes which have been processed at 50% breakthrough. Distribution coefficients are often given in terms of the proportion of a metal adsorbed or not adsorbed (mL solution per gram dry resin) by an ion-exchange resin.²² Distribution coefficients of 879 mL solution per mL resin (1730 mL solution per gram dry resin) and 631 mL solution per mL resin (1245 mL solution per gram dry resin) were measured for strontium and calcium, respectively, during continuous loading on the ion-exchange resin.

3.2.2 Experimental Elution Curves

A test was performed to determine the removal and separation factor of strontium and calcium from the loaded resin as a function of 1 M NaCl and 5 M NaCl (eluent)

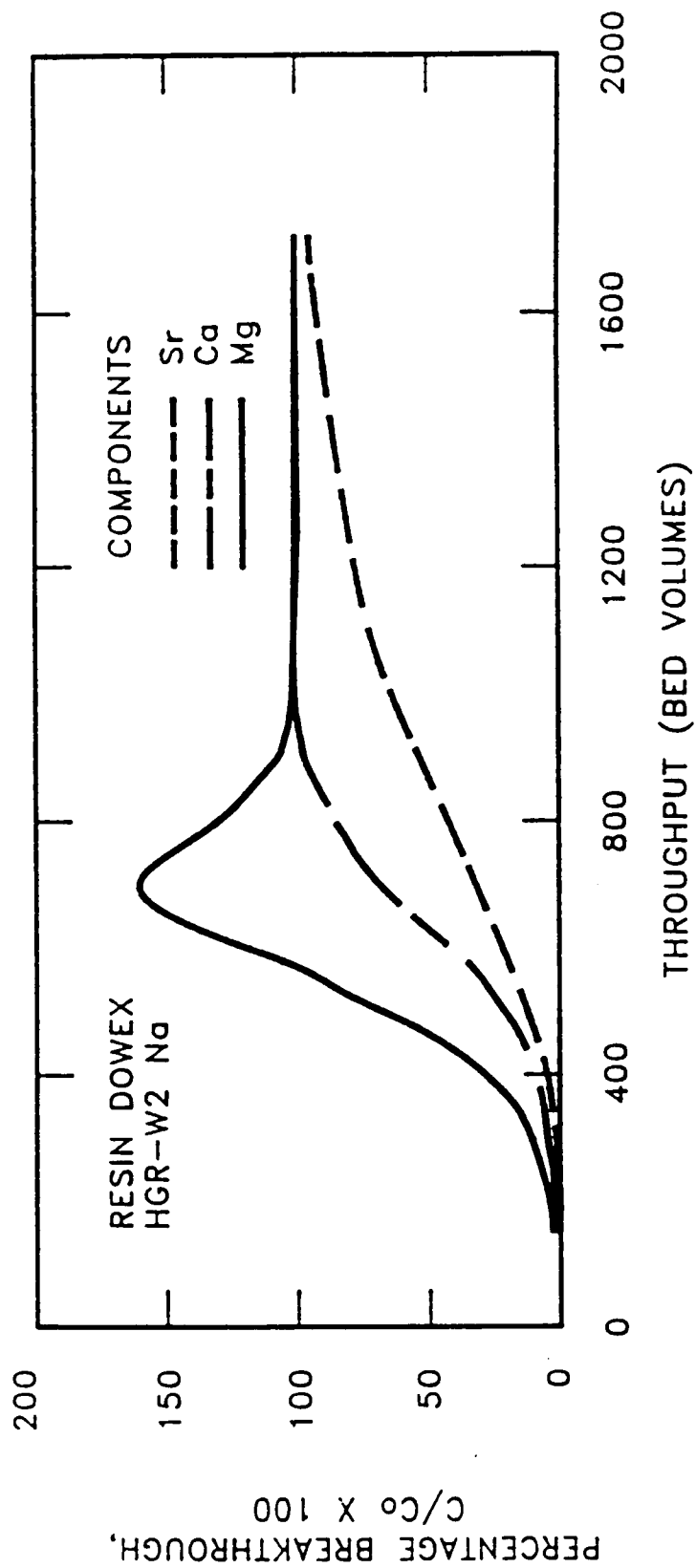


Fig. 3. Breakthrough curve for bench-scale column using ORNL process wastewater and Dowex HGR-W2 sodium form resin.

concentration. Strontium and calcium were removed from the loaded resin by scrubbing (eluting) with 1 M NaCl solution at a flow rate of 1 mL/min (1/3 bed volume/min).²³ The elution curves (Fig. 4) were obtained by plotting the concentration in the effluent divided by the mean concentration on the resin. A similar test was repeated using 5 M NaCl eluent. Separation factors between monovalent and divalent ions will change greatly between dilute and concentrated solutions because of Donnan effects (ie., electric potential differences between the solution and ion exchange resin that results when ions migrate between the two phases).³ Donnan potential excludes lower valence counter ions (Na^+) more efficiently than higher valence counter ions (Sr^{+2} , Ca^{+2} , etc.). Donnan potential is greater when the concentration difference between the ion exchange resin and solution is larger. Thus, for maximum efficiency, elution with Na^+ ions should be done at high concentrations, and loading with Sr^{+2} and Ca^{+2} ions will be best at low concentrations.

Results from the elution curves suggest that the Sr-Ca separation can be performed by removing most of the calcium from the loaded resin using the appropriate volume of dilute salt (1 M NaCl) solutions. Strontium and remaining cations can then be efficiently removed from the resin using a 5 M NaCl solution. Ultimately, the separation can be achieved using repeated volumes of dilute and concentrated salt solutions while simultaneously regenerating the resin (ie., loading resin with Na^+ ions).

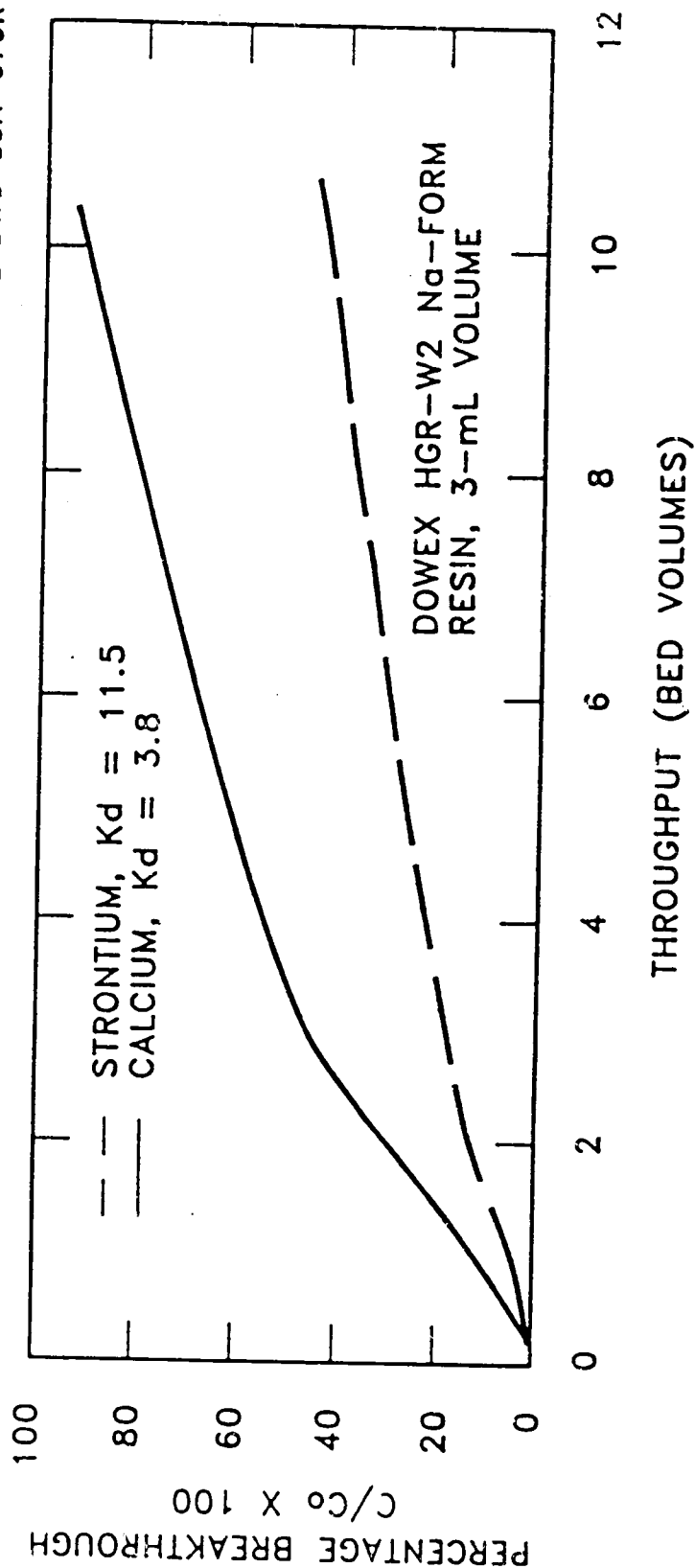


Fig. 4. Elution curve for removal of strontium and calcium from Dowex HGR-W2 sodium form resin using 1N NaCl in a bench-scale column.

3.3 PILOT-SCALE TESTS

3.3.1 Pilot-Scale Demonstration Test Plan

The primary objectives in demonstrating the pilot-scale CCIX system for removal of strontium from ORNL process wastewater were:

1. Develop operating parameters for near-steady-state operation of the CCIX system while simultaneously decontaminating the process wastewater stream via strontium separation from the process wastewater.
2. Demonstrate the removal efficiency of trace quantities of strontium from multicomponent ions (Ca, Mg, Na, etc.) in ORNL process wastewaters at near-steady-state operating conditions.
3. Determine the effect(s) of variations in feed stream compositions and flow rates on the removal efficiency of strontium from the process wastewater stream and on the separation factor between strontium and calcium on the loaded resin.
4. Evaluate the feasibility of the CCIX system as an alternative treatment method for decontaminating contaminated process wastewaters. Determine the expected volume reduction factors in terms of secondary waste generation.
5. Determine if models for Sr removal developed from batch and fixed-bed column experiments can be used to describe the CCIX behavior.

Feed stream compositions and flow rates were varied during test runs to demonstrate the column operations.

3.3.2 Continuous Countercurrent Ion-exchange (CCIX) System

The mobile pilot-scale CCIX system tested at ORNL for selective removal of strontium from process wastewater prior to discharge into the environment is shown in Fig. 5. This system is mounted on a standard, flat bed over-the-road type trailer approximately 40 ft (1219 cm) in length and 8 ft (244 cm) wide to allow easy transport. A 4 in. (10.2 cm) drip rail is welded around the perimeter of the trailer to contain any spills. A 1 1/2 in. (3.8 cm) diameter hand rail is installed around the work area for safety purposes. Six drain connections are installed on the bed to route all discharge liquids through a common drain header.

The trailer bed is equipped with (1) a control room [8 ft (244 cm) wide, 7 ft (213 cm) high, and 11 ft (335 cm) length], which houses the control panels, electrical systems (480 volt, single phase power supply input required), and work desk area; (2) five process tanks -- one feed tank [200 gal (756 L) tank, 36 in (91 cm) diameter, 51 in. (130 cm) length], four other tanks (strip feed, scrub feed, strip waste, and product effluent) each tank capacity is 59 gal (224 L), 22 in (56 cm) diameter, 36 in (91 cm) length; (3) three feed pumps, one two-stage carbon ceramic seal centrifugal 1 hp (.75 kw) motor Feed pump, and two diaphragm pumps for Scrub and Strip feed; (4) one single stage, two cylinder air compressor with a 30 gallon, ASME certified receiver and a 2 hp (1.5 kw), 117 VAC motor that supplies air for actuating valves located on the ion-exchange column; and (5) a double acting hydraulic piston lift system (117 VAC motor) for raising and lowering the pilot CCIX column which is hinged on the end of the trailer bed.

The column is raised to a vertical position during processing and is lowered onto the trailer bed during transport. The column is 27 ft (823 cm) in height and is sized to treat 3 gpm (11 L/min) of process wastewater as a test demonstration. The column is composed of four subsections -- (1) loading, (2) pulse, (3) scrub, and (4) a strip/rinse section -- each

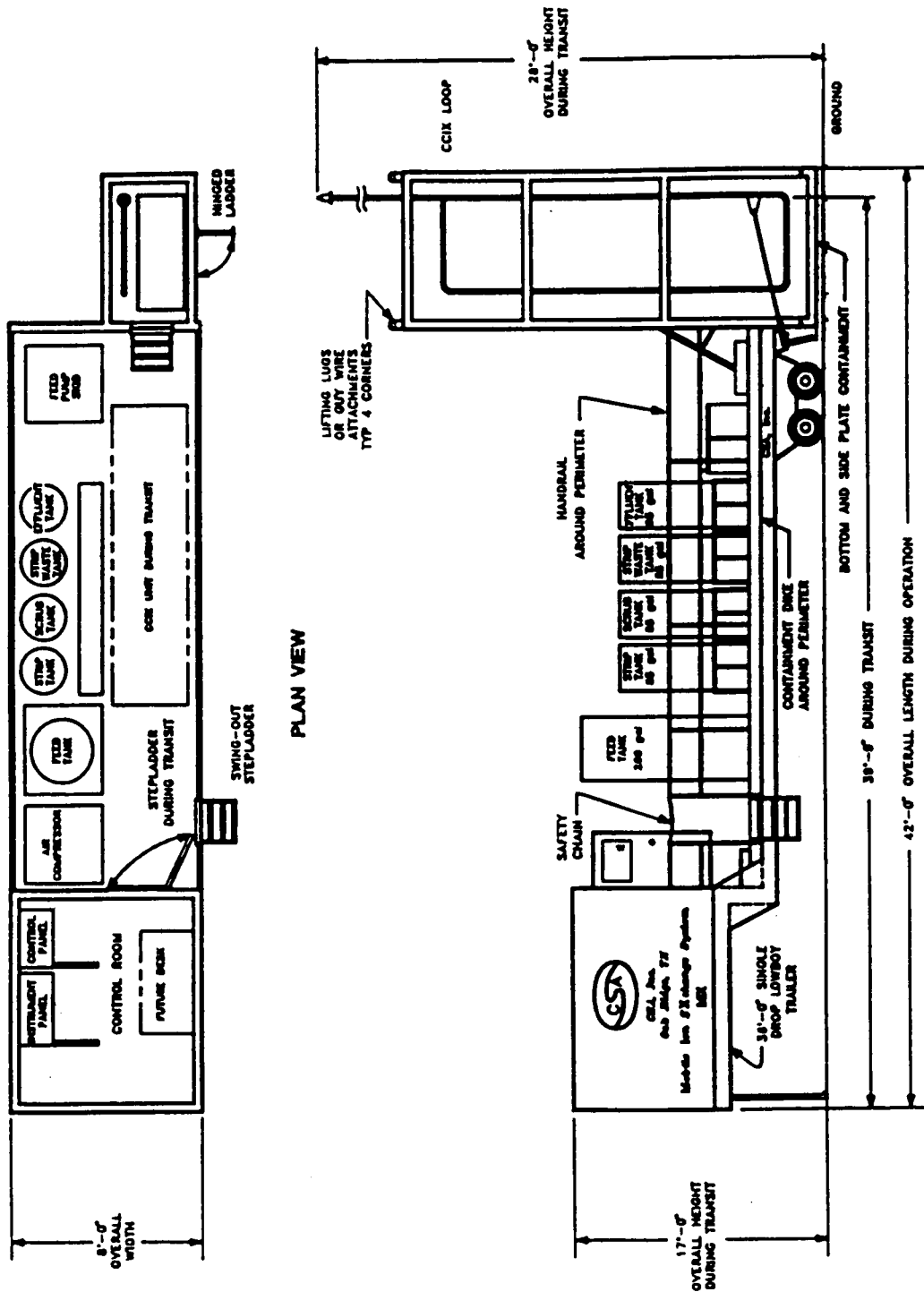


Fig. 5. Mobile Ion-Exchange (MIX) system for treatment of low-level radioactively contaminated wastewater.

connected in a closed loop separated by opening and closing of air operated 316 stainless steel ball valves.²⁴ A clear glass section [2 in. (5 cm) id pipe, 12 in. (30 cm) length] is located at the top of the strip/rinse section. This section is a sight-viewing observation point for monitoring the amount of resin movement per cycle. A plastic secondary containment shelter is installed around the column section to avoid potential spread of contamination to the environment in the event of a line rupture, valve failure, etc.

A Dowex HGR-W2 cation-exchange resin (10% cross linkage) originally in the sodium form is chosen by the CCIX manufacturer to perform the separation between the multicomponents based on the resin's affinity for Ca and Sr relative to Na, cost and availability, and high throughput capability. The resin is added to the column using a 50 psig (344 kPa) water supply and pulsed using a Procon Model 3611 high pressure pump around the column in a clockwise direction countercurrent with respect to the feed flow.

3.3.2.1 CCIX Loading Section

A schematic of the pilot-scale CCIX column is shown in Fig. 6. Stream compositions given are based on experimental results obtained at ORNL during pilot testing. Resin [(20-50 mesh) 0.84 - 0.30 mm] is initially charged into the CCIX column. The column loading section is a 5 ft (150 cm) length, 4 in. (10 cm) ID PVC pipe. The column is operated in cycles that are usually 30 to 40 minutes in length. At the end of each loading cycle, a regenerated volume of resin is introduced in the bottom of the loading section. Resin is generally pulsed a distance of ~1 ft (30 cm) at the end of each loading cycle around the column loop using approximately one gallon (3.8 L) of 50 psig (344 kPa) water supply per pulse. The volume of pulsed resin [618 mL, for a distance of 1 ft (30 cm) in a 2 in. (5 cm) id pipe] is set at the start of a run in the column pulse section by varying the length of the pulse stroke which is

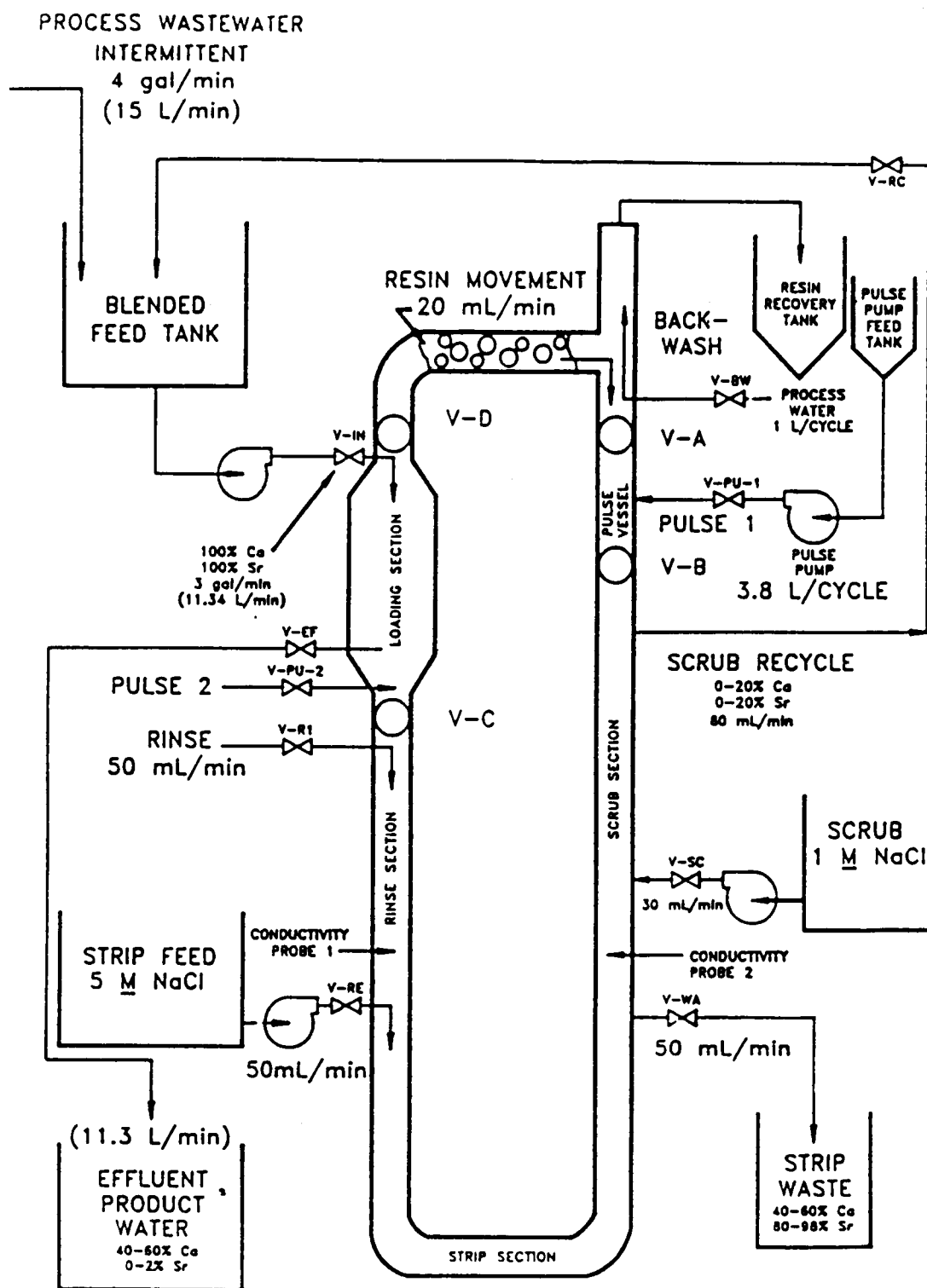


Fig. 6. Schematic of CCIX column tested for strontium removal from ORNL process wastewater.

controlled by ultrasonic probes that detect resin in the chamber and output an electrical signal to control the length of time the pulse pump operates thus regulating the volume movement of resin per cycle. Normally, there is a maximum interval of ten seconds between the end of one loading cycle and start of the consecutive loading cycle. This interval is the intermittent semi-continuous operating cycle for the CCIX system.

The length of loading cycle can be adjusted, however, to achieve optimum results and minimize the amount of strontium breakthrough in the effluent stream. During a loading cycle, the ion-exchange column loading section contains a fixed volume of resin [maximum volume is approximately equal to 12.3 L, i.e., the volume of a 5 ft (150 cm) length, 4 in. (10 cm) ID PVC pipe]. Process wastewater feed to the ion-exchange column is continuous during a loading cycle. Therefore, increasing the loading cycle is proportional to increasing the number of bed volumes processed through the ion-exchange column.

Process wastewater feed to the pilot-scale CCIX column is taken out of an equilization basin which collects all ORNL process wastewater to be treated at the existing PWTP. The process wastewater feed is blended with the scrub recycle in the 200 gal (756 L) blended feed tank. Process wastewater feed to the blended feed tank is controlled by a level controller switch in the blended feed tank. As the liquid level declines in the blended feed tank, a signal is sent to a solenoid valve to open the inlet valve to the blended feed tank and start the process wastewater feed pump [normally, the process wastewater feed pump delivers 4 gal/min (15 L/min)]. The blended feed is pumped to the column during the loading cycle at a constant flow rate of 3 gpm (11 L/min) in a countercurrent direction with respect to the resin flow. The pressure drop at this flow rate is normally in the range of 30 to 40 psig (207 to 275 kPa). Strontium and calcium are loaded on the resin in the loading section. Magnesium and the other components of the process wastewater are only partially loaded on the resin

because of calcium competition and higher resin selectivity for strontium and calcium, respectively (see breakthrough curve, Fig. 3, Section 3.2.1). As a result, magnesium and all other components breakthrough into the effluent stream. The effluent stream is collected in the effluent tank at a rate equal to the blended feed rate to the ion-exchange column. Samples of the blended feed and effluent are analyzed for calcium after the start of a run. Normally, the column is operated to allow 50% of the calcium originally in the blended feed to breakthrough in the effluent stream, leaving calcium (50%) and strontium (100%) loaded on the resin. The remaining calcium (50%) on the resin is removed in the scrub section and recycled to the blended feed tank. Strontium loaded on the resin is removed in the strip section of the column. At optimum conditions, the effluent contains 100% of the calcium and magnesium and essentially 0% strontium originally in the blended feed. The effluent stream can not contain more than 11 Bq/L strontium to allow discharge in the environment.

The loading section is isolated from each of the other sections of the CCIX loop by closing the stainless steel ball valves (V-C and V-D) during the loading cycle. Valve operations on the column are controlled by a programmable controller which is programmed to close each valve automatically at the start of the loading cycle and open each valve at the end of each loading cycle.

3.3.2.2 CCIX Pulse Section

Resin, loaded primarily with calcium and strontium, is pulsed up into the backwash section, where the resin is fluidized to remove any fine particles that might accumulate during processing. Fine particles are recovered in the Resin Recovery Tank. The backwashed, loaded resin drops down into the pulse vessel by gravity flow (Fig. 6) when valve V-A is automatically opened during the programmed cycle. The pulse vessel is fabricated from 3 in.

(7.6 cm) schedule 10, 316L stainless steel pipe. The pulse chamber is equipped with ultrasonic probes to indicate resin levels and thus provide an evenly measured volume of resin during each pulse cycle. When the resin level reaches the top resin level sensor, the resin level controller closes valve V-A. The overall resin flow rate may be controlled over a wide range by varying the length of time the pulse pump operates and/or by adjusting a pressure relief valve on the pump discharge to vary the amount of back pressure resistance seen by the pump which alters the volume discharged by the pump per cycle. Generally, the pressure relief valve is set to relieve at 120 psig (827 kPa), and the pulse pump is allowed to operate a maximum of 10 seconds before the ultrasonic probe detector automatically shuts off the pump. The volume of resin movement per cycle is set at the start of a run and remains constant during operation.

3.3.2.3 CCIX Scrub Section

Resin loaded with strontium and calcium is pulsed from the pulse section into the scrub section. The column scrub section is a 9 ft (2.7 m) length, 2 in. (5 cm) id PVC pipe. A 0.5 to 1.0 M NaCl solution is pumped to the scrub section countercurrent with respect to the resin flow to selectively remove calcium from the resin. Approximately 80 to 100% of the strontium remains on the resin. Since calcium has a lower affinity than strontium, calcium is preferentially eluted using the dilute salt scrub solution. The resulting solution is collected in the scrub recycle stream and blended with the process wastewater feed. The amount of calcium that is removed from the resin can be controlled by varying the concentration of the salt (NaCl) scrub feed solution and the pump rate. The objective is to adjust the flow ratio of scrub-to-resin, Sc/R, so that bulk calcium is removed by the scrub solution leaving bulk

strontium on the resin. The scrub pump rate is controlled by a programmable timer that is set to vary the length of time the pump is operated.

3.3.2.4 CCIX Strip/Rinse Section

Resin, loaded primarily with strontium, is pulsed around the CCIX loop from the scrub section into the strip/rinse section. The column strip/rinse section is a 14 ft (4.3 m) length, 2 in. (5 cm) id PVC pipe. A 3.5 to 5 M NaCl solution is pumped to the strip/rinse section countercurrent with respect to the resin flow to remove strontium from the resin. The strip section feed pump is controlled by a programmable timer to vary the volume of strip solution feed to the column per cycle. Conductivity probe 2 is used to control the interface between dilute salt (0.5 to 1.0 M NaCl scrub feed) and strong salt (3.5 to 5.0 M NaCl strip feed) solutions. Conductivity readings for 3.5 to 5.0 M NaCl solutions are initially measured using conductivity probe 2. These readings become the high level set point for conductivity probe 2. At the high-level setpoint (detection of strong salt solutions), an electrical signal is sent from conductivity probe 2 to a solenoid valve to open valve V-WA allowing strontium rich eluate collection in the strip waste tank.

After strontium is removed, the resin is then washed with clean rinse water prior to entering the bottom of the column loading section. The volume of rinse water is controlled by conductivity probe 1. At the start of a run, the conductivity of the strip salt solution feed is measured using conductivity probe 1. This conductivity reading becomes the high setpoint for conductivity probe 1. At the high setpoint (strong salt solution detection), an electrical signal is sent to a solenoid valve to open the rinse valve V-R1 allowing water to flow down into the strip section thus rinsing the resin free of salt solution.

Strontium-rich eluate collected in the strip waste tank is precipitated as the carbonate by addition of sodium carbonate. Strontium and any residual calcium precipitates are filtered and ultimately disposed as solid waste.

3.3.3 CCIX System Operating Parameters

Operating parameters for the CCIX system are defined in terms of a ratio of (1) feed (F) flow rate to resin (R) flow rate (F/R), (2) scrub (Sc) flow rate to resin flow rate (Sc/R), and (3) strip (St) flow rate to resin flow rate (St/R). The F/R ratio is varied in the column loading section by increasing and/or decreasing the length of loading cycle time or resin movement since the feed rate to the ion-exchange column is constant (see Section 3.3.2.1). Feed rates for the scrub and strip streams are varied during consecutive runs to change the Sc/R and St/R ratios.

Composition of the flowing streams in the CCIX system vary as a result of the cyclic operation. Concentration variables are (1) the composition of multicomponent ions in the process wastewater feed as shown in Table 1 and Table 2 (see Section 2.2.1), (2) the composition of scrub feed which is varied in the range of 0.5 to 1.0 N NaCl, and (3) the composition of strip feed which is varied in the range of 3.5 to 5 N NaCl.

3.4 CCIX EXPERIMENTAL RESULTS

Testing of the pilot-scale CCIX system was designed to establish operating parameters for an actual operating system when system parameters often vary. The composition of the blended feed to the CCIX column was a noted variable that changed gradually as the process wastewater feed composition varied and as the composition of the scrub recycle stream varied. Typically, the blended feed composition was in the range of 0.1 to 0.3 mg/L (300 µg/L) total

strontium and 1200 Bq/L ^{90}Sr , 40 to 60 mg/L Ca, 10 mg/L Mg, 20 to 40 mg/L Na, 100 Bq/L ^{137}Cs , and 2410 Bq/L gross beta. The process wastewater feed to the CCIX system was taken directly from a centralized equalization basin. Variations in the basin composition resulted from changes in generator inputs and environmental conditions (rain, snow, etc.). Table 6 shows a typical variation in the basin compositions for a given day.

Under normal operating conditions, compositions of the scrub and strip feed streams and flow rates were 1.0 M NaCl at a feed rate of 30 mL/min and 5.0 M NaCl at a feed rate of 50 mL/min, respectively. These variables were generally constant in a given test run. The concentrations of the scrub and strip feed solutions and flow rates were changed in some of the pilot test runs to determine how each parameter affects the removal efficiency between strontium and calcium loaded on the resin. These tests were noted in the following discussion of results. Strontium material balances were made for each run to indicate strontium distribution in the effluent, scrub recycle, and strip waste streams in terms of mass fractions of the blended feed inlet stream.

The CCIX system process dynamics were found to vary due to the intermittent operation of the system. Normally, the CCIX system was operated continuously for a 30 minute loading cycle, then the operation was interrupted for a maximum of 10 seconds to pulse a volume of regenerated resin into the bottom of the loading section; and finally, the operation cycle was repeated. Since the blended feed composition was an uncontrolled variable, test runs were made at constant flow rates and compositions in scrub and strip feed streams to determine the number of operating cycles required to obtain a near-steady-state condition.

One of the primary advantages of the CCIX system was its potential to remove strontium from the wastewater while simultaneously eliminating additional secondary waste

Table 6. Typical daily variation in process wastewater feed and blended feed streams

Date	Sample time (hrs)	CCIX blended feed assay				Process wastewater feed assay			
		Component composition:				Component composition:			
		Sr mg/L	Ca mg/L	Mg mg/L	Na mg/L	Sr mg/L	Ca mg/L	Mg mg/L	Na mg/L
6/14/89									
	1000	3.2	89	13	73	0.13	51	10	26
	1200	4.0	99	12	96	0.14	55	10	22
	1400	2.4	76	12	65	0.13	53	10	20
	1800	2.3	76	11	71	0.14	55	10	20
	2200	1.9	170	12	60	1.5	90	12	58
6/15/89									
	0200	1.6	110	15	62	1.4	74	11	72
	0600	1.4	130	12	88	2.4	60	4.8	120
	1000	0.55	62	11	41	0.14	51	9.9	25
	1400	<u>0.44</u>	<u>58</u>	<u>11</u>	<u>33</u>	<u>0.13</u>	<u>49</u>	<u>9.7</u>	<u>24</u>
	Mean:	1.98	97	12	65	0.68	60	10	43

streams by recycling the 5 M strip waste streams used to separate strontium and calcium from the loaded resin (see flowsheet Fig. 2, Section 2.2.3). Preliminary batch precipitation tests were performed using the CCIX strip waste stream and a sodium carbonate solution to confirm that the strip waste streams could be recycled as strip feed. Results from these tests were needed to estimate the amount of radioactivity that would remain in the supernate solution after strontium and calcium had been removed by chemical precipitation. Removal of strontium and radioactivity from the stream would minimize the generation of an additional waste stream that would require further treatment prior to discharging to the environment.

3.4.1 Process Dynamics

The operating conditions for the experimental CCIX runs are summarized in Table 7. Runs 1-8 ("cold runs") were made using simulated ORNL process wastewater feed (tap water spiked with nonradioactive strontium). Runs 9-33 ("hot runs") were made using actual ORNL process wastewater. The principal operating parameters (defined in Section 3.3.3) were liquid flow rates, feed stream compositions, and resin pulse rates. Liquid flow rates and resin pulse rates were maintained by a programmable controller. Blended feed stream compositions were uncontrolled variables.

The CCIX process dynamics (Fig. 7) for a typical blended feed composition are periodic as a result of the intermittent nature of the system operation. The blended feed residence time in the column loading section was approximately equal to one minute. There was an initial transient period in the stream compositions after which cyclic steady-state was attained. A schematic of the pilot-scale CCIX system (Fig. 6, Section 3.3.2.1) gives the integral relation of the loading, pulse, scrub, and strip/rinse sections. Since each section was connected in a closed loop, cyclic variations in one section tended to generate similar delayed variations

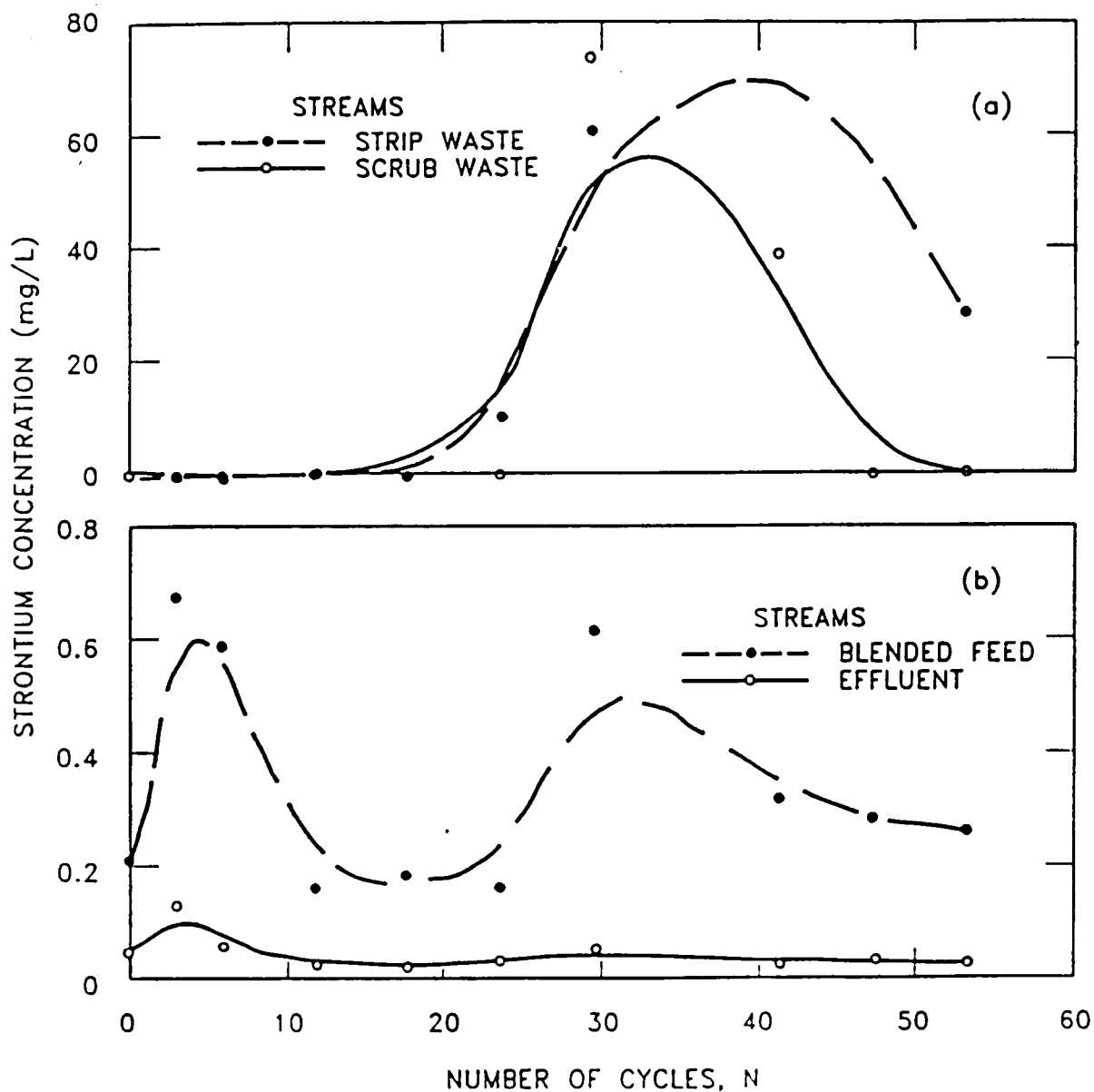


Fig. 7. Dynamic profile of CCIX system continuous operation.

Table 7. Operating conditions for CCIX pilot-scale tests

Run No.	Run time (hrs)	Operating cycles No.	Date	Flow ratios			Average flow rates									
				F / R	St / R	Sc / R	Bfeed rate L/min	Strip rate mL/min	Scrub rate mL/min	Strip waste mL/min	Recycle rate mL/min	Resin rate mL/min	Rinse rate mL/min			
Cold Runs																
"	1	24	48	1/10/89	438	1.0	0.6	11.4	26.0	14.7	34.2	40.0	26.0	33.5		
"	2	24	48	1/11/89	438	1.0	0.6	11.4	26.0	14.7	34.2	40.0	26.0	33.5		
"	3	20	40	1/16/89	438	1.0	0.6	11.4	26.0	14.7	34.2	40.0	26.0	33.5		
"	4	24	48	1/17/89	602	2.3	1.7	11.4	43.8	32.0	65.1	40.0	19.0	29.3		
"	5	21	42	1/18/89	673	2.6	1.9	11.4	43.8	32.0	65.1	40.0	17.0	29.3		
"	6	13	26	1/30/89	606	3.1	1.7	12.1	62.3	34.6	6.6	90.6	20.0	0.3		
"	7	29	58	1/31/89	525	2.7	1.7	11.4	58.8	36.3	45.0	74.6	21.7	24.4		
"	8	42	84	2/02/89	543	2.9	1.4	11.5	60.6	29.4	46.7	70.4	21.2	27.1		
Hot Runs																
"	9	18	36	2/4/89	474	2.7	1.4	11.4	64.0	34.6	54.5	70.4	24.0	26.2		
"	10	11	22	2/22/89	509	2.8	1.6	11.6	64.0	36.3	51.9	82.7	22.9	34.2		
"	11	11	22	2/23/89	559	2.9	0.9	11.8	60.6	19.7	40.5	83.0	21.1	43.2		
"	12	11	22	2/28/89	*	*	*	11.8	60.2	18.7	40.1	70.2	20.2	31.4		
"	13	11	22	3/1/89	618	2.9	2.4	11.7	55.4	45.7	37.0	107.0	18.9	42.6		
"	14	11	22	3/2/89	621	2.5	2.6	11.7	47.5	49.4	30.7	106.0	18.9	39.4		
"	15	11	22	3/3/89	621	6.0	2.4	11.7	112.0	45.2	74.8	133.0	18.9	50.2		
"	16	10	20	3/16/89	542	3.5	1.5	11.2	72.1	31.2	56.2	128.0	20.6	80.8		
"	17	11	22	3/18/89	595	3.8	1.6	11.4	73.6	31.2	51.9	69.5	19.2	16.7		
"	18	10	20	3/22/89	561	2.0	1.1	11.6	41.9	23.0	20.9	77.1	20.6	33.1		
"	19	10	20	3/29/89	561	1.8	1.6	11.6	37.4	33.0	20.8	85.8	20.6	36.2		

Table 7 (Continued)

Run No.	Run time (hrs)	Operating cycles No.	Date	Flow ratios			Average flow rates							
				F / R	St / R	Sc / R	Bleed rate L/min	Strip rate mL/min	Scrub rate mL/min	Strip waste mL/min	Recycle rate mL/min	Resin rate mL/min	Rinse rate mL/min	
"	20	10	20	4/5/89	561	1.9	1.4	11.6	37.4	33.0	20.8	85.8	20.6	36.2
"	21	30	60	4/11/89	564	2.0	1.6	11.0	39.8	29.5	43.3	64.7	19.5	38.7
"	22	43	86	4/13/89	579	2.5	1.6	10.9	47.4	30.5	47.4	64.3	18.9	33.8
"	23	45	90	4/16/89	545	2.4	1.6	10.8	46.8	31.5	48.6	64.3	19.7	34.7
"	24	10	20	4/20/89	488	2.1	1.7	11.2	48.9	39.9	57.7	69.7	22.9	38.6
"	25	56	112	5/9/89	521	2.5	1.9	11.3	53.3	40.3	65.2	106.0	21.7	77.2
"	26	24	48	5/12/89	529	2.1	1.9	11.5	46.7	40.3	74.7	132.0	21.7	120.0
"	27	24	48	5/13/89	529	2.2	1.4	11.5	48.6	30.7	37.6	101.0	21.7	59.4
"	28	24	48	5/14/89	509	2.1	2.1	11.1	46.5	49.7	70.9	135.0	21.7	109.0
"	29	29	58	5/15/89	542	2.3	1.8	11.5	48.5	39.1	17.8	125.0	21.2	55.0
"	30	32	32	6/5/89	624	2.3	1.6	11.8	42.7	29.7	7.1	100.0	18.9	34.7
"	31	31	31	6/14/89	1119	2.7	1.7	11.5	28.1	17.7	59.3	100.0	10.3	114.0
"	32	36	53	6/21/89	977	4.5	2.7	11.2	51.8	30.8	79.9	87.2	11.4	84.5
"	33	12	18	6/26/89	1289	5.7	3.0	11.4	50.5	26.3	49.6	75.0	8.9	47.7

* No samples taken; volume low

in adjacent sections, ultimately effecting the overall system performance. Under normal operating conditions, near-steady-state results in the effluent stream compositions (strontium concentrations given in the bottom half of Fig. 7) appear to be attained after 20-25 operating cycles (10 to 12 hours semi-continuous operation for a 30 minute loading cycle) which translates to one half the distance around the column for most of the CCIX test runs.

Resin loaded primarily with strontium and calcium exiting the column loading section (clockwise direction) during the pulse event (see Fig. 6, and Section 3.3.2.1) was initially contacted with dilute salt solution (1 M NaCl) in the column scrub section after 8 to 10 operating cycles. The loaded resin would be contacted with concentrated salt solution (5 M NaCl) in the column strip section after 12 to 15 operating cycles. Strontium concentration profiles for the strip waste and scrub recycle streams are given in the top half of Fig. 7. The CCIX column was operated semi-continuously on the average of 21 hours/run (42 cycles/run) during the initial test runs. During the final test runs, the column was operated semi-continuously on the average of 12 hours/run (24 cycles/run).

3.4.2 Operating Parameter Effects on Strontium Removal

Flow parameters (F/R , St/R , and Sc/R) were adjusted in consecutive test runs to determine the effect(s) of feed composition and flow rates on the removal efficiency of strontium and separation of strontium and calcium from the loaded resin at conditions near-steady-state. In test Runs 1-12, resin in the loading section was loaded for less than 30 minutes (30 bed volumes) per cycle to intentionally minimize breakthrough of strontium in the effluent stream. Samples of the blended feed, effluent, scrub recycle, and strip waste collection were taken at the end of each run. Results from these runs (Tables 8 & 9) revealed that magnesium and sodium offer little competition for sites on the resin relative to

strontium and calcium. These results were anticipated from the bench-scale breakthrough curves (see Fig. 3, Section 3.2.1).

3.4.2.1 Feed to Resin Ratio Parameter

The feed to resin (F/R) ratio was a measurement of the column throughput in bed volumes. This ratio coupled with (1) resin regeneration efficiency, (2) axial diffusion, (3) resin mixing during the pulse cycle, and (4) channeling in the column were factors that would increase the fractional breakthrough. These factors were identified in the modeling of the ion-exchange system (see Section 4). The pilot-scale results, in Runs 1-4, indicated that the strontium fractional breakthrough in the effluent stream increased nearly a factor of 8 when the F/R ratio was increased only 40%. The effects of the individual factors listed above on the fractional breakthrough of strontium in the effluent stream were not determined independently in the pilot-scale testing since the blended feed compositions varied continuously.

3.4.2.2 Scrub to Resin Ratio Parameter

Separation factors (ratio of distribution coefficients) between strontium and calcium were determined in Section 3.2.1 and Section 3.2.2. Resin elution is more efficient at high Na^+ concentrations (5 M NaCl) than dilute (1 M NaCl) concentrations. The salt concentration of the scrub feed solution significantly affected the removal efficiency of strontium and calcium from the loaded resin. In Run 7 and Run 8, the salt concentration was increased from 1 M NaCl to approximately 3 M NaCl due to mixing (5 M NaCl strip feed solution mixing with 1 M NaCl scrub feed solution) that resulted from intermittent

Table 8. CCIX pilot-scale test blended feed and effluent stream assays

Run No.	Date	Blended feed assay					Effluent stream assay						
		Sr (mg/L)	Na (mg/L)	Cl (M)	CaCO ₃ T Hard (mg/L)	Ca (mg/L)	Mg (mg/L)	Sr (mg/L)	Na (mg/L)	Cl (M)	CaCO ₃ T Hard (mg/L)	Ca (mg/L)	Mg (mg/L)
1	1/10/89	0.41	53.0	0.01	92.6	74.1	18.5	0.01	190	0.01	15.7	2.7	13.0
2	1/11/89	0.66	100	0.01	119	100.0	19.0	0.03	160	0.01	21.0	5.0	16.0
3	1/16/89	0.28	150	0.01	93.0	82.0	11.0	0.02	270	0.01	15.7	10.0	5.7
4	1/17/89	0.17	380	0.02	62.4	53.0	9.4	0.16	390	0.02	67.1	58.0	9.1
5	1/18/89	0.30	720	0.04	95.0	84.0	11.0	0.01	330	0.02	12.0	8.4	3.6
6	1/30/89	0.48	60.0	0.01	98.0	88.0	10.0	0.12	60.0	0.00	18.2	9.0	9.2
7	1/31/89	0.54	52.0	0.01	88.0	77.0	11.0	0.05	52.0	0.00	22.0	11.0	11.0
8	2/2/89	0.20	67.0	0.01	48.0	38.0	10.0	0.05	67.0	0.00	11.8	0.8	11.0
9	2/4/89	5.70	43.0	0.01	100	89.0	11.0	0.07	43.0	0.01	61.8	52.0	9.8
10	2/22/89	0.53	350	0.02	130	120	9.6	0.08	440	0.02	63.6	54.0	9.6
11	2/23/89	0.25	8.70	0.00	64.6	55.0	9.6	0.07	120	0.01	18.6	14.0	4.6
12	2/28/89	NO SAMPLES TAKEN, SYSTEM VOLUME TOO LOW											
13	3/1/89	0.85	580	0.03	149	140	9.4	0.63	650	0.03	101.4	92.0	9.4
14	3/2/89	0.35	73.0	0.01	75.7	67.0	8.7	0.01	140	0.01	6.5	2.7	3.8
15	3/3/89	0.30	41.0	0.01	68.0	68.0	9.6	0.05	123	0.01	43.3	34.0	9.3
16	3/16/89	23.90	384	0.03	169	150	19.2	12.7	107	0.01	10.1	6.6	3.5
17	3/18/89	0.50	202	0.01	108	95.0	13.0	0.13	306	0.02	60.5	50.0	10.5
18	3/22/89	0.33	92.1	0.01	75.4	66.2	9.2	0.05	576	0.00	0.1	0.1	0.0
19	3/29/89	0.18	483	0.02	70.2	60.2	10.0	0.01	124	0.01	10.8	8.3	2.5
20	4/05/89	0.18	52.0	0.01	51.6	51.6	11.0	0.01	124	0.01	64.3	54.3	10.0
21	4/11/89	0.06	23.0	0.00	46.2	46.2	9.7	0.01	23.0	0.00	11.2	0.2	11.0
22	4/13/89	0.10	43.0	0.01	67.9	67.9	11.0	0.00	43.0	0.00	10.9	0.9	10.0
23	4/16/89	0.03	52.0	0.01	58.0	58.0	10.0	0.01	52.0	0.00	14.8	5.2	9.6
24	4/20/89	0.04	28.0	0.00	57.9	57.9	9.6	0.01	28.0	0.00	14.2	4.8	9.4
25	5/09/89	0.17	23.0	0.01	81.2	81.2	9.4	0.01	23.0	0.00	17.9	8.6	9.3
26	5/12/89	0.29	24.0	0.01	106	106	9.7	0.01	24.0	0.00	28.8	18.8	10.0

Table 8. (Continued)

Run No.	Date	Blended feed assay					Effluent stream assay						
		Sr (mg/L)	Na (mg/L)	Cl (M)	CaCO ₃ T Hard (mg/L)	Ca (mg/L)	Mg (mg/L)	Sr (mg/L)	Na (mg/L)	Cl (M)	CaCO ₃ T Hard (mg/L)	Ca (mg/L)	Mg (mg/L)
27	5/13/89	0.24	43.0	0.01	106	106	9.5	0.01	43.0	0.00	29.8	18.8	11.0
28	5/14/89	0.21	44.0	0.01	84.7	84.7	8.7	0.01	44.0	0.00	25.8	14.8	11.0
29	5/15/89	7.38	26.0	0.01	84.1	84.1	11.0	1.15	28.0	0.00	63.7	52.7	11.0
30	6/5/89	3.90	730	0.04	164	150	14.0	0.96	770	0.04	53.0	41.0	12.0
31	6/14/89	1.98	65.4	0.01	109	96.7	12.1	0.61	115	0.01	48.3	36.1	12.2
32	6/21/89	0.69	27.5	0.01	107	94.4	13.1	0.55	93.2	0.01	56.8	46.1	10.7
33	6/26/89	0.35	47.3	0.01	120	109	11.3	0.45	78.8	0.01	90.8	79.3	11.5

Table 9. CCIX pilot-scale test scrub recycle and strip waste stream assays

Run No.	Date	Scrub recycle assay					Strip waste assay						
		Sr (mg/L)	Na (mg/L)	Cl (M)	CaCO ₃ T Hard (mg/L)	Ca (mg/L)	Mg (mg/L)	Sr (mg/L)	Na (mg/L)	Cl (M)	CaCO ₃ T Hard (mg/L)	Ca (mg/L)	Mg (mg/L)
1	1/10/89	31.0	7100	0.91	10900	9200	1700	97.0	36000	1.68	2174	2100	74.0
2	1/11/89	19.0	5200	0.43	3750	3300	450	37.0	40000	2.02	5430	5300	130
3	1/16/89	0.01	110	0.00	2.5	2.3	0.22	0.14	1600	0.07	42.9	41.0	1.9
4	1/17/89	0.07	390	0.02	22.3	20.0	2.30	6.40	29000	1.29	631	610	21.0
5	1/18/89	21.0	15000	0.88	4480	4300	180	4.90	34000	1.50	383	370	13.0
6	1/30/89	2.00	13000	0.58	306	190	116	19.0	36000	1.60	725	699	26.0
7	1/31/89	72.0	13000	1.06	9772	9600	172	17.0	28000	1.26	793	780	13.0
8	2/2/89	53.0	13500	1.15	11166	11000	166	29.0	28000	1.35	1723	1700	23.0
9	2/4/89	32.0	14000	1.01	7993	7900	93.0	16.0	29000	1.32	1216	1200	16.0
10	2/22/89	41.0	7000	0.39	1597	1500	97.0	11.0	11000	4.83	885	860	25.0
11	2/23/89	65.0	37000	2.15	10480	10000	480	16.0	12000	5.26	914	890	24.0
12	2/28/89				NO SAMPLES TAKEN, SYSTEM VOLUME TOO LOW								
13	3/1/89	52.0	29000	1.62	7000	6700	300	16.0	84000	3.68	521	510	11.0
14	3/2/89	52.0	23000	1.38	7290	7000	290	12.0	85000	3.73	652	640	12.0
15	3/3/89	38.0	23500	1.30	5288	5000	288	11.0	85000	3.72	531	520	11.0
16	3/16/89	25.7	13000	0.78	4081	3680	401	7.9	8820	0.39	123	111	11.5
17	3/18/89	62.0	27000	1.66	9458	8960	498	24.6	99500	4.38	1065	1050	15.3
18	3/22/89	62.0	27000	1.66	9458	8960	498	29.0	85300	3.77	1154	1140	13.9
19	3/29/89	34.8	14560	1.02	7330	6860	470	23.3	74400	3.34	2004	1990	14.0
20	4/05/89	34.8	14560	0.94	5875	5520	355	23.3	73000	3.30	2516	2503	13.0
21	4/11/89	17.1	13700	0.82	4166	3764	401	23.0	78000	3.68	5682	5670	12.0
22	4/13/89	9.4	23660	1.32	5584	5316	268	19.7	72000	3.60	9439	9428	11.0
23	4/16/89	13.0	23000	1.38	7284	6929	355	15.1	71000	3.49	7973	7950	23.0

Table 9. (Continued)

Run No.	Date	Scrub recycle assay					Strip waste assay						
		Sr (mg/L)	Na (mg/L)	Cl (M)	CaCO ₃ T Hard (mg/L)	Ca (mg/L)	Mg (mg/L)	Sr (mg/L)	Na (mg/L)	Cl (M)	CaCO ₃ T Hard (mg/L)	Ca (mg/L)	Mg (mg/L)
24	4/20/89	11.4	24000	1.41	7082	6792	290	14.4	68000	3.34	7614	7591	23.0
25	5/09/89	15.5	23688	1.34	5993	5616	377	0.85	66000	2.89	400	389	11.0
26	5/12/89	9.9	23780	1.18	2751	2584	167	3.60	71000	3.12	615	604	11.0
27	5/13/89	10.2	23457	1.16	2700	2584	116	1.72	33000	1.47	628	604	24.0
28	5/14/89	20.7	12347	0.78	4739	4567	172	2.08	36000	1.58	324	313	11.0
29	5/15/89	388	13700	0.73	2375	2237	138	6.40	36500	1.61	481	470	11.0
30	6/5/89	388	13789	0.74	2505	2237	268	6.40	57000	2.50	481	470	11.0
31	6/14/89	176	3736	0.41	4631	4341	290	160	35511	1.59	796	784	11.9
32	6/21/89	66.3	12430	0.74	3831	3563	268	90.8	52700	2.34	878	869	9.0
33	6/26/89	37.3	7447	0.63	5814	5413	401	35.5	71000	3.14	957	948	9.5

failure of valve V-WA (see Fig. 6, and Section 3.3.2.1). The result was nearly a factor of four increase (0.27 for Run 1 to 0.87 Run 7, see Table 10) of strontium in the Scrub recycle stream. At constant salt concentrations in the scrub section, increases in the scrub to resin (Sc/R) ratio from 0.6 to 3.0 had little effect on the amount of strontium removed from the loaded resin in the scrub section of the column.

3.4.2.3 Strip to Resin Ratio Parameter

The resin regeneration efficiency in the strip section was critical in minimizing the fractional breakthrough of feed components in the column loading section. The overall performance results of the CCIX system was dependent on introduction of thoroughly regenerated resin (free of strontium and calcium) from the column strip section into the column loading section. The efficiency of resin regeneration was increased at high salt concentrations (5 M NaCl) which was anticipated qualitatively from Donnan effects. The loaded resin was more thoroughly stripped of strontium and calcium at higher salt concentrations. A dilution in salt concentration would decrease the resin regeneration efficiency leaving strontium and calcium on the resin resulting in increased fractional breakthrough in the effluent stream from the column loading section.

In Run 4, the salt concentration in the strip section was reduced from 5 M NaCl to approximately 1 M NaCl when valve V-C (see Fig. 6 and Section 3.3.2.4) failed to close during the loading cycle. This resulted in 93% fractional breakthrough of strontium in the effluent stream (see Table 10).

Table 10. Strontium material balance distributions in the CCIX pilot-scale tests

Run No.	Flow ratios			Strontium material balances and distributions								Accumulation	
				BF _{Feed} mass input mg/min	Effluent stream		Scrub recycle		Strip waste		Valve failures	ratio mass out/ mass in	
	F/R	Si/R	Sc/R		mg/min	frac	mg/min	frac	mg/min	frac			
1	438	1.0	0.6	4.66	0.08	0.02	1.24	0.27	3.32	0.71		1.00	
2	438	1.0	0.6	7.54	0.32	0.04	0.76	0.10	1.27	0.17		0.31	
3	438	1.0	0.6	3.21	0.17	0.05	0.00	0.00	0.00	0.00		0.05	
4	602	2.3	1.7	1.96	1.82	0.93	0.00	0.00	0.42	0.21		1.14	V-C
5	673	2.6	1.9	3.44	0.08	0.02	0.84	0.24	0.32	0.09		0.36	
6	606	3.1	1.7	7.09	1.46	0.21	0.18	0.03	0.11	0.02		0.25	
7	525	2.7	1.7	6.18	0.51	0.08	5.37	0.87	0.76	0.12		1.07	V-WA
8	543	2.9	1.4	2.30	0.52	0.23	3.73	1.62	1.35	0.59		2.43	
9	474	2.7	1.4	64.9	0.80	0.01	2.25	0.03	0.87	0.01		0.06	
10	509	2.8	1.6	6.18	0.93	0.15	3.39	0.55	0.57	0.09		0.79	
11	559	2.9	0.9	2.96	0.83	0.28	5.39	1.82	0.65	0.22		2.32	
12					No samples taken, system volume too low								
13	618	2.9	2.4	10.4	7.34	0.71	5.55	0.53	0.59	0.06		1.30	V-R1
14	621	2.5	2.6	4.12	0.08	0.02	5.49	1.33	0.37	0.09		1.44	
15	621	6.0	2.4	3.55	0.59	0.17	5.06	1.43	0.82	0.23		1.82	
16	542	3.5	1.5	267	142	0.53	3.29	0.01	0.44	0.00		0.55	
17	595	3.8	1.6	5.73	1.48	0.26	4.31	0.75	1.28	0.22		1.23	
18	561	2.0	1.1	3.94	0.58	0.15	4.78	1.21	0.61	0.15		1.52	
19	561	1.8	1.6	2.05	0.08	0.04	2.98	1.45	0.48	0.23		1.73	
20	561	1.9	1.4	2.05	0.08	0.04	2.98	1.45	0.48	0.23		1.73	
21	564	2.0	1.6	0.46	0.08	0.17	0.61	1.33	1.15	2.50		4.00	
22	579	2.5	1.6	1.09	0.00	0.00	0.61	0.56	0.93	0.85		1.42	
23	545	2.4	1.6	0.33	0.08	0.24	0.84	2.55	0.73	2.21		5.00	
24	488	2.1	1.7	0.46	0.08	0.17	0.79	1.72	0.83	1.80		3.70	
25	521	2.5	1.9	1.94	0.08	0.04	1.64	0.85	0.06	0.03		0.92	
26	529	2.1	1.9	3.34	0.08	0.02	1.30	0.39	0.27	0.08		0.49	

Table 10. (Continued)

Run No.	Strontium material balances and distributions										Accumulation ratio mass out/ mass in	Valve failures
	Flow ratios			BFeed mass input mg/min	Effluent stream		Scrub recycle		Strip waste			
	F/R	S/R	Sc/R		mg/min	frac	mg/min	frac	mg/min	frac		
27	529	2.2	1.4	2.76	0.08	0.03	1.03	0.37	0.06	0.02	0.42	
28	509	2.1	2.3	2.33	0.08	0.03	2.79	1.20	0.15	0.06	1.30	
29	542	2.3	1.8	84.6	13.2	0.16	48.4	0.57	0.11	0.00	0.73	
30	624	2.3	1.6	46.0	11.3	0.25	38.8	0.84	0.05	0.00	1.09	
31	1119	2.7	1.7	22.8	7.03	0.31	17.6	0.77	9.50	0.42	1.49	
32	977	4.5	2.7	7.72	6.15	0.80	5.78	0.75	7.25	0.94	2.48	
33	1289	5.7	3.0	4.00	5.15	1.29	2.79	0.70	1.76	0.44	2.43	

A similar result occurred in Run 13 when conductivity probe 1 failed to properly control the water rinse valve V-R1 and introduced large volume additions of rinse water in the strip section (see Fig. 6) resulting in 71% fractional breakthrough of strontium in the effluent stream.

Increases in the strip to resin ratio (St/R) increased the efficiency of strontium removal from the loaded resin. This effect was noted in Run 5. Resin entering the bottom of the loading section was more efficiently stripped which resulted in only 2% strontium breakthrough (98% removal from the blended feed inlet stream) even though the F/R and Sc/R ratios were increased from Run 4. Increasing the St/R ratio has little effect on overall chemical usage and cost since the strip waste stream could be recycled after precipitating strontium and calcium by addition of sodium carbonate as shown in Section 3.1.2.

3.4.2.4 Feed Stream Concentration Variables

Multicomponent (Mg, Ca, Sr, Na, etc) compositions in the blended feed streams had a significant effect on loading of strontium on the resin. From the bench-scale breakthrough curves (see Fig. 3, Section 3.2.1), magnesium and sodium offer little competition for sites on the resin. The magnesium and sodium loading zones ride ahead of calcium. Samples of loaded resin taken from the pilot-scale testing were stripped using 4N HNO₃. Composition on the resin was found to be 2 meq/mL (90%) Ca, 0.17 meq/mL (8%) Sr, Mg (not detected), and 0.04 meq/mL (2%) Na. Hence, the multicomponent system acted like a binary system consisting of calcium and strontium, with strontium concentration given in tracer quantities relative to calcium. In Run 29, the blended feed solution was spiked with nonradioactive strontium to increase the total strontium concentration to 75 times higher than normal. Results (Table 10) showed a fractional breakthrough in the effluent stream of 16% strontium

(84% removal from the blended feed stream). In Run 30, the blended feed solution was spiked with calcium to test the effect of doubling the calcium concentration. This resulted in a fractional breakthrough of 31% strontium (69% removal from blended feed stream) in the effluent stream.

3.4.3 Material Balances

Strontium material balances for the pilot-scale testing of the CCIX system are given in Table 10. The material balances show that many of the pilot-test runs were not at steady-state. Strontium mass in the effluent stream varied between 1% (99% removal from the blended feed stream) and 93% (only 7% removal from the blended feed stream) which occurred during intermittent valve failures. The mean strontium concentration in the effluent stream (excluding valve failures) was 10% (90% removal from the blended feed stream). The output to input ratio was an indication of mass accumulation in the CCIX system. For values less than one, the mass input would be greater than the mass output, and feed solutes would be loaded (accumulated) on the resin. Output to input ratios of units suggested that the system could have been at steady-state. Values greater than one indicated that the resin originally contained feed solutes at the start of a run that were stripped from the resin during the run.

Typical variations in the effluent stream strontium compositions, as indicated in previous sections, resulted from (1) unsteady-state conditions, (2) increased blended feed stream compositions which varied almost continuously during the run, (3) mixing of salt solutions in the scrub section which resulted in high removal of strontium in the scrub recycle stream, and (4) inefficient resin regeneration in the strip section, in addition to the F/R throughput ratio

coupled with axial diffusion, resin mixing during the pulse cycle, and channeling in the column (see model derivation given in Section 4.2).

3.4.4 Equipment Failures

The CCIX pilot-scale system contains several valves and pumps that could potentially fail and result in significant downtime while waiting for repairs. During the pilot-test demonstrations, there were (1) two pump failures -- feed pump to loading section of ion-exchange column and resin pulse pump, (2) two valve failures -- valve V-C, located at the bottom of loading section closed loop (see Fig. 6) and valve V-WA, strip waste exit valve, (3) conductivity probe 1 operational failure of rinse valve V-R1, and (4) a glass pipe observation section rupture (see Section 3.3.2).

The pilot-scale CCIX system used in the test demonstration contained mostly used equipment parts. Therefore, most of the equipment failures mentioned were believed to have resulted from normal wear as a result of extended operations. The glass section rupture was believed to have been caused from stress due to temperature variations in the environment and column vibrations during pulse cycles. Temperatures were noted to vary between 60 F (16 C) at night to 120 F (49 C) by mid-day. The glass section was replaced with clear PVC pipe. All of the equipment failures were repaired within one week after system shutdown.

3.4.5 Overall Performance and Treatment Results

Test results from the near-steady-state operation of the CCIX system (for less than 50 hours semi-continuous operation) have indicated that the maximum removal efficiency (greater than 99.7%) of strontium from the blended feed stream can be achieved. These results were obtained for a typical blended feed stream composition [0.3 mg/L (300 µg/L)

total strontium and 1200 Bq/L ^{90}Sr , 40 to 60 mg/L Ca, 10 mg/L Mg, 20 to 40 mg/L Na, and 100 Bq/L ^{137}Cs]. At these operating conditions, the effluent stream from the loading section of the column typically contains less than 0.005 mg/L (5 $\mu\text{g/L}$) total strontium and approximately 3.4 Bq/L ^{90}Sr which is below the discharge limit of <11 Bq/L ^{90}Sr and 91 Bq/L ^{137}Cs . The strip waste stream from the CCIX system would contain 40 to 60% of the calcium and 90 to 99% of the strontium originally in the blended feed. Radioactivity in the strip waste stream contains $1.8\text{E}+05$ Bq/L to $2.4\text{E}+05$ Bq/L ^{90}Sr and 230 Bq/L ^{137}Cs .

Preliminary batch precipitation tests were performed using strip waste solutions obtained from pilot-test Runs 25 and 31. A stoichiometric addition of 2 N sodium carbonate solution (with 0.3N excess) was added to the strip waste solution from Run 25 (composition equal 6900 Bq/L ^{90}Sr (0.84 mg/L total strontium), 87 Bq/L ^{137}Cs , $1.3\text{E}+04$ Bq/L gross beta, and 388.6 mg/L Ca). The mixture was stirred at 160 rpm for 30 minutes to precipitate a carbonate sludge. The precipitate was allowed to settle for 30 minutes. The supernate was then decanted and analyzed to be 810 Bq/L ^{90}Sr , 67 Bq/L ^{137}Cs , 1800 Bq/L gross beta, and 38.9 mg/L Ca.

The batch precipitation test procedure was repeated using strip waste feed from Run 31. The strip waste feed contained $7.2\text{E}+04$ Bq/L ^{90}Sr (160.2 mg/L total strontium), 200 Bq/L ^{137}Cs , $1.5\text{E}+04$ Bq/L gross beta, and 783.9 mg/L Ca. The decanted supernate concentration was 103 Bq/L ^{90}Sr , 160 Bq/L ^{137}Cs , 390 Bq/L gross beta, and 78 mg/L Ca. These results revealed that 88% to 99% of the strontium and 90% of the calcium in the strip waste stream were chemically precipitated by addition of sodium carbonate solution.

In the CCIX system treatment process, strontium remaining in the supernate (1% to 12%) would need to be removed to minimize potential for introducing strontium or additional radioactivity in the effluent stream from the bottom of the loading section. These results

indicate that the supernate solution would have to be treated further to allow recycle as the strip waste feed solution. The CSA company performed tests using similar ORNL feed solutions and estimated that the remaining strontium could be removed using a Duolite C-467 phosphonic resin (see flowsheet Fig. 2, Section 3.2).²⁵ However, no further tests were performed at ORNL to verify additional removal of strontium using the Duolite resin.

4. MODELING OF EXPERIMENTAL RESULTS

The batch equilibrium data obtained using ORNL process wastewater feed and Dowex HGR-W2 cation resin (given in Section 3.1) was fitted to a Langmuir model to determine the equilibrium constants for the multicomponent system. Parameters obtained in the multicomponent Langmuir model are nonlinear resulting from the partial differential equations used to describe the equilibrium relation. A modification of the Levenberg- Marquardt algorithm was used to determine the regression parameter values for the multicomponent equilibrium constants.^{26,27}

A mathematical model was derived using the shell balance method to describe the diffusional mass transfer rate controlling step in the ion exchange process for the multicomponent system studied in this report. The continuity equation and the equation of motion are employed in the derivation of the mathematical model that describes the ion-exchange system.²⁸ This model derivation in the dimensionless form leads to a partial differential equation for which the original solution was worked out by Thomas (1944) for the Langmuir isotherm equation.^{29,30}

One of the most critical aspects of the scale-up of ion-exchange systems involves prediction of the effluent concentration profile as a function of throughput. This profile, the breakthrough curve, represents the specific combination of equilibrium and rate factors that control process performance in a particular application. In this study, only the strontium breakthrough data from the bench-scale and pilot-scale columns were modeled using the Thomas equation parameters. The Thomas equation gives a solution for a single fixed-bed ion-exchange col-

umn. The Thomas model assumes a Langmuir isotherm, and ion-exchange mass transfer can be approximated by a second-order Langmuir kinetic equation and modeled by the following three parameters: (a) T , a throughput parameter; (b) N , column height as transfer units; and (c) R , the constant separation factor. The multicomponent equilibrium constants obtained in this report were used to determine R for the Thomas model. The value of N was determined from bench-scale experimental breakthrough curves and used to predict scaleup for the pilot-scale CCIX system.

The Thomas model was extended by R. M. Wallace to predict operation of several columns in series much like the sequential operation of the CCIX system. Wallace used a numerical analysis solution of the Thomas equation with input values of R , N , and K_d .³¹ In the Wallace calculations, a series of columns was loaded until a specified breakthrough occurs. At that time, a fresh column was added to the front (outlet end) of the series, and a column was removed from the back (inlet end) of the series. The columns again operated until a specified breakthrough occurred, and the sequence was repeated. This sequence of operations with a series of fixed beds simulates the behavior of a CCIX loading section. In this study, the Wallace model was expanded to estimate the performance of the pilot-scale CCIX system. The cyclic pulse operation in the CCIX column was modeled as several columns in series where the volume of each column was equal to the volume of freshly regenerated resin per pulse cycle. A procedure was developed to estimate operating parameters for the pilot-scale CCIX system from the experimental breakthrough curves.

Application of the Wallace model to predict steady-state operating conditions for a CCIX system has not been reported. However, this approach may be feasible if accurate parameter values for the Thomas model equation are available which represent the controlling mass transfer mechanism in the ion-exchange process.

4.1 MULTICOMPONENT LANGMUIR EQUILIBRIUM MODEL

The equilibrium relation q_i^* , which is usually called the adsorption isotherm is, in general, a complicated nonlinear function of C_i in which mutual interactions among different solutes are taken into account. The model representing this relation was first introduced by Langmuir (1916) to describe an ideal localized monolayer sorption of gases on a solid surface.³² The Langmuir relation has been extensively employed for gases and liquids not only for single solute systems but also for multiple solutes.^{33,34,35} An appropriate form of the Langmuir equation for multicomponent systems expressed in terms of the weight of uptake by the resin and concentrations of solute in the fluid phase surrounding the resin is given by Eq. 1,

$$q_i^* = \frac{Q' K'_i C_i}{1 + \sum_{j=1}^m K'_j C_j} \quad \text{for } i = 1 \text{ to } m \quad (1)$$

where

q_i^* = equilibrium uptake of solute i by the adsorbent, meq/g resin,

Q' = asymptotic maximum solid phase concentration, meq solute/g resin,

C_i = equilibrium concentration solute i in liquid phase, meq/L,

K'_i = equilibrium constant for individual solute component i , L/meq,

m = number of solute components in the feed solution.

For the multicomponent process wastewater, the feed solution was considered to contain four major cations (Sr^{+2} , Ca^{+2} , Mg^{+2} , and Na^{+}) that compete for sites on the ion-exchange resin. Note that the multicomponent Langmuir model has a common denominator, however, the numerator as shown in Eq. 1 changes for each solute component i concentration. Therefore, values for q_i^* are proportional to the solute component i and equilibrium constant K'_i in the numerator.

4.1.1 Nonlinear Parameter Estimation

There are a number of different methods for obtaining nonlinear parameters estimates. The three most widely used computer based routines include linearization, steepest decent, and Levenberg-Marquardt's compromise (Draper and Smith 1981). Of these three, the Levenberg-Marquardt's compromise method is employed in this study, because of its ability to combine the best features of both the linearization (or Taylor series) method and the steepest descent method while avoiding their most serious limitations to successfully solve many nonlinear problems.³⁶

The linearization method uses the results of linear least squares in a succession of steps. This is shown by assuming that the proposed model is given by Eq. 2,

$$Y^E = f(\eta_1, \eta_2, \dots, \eta_k; \theta_1, \theta_2, \dots, \theta_p) + \epsilon \quad (2)$$

where

η_k = the independent variable,

θ_p = parameter estimates,

and choosing the initial parameter estimates, $\theta_1^\circ, \theta_2^\circ, \dots, \theta_n^\circ$ for the parameters $\theta_1, \theta_2, \dots, \theta_n$. A Taylor series expansion of $f(\eta_j, \theta)$ is carried out about the point θ° (i.e., $\theta_1^\circ, \theta_2^\circ, \dots, \theta_p^\circ$). The series is then truncated after the first derivatives,

$$f(\eta_j, \theta) = f(\eta_j, \theta^\circ) + \sum_{i=1}^p \left[\frac{\partial f(\eta_j, \theta)}{\partial \theta_i} \right]_{\theta=\theta^\circ} (\theta_i - \theta_i^\circ), \quad (3)$$

where

$$\eta_j = \begin{bmatrix} \eta_{11} & \eta_{12} & \dots & \eta_{1j} \\ \eta_{21} & \eta_{22} & \dots & \eta_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ \eta_{n,1} & \eta_{n,2} & \dots & \eta_{n,j} \end{bmatrix}. \quad (4)$$

Letting

$$f_j^\circ = f(\eta_j, \theta^\circ)$$

$$\Delta_i^\circ = \theta_i - \theta_i^\circ$$

$$Z_i = \left[\frac{\partial f(\eta_j, \theta)}{\partial \theta_i} \right]_{\theta=\theta^\circ}$$

Eq. 3 becomes

$$Y^E - f_j^\circ = \sum_i \Delta_i Z_{ij}^\circ + \epsilon_j. \quad (5)$$

Eq. 5 is linear in terms of θ ; and therefore, the linear least squares theory may be applied. In vector notation, $\mathbf{b}_0^p$, the estimates of Δ° are obtained by solving the following equation:

$$\mathbf{b}_0^p = (\mathbf{Z}'^o \mathbf{Z}^o)^{-1} \mathbf{Z}'^o (\mathbf{Y}^E - \mathbf{f}^o). \quad (6)$$

Since linear least squares theory is applied, $\mathbf{b}_0^p$ will minimize the sum of squares

$$SS(\theta) = \sum_{j=1}^n \left[Y_j^E - f(\eta_j, \theta^\circ) - \sum_{i=1}^p \Delta_i^\circ Z_{ij}^\circ \right]^2 \quad (7)$$

with respect to Δ_i° , $i = 1, 2, \dots, p$. New values of $\theta_{i(k+1)}$ are obtained by letting $\theta_{k+1} = \theta_k + \mathbf{b}_k$, where k is the number of iterations. This iterative process is continued until the solution converges, that is, until in successive iterations k , $(k+1)$,

$$\left| \frac{\theta_{i(k+1)} - \theta_{ik}}{\theta_{ik}} \right| < \delta \quad (8)$$

or

$$\left| \frac{SS(\theta_{k+1}) - SS(\theta_k)}{SS(\theta_k)} \right| < \delta_s, \quad (9)$$

where δ and δ_s are some specified amount (e.g., 0.000001). At each stage of the iterative process, $SS(\theta)$ should be evaluated to assess whether a reduction in its value has actually been achieved.

The linearization method has several possible drawbacks for some problems in that

1. It may converge very slowly, i.e. a very large number of iterations may be required before the solution stabilizes even though the sum of squares

$SS(\theta)$ may decrease consistently as k increases. This sort of behavior is not common but can occur.

2. The estimate may oscillate widely, continually reversing direction, and often increasing, as well as decreasing the sum of squares. Nevertheless the solution may stabilize eventually.
3. It may not converge at all, and even diverge, so that the sum of squares increases without bound. This will probably occur if the initial estimates are not good guesses or if the proposed model is incorrect.

As is seen from the definition of Z , it is necessary to compute the partial derivative of the function f with respect to each of the parameters. This may be done by determining the analytical expression for each of the derivatives which in some cases may be difficult to obtain or by computing the ratio

$$\frac{f(\eta_j; \theta_1^o, \theta_2^o, \dots, \theta_{i+h_i}^o, \dots, \theta_p^o) - f(\eta_j; \theta_1^o, \theta_2^o, \dots, \theta_i^o, \dots, \theta_p^o)}{h_i} \quad (10)$$

where $i = 1, 2, \dots, p$ and h_i is a small increment. A number of nonlinear computer algorithms employ the latter method to compute the derivatives.

The steepest decent method focuses on the sum of squares function,

$$SS(\theta) = \sum_{j=1}^n [Y_j^E - f(\eta_j, \theta^o)]^2 \quad (11)$$

and uses an iterative process to find the minimum of this function. One obvious disadvantage of the steepest decent method is the slowness of the convergence. Initially, this method tends to proceed rapidly in the direction of convergence. Near convergence, there is a slight reduction in $SS(\theta)$, and the rate of approach decreases. The steepest decent method is slightly less favored than the lineariza-

tion method, but will converge for many nonlinear problems. The method of Levenberg-Marquardt uses the best combination of both techniques while avoiding their general limitations.

A comparison of the sum of squares surfaces for linear and nonlinear models is given in Figs. 8a and 8b, respectively. The surface contour for the linear model is ellipsoidal and has a single local and global minimum height, $S(\theta)$, at the least squares estimator $\hat{\theta}$. For nonlinear models, the contours are not ellipsoidal but tend to be irregular and often "banana-shaped". The model may also consist of several local minima and perhaps with more than one global minimum.

The linearization technique converts the problem of finding the minimum height of $S(\theta)$ for a nonlinear model starting from an initial point θ^0 , into a series of linear models. The initial linearization of $f(\eta, \theta)$ about θ^0 replaces the irregular $S(\theta)$ bowl by an elliptical bowl $SS(\theta)$ with a "psuedo right shape", i.e. it has the same first derivatives of the corresponding model function right at θ^0 . The accuracy with which this technique approximates the actual $S(\theta)$ contours depends on the model assumed, the data available, and the relative positions of θ^0 and $\hat{\theta}$ in the θ -space. In any event, the linearization method solves the problem at θ^0 by moving to the bottom point of the linearized bowl at θ^0 to reach θ as shown in Fig. 9.³⁷ The process is repeated at θ_1 . With successive iterations, it is hopeful that the procedure will converge to $\hat{\theta}$, as is shown in Fig. 10.

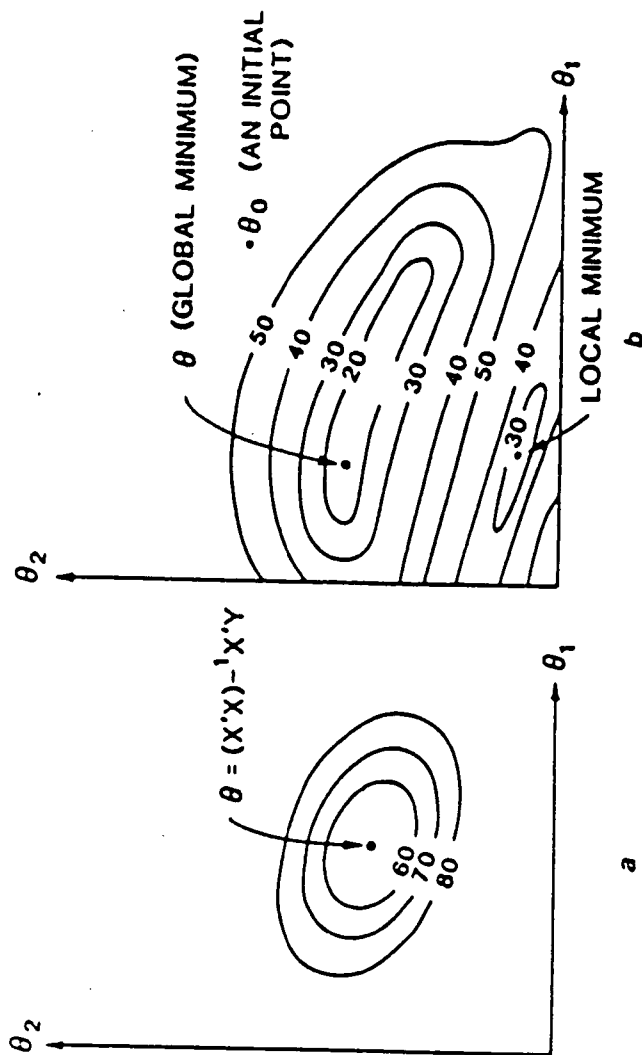


Fig. 8. Sum of squares surfaces for linear and nonlinear models:
(a) linear model (b) nonlinear model.

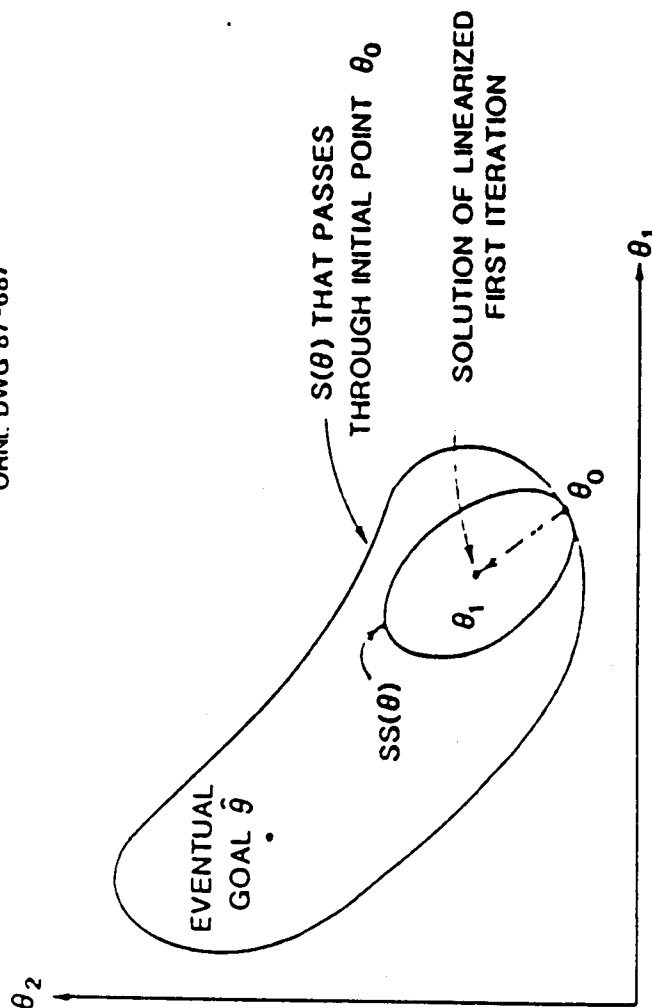


Fig. 9. Comparison between nonlinear and linearized first iteration.

Source: M. T. Harris, and C. H. Byers, "An Advanced Technique for Interfacial Tension Measurement in Liquid-Liquid Systems," ORNL/TM-10734, Oak Ridge National Laboratory, Oak Ridge, TN, 1989.

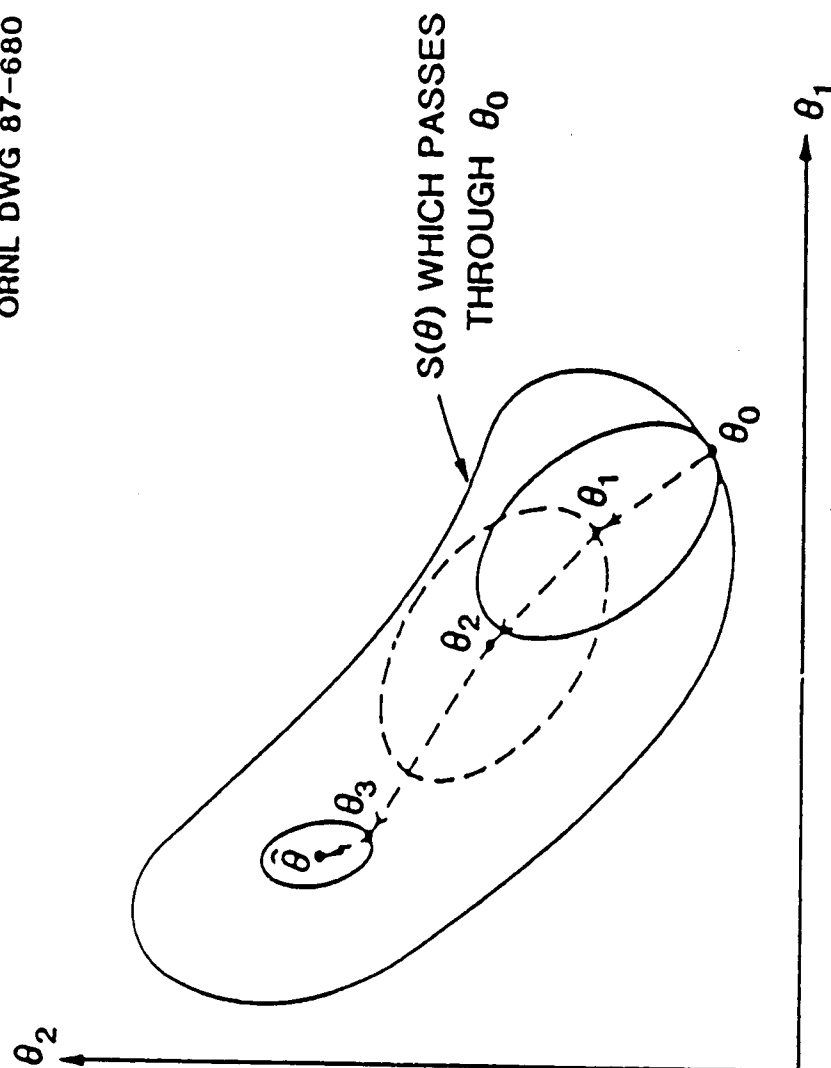


Fig. 10. Successive iteration of linearized model.

Source: M. T. Harris, and C. H. Byers, "An Advanced Technique for Interfacial Tension Measurement in Liquid-Liquid Systems," ORNL/TM-10734, Oak Ridge National Laboratory, Oak Ridge, TN, 1989.

4.1.2 Evaluation of Equilibrium Constants

The multicomponent equilibrium data given in Table 4 (Section 3.2.2) was fitted to a Langmuir model to determine the multicomponent equilibrium constants (K'_i). The equilibrium constants are parameters obtained when fitting equilibrium data to the nonlinear parameter model given in Eq. 1. A modification of the Levenberg-Marquardt algorithm was employed to solve the nonlinear model equation and determine the equilibrium constants.^{26,27,38} This algorithm linearizes the nonlinear input function ($q_i^*(C_i, K'_i)$ for $i = 1$ to m , where $m = 4$ for the process wastewater system under consideration) with respect to each of the parameters by taking the partial derivatives ($\frac{\partial q_i^*}{\partial K'_i}$) and performing a Taylor series expansion. The residual sum of error squared $SS(\theta)$ for the model is minimized in the algorithm, and the parameter values are obtained. The appropriate Jacobian input matrix, i.e., the mathematical expression for the partial derivatives ($\frac{\partial q_i^*}{\partial K'_i}$) are entered in a subroutine to minimize the convergence time required for the algorithm. A copy of this computer program is given in the Appendix. When modeling the four component process wastewater systems (Sr^{+2} , Ca^{+2} , Mg^{+2} , Na^+), there are four independent concentration variables (C_i), four dependent variables (q_i^*), and four equilibrium constant parameters (K'_i). Q' was calculated to be approximately 4 meq/g dry resin which is in good agreement with the manufacturer's data.

The nonlinear model gives a four dimensional representation of the multicomponent equilibrium data with a convergence tolerance set at 10^{-10} for the residual sum of error. Equilibrium constants calculated in the regression are given in Table 11. Solute concentrations in the liquid phase (C_i) are given

in the first four columns (bottom half of Table 11). Column 5 gives the solute ion (i) used in the numerator of Eq. 1. The observed solid phase concentrations (q_i^*) are given in Column 6. A comparison of observed solute concentrations on the resin divided by Q' versus predicted solute concentrations using Eq. 1 is given in the last three columns. Note that the nonlinear model represents the Sr^{+2} - Ca^{+2} data reasonably well at high concentrations absorbed on the resin. However, the residual error term tends to increase at lower concentrations. A plot of the calculated values predicted by the nonlinear model versus observed equilibrium values is given in Fig. 11.

The multicomponent equilibrium data are plotted in Fig. 12. As shown, Sr^{+2} and Ca^{+2} data (Figs. 12a and 12b), clearly resemble favorable equilibrium curves and are accurately modeled using the multicomponent equilibrium constants. However, the Langmuir relation can not adequately model the Mg^{+2} "irregular-shaped" displacement (Fig. 12c) which occurs as Ca^{+2} ions displace Mg^{+2} ions on the loaded resin (see breakthrough curve, Fig. 3, Section 3.2). The lack of fit generates gross errors in the nonlinear model exercise. A fraction of the gross errors is attributed to the experimental technique as noted in the general material balance calculation given in the Appendix.

The multicomponent equilibrium constants were used to predict the distribution coefficients based on the average feed composition for ORNL process wastewater. As shown in Table 12, the predicted values are in good agreement with the observed values for Sr^{+2} and Ca^{+2} distributions. Deviations which occur in Mg^{+2} and Na^+ data result from the many uncertainties in the data accuracy at the lower concentration ranges. However, since in a column oper-

Table 11. Multicomponent equilibrium constants obtained from nonlinear parameter model of simulated ORNL wastewater at 23 C

Part I. Multicomponent equilibrium constants and separation factors				
Solute	Equilibrium Constant K' , L/meg	Alphas $K(i)/K(\text{Ca})$		
Strontium	90.8	1.53		
Calcium	59.2	1.00		
Magnesium	20.3	0.34		
Sodium	0.207	3.49E-03		

Part II. Comparison of observed and calculated values									
Equilibrium concentrations				Solid phase		Observed		Calculated	
Liquid phase, C(i)s, meq/L				meq/g resin		value		value	
Sr	Ca	Mg	Na	Solute (i)	q*(i)	q*(i)/Q' in Eq. (1)	q*(i)/Q' in Eq. (1)	Residual value (calculated - observed)	
0.0106	0.0305	0.0926	10.7	Sr	0.817	0.204	0.123	-0.0818	
0.318	0.701	1.56	7.44	Sr	1.13	0.281	0.276	-0.0050	
0.572	1.13	1.64	8.36	Sr	1.18	0.295	0.335	0.0401	
0.0006	0.0043	0.0119	11.7	Sr	0.361	0.090	0.014	-0.0765	
0.0065	0.0154	3.28	8.82	Sr	0.706	0.176	0.0083	-0.1681	
0.802	1.51	1.73	6.65	Sr	1.41	0.352	0.364	0.0124	
0.0301	0.0815	0.0729	10.8	Sr	0.948	0.237	0.223	-0.0142	
0.01	0.0292	0.0771	11.4	Sr	0.769	0.192	0.120	-0.0721	
				Ca	1.19	0.299	0.230	-0.0690	
				Ca	1.53	0.382	0.397	0.0147	
				Ca	1.55	0.386	0.432	0.0461	
				Ca	1.95	0.487	0.428	-0.0590	
				Ca	1.03	0.259	0.013	-0.246	
				Ca	1.78	0.444	0.448	0.0037	
				Ca	1.38	0.344	0.393	0.0490	
				Ca	1.12	0.281	0.229	-0.0525	

Table 11. (Continued)

Table 11. (Continued)

Equilibrium concentrations			Solid phase		Observed value $q^*(i)/Q'$ in Eq. (1)	Calculated value $q^*(i)/Q'$ in Eq. (1)	Residual value (calculated- observed)
Liquid phase, $C(i)$ s, meq/L			meq/g resin				
Sr	Ca	Mg	Solute (i)	$q^*(i)$			
			Mg	1.12	0.281	0.240	-0.0409
			Mg	0.988	0.247	0.303	0.0561
			Mg	1.13	0.282	0.215	-0.0667
			Mg	0.505	0.126	0.061	-0.0655
			Mg	0.039	0.010	0.939	0.929
			Mg	1.45	0.363	0.176	-0.1869
			Mg	1.32	0.330	0.121	-0.2091
			Mg	1.06	0.265	0.207	-0.0578
			Na	1.08	0.270	0.281	0.0106
			Na	1.12	0.281	0.015	-0.2664
			Na	0.00	0.000	0.011	0.0111
			Na	2.56	0.640	0.610	-0.0301
			Na	2.03	0.507	0.026	-0.481
			Na	0.011	0.003	0.007	0.0041
			Na	0.556	0.139	0.181	0.0422
			Na	1.02	0.255	0.312	0.0566

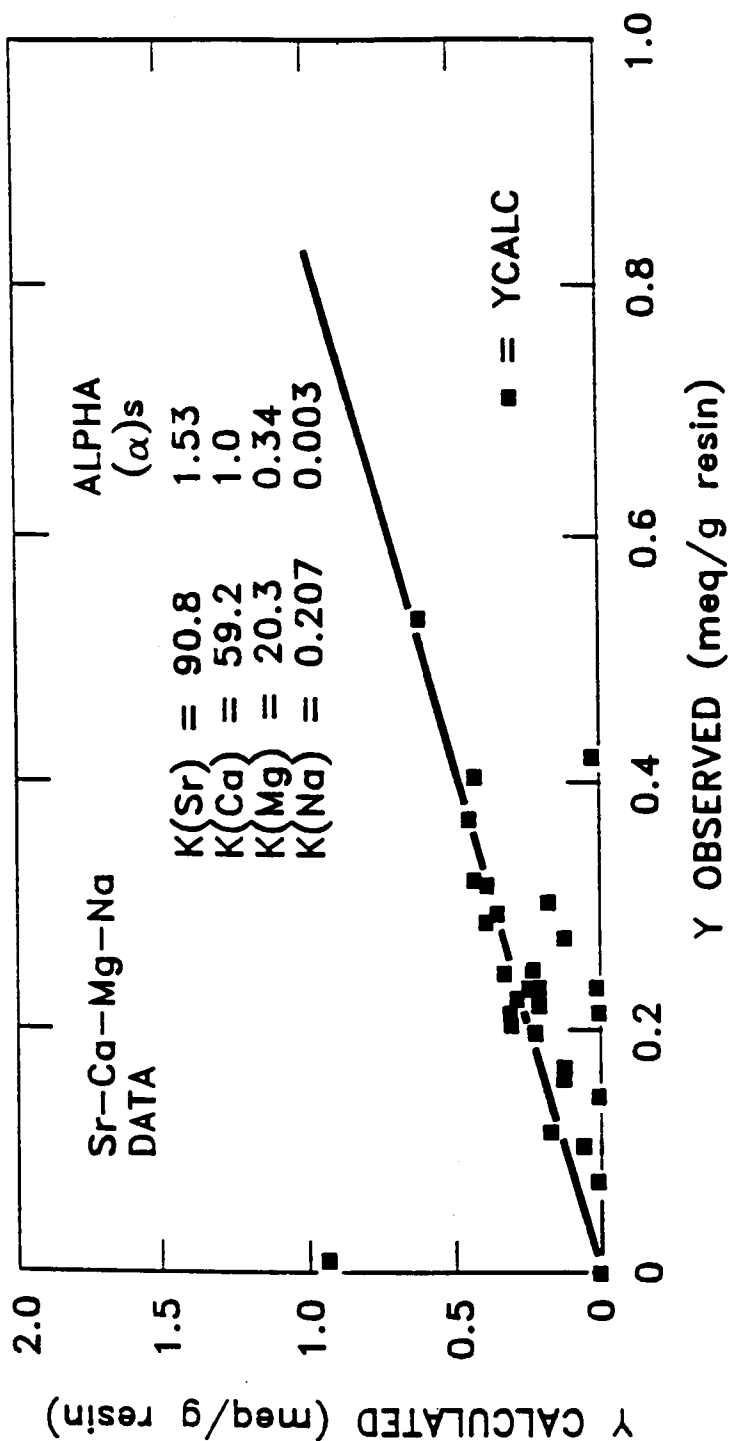


Fig 11. Plot of observed values versus predicted from the nonlinear multicomponent Langmuir isotherm regression model.

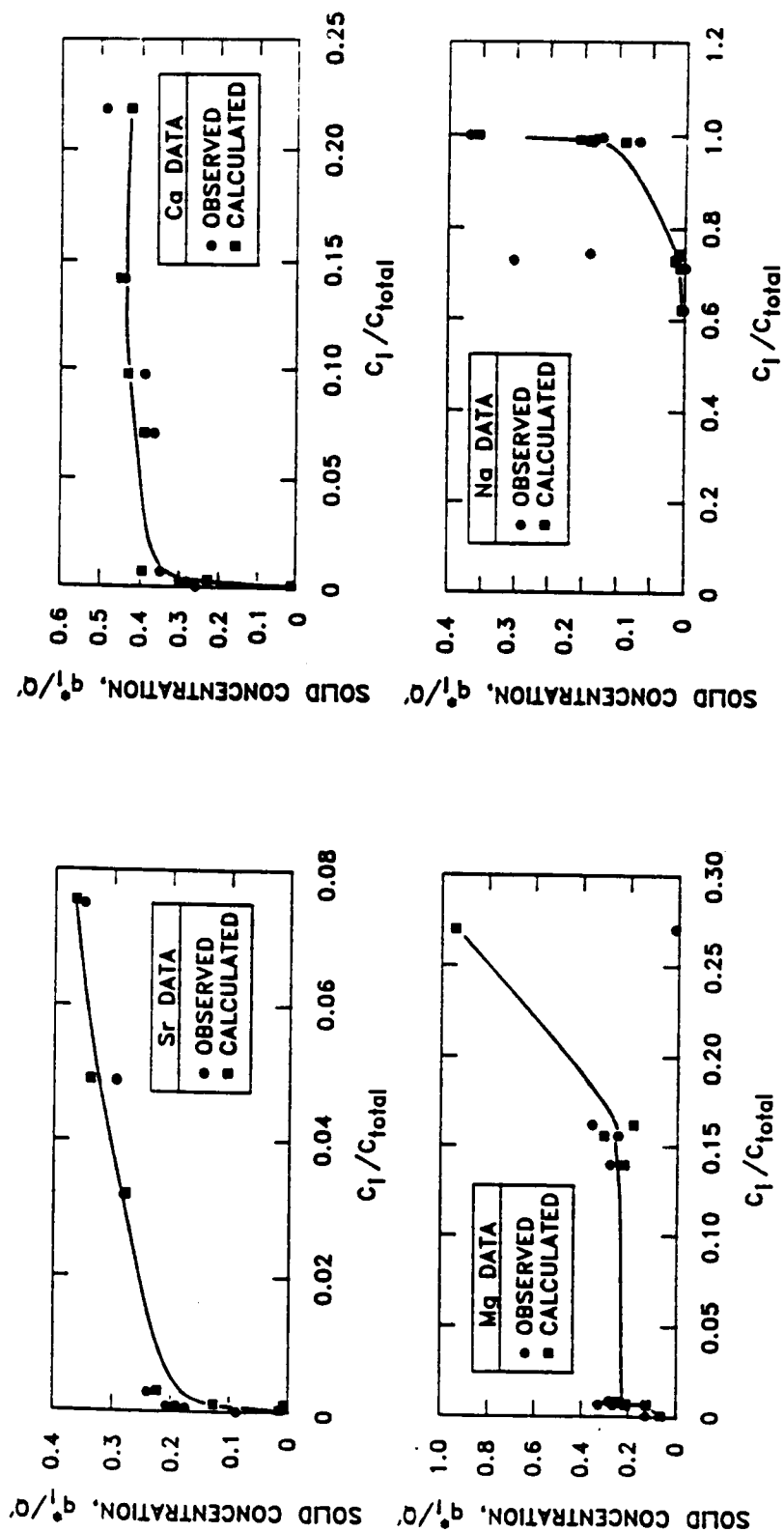


Fig. 12. Multicomponent (Sr-Ca-Mg-Na) equilibrium data for simulated ORNL process wastewater.

Table 12. Comparison of predicted distribution coefficients vs. observed

Feed Component	Equilibrium Constant (L/meq)	Predicted ^a K_d (mL/g resin)	Observed K_d (mL/g resin)
Sr ⁺²	90.8	1850	1730
Ca ⁺²	59.2	1206	1245
Mg ⁺²	20.3	414	917
Na ⁺	0.207	4.21	569

^a Distribution coefficient calculated using equilibrium constants and initial feed concentrations.

ation Mg⁺² and Na⁺ ions are displaced from the loaded resin in the effluent stream by Ca⁺² and Sr⁺² ions, the Langmuir model is applicable for modeling Sr⁺²-Ca⁺² binary data.

4.1.3 Development of Binary Equilibrium Isotherm Using Multicomponent Equilibrium Constants

The binary (Sr⁺²-Ca⁺²) equilibrium data given in Table 3 (Section 3.1) produced slightly lower distribution coefficients and separation factors than observed in the multicomponent (Sr⁺²-Ca⁺²-Mg⁺²-Na⁺) equilibrium data (Table 4, Section 3.1). This difference may merely represent statistical errors in the experimental techniques.

The concept of multicomponent interactions was presented in depth by Glueckauf (1949).³⁴ The general theory of multiple solutes following nonlinear isotherms in a batch operation is perhaps best understood when considering

frontal analysis and displacement development of chromatographic processes. In frontal analysis, for the multicomponent system (Sr^{+2} , Ca^{+2} , Mg^{+2} , Na^{+}), the feed solution is forced through the column containing adsorbent (resin) previously washed with pure solvent. The resin in the column has a higher selectivity for Sr^{+2} ions than Ca^{+2} , Mg^{+2} , Na^{+} , respectively. Sodium ions are therefore easily displaced by Mg^{+2} ions. This essentially reduces the treatment of the multicomponent system to a ternary system (Sr^{+2} - Mg^{+2} - Ca^{+2}). Breakthrough curves are determined by plotting the concentration of effluent as a function of the volume which has passed through the bed, thus producing characteristic curves showing one step or transition for each solute. The concentration of the least absorbed solute in the ternary system (Mg^{+2}) gradually becomes greater in the effluent stream than the original feed concentration as a result of adsorption displacement which means that when Ca^{+2} is passing down the column and adsorbed, it will "knock off" some already adsorbed molecules of Mg^{+2} from the resin, and consequently the Mg^{+2} concentration is higher than in the original solution. This characteristic is noted in the breakthrough curve given in Fig. 3 (see Section 3.1.1) for magnesium and sodium (not shown in Fig. 3) data. This process is repeated for the binary system Sr^{+2} - Ca^{+2} as more feed is added to the column. Ultimately, Ca^{+2} concentration becomes slightly higher in the effluent as it is displaced by Sr^{+2} ions.

A general understanding of the kinetics in ion-exchange systems would require data generated from a column operation. Although local equilibrium between liquid and sorbent in the layers of the column bed is very seldom obtained, as noted by Helfferich, ion-exchange kinetics are generally rapid and produce results that are close to equilibrium values. Modeling of the ion-exchange column

operation for the multicomponent system studied in this report was reduced to a binary system model consisting of strontium and calcium. The separation factor (α) between strontium and calcium is equal to the ratio of the distribution coefficients

$$\alpha = \frac{K_d(Sr)}{K_d(Ca)} \quad (12)$$

where the distribution coefficient is defined as the ratio of the solute ion concentration in the solid phase (Y) that is in equilibrium with the liquid phase concentration (X). Rewriting Eq. 12 in terms of the above expressions for the binary system gives

$$\alpha = \frac{Y(Sr)/X(Sr)}{Y(Ca)/X(Ca)} \quad (13)$$

Note that when the separation factor technique in Eq. 13 is applied to the multicomponent Langmuir equilibrium model given in Eq. 1, the denominator term cancels and the net result becomes

$$\alpha = \frac{K'(Sr)}{K'(Ca)} \quad (14)$$

For a binary system it is convenient to express the solute concentrations in equivalent fractions units. Thus, the concentrations of only one solute is needed to determine the binary system concentrations. For example, strontium concentrations in the liquid and solid phases are given by

$$X(Sr) = 1 - X(Ca) \quad (15)$$

and

$$Y(Sr) = 1 - Y(Ca) . \quad (16)$$

Rewriting Eq. 13 in terms of strontium concentration only, one obtains

$$\alpha = \frac{Y(Sr)[1 - X(Sr)]}{X(Sr)[1 - Y(Sr)]} \quad (17)$$

The batch multicomponent equilibrium data (given in Table 4, Section 3.1) was fitted to the multicomponent Langmuir equation (Eq. 1) using the Levenberg-Marquardt algorithm. Values for the multicomponent equilibrium parameters $K'(Sr)$ and $K'(Ca)$ were determined to be 90.8 L/meq and 59.2 L/meq, respectively, yielding a separation factor (α) approximately equal to 1.53 (see Table 11, Section 4.1.2). Using this separation factor in Eq. 17, the multicomponent equilibrium data was modeled as a binary (Sr-Ca) system as shown in Fig. 13. The concentration of Sr on the resin (q^*) divided by the saturation concentration (q_s^*) plotted as a function of the Sr liquid phase concentration (C) divided by the feed concentration (C_0) using the multicomponent separation factor approximates the binary equilibrium data.

4.2 MODELING OF BREAKTHROUGH PHENOMENA IN PACKED BEDS

The primary sequence of molecular scale processes involved in ion exchange, ie., in replacement of a counter ion A in the flowing fluid by another counter ion B originally on the resin, may be grouped into the following three steps:

1. External diffusion, which is also known as film diffusion. Film diffusion is the counterdiffusion of A from the bulk fluid to the outer surface of the

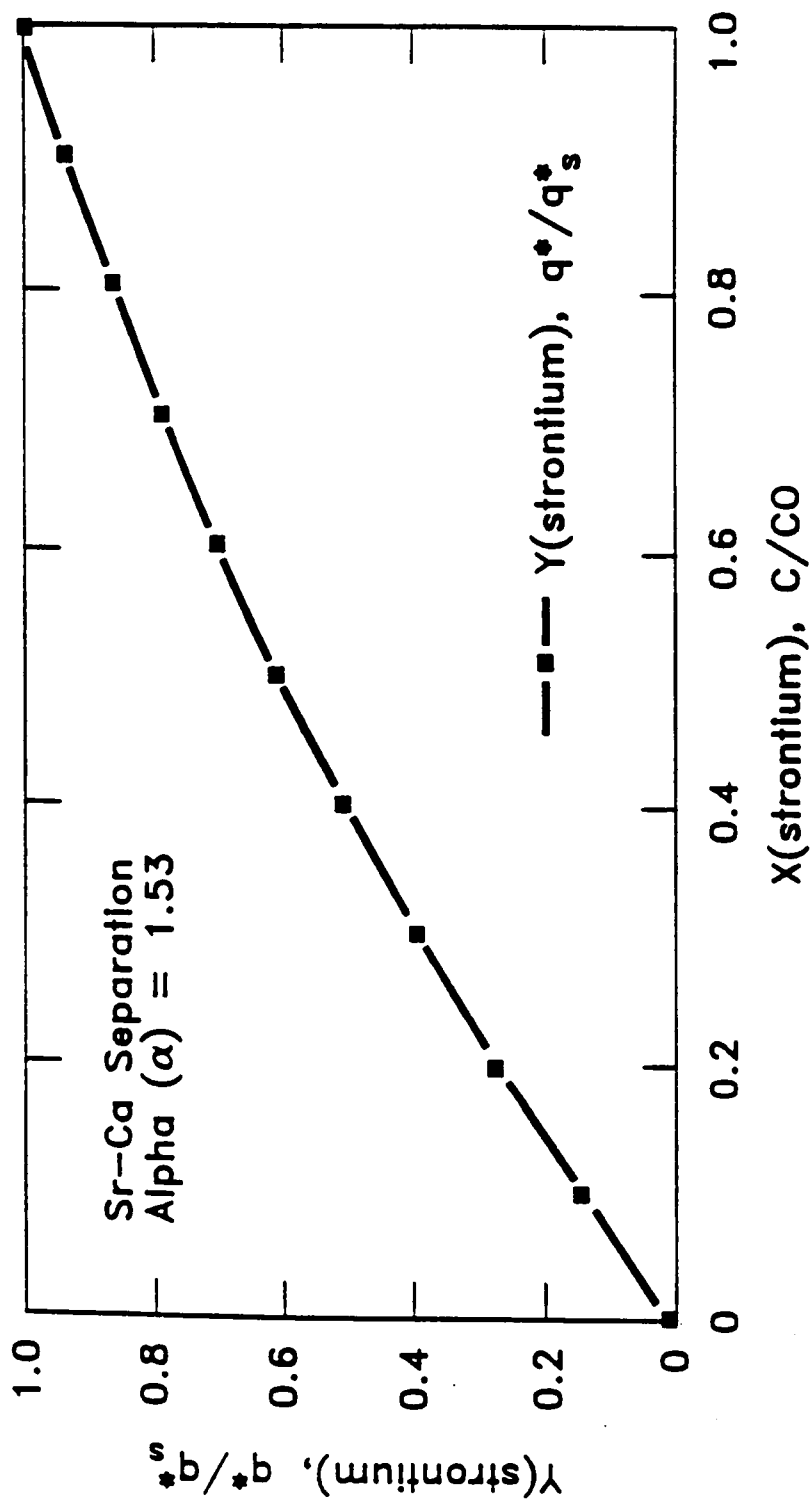


Fig. 13. Strontium-calcium binary equilibrium curve predicted from multicomponent.

solid particle (resin) and of B from the resin to the bulk fluid.

2. Internal diffusion, which is also known as particle or pore diffusion. Pore diffusion is the counterdiffusion of A through the pores of the resin to the point where exchange occurs and of B from the exchange point back to the outer surface of the particle.
3. Reaction kinetics, which is the desorption of B from the solid phase and adsorption of A in its place.

Reaction kinetics, for ion-exchange systems, is much faster than film or particle diffusion rates (Helfferich 1962). The rate determining steps that control the overall ion-exchange process are the diffusion mechanisms. A model is developed in the following sections that describe the general mass transfer relations for ion-exchange systems. The model includes a mathematical expression for film or pore diffusion resistances and the axial diffusion expression generated as a result of fluid flow in a packed bed.

4.2.1 General Mass Balance Equation For Packed Beds

Mass transfer in ion-exchange systems can be modeled using the shell balance method to derive an equation that describes the transport of mass from the flowing fluid phase to the fixed ion-exchange matrix (resin phase). Consider an ion-exchange column of length Z that is randomly packed with ion-exchange resin. For the differential column section ΔZ , as shown in Fig. 14, the general mass balance equation for solute A is

$$(\text{rate of } A \text{ in}) - (\text{rate of } A \text{ out}) = (\text{rate of } A \text{ accumulation}) . \quad (18)$$

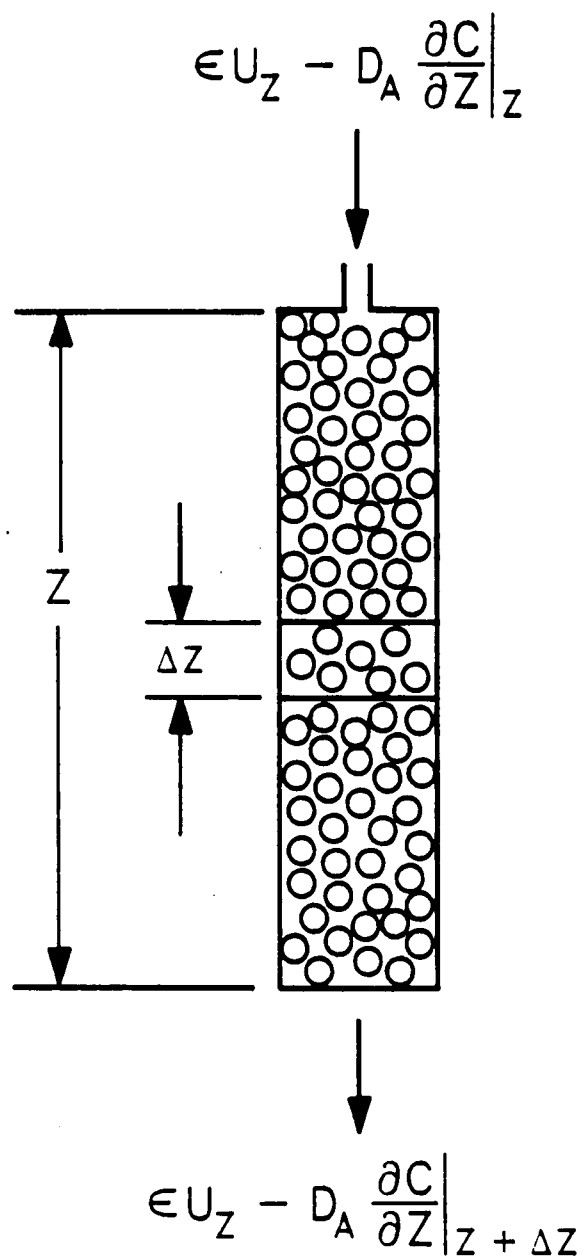


Fig. 14. Model for a fixed-bed ion exchange column.

Solute A is exchanged through the differential column element by both diffusion and bulk flow, and is accumulated on the ion-exchange matrix. The mass balance equation becomes

$$\begin{aligned} \epsilon S \left[-D_A \frac{\partial C}{\partial Z} + CU_z \right]_{z,t} - \epsilon S \left[-D_A \frac{\partial C}{\partial Z} + CU_z \right]_{z+\Delta z,t} \\ = \left[\epsilon S \Delta Z \frac{\partial C}{\partial t} \right]_z + \left[S \Delta Z (1 - \epsilon) \frac{\partial C_s}{\partial t} \right]_z \end{aligned} \quad (19)$$

where

ϵ = void fraction in the bed,

C = concentration of A in the fluid phase, mol/cm³,

C_s = average concentration of A in the solid phase, mol/cm³,

D_A = effective axial diffusion coefficient of A, cm²/s,

S = cross-sectional area of the column, cm², and

U_z = interstitial velocity, cm/s.

Film or pore resistances are included in the expression that relates the change in solute concentration on the solid phase per unit time. Rearranging Eq. (19) and dividing both sides by $\epsilon S \Delta Z$ gives

$$\begin{aligned} \frac{D_A \frac{\partial C}{\partial Z} \big|_{z+\Delta z} - D_A \frac{\partial C}{\partial Z} \big|_{z,t}}{\Delta Z} - \frac{CU_z \big|_{z+\Delta z,t} - CU_z \big|_{z,t}}{\Delta Z} \\ = \frac{\partial C}{\partial t} \bigg|_z + \frac{1 - \epsilon}{\epsilon} \frac{\partial C_s}{\partial t} \bigg|_z. \end{aligned} \quad (20)$$

By definition of derivative,

$$\frac{\partial C}{\partial Z} = \lim_{\Delta Z \rightarrow 0} \left[\frac{C|_{Z+\Delta Z} - C|_Z}{\Delta Z} \right] \quad (21)$$

Applying the limiting process for ΔZ and assuming that the axial diffusion coefficient and velocity are constant, one obtains

$$\left(D_A \frac{\partial^2 C}{\partial Z^2} \right)_t - \left(U_z \frac{\partial C}{\partial Z} \right)_t = \left(\frac{\partial C}{\partial t} \right)_z + \left(\frac{1 - \epsilon}{\epsilon} \frac{\partial C_s}{\partial t} \right)_z \quad (22)$$

The continuity equation and the equation of motion given in Bird, Stewart, and Lightfoot (1960) can be employed to simplify the solution to Eq. 22. For an isothermal operation, the energy balance for the column can be neglected, and the solution density is constant. Thus, the change in velocity profiles given in the equation of continuity equals to zero. If one assumes a plug flow velocity profile and a small pressure drop through the bed, the velocity profiles in the X-direction and Y-direction given in the continuity equation and the equation of motion reduce to zero and can be eliminated. With a small pressure drop through the bed, the differential pressure term in the equation of motion also reduces to zero. The solution to Eq. 22 is simplified even further by assuming that any concentration gradients in the radial direction are negligible, and concentration gradients exists only in the axial direction. Therefore, if one neglects axial diffusion in the ion-exchange column, Eq. 22 reduces to

$$- \frac{\epsilon U_z}{1 - \epsilon} \left(\frac{\partial C}{\partial Z} \right)_t - \frac{\epsilon}{1 - \epsilon} \left(\frac{\partial C}{\partial t} \right)_z = \left(\frac{\partial C_s}{\partial t} \right)_z \quad (23)$$

Introducing $\rho_s = \rho_b (1 - \epsilon)$ and $q^* = C_s / \rho_s$ in Eq. 23 gives

$$\left(\frac{\partial q^*}{\partial t}\right)_z = -\frac{\epsilon U_z}{\rho_b} \left(\frac{\partial C}{\partial Z}\right)_t - \frac{\epsilon}{\rho_b} \left(\frac{\partial C}{\partial t}\right)_z \quad (24)$$

where

ρ_s = particle density, g/cm³, and

ρ_b = bulk density of sorbent bed, g/cm³.

If the distribution coefficient of the feed solute ions is large, or if the void fraction of fluid in the bed (void volume) is small compared to the total volume of fluid throughput, the second term in Eq. 24 can be neglected as indicated by Hougen and Marshall.³⁹ Thus, the general mass balance equation for the ion-exchange system assuming negligible axial diffusion is

$$\left(\frac{\partial q^*}{\partial t}\right)_z = -\frac{\epsilon U_z}{\rho_b} \left(\frac{\partial C}{\partial Z}\right)_t \quad (25)$$

A mass transfer mechanism describing the film or pore resistances (i.e., the rate of change in solute ion concentration on the resin per unit time) generated in the transfer of solute A to the ion-exchange matrix would be required to obtain a solution to Eq. 25. A second order reversible surface reaction model was first proposed by Thomas (1944) for the Langmuir isotherm equation to represent the mass transfer mechanism for an ion-exchange system.

4.2.2 Thomas Model For Ion-Exchange Systems

Thomas used experimental data to account for the equilibrium Langmuir relationship between solute A in solution and concentration A in the resin phase.

The mass transfer between solute A and the resin counter ion B was approximated by a second-order kinetic equation. Thomas assumed that the rate of adsorption of a single component on a resin can be represented by an expression suggested by the stoichiometry of the ion-exchange reaction:



where A and B are the concentrations of the cations in the solution; PA and PB are the concentrations of the respective cations adsorbed on the resin, P , and n is the valence ratio of B to A . (Note: For exchange of ions with unequal valences (where $n \neq 1$), equivalent concentrations should be used instead of molar concentrations). The concentration of A in the solution and resin at equilibrium is denoted by C and q^* , respectively. The second-order kinetic rate equation may be expressed as the net rate of uptake for component A which is equal to the rate of adsorption minus the rate of desorption. Assuming Q' and C_0 are the total resin sites available and the total molar concentration in the solution, the second-order kinetic rate equation becomes

$$\frac{\partial q^*}{\partial t} = k_a C (Q' - q^*) - k_{de} q^*, \quad (27)$$

where k_a is the mass-transfer adsorption coefficient and k_{de} is the mass-transfer desorption constant which are dependent on the controlling mass transfer mechanism.

The Langmuir equation for a single adsorbate is given by

$$q_s^* = \frac{Q' K' C_0}{1 + K' C_0} \quad (28)$$

where q_s^* is the concentration of solute A on the surface of the solid at saturation, K' is the adsorption equilibrium constant which is equal to the ratio of the adsorption constant to desorption constant ($\frac{k_a}{k_{ds}}$). From Eq. 28,

$$Q' = \frac{q_s^*(1 + K'C_0)}{K'C_0} \quad (29)$$

Rewriting Eq. 27 in terms of K' , gives

$$\frac{\partial q^*}{\partial t} = k_a \left[C(Q' - q^*) - \frac{q^*}{K'} \right] \quad (30)$$

Substituting Q' expression from Eq. 29 into Eq. 30, one obtains

$$\frac{\partial \left(\frac{q^*}{q_s^*} \right)}{\partial t} = k_a \frac{1 + K'C_0}{K'} \left[\frac{C}{C_0} \left(1 - \frac{q^*}{q_s^*} \right) - \frac{1}{1 + K'C_0} \frac{q^*}{q_s^*} \left(1 - \frac{C}{C_0} \right) \right] \quad (31)$$

For Langmuir kinetics we thus have

$$\frac{\partial \left(\frac{q^*}{q_s^*} \right)}{\partial t} = \Omega_a \left[\frac{C}{C_0} \left(1 - \frac{q^*}{q_s^*} \right) - r^* \frac{q^*}{q_s^*} \left(1 - \frac{C}{C_0} \right) \right] \quad (32)$$

where

$$\Omega_a = k_a \frac{1 + K'C_0}{K'} \quad (33)$$

and

$$r^* = \frac{1}{1 + K'C_0} \quad (34)$$

r^* is the variable separation factor determined from the equilibrium isotherm.

The constant separation factor, R , as derived by Vermeulen and Hiester, is an

explicit function of the variable equilibrium separation factor, r^* given by

$$R = \frac{r^* + x' - r^* x'}{r^* + x'' - r^* x''}, \quad (35)$$

where x' is the starting liquid phase equilibrium concentration and x'' is the final liquid phase concentration.⁴⁰ R is conveniently used in the Thomas model to predict breakthrough. For a partial equilibrium isotherm, R is more linear (≈ 1) than r^* which ranges between 0.62 to 0.83 for strontium data in the ORNL dilute process wastewater feed.

Eq. 32 can be written in dimensionless form by defining bed-length and time parameters. The dimensionless groups are:

$$N = \frac{K'_d(1 - \epsilon) Z \Omega_a}{\epsilon U_z}, \quad (36)$$

$$NT = \Omega_a \left(t - \frac{Z}{U_z} \right), \quad (37)$$

$$T = \frac{\epsilon U_z \left(t - \frac{Z}{U_z} \right)}{(1 - \epsilon) Z K'_d}, \quad (38)$$

$$X = \frac{C}{C_0}, \quad (39)$$

$$Y = \frac{q^*}{q_s^*}, \quad (40)$$

where

K'_d = the distribution coefficient $\left(\frac{q_s^*}{C_0} \right)$ when $X = 1$,

N = represents the length of exchange column in transfer units,

NT = represents the time parameter for the system,

T = represents the throughput parameter,

and t is the elapsed time at a point Z after a fluid particle has arrived at that point in the column having started at the entrance to the bed at time $t=0$.

Introducing the dimensionless groups into Eq. 32, one obtains

$$\frac{\partial Y}{\partial(NT)} = X(1 - Y) - RY(1 - X). \quad (41)$$

If the general material balance equation, Eq. 25, is written in dimensionless form using the above dimensionless groups, it becomes

$$\left(\frac{\partial Y}{\partial(NT)} \right)_N = - \left(\frac{\partial X}{\partial N} \right)_{NT}. \quad (42)$$

Upon combining Eq. 30 and Eq. 31, one obtains

$$\left(\frac{\partial Y}{\partial(NT)} \right)_N = X(1 - Y) - RY(1 - X) \quad (43)$$

and

$$\left(\frac{\partial X}{\partial N} \right)_{NT} = -X(1 - Y) + RY(1 - X) \quad (44)$$

For an ion-exchange system initially free of adsorbate, the boundary conditions are

$$X = \frac{C}{C_0} = 1 \text{ at } N = 0 \text{ for all } T, \quad (45)$$

and

$$Y = \frac{q}{q_s^*} = 0 \text{ at } T = 0 \text{ for all } N. \quad (46)$$

When Eq. 43 and Eq. 44 are integrated, assuming the above boundary conditions, the solution obtained by Thomas is:

$$X = \frac{J(RN, NT)}{J(RN, NT) + [1 - J(N, RNT)] \exp[(R-1)N(T-1)]} \quad (47)$$

and

$$Y = \frac{1 - J(RN, NT)}{J(RN, NT) + [1 - J(N, RNT)] \exp[(R-1)N(T-1)]}, \quad (48)$$

where J is a zero order Bessel function.

For an ion-exchange system, the throughput parameter, T , is often expressed as the ratio of the number of bed volumes of solution (V) that has passed through the bed, per unit volume of ion-exchange bed (v). Using Eq. 38, V can be shown to equal $\epsilon U_x S(t - Z/Uz)$ and v is equal to SZ . When ρ_b is constant, the volume-based distribution coefficient is defined as $K_d = q_v/C_0$, where q_v is the concentration of the solute ion per unit volume of sorbent bed (sorbent plus void space), and C_0 is the concentration in the feed. Equations 36 and 38 can then be expressed in terms of the volume-based distribution coefficient as

$$N = K_d K_a \left(\frac{v}{f} \right), \quad (49)$$

where

$f = \epsilon U_x S$ which is the volumetric flow rate through the column,

$K_a =$ the system mass transfer coefficient, Ω_a ,

$K_d =$ the volume-based distribution $\left(\frac{q^*}{C_0} \right)$ when $X = 0.5$,

$$T = \frac{(V/v)}{K_d}. \quad (50)$$

A plot of T (or V/v) versus X (or C/C_0) produces S-shaped curves known as concentration profiles or breakthrough curves. Plotting these variables on logarithmic-probability scales eliminates the curvature of such plots and allows direct comparison with theoretical curves. The stoichiometric-equivalence point or "enter of mass" is the value of X at $T = 1$ for which the area below and to the left of the breakthrough curve equals the area above and to the right of the breakthrough curve. To a first approximation, X remains constant at this stoichiometric point. For large values of RN , $X \approx 0.5$ when $T = 1$.

Experimental data can be used to construct breakthrough curves of X versus T (or V/v). The value of K_d is approximately equal to V/v where $X \approx 0.5$. Values for N can be obtained by comparing the experimental breakthrough curves (plotted on logarithmic-probability paper) with theoretical values available in many reference books.⁴¹ The value of K_a can then be obtained from Eq. 49.

Once values of R , N , and T are obtained, these values can be used to predict the performance of columns at different operating conditions. The breakthrough curve at the new set of conditions will pass through the stoichiometric point, but the slope of the breakthrough curve will change. It can be seen from Eq. 49 that the value of N will vary with K_a , K_d , v , and f . Vermeulen developed equations to show how N changes for different mass transfer controlling mechanisms as a function of diffusion coefficient in the liquid and solid phases, the volumetric flow rate, the particle radius, and Langmuir kinetics.⁴² These equations have been reduced to

$$\frac{N}{Z} \propto S^{-a} f^{a-1} d^{a-2} D^{1-a}, \quad (51)$$

where S is the cross sectional area of the column; d is the particle diameter; Z is the bed length; and D is the respective diffusion coefficient. Here $a = 0$ for particle or pore diffusion, 0.5 for film diffusion, 1.0 for axial dispersion, and 2.0 for molecular diffusion.

4.3 APPLICATIONS OF ION-EXCHANGE MODELS

A general procedure for predicting column breakthrough curves using the Thomas model is given in the following sections. Experimental breakthrough data obtained from the bench-scale column (Section 3.1.1) are used to predict scaleup parameters for the pilot-scale CCIX column. A comparison of the predicted pilot-scale column performance (based on column length in number of transfer units, N) and the observed performance is made. Differences in the bench-scale fixed-bed column and pilot-scale CCIX column are noted.

The Thomas model, which was designed for a single fixed-bed ion-exchange column, was extended by R. M. Wallace to predict operation of several columns in series.³¹ Wallace used a numerical analysis solution of the Thomas equation with input values of R , N , and K_d . The Wallace model was expanded in this section to estimate the steady-state performance of the pilot-scale CCIX system. A procedure was presented to estimate the operating parameters for the pilot-scale CCIX system.

4.3.1 Fitting Column Breakthrough Curves to Thomas Model

Strontium breakthrough curves obtained for the bench-scale and pilot-scale data taken in this study were plotted as Sr^{+2} concentration (C/C_0) versus the normalized throughput (T), measured in bed volumes (bv), on logarithmic paper. The breakthrough data were modeled using the Thomas model. A statistical regression analysis program was written to produce the regression coefficients and best fit parameters for the modeled data.³⁶ Normalized Sr^{+2} breakthrough profiles for the ion-exchange columns were obtained by first dividing the throughput data by the volume-based distribution, K_d , value and then performing a linear regression of the normalized throughput versus the observed concentration data. The normalized experimental data was then compared to the normalized breakthrough data predicted by the Thomas model to determine the number of transfer units, N , contained in the bench-scale and pilot-scale ion-exchange columns.

Normalized experimental data obtained in the bench-scale ion-exchange column breakthrough tests are given in Table 13. Sr^{+2} 50% breakthrough occurs at $T = \approx 879$ bed volumes (see Fig. 3, Section 3.2.1). The normalized throughput (NBV) are given for the observed and predicted breakthrough (C/C_0) data. A comparison of the Thomas model parameters ($R=1$ versus various N values) are given in Table 14. The best statistical fit for the Thomas model parameters are obtained when $N = 6$ and $R = 1$ for the bench-scale column data. A plot of the resulting breakthrough curves is shown in Fig. 15. The Thomas model predicted the experimental data reasonably well. However, the model was less

Table 13. Thomas Model of bench-scale column breakthrough

(bv) ^a	(NBV) ^b	Observed (C/C ₀)	Predicted ^c (C/C ₀)
176	0.2	0.010	0.045
264	0.3	0.067	0.085
352	0.4	0.124	0.138
440	0.5	0.181	0.200
527	0.6	0.238	0.270
615	0.7	0.294	0.343
703	0.8	0.351	0.416
791	0.9	0.408	0.489
879	1	0.465	0.558
967	1.1	0.522	0.622
1055	1.2	0.579	0.681
1143	1.3	0.636	0.733
1231	1.4	0.693	0.779
1319	1.5	0.749	0.818
1406	1.6	0.806	0.852
1494	1.7	0.863	0.881
1582	1.8	0.920	0.905
1670	1.9	0.977	0.924

^a Column throughput measured in bed volumes (bv).

^b Normalized bed volume (NBV) equals actual bv divided by bv at 50% distribution.

^c Using Thomas Model parameters: $R = 1, N = 6$.

Table 14. Statistical comparison of Thomas Model parameters

<i>N</i>	(Error ²) ^a	(R ²) ^b
1	1.25	0.453
2	0.472	0.519
3	0.232	0.666
4	0.134	0.798
5	0.090	0.919
6	0.076	0.993 ^c
7	0.094	0.953
8	0.083	0.860
9	0.095	0.816
10	0.111	0.779
11	0.127	0.595
12	0.145	0.425

^a Residual sum of errors squared between bench-scale observed data and predicted Thomas model data.

^b Statistical regression coefficient.

^c Best fit for Thomas model of bench-scale data.

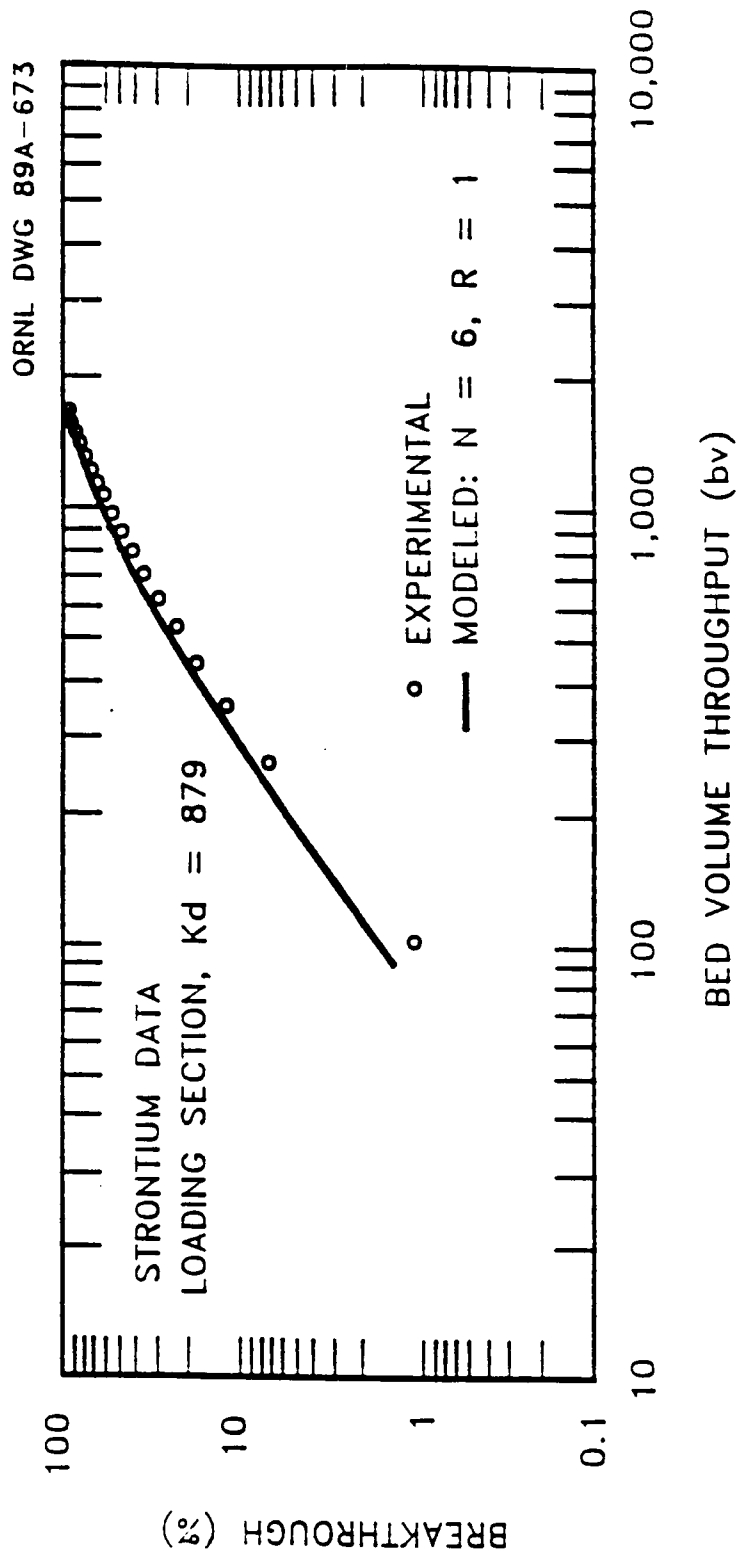


Fig. 15. Modeling of bench-scale column breakthrough curve using Thomas Model.

accurate for the initial portion of the breakthrough curve where analytical techniques make the experimental data questionable for extremely low values of strontium.

Strontium breakthrough data in the pilot-scale column tests are summarized in Table 10 (Section 3.4.2.2). The column throughput, measured in bed volumes (bv) is the feed-to-resin ratio. The observed fractional breakthrough data (C/C_0) are given as mass fractions of the effluent stream. These data were fitted to the Thomas model using the predicted distribution coefficient, K_d , measured from the batch equilibrium data (Table 12) to determine the values of N for the pilot-scale CCIX column tests. As shown in Fig. 16, the pilot test results can be grouped within a band with values of the Thomas model parameters in the range $30 \leq N \leq 50$ for $R = 1$. The observed data points outside of the band are attributed to (1) variations in the feed concentrations, (2) inefficient regeneration of resin entering the column loading section (i.e., strontium and calcium were not 100% removed from the resin and replaced with sodium ions in the column strip section. Consequently, these solute ions on the loaded resin breakthrough in the effluent stream.), (3) resin mixing in the CCIX column during the pulse cycle, and (4) poor distribution of feed and channeling in the larger diameter CCIX column.

Channeling, coupled with radial and axial dispersion in large diameter-columns, will cause the breakthrough curve to be "broad" (similar to the solid curve shown in Fig. 16 for $N = 30$), reducing the slope of the curve and producing low N values.^{43,44} This phenomenon and laminar or turbulent mixing of resin during the pulse cycle would tend to reduce the effective value of N . At optimum conditions, the resin in the top sections of the CCIX column would be

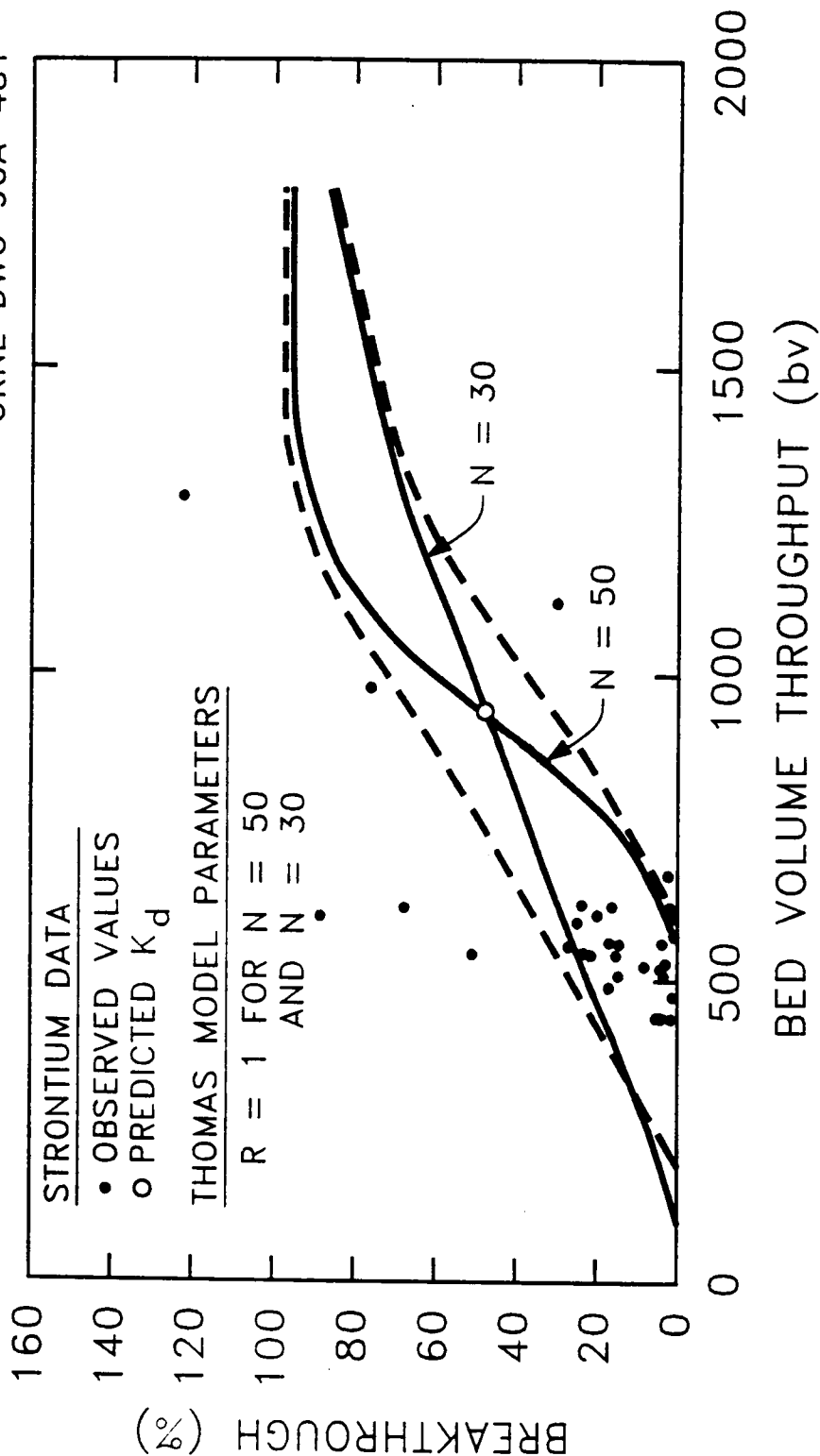


Fig. 16. Modeling of pilot-scale fixed bed column breakthrough curve using Thomas Model.

essentially exhausted. The exhausted region would be pulsed out of the column into the column scrub section during the pulse cycle. Resin mixing, however, could create regions of exhausted and unexhausted resin within the column. The net result would be a reduction in the overall number of transfer units.

4.3.2 Scaleup

The scaleup of small ion-exchange systems to pilot and industrial units can be performed once values of R , N , and K_d are obtained. These values are obtained from empirical measurements and can be used to predict the performance of columns at different operating conditions. During scaleup, the rate parameter (i.e., the mass-transfer coefficient, K_a) will not change. For constant-sorption material and feed composition, the particle diameter and value of K_d were constant during scaleup. Therefore, from Eq. 49, N was assumed to be a function of v/f only.

The bench-scale and pilot-scale CCIX column diameters were 7 mm id and 102 mm id, respectively. Each column was loaded with Dowex HGR-W2 resin originally in the sodium form. The columns had length-to-diameter ratios of 11 and 15, respectively. Feed flow rates were constant with a 1-minute residence time in each column. The calculated equilibrium constant for strontium given in Table 11 ($K' = 90.8$ L/meq) was used in Eq. 34 to determine that the values of R for strontium data in this report were in the range of 0.94 to 0.99. For the modeling exercises in this study, a value of 1.0 was used for R in the Thomas equation.

The bench-scale column data were used to predict scaleup. Using Eq. 51, the total number of transfer units, N , for the CCIX column loading section should equal 120. However, direct modeling of the CCIX column breakthrough curve (shown in Fig. 16) showed the effective N to be a maximum of 50 transfer units. The scaleup results are summarized in Table 15. Deviations between predicted and observed N values are attributed to resin mixing during the pulse cycle and inefficient resin regeneration in the strip section of the CCIX column.

Table 15. Scaleup parameters for predicting N

Column	Diameter (mm)	Resin volume (mL)	K_d	N
Bench-scale	7	3	879	6
Pilot-scale	102	1.24e+04	940 ^a	120

^a Predicted Distribution from batch equilibrium data.

The Thomas equation can be used to model trace multicomponent systems. However, accurate scaleup predictions cannot be made unless the controlling mass-transfer mechanism is known or the fractional combination of controlling mechanisms is known. The axial diffusion term in Eq. 22 must also be known in order to predict how the number of theoretical transfer units change with operating conditions. Once these values are known, the slope of the new breakthrough curve can be accurately predicted from bench-scale data.

4.3.3 Predicting Breakthrough as a Step-Function of Feed Concentration Variables

The effect of increasing feed solute concentrations on the fractional breakthrough (X) can be predicted using the Thomas model parameters (R, N , and T). The fractional breakthrough of strontium in the effluent stream was predicted within 11% and 23% when (a) the strontium composition in the process wastewater feed was increased 75 times the normal concentration (Run 29, Section 3.4.2.4) and (b) the calcium composition in the process wastewater feed was double the normal concentration, respectively, using the following procedure.

Note that the throughput ratio, T , given in Eq. 50 is proportional to the volume processed and inversely proportional to the volume-based distribution coefficient, K_d . Typically in ion-exchange, separation factors (ratio of distribution coefficients) depend on the total concentration of the solution, temperature, and the equivalent ionic fraction of solute components in solution.³ The distribution coefficient, K_d , is essentially constant for isothermal operations with only slight changes in solution concentration or equivalent ionic fractions. Given constant K_d and R for the system, if the fractional breakthrough is known at a reference feed concentration and flow rate, the number of transfer units in the column, N , can be assumed constant using Eq. 49. Values for the throughput parameter, T , can then be calculated at the reference conditions using Eq. 47 or can be read from tables. At the different feed concentrations, the new value of T (T_{new}) can be calculated by ratioing the new equivalent ionic fractions by the reference ionic fractions multiplied by the reference value of T . The predicted breakthrough (X) is then determined at T_{new} using the same N and R expressions.

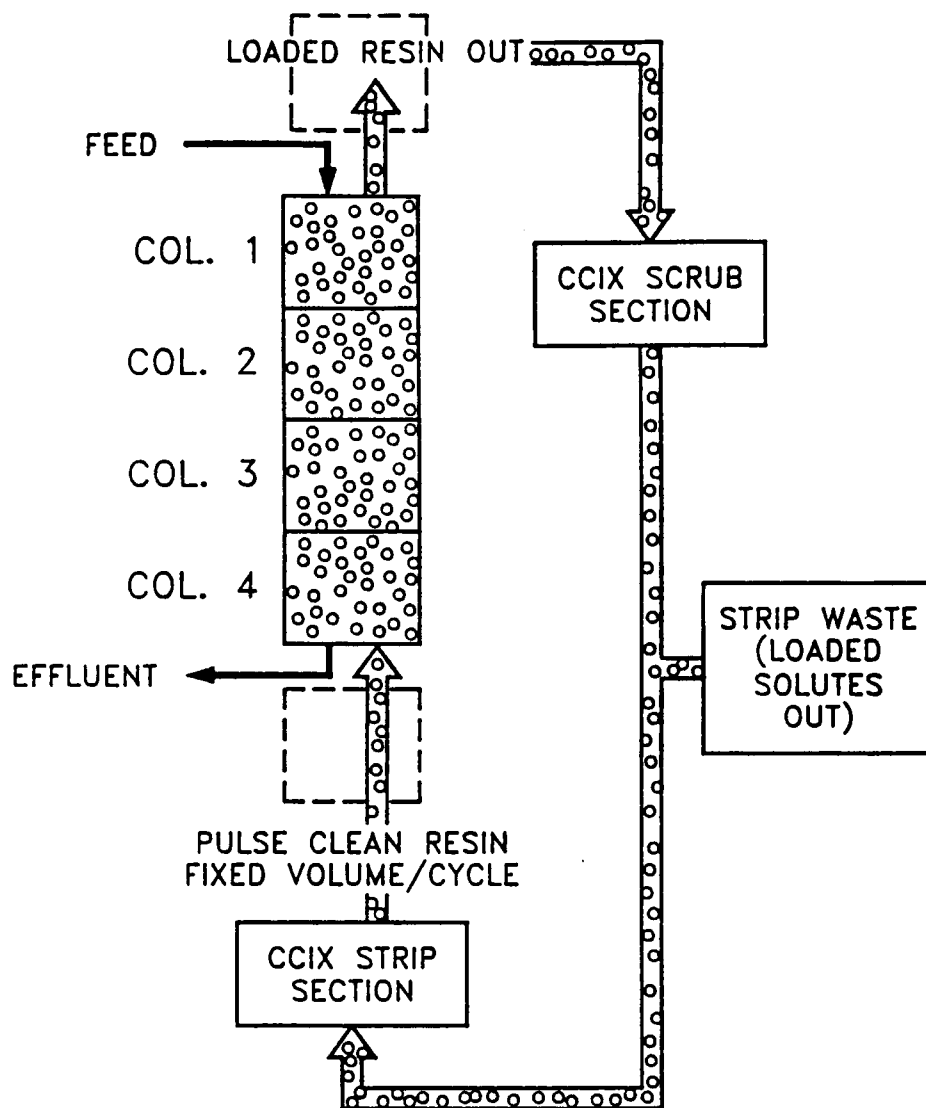
4.3.4 Wallace Model Prediction of CCIX System Operating Parameter Values

Model parameters (R , N , T , and K_d) obtained from the Thomas equation were used in the Wallace model to predict effluent concentrations for the CCIX pilot-scale Run 31. The Wallace model was also used to predict the number of cycles required to reach steady-state in the pilot-scale CCIX system. A schematic of the Wallace Model representation of a CCIX loading section is illustrated in Fig. 17. The CCIX column was modeled as four fixed-bed columns in series. The series of columns was loaded until a specified breakthrough occurred. At that time, a fresh column was added to the front (effluent outlet end), and a column was removed from the back (feed inlet end) of the series. This model would represent a case where the loading cycle is 30 minutes and length of resin pulse in the column loading section (see Section 3.3.2.1) is equal to 15 inches (38 cm) per cycle. Each cycle adds a freshly regenerated column bed equal to 15 inches (38 cm). Column loading during each cycle is predicted in the mathematical model as illustrated in Fig. 18. A copy of the computer program for the Wallace model is given in the Appendix.

4.3.4.1 Estimation of CCIX Steady-State Performance

Results of the Wallace model of the pilot-scale CCIX system (Fig. 18) indicate that approximately 20 to 25 cycles are required to reach steady-state under conditions where the composition of the feed was constant and the resin entering the bottom of the loading section was thoroughly stripped (100% removal

CCIX LOADING SECTION



OPERATION SEQUENCE

1. FEED ENTERS DURING LOADING CYCLE; LOADING ENDS.
2. COLUMN 1 IS REMOVED FROM TOP AT END OF LOADING CYCLE.
3. OTHER COLUMNS ARE ADVANCED ONE POSITION.
4. NEW COLUMN IS ADDED AT BOTTOM POSITION.
5. REPEAT SEQUENCE.

Fig. 17. Schematic representation of Wallace Model for a CCIX system.

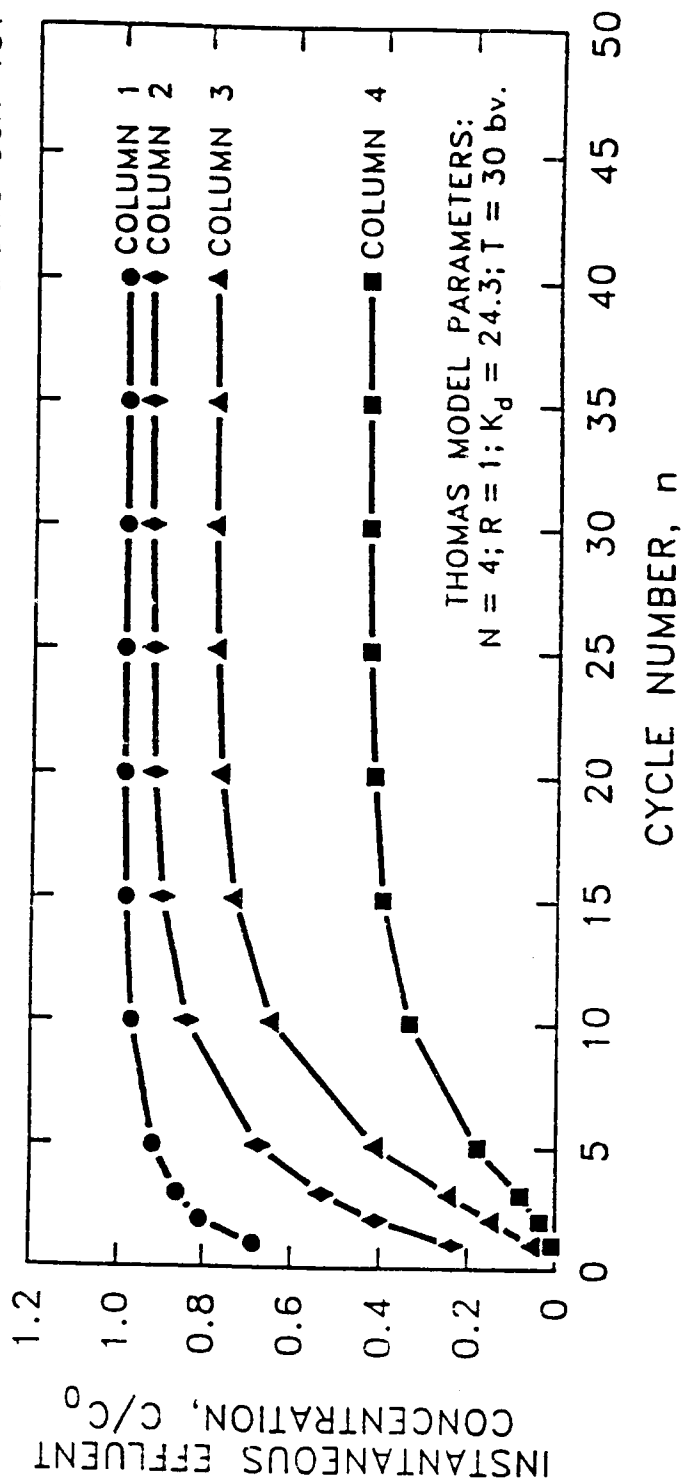


Fig. 18. Wallace Model prediction of CCIX steady-state performance.

of strontium and calcium, leaving only sodium ions on the resin). Estimates of the instantaneous breakthrough curve and effluent concentrations are given for each column in series. These results are used to estimate the length of loading cycle, pulse cycle, and feed-to-resin ratio, required to give target effluent compositions. The length of loading cycle is directly proportional to the bed volume throughput at constant feed flow rate. Increasing the bed volume throughput is analogous to increasing the feed-to-resin ratio.

4.3.4.2 Procedure For Evaluating CCIX Operating Parameters

A general procedure for estimating the operating parameter values for the CCIX system was developed. This procedure would be of general application in industry for predicting CCIX performance when accurate Thomas model parameters (R , N , T , and K_d) are known. The basic procedure involves (a) measuring breakthrough curves from the CCIX column loading section, (b) determining the 50% breakthrough for the solute component of interest, and (c) performing iterations using the Wallace model to determine operating parameter settings.

This procedure was applied to the conditions given in Run 31 (see Section 3.4). Initially, breakthrough curves were obtained from samples of the effluent stream taken during the loading cycle prior to pulsing the resin. These results revealed approximately 50% breakthrough of strontium occurred after processing only 24.3 bed volumes through the column. The test was repeated for confirmation of the initial breakthrough data. The results, however, were similar for each test since the resin had not been efficiently regenerated. These results are used only to illustrate how the Wallace model can be utilized to de-

termine the needed operating parameter adjustments for the CCIX system. The basic procedure for estimating the CCIX system parameter adjustments was as follows:

1. Given the strontium target effluent composition (0.005 mg/L total strontium, which would equal an instantaneous fractional breakthrough of 0.0016 since the blended feed composition for Run 31 was 3.2 mg/L strontium), the bed volume throughput was iterated in the Wallace model until the effluent composition exiting the last column in series (Col 4 in this model) equals the target composition.
2. The loading cycle time was estimated by dividing the bed volume throughput by the feed pump flow rate (bed volume/unit time).
3. The length of each column in series was equal to the resin movement per loading cycle. Hence, the rate of resin movement would be equal to the volume of resin movement (length of resin movement times cross sectional area of column in appropriate volume units) divided by the loading cycle time.
4. The feed-to-resin ratio was estimated by dividing the feed pump rate by the resin rate.

Results of this iterative procedure suggest that the loading cycle time for Run 31 would be equal to 15 minutes [15 bed volumes per cycle divided by pump rate which equals 1 bed volume per minute yields 15 minutes per cycle] to obtain a value of 0.005 mg/L strontium in the effluent stream. The pulse cycle would equal the loading cycle by definition of CCIX system normal operation. The resin movement would need to be set at 3.1 L [15 in. (38.1 cm) movement

in a 4 in. (10.1 cm) id pipe] per 15 minute cycle (207 mL/min). The resulting feed-to-resin ratio would be equal to 55 [Feed rate equal 15 bed volumes per cycle x 11.3 L per bed volume which equals 169.5 L per cycle divided by 3.1 L of resin per cycle]. The model predicts steady-state results after 24 operating cycles at these operating conditions. These results may be undesirable in an industrial-scale process, however, since the number of valve operations for the CCIX system would be doubled which may increase the number of mechanical failures (pumps, valves, etc.) as a result of extended operations.

4.3.4.3 Wallace Model Results

In summary, given parameters from the Thomas model that accurately predict scale-up, a procedure has been suggested which uses the Wallace model to estimate the operating parameters, ie., feed-to-resin ratio, resin rate, length of loading and pulse cycles, and the number of operating cycles required to reach steady-state for a CCIX loading section. The Wallace model can also be extended to predict results for the scrub and strip/rinse sections of the CCIX system given appropriate Thomas model parameters for the respective sections, which may be obtained from bench-scale tests.

5. ECONOMIC ANALYSIS

Cost comparisons for (1) a CCIX industrial-scale process (shown in Fig. 2, Section 2.2.3), (2) the current process waste treatment plant at ORNL, (3) the proposed upgraded process waste treatment plant at ORNL, and (4) an alternative process waste treatment plant using zeolite columns in series were made by calculating the "future costs" of each plant based on a start-up date of 1998 and a plant life of 20 years.⁴⁵ The cost estimates were based on the assumption that the given flow sheet would be used to replace the existing PWTP facility. Most major equipment items were replaced with upgraded equipment, but it was assumed that the existing building would be used. Costs for post-treatment of the waste generated at the PWTP were estimated in the disposal costs, but facility costs were excluded from this study. The inflation rate was assumed to be constant at 5% per year. It should be noted that these costs are based on order-of-magnitude estimates and should be used for comparison purposes only.

5.1 COST ESTIMATE FOR INDUSTRIAL-SCALE CCIX PROCESS

An industrial-scale CCIX process would need to be coupled with a zeolite system for removal of ^{137}Cs in order to meet new federal regulations on environmental discharge limits for ^{90}Sr and ^{137}Cs . A flow diagram of the CCIX industrial-scale process is shown in Fig. 19. An order-of-magnitude cost estimate for this flowsheet was made to estimate the future value of the process in the year 2018. Start-up was assumed to be in 1998, a 20-year operating life, and inflation rate constant at 5% per year. Operating and capital costs for the industrial-scale CCIX process were adapted from Robinson's cost estimate of alternative flowsheets for upgrading the PWTP.¹⁴ Estimates for zeolite disposal costs were adapted from Kent's data.⁴⁶ Since the sludge from both processes consists mainly of calcium carbonate, sludge disposal

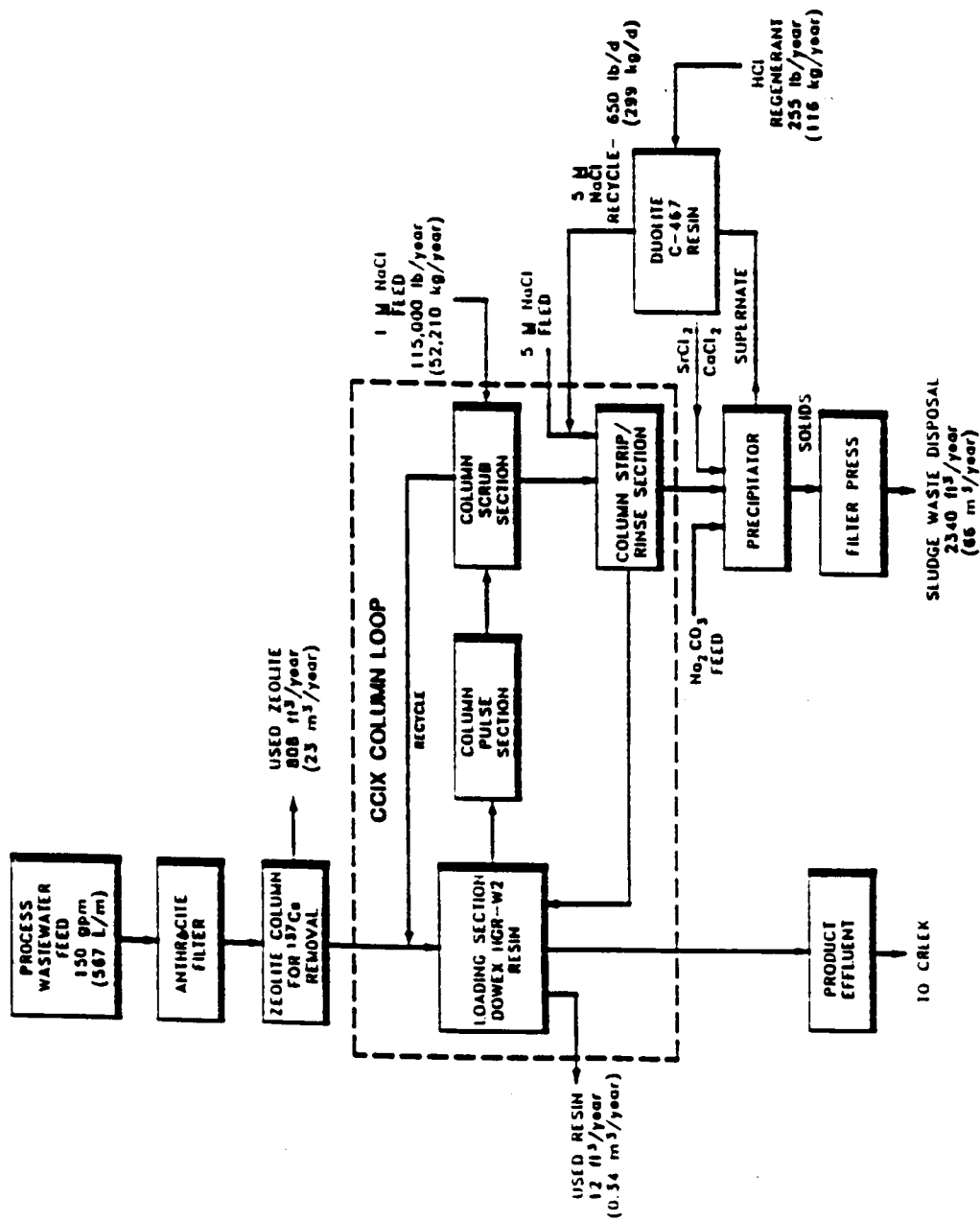


Fig. 19. Flowsheet for industrial-scale CCIX system based on experimental pilot scale results.

costs were estimated from pilot-scale CCIX test results by ratioing the calcium composition in the strip waste stream (60%) divided by the amount of calcium removed by the softener precipitations (90%) at the current PWTP. Table 16 contains the overall cost estimate for an industrial-scale CCIX system.

5.2 COST ESTIMATE FOR ORNL CURRENT PROCESS WASTE TREATMENT PLANT (PWTP) AND UPGRADED PROCESS WASTE TREATMENT PLANT

A flow diagram of the current PWTP system at ORNL is shown in Fig. 20. The PWTP generates both concentrated and dilute low-level liquid waste (LLLW) and solid sludge precipitates that consists primarily of calcium carbonate and trace amounts of radioactive strontium and cesium. The dilute waste is generated during column regeneration with nitric acid and comprises approximately 5800 gallons/year ($22 \text{ m}^3/\text{year}$). Dilute waste is evaporated in the LLLW evaporator and disposed at a cost of \$7/gallon (\$1.8/L). The concentrated waste [4200 gallons/year ($16 \text{ m}^3/\text{year}$)] is combined with LLLW evaporator concentrate and stored for future processing. Disposal cost for concentrated LLLW is estimated to be \$50/gallon (\$13/L). Approximately 3900 ft^3 (114 m^3) of sludge is generated at the PWTP each year as a result of the clarifier precipitations. Sludge is disposed at a cost of \$40/ ft^3 (\$1400/ m^3). Total waste disposal costs for the current PWTP are on the order of \$500,000/year. Cost estimates for the current PWTP are given in Table 17.

Upgrades to the PWTP are expected to improve the overall performance and reduce operating and disposal costs. A total cost order-of-magnitude estimate for the upgraded PWTP (Table 18) was made using the information extracted from Kent's data.⁴⁶

Table 16. Cost estimate for industrial-scale CSA CCIX process.

CATEGORY	1988\$/yr	1989\$/yr
Operating Costs		
Labor	400,000	
Chemicals (based on vendor's retail cost)		
Na_2CO_3 (9.3 lb/d @ 365 d/yr @ \$0.085/lb)	290	
NaCl (115,000 lb/yr @ \$0.085/lb)	9,775	
HCl (255 lb/yr @ \$0.78/lb)	200	
IX Materials		
Dowex HGR-W2 resin (12 ft ³ /yr @ \$100/ft ³)	1,200	
Duolite C-467 resin (5 ft ³ /yr @ \$100/ft ³)	500	
TSM-300 zeolite (808 ft ³ @ \$53/ft ³)	42,824	
Utilities (Kent's data)	50,000	
Analytical Services (Kent's data)	<u>200,000</u>	
Total	704,789	740,924
Capital Costs		
Three Zeolite Columns with		
Zeolite Loading Equipment	79,800	
Precipitator (calculated from costs of 18-ft		
diameter unit using capacity ratio equation		
from <u>Peters and Timmerhaus</u> for 270 gpd unit)	2,300	
One 0.3-m ³ skid-mounted columns with		
regeneration equipment (R. Kunin)	32,000	
One 30-in (76 CM) CCIX column (I. Higgins)		
with instrumentation and controls	290,000	
Total installation costs (260% of		
purchased equipment costs as estimated in		
<u>Peters and Timmerhaus</u> for fluid-processing		
plants without building and land costs)	<u>1,050,660</u>	
Total	1,454,760	1,529,347
Disposal Costs		
Liquid Wastes (no secondary liquid waste generated)		0
Solid Wastes		
Sludge waste disposal (60% Ca in strip		
waste @ 3900 ft ³ /yr per 90% Ca @ \$40/ft ³		
taken from Kent's PWTP waste data)		104,000
IX Resin (12 ft ³ /yr @ \$40/ft ³)		480
Zeolite (808 ft ³ /yr estimated for cesium removal only		
@ \$40/ft ³ (T. E. Kent))		32,320
Containers (\$14,500 each (\$1988) @ 6/yr		
@ 5% inflation/yr)		<u>91,461</u>
Total		228,261

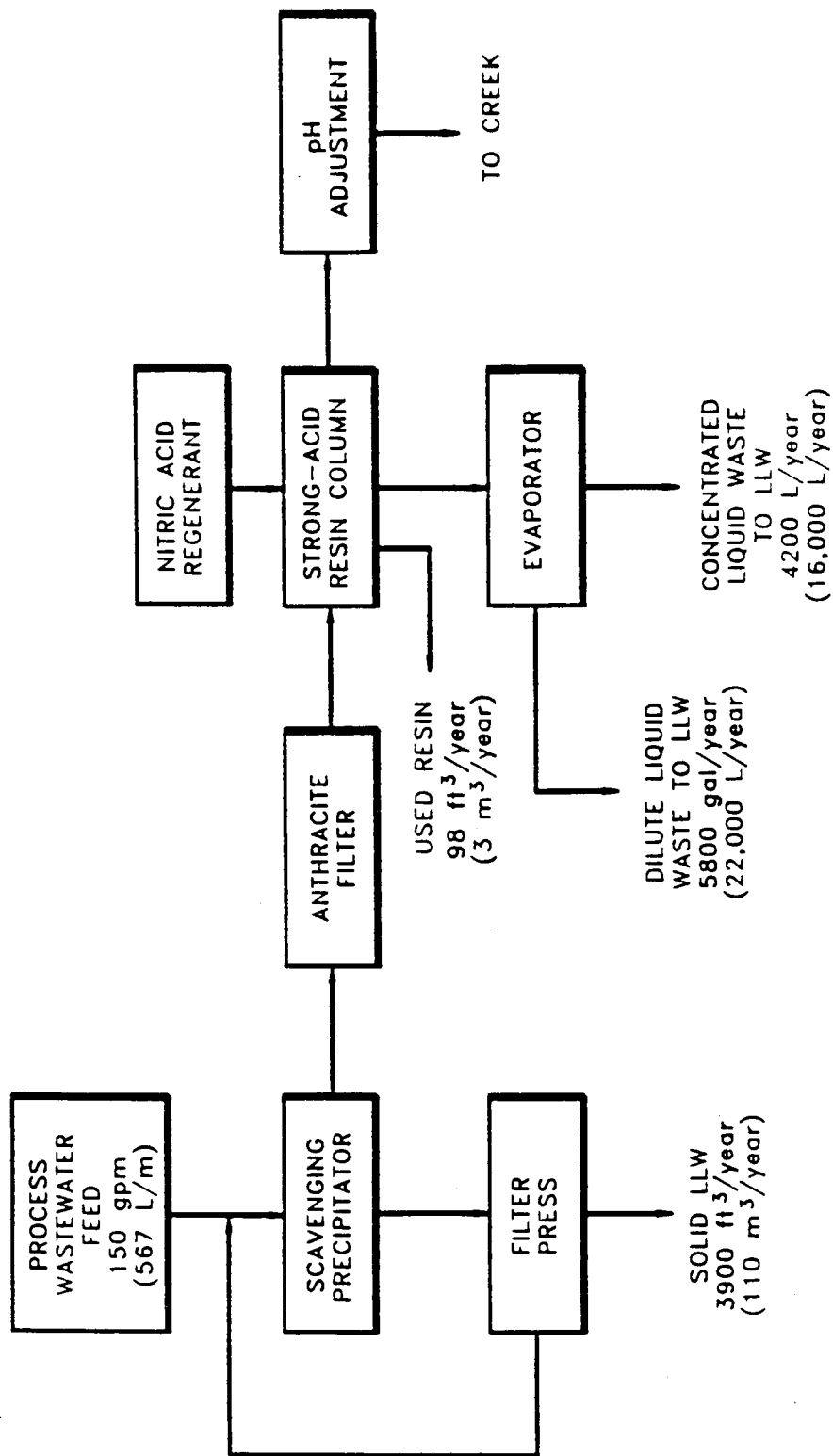


Fig. 20. Flow sheet for ORNL process wastewater treatment plant.

Table 17. Cost estimate for ORNL current PWTP.

CATEGORY	1988\$/yr	1989\$/yr
Operating Costs		
Labor (T. E. Kent)	400,000	
Chemicals		
NaOH (24,800 gal/yr @ \$1.00/gal)	24,800	
HNO ₃ (4,180 gal/yr @ \$0.61/gal)	2,550	
H ₂ SO ₄ (6780 gal/yr @ 0.52/gal)	3,526	
Ferrifloc (1,400 gal/yr @ 0.93/gal)	1,300	
Polymer (40 gal/yr @ \$12.50/gal)	500	
IX Materials		
HCRS resin (50 ft ³ /yr @ \$60/ft ³)	3,000	
Utilities	50,000	
Analytical	<u>200,000</u>	
Total	685,676	720,831
Capital Costs		
No new capitol costs		
Total	0	0
Disposal Costs		
Liquid Wastes (T. E. Kent)		
Concentrated (4200 gal/yr @ \$50/gal)		210,000
Dilute (5800 gal/yr @ \$7/gal)		40,600
Solid Wastes		
Sludge (composition consists of 90% Ca originally in feed stream, 3900 ft ³ /yr generated @ \$40/ft ³)		156,000
IX Resin (HCRS 50 ft ³ /yr @ \$40/ft ³)		<u>2,000</u>
Total		408,600

Table 18. Cost estimate for ORNL PWTP upgrade plan.

CATEGORY	1988\$/yr	1989\$/yr
Operating Costs		
Labor (T. E. Kent)	400,000	
Chemicals		
NaOH (24,800 gal/yr @ \$1/gal)	24,800	
HNO ₃ (4,180 gal/yr @ \$0.62/gal)	2,600	
H ₂ SO ₄ (6,780 gal/yr @ \$0.52/gal)	3,500	
Ferrifloc (1,400 gal/yr @ \$0.93/gal)	1,300	
Polymer (40 gal/yr @ \$12.5/gal)	500	
IX Materials		
HCR-S resin (33 ft ³ /yr @ \$60.6/ft ³)	2,000	
Zeolite (808 ft ³ /yr @ \$53/ft ³)	42,824	
Utilities	50,000	
Analytical	<u>200,000</u>	
Total	727,524	764,825
Capital Costs		
Softener	90,000	
Three Zeolite Columns with Zeolite Loading Equipment	79,800	
Condensate Tank	25,000	
pH Adjust System	7,000	
Total installation costs (260% of purchased equipment costs as estimated in <u>Peters and Timmerhaus</u> for fluid-processing plants without building and land costs)	<u>524,680</u>	
Total	726,480	763,727
Disposal Costs		
Liquid Wastes (T. E. Kent)		
Concentrated (2350 gal/yr @ \$50/gal)		117,500
Dilute (Eliminated by condensate recycle tank in upgrade system was 5800 gal/yr @ \$7/gal)		0
Solid Wastes		
Sludge (composition consists of 90% Ca originally in feed stream, 3900 ft ³ /yr generated @ \$40/ft ³)		156,000
IX Resin (HCR-S resin, 33 ft ³ /yr @ \$40/ft ³)		1,320
Zeolite (808 ft ³ /yr estimated for cesium removal only @ \$40/ft ³ (T. E. Kent))		32,320
Containers (\$14,500 each (\$1988) @ 6/yr @ 5% inflation/yr)		<u>91,461</u>
Total		398,601

5.3 COST COMPARISON OF A ZEOLITE COLUMN WASTE TREATMENT SYSTEM

The operation of zeolite columns in series was proposed as an alternative treatment plant for removal of both ^{137}Cs and ^{90}Sr from process wastewaters generated at ORNL.⁴⁷ This flowsheet loads strontium and cesium on four zeolite columns in series. The first column in the series is removed at some point after strontium breakthrough occurs. The remaining columns are moved one position forward (countercurrent to the feed flow), and a fresh column is placed in the last position in the series to maintain the desired effluent concentrations. Repetitive cycles of this type (called the merry-go-round technique) are continued throughout the process. Cost estimates for the zeolite process are given in Table 19. This estimate was made to estimate the future value of the process in the year 2018. Start-up was assumed to be in 1998, a 20-year operating life, and inflation rate constant at 5% per year. Cost estimate data were also extracted from the information given in Kent's data.⁴⁶

5.4 COST COMPARISON OF CCIX SYSTEM TO CURRENT METHODS AT ORNL PWTP

Cost comparisons of the CCIX system versus the upgraded PWTP, current PWTP, and zeolite systems are given in Table 20. The systems were compared on the basis of yearly operating costs, capitol investment costs, and yearly disposal costs. The future value of the initial capitol investment costs were determined over the 20-year expected operating life of the project assuming no credit for depreciation recovery costs and zero salvage value at the end of the project life. A summary of the formulas used in the economic analysis is given in the Appendix. Results of this cost comparison show the CCIX system to offer a potential savings of \$200,000 per year over the upgraded PWTP system and \$500,000 per year over the currently used PWTP treatment methods. The CCIX process was shown to offer a potential

Table 19. Cost estimate for zeolite column waste treatment system.

CATEGORY	1988\$/yr	1989\$/yr
Operating Costs		
Labor (T. E. Kent)	400,000	
Zeolite Columns (2674 ft ³ @ \$53/ft ³)	141,722	
Chemicals		
NaOH and H ₂ SO ₄	2,500	
Utilities	50,000	
Analytical	<u>200,000</u>	
Total	794,222	834,943
Capitol Costs		
Zeolite Columns (5 @ 11.1 m ³ ea)	560,000	
Feed Tank	20,000	
Feed Pumps (2)	10,000	
Multimedia Filters (2)	130,000	
Zeolite Loading and Unloading Equipment	<u>100,000</u>	
	820,000	
Installation (260% of purchased equipment costs)	<u>2,132,000</u>	
Total	2,952,000	3,103,352
Disposal Costs		
Liquid Wastes (No secondary liquid waste generated)		0
Solid Wastes		
Zeolite (2674 ft ³ /yr @ \$40/ft ³)		106,960
Containers (High Integrity Containers, 130 ft ³ ea., 20.6/yr @ \$6,000 ea)		<u>123,600</u>
Total		230,560

Table 20. Cost estimate comparison of CCIX system to ORNL current PWTP, upgraded PWTP, and zeolite system

Cost Summary				
<u>1989\$/yr</u>				
	CCIX System	Current PWTP	PWTP Upgrade	Zeolite
Capital Costs	1,529,347	No New Costs	763,727	3,103,352
Operating Costs/yr	740,924	854,984	398,601	230,560
Disposal Costs/yr	<u>228,261</u>	<u>408,600</u>	<u>398,601</u>	<u>230,560</u>
Total Yearly Costs	969,185	1,263,494	1,163,426	1,065,503
Future Value Costs				
<u>2018\$/yr</u>				
	CCIX System	Current PWTP	PWTP Upgrade	Zeolite
20-Year Operating and Disposal Costs (5% Inflation/yr)	33,306,659	43,420,775	39,981,875	36,616,689
Total Disposal Costs Savings (\$/yr) Using CCIX System Versus Alternatie Methods		505,705	333,760	165,501
20-Year Future Value Capital Costs at Startup in 1998	4,157,196	No new costs	2,076,025	8,435,785
Total Value Capital Costs Plus Disposal Costs (2018\$/yr)	37,463,855	--	42,057,900	45,052,474
Total Yearly Cost Savings of CCIX Versus Alternatives			229,702	379,430

savings of \$400,000 per year over the zeolite process as a result of the higher initial capital investment for the zeolite system. However, excluding the initial capital investment, the zeolite process would be comparable to the CCIX process on yearly cost savings.

6. CONCLUSIONS AND RECOMMENDATIONS

This study has successfully demonstrated the feasibility of using the CSA CCIX system as an alternative for strontium removal from ORNL process wastewaters. Results from operation of the pilot-scale CCIX system during short runs (<50 hours semi-continuous operation) have demonstrated the potential economic cost savings of separating strontium from calcium and recycling of strip waste streams to minimize generation of additional secondary waste streams. Application of the mobile pilot-scale CCIX system would be exceptionally attractive for treatment of contaminated wastewaters with essentially constant feed compositions at remote sites. However, the CCIX process contains several intricate mechanical parts that are vital to maintaining continuous operation. Mechanical failures requiring valve replacements could potentially lead to significant downtime waiting for repairs and re-startup. Therefore, additional demonstration studies are needed to evaluate the mechanical reliability and overall long-term operating performance results of the pilot-scale system prior to recommending industrial scale application of the CCIX system.

Continuous countercurrent ion exchange (CCIX) offers a range of operating flexibility over traditional fixed-bed ion-exchange systems. Operating parameters for CCIX systems can be adjusted to accommodate variable loadings resulting from changes in the total ionic strength of variable feed stream compositions. Instrumentation and controls for the CCIX system could potentially be automated using proportional integrated derivative (PID) controllers which could tremendously enhance the overall compensation process. Current operation of a CCIX system under conditions where the feed compositions and flow rates vary over a large range would require attentive operators and perhaps one engineer to monitor the data, interpret results, and to provide instruction on adjustments needed to

maintain target results. Installation of an inline analyzer for monitoring one feed component variable, eg. calcium composition in the feed stream, is recommended in conjunction with the PID controller to adjust system parameters automatically and improve the overall versatility of the CCIX process.

One key feature of the CCIX system is its potential to eliminate secondary waste streams generated in the treatment process by recycling of the 5 M strip feed streams used to separate strontium and calcium from the loaded resin. Preliminary batch precipitation tests partially confirms that the majority of the strontium and calcium are chemically removed by sodium carbonate precipitation. However, radioactivity remaining in the supernate (recyclable solution) will need to be further decontaminated to (a) eliminate the generation of an additional secondary waste stream and (b) to recycle the supernate solution as the strip feed solution and avoid accumulating radioactivity on the loaded resin which may reduce resin regeneration efficiency and increase fractional breakthrough in the column loading section. Development of post-treatment precipitation processes are needed to demonstrate the feasibility of the decontamination process and continuous recycle of the strip waste supernate stream.

Fundamental studies are needed to optimize the CCIX system and minimize the amount of chlorine in the scrub recycle stream that would ultimately be discharged in the environment. These basic studies should be conducted in two steps. The first step should be designed to determine the conditions yielding maximum (optimum) separation factors between calcium and strontium in various concentrations of salt (NaCl) solutions. These data can be obtained from batch equilibrium data using resin loaded with strontium and calcium and mixed with various concentrations of NaCl solutions in the range of 0.25 M to 5 M. The second step should be designed to obtain kinetic rate data from ion exchange column tests.

The column should be preloaded with strontium and calcium loaded resin. By varying the flow rates of the optimum salt (NaCl) solution in the column, kinetic rates can be correlated. With these kinetic rates and the separation factors from the batch equilibrium tests, the CCIX scrub section can be optimized to improve the overall system performance.

Models for ion exchange systems have been presented in this study to predict the performance of fixed-bed ion-exchange columns from experimental data obtained in laboratory tests. Given accurate controlling mass transfer mechanisms, these traditional models can be used to scaleup laboratory-sized ion-exchange systems to industrial-scale systems. These modeling techniques can also be employed to predict the performance of a CCIX system. The pilot-scale tests results suggest that combinations of controlling mass transfer mechanisms may occur in the CCIX system. Fundamental studies of mass transfer mechanisms are needed to develop models that could be used to design columns for maximum efficiency and that would eliminate extensive pilot-scale testing in the future. This type of model could amount to significant cost savings, as more waste streams require treatment and disposal costs increase. Additionally, data are needed to accurately predict CCIX performance. Tests should be designed to determine the effect of axial diffusion and channeling in the CCIX column. Feed stream inlet distributions and configurations for the CCIX loading section need to be tested and reviewed to determine the effect of channeling on fractional breakthrough in the effluent stream. Breakthrough curves need to be obtained initially using clean resin to eliminate the question of resin regeneration efficiency. These curves can then be compared with the laboratory-scale breakthrough curves to confirm the scaleup model equation. Once the effect of channeling is known, the axial diffusion effect can be determined. The ion-exchange model developed in this study does not account for

axial diffusion. Therefore, a correction factor for the known axial diffusion effect can be used to reduce the relative error of the proposed ion exchange model.

In summary, the Wallace model effectively simulates the continuous countercurrent ion-exchange system and predicts the effects of operating parameters and variable feed concentrations on ion-exchange column behavior. Additionally, the pilot-scale CCIX process can be viewed as a potentially cost effective technique for removing strontium from low-level radioactively contaminated wastewaters. Recycling of regeneration streams, although partially confirmed, and separating strontium from calcium in the process wastewater significantly reduces waste disposal costs. Savings of more than \$200,000 per year compared to the upgraded PWTP system could be realized for an industrial-scale process based on the pilot-scale test demonstration results.

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APPENDICES

APPENDIX A
EXPERIMENTAL DATA FILES

BATCH EQUILIBRIUM DATA AND MATERIAL
BALANCES ARE GIVEN IN THE FOLLOWING SECTION

Batch Equilibrium Data for Simulated ORNL Process Wastewater
March 2, 1990

Resin Weight, g	Sample ID	Concentrations				Material Balances*			
		Sr mg/L	Ca mg/L	Mg mg/L	Na mg/L	REX meq	SOLEX meq	NET Exchange	Relative Error, %
0.2958	S1	0.47	0.61	1.12	246	0.92	0.863	0.064	6.88%
0.4784	S2	0.03	0.14	0.27	260	0.9370	0.926	0.011	1.21%
0.1875	S3	14.0	14.02	18.95	171	0.683	0.539	0.143	21.01%
0.1574	S4	25.2	22.65	19.91	192	0.606	0.631	-0.025	-4.17%
0.0564	S5	64.8	49.33	35.52	102	0.254	0.241	0.013	5.16%
0.6728	S6	0.026	0.09	0.14	270	0.939	0.969	-0.030	-3.19%
0.3433	S7	0.29	0.31	39.83	203	0.610	0.678	-0.067	-11.00%
0.1156	S8	35.3	30.2	21.0	153	0.530	0.461	0.075	13.96%
0.2529	S9	1.32	1.63	0.89	247	0.922	0.871	0.051	5.55%
0.3145	S10	0.44	0.58	0.94	262	0.929	0.937	-0.008	-0.86%
FEED#1		107	71.8	35.1	49.6				
FEED#2		107	71.0	45.0	45.5				
FEED#3		107	71.0	44.2	45.9				
Avg FEED		107	71.3	41.4	47.0				

*Resin Exchange (REX) = solutes exchanged on resin.

Solution Exchange (SOLEX) = Na ions exchanged from resin to solution.

$\text{Vol(L)}[(\text{Sr}/88 + \text{Ca}/40 + \text{Mg}/24.3)] * 2 - \text{Na}/23] = \text{Net meq exchanged}$

If Net meq exchanged is negative, more sodium was kicked resin than was replaced by feed solutes.

Relative Error = Net Exchanged/Resin Exchange *100

Batch Equilibrium Data for Simulated ORNL Process Wastewater
March 2, 1990 (Continued)

	Calculated Alphas*				Sample
	K(SR)/ K(Ca)	K(Mg)/ K(Ca)	K(Na)/ K(Ca)		
1.96	0.31	0.01			S1
8.02	0.30	0.00			S2
1.62	0.29	0.18			S3
1.51	0.50	0.35			S4
1.45	0.37	1.22			S5
4.99	0.35	0.00			S6
1.62	0.00	0.00			S7
1.49	0.71	0.51			S8
1.87	1.07	0.02			S9
1.99	0.36	0.01			S10
Means:					
Standard deviations:	2.65	0.43	0.23		
Two times st. dev.:	2.05	0.27	0.37		
	4.10	0.55	0.74		

** Values larger than two standard deviations are taken as erroneous measurements.
These points (#2 for Sr, and #5 for Sodium) were not used in the Nonlinear Modeling exercise.

CCIX RAW DATA FILE

RUN # (01)

DATE: 1-10-89

Determine optimum operating conditions of a CCIX unit using process H₂O. The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The scrub solutions are 5M NaCl and 1M NaCl respectively. The programmable controller is set for 30 min. cycles.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BLEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
01/10	17:00	26.5	15.0	3.5	40.0	0.0	30.0	27.0	1.0	80.0	40.0	11.4	26.0	20.8	26.0	40.0	0.0	40.0
01/10	19:00	26.0	14.6	4.0	40.0	15.2	30.0	23.0	1.0	100.0	40.0	11.4	26.0	20.8	26.0	40.0	26.0	19.2
01/10	21:00	25.5	14.4	4.5	40.0	15.2	29.0	37.0	1.0	75.0	40.0	11.4	26.0	15.6	26.0	40.0	26.0	24.4
01/10	23:05	24.0	14.0	5.2	40.0	15.2	29.0	38.0	2.0	60.0	40.0	11.4	29.0	17.1	29.0	40.0	26.0	22.9
01/11	01:00	24.4	13.8	5.8	40.0	15.2	29.0	43.0	2.0	90.0	40.0	11.4	27.3	15.6	29.9	40.0	26.0	27.0
01/11	03:00	24.0	13.5	7.0	40.0	15.2	32.0	26.0	2.0	80.0	40.0	11.4	26.0	15.6	36.3	40.0	26.0	34.8
01/11	05:00	23.5	13.1	7.9	40.0	15.2	31.0	22.0	2.0	85.0	40.0	11.4	26.0	16.4	38.1	40.0	26.0	35.7
01/11	07:00	23.0	12.9	8.4	40.0	15.2	28.0	21.0	2.0	90.0	40.0	11.4	26.0	15.6	36.3	40.0	26.0	34.8
01/11	09:00	22.6	12.5	8.9	40.0	15.2	29.0	24.0	2.0	80.0	40.0	11.4	26.6	16.2	35.0	40.0	26.0	32.2
01/11	13:00	21.3	12.0	10.0	40.0	15.2	30.0	36.0	2.0	85.0	40.0	11.4	27.0	15.6	33.7	40.0	26.0	31.2
01/11	15:00	21.0	11.8	11.0	40.0	15.2	29.0	24.0	2.0	80.0	40.0	11.4	26.0	15.1	35.4	40.0	26.0	31.3
01/11	17:00	20.5	11.6	11.4	40.0	15.2	29.0	21.0	2.0	80.0	40.0	11.4	26.0	14.7	34.2	40.0	26.0	33.5
AVERAGES:																		
													11.4	14.7	34.2	40.0	26.1	33.5
FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.																		
													F/R	ST/R	SC/R			
													438	1.0	0.6			

CCIX RAW DATA FILE

RUN # (02)

DATE: 1-11-89

Determine optimum operating conditions of a CCIX unit using process M20. The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The scrub solutions are 5M NaCl and 1M NaCl respectively. The programmable controller is set for 30 min. cycles.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BPEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
01/11	13:00	21.5	12.0	9.2	40.0	15.0	30.0	36.0	2.0	---	40.0	11.4	---	---	---	40.0	25.8	---
01/11	15:00	21.0	11.8	10.4	40.0	15.0	29.0	24.0	2.0	85.0	40.0	11.4	26.0	10.4	62.3	40.0	25.8	66.0
01/11	17:00	20.5	11.6	11.4	40.0	15.0	29.0	21.0	2.0	80.0	40.0	11.4	26.0	10.4	57.1	40.0	25.8	60.8
01/11	19:00	20.0	11.2	12.0	40.0	14.0	31.0	21.0	2.0	80.0	40.0	11.4	26.0	13.8	48.5	40.0	24.0	48.7
01/11	21:00	19.5	11.0	12.3	40.0	14.0	31.0	23.0	2.0	75.0	40.0	11.4	26.0	13.0	40.2	40.0	24.0	41.3
01/11	23:00	19.0	10.7	13.9	40.0	14.0	30.0	22.0	2.0	78.0	40.0	11.4	26.0	13.5	48.8	40.0	24.0	49.3
01/12	01:00	18.5	10.5	14.2	40.0	14.0	31.0	22.0	2.0	90.0	40.0	11.4	26.0	13.0	43.3	40.0	24.0	44.3
01/12	03:00	18.0	10.0	14.9	40.0	14.0	31.0	21.0	2.0	90.0	40.0	11.4	26.0	14.8	42.3	40.0	24.0	41.5
01/12	05:00	17.5	9.8	15.0	40.0	14.0	31.0	24.0	2.0	80.0	40.0	11.4	26.0	14.3	37.6	40.0	24.0	37.4
01/12	07:00	17.0	9.5	16.0	40.0	14.0	31.0	24.0	2.0	95.0	40.0	11.4	26.0	14.6	39.2	40.0	24.0	38.8
01/12	09:00	16.7	9.2	16.4	40.0	18.0	30.0	28.0	2.0	80.0	40.0	11.4	25.9	14.5	37.4	40.0	30.9	37.9
01/12	11:00	16.1	8.9	16.4	40.0	18.0	31.0	35.0	2.0	75.0	40.0	11.4	25.5	14.6	34.0	40.0	30.9	33.9
01/12	13:00	15.5	8.6	16.1	40.0	18.0	29.0	22.0	2.0	65.0	40.0	11.4	26.0	14.7	29.9	40.0	30.9	29.2

AVERAGES:

11.4	26.0	14.7	34.2	40.0	26.0	33.5
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FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R	ST/R	SC/R
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438	1.0	0.6
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CCIX RAW DATA FILE

RUN # (03)

DATE: 1-15-89

Determine optimum operating conditions of a CCIX unit using process H2O. The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The scrub solutions are 5M NaCl and 1M NaCl respectively. The programmable controller is set for 30 min. cycles.

DATE	TIME	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RATE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
01/15	16:30	23.2	28.3	13.5	40.0	15.0	30.0	39.0	1.0	80.0	30.0	11.4	20.8	10.4	46.7	40.0	25.8	55.6
01/15	18:30	22.8	28.1	14.4	40.0	15.0	30.0	38.0	1.0	100.0	32.0	11.4	26.0	13.0	28.6	40.0	25.8	29.6
01/15	20:30	22.2	27.8	14.6	40.0	15.0	30.0	32.0	2.0	60.0	30.0	11.4	24.2	13.8	28.0	40.0	27.5	27.9
01/15	22:30	21.8	27.5	15.0	40.0	16.0	30.0	32.0	2.0	100.0	30.0	11.4	22.1	14.3	29.9	40.0	27.5	33.5
01/16	00:30	21.5	27.2	15.8	40.0	16.0	30.0	38.0	2.0	85.0	32.0	11.4	24.9	14.5	26.0	40.0	25.8	26.5
01/16	02:30	20.8	26.9	16.0	40.0	15.0	30.0	38.0	2.0	100.0	32.0	11.4	23.4	13.8	29.4	40.0	25.8	32.2
01/16	04:30	20.5	26.7	16.9	40.0	14.0	30.0	22.0	2.0	80.0	32.0	11.4	24.5	14.8	29.7	40.0	24.0	30.4
01/16	06:30	19.9	26.3	17.5	40.0	14.0	30.0	32.0	1.5	80.0	32.0	11.4	24.7	14.9	29.2	40.0	24.0	29.6
01/16	08:30	19.4	26.0	18.0	40.0	14.0	30.0	25.0	1.5	100.0	33.0	11.4	24.2	15.0	30.6	40.0	26.0	31.3
01/16	10:30	19.0	25.7	18.8	40.0	14.0	30.0	20.0	1.5	80.0	33.0	11.4	23.9	15.1	31.2	40.0	27.5	32.2
01/16	12:30	18.6	25.4	19.5	40.0	16.0	30.0	20.0	1.5	80.0	33.0	11.4	24.5	15.1	31.6	40.0	27.5	32.0
01/16	14:30	18.0	25.1	20.2	40.0	16.0	30.0	22.0	1.5	80.0	33.0	11.4	26.0	14.7	34.2	40.0	27.5	33.5
01/16	16:30	17.2	24.9	21.4	40.0	16.0	30.0	22.0	1.5	80.0	33.0	11.4	26.0	14.7	34.2	40.0	26.0	33.5
AVERAGES																		
													11.4	26.0	34.2	40.0	26.0	33.5

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

438 1.0 0.6

CCIX RAW DATA FILE

RUN # (04)

DATE: 1-16-89

Determine optimum operating conditions of a CCIX unit using process #20. The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The scrub solutions are 5N HCl and 1N NaCl respectively. The programmable controller is set for 30 min. cycles.

DATE	TIME	STRIP RATE (inches)	STRIP RATE (inches)	STRIP WASTE (inches)	STRIP RECYCLE (ml/min)	SCRUB RATE (inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
01/16	19:10	16.0	23.1	1.8	40.0	---	29.0	26.0	1.0	80.0	34.0	11.4	---	---	---	---	---	---
01/16	19:50	15.1	23.0	1.9	40.0	15.0	32.0	23.0	1.5	100.0	34.0	11.4	140.2	15.6	15.6	40.0	40.0	100.2
01/16	22:00	14.7	22.3	3.0	40.0	13.0	31.0	23.0	1.0	100.0	34.0	11.4	47.6	29.3	44.0	40.0	22.3	7.0
01/17	00:00	14.0	21.6	4.0	40.0	11.0	31.0	30.0	2.0	100.0	35.0	11.4	43.0	32.2	47.3	40.0	18.9	12.1
01/17	02:00	13.1	21.0	5.0	40.0	10.0	31.0	34.0	2.0	100.0	37.0	11.4	44.1	31.9	48.6	40.0	17.2	12.6
01/17	04:00	12.4	20.4	5.9	40.0	9.5	29.0	22.0	2.0	100.0	38.0	11.4	42.3	31.7	48.2	40.0	16.3	14.1
01/17	06:00	11.5	20.0	7.6	40.0	9.0	29.0	29.0	2.0	100.0	40.0	11.4	43.1	29.7	55.6	40.0	15.5	22.7
01/17	09:30	10.0	19.4	10.8	40.0	9.0	31.0	40.0	2.0	100.0	40.0	11.4	43.5	26.8	65.2	40.0	15.5	34.9
01/17	10:30	9.8	18.8	11.9	40.0	11.0	31.0	31.0	2.0	100.0	40.0	11.4	42.0	29.1	68.4	40.0	18.9	37.3
01/17	12:30	8.8	18.2	12.9	40.0	11.0	31.0	23.0	2.0	110.0	41.0	11.4	43.1	29.6	66.5	40.0	18.9	34.0
01/17	13:00	8.5	17.6	13.0	40.0	12.0	30.0	21.0	2.0	60.0	41.0	11.4	43.8	32.0	65.2	40.0	20.6	29.4
AVERAGES													11.4	32.0	65.2	40.0	19.0	29.4

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

601 2.3 1.7

CCIX RAW DATA FILE

RUN # (05)

DATE: 1-17-89

Determine optimum operating conditions of a CCIX unit using process H₂O. The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The scrub solutions are 5M NaCl and 1M NaCl respectively. The programmable controller is set for 30 min. cycles.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BPEED RATE (LPH)	STRIP RATE (mL/min)	SCRUB RATE (mL/min)	STRIP WASTE (mL/min)	SCRUB RECYCLE (mL/min)	RESIN RATE (mL/min)	RINSE RATE (mL/min)
01/17	17:00	28.7	31.4	3.0	40.0	---	30.0	25.0	1.0	70.0	31.0	11.4	---	---	---	40.0	---	---
01/17	19:00	27.9	30.8	3.7	40.0	9.0	32.0	32.0	1.5	70.0	43.0	11.4	41.5	31.1	36.3	40.0	15.5	3.7
01/17	21:00	27.0	30.3	4.9	40.0	10.0	29.0	22.0	1.0	70.0	43.0	11.4	44.1	28.6	49.3	40.0	17.2	16.6
01/17	23:00	26.2	29.6	5.1	40.0	10.0	32.0	29.0	2.0	80.0	43.0	11.4	43.3	31.1	36.3	40.0	17.2	1.9
01/18	01:00	25.4	29.0	6.8	40.0	10.0	30.0	34.0	2.0	70.0	44.0	11.4	42.8	31.1	49.3	40.0	17.2	15.3
01/18	03:00	24.6	28.5	8.2	40.0	10.0	30.0	24.0	2.0	70.0	43.0	11.4	42.6	30.1	54.0	40.0	17.2	21.3
01/18	05:00	23.8	27.8	9.6	40.0	10.0	30.0	24.0	2.0	70.0	45.0	11.4	42.4	31.1	57.1	40.0	17.2	23.6
01/18	07:00	23.0	27.1	10.9	40.0	10.0	30.0	33.0	2.0	75.0	47.0	11.4	42.3	31.9	58.6	40.0	17.2	24.4
01/18	09:00	22.0	26.6	12.3	40.0	10.0	30.0	25.0	2.0	75.0	50.0	11.4	43.5	31.1	60.4	40.0	17.2	25.7
01/18	10:00	21.5	26.2	13.7	40.0	10.0	30.0	24.0	2.0	75.0	50.0	11.4	43.8	32.1	65.0	40.0	17.2	29.2

AVERAGES 11.4 43.8 32.1 65.0 40.0 17.0 29.2

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

672 2.6 1.9

CCIX RAW DATA FILE

RUN # (06)

DATE: 1-30-89

 Determine optimum operating conditions of a CCIX unit using
 process H2O. The unit employs a Dowex Cation Exchange Resin to
 selectively remove Sr and Ce from process wastewater streams.
 The scrub solutions are 5M NaCl and 1M NaCl respectively. The
 programmable controller is set for 30 min. cycles.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BPEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
01/30	01:00	28.0	29.1	1.6	---	---	36.0	57.0	2.0	---	---	12.1	---	---	---	---	---	---
01/30	03:00	26.7	28.5	1.7	---	12.5	33.0	51.0	2.0	60.0	42.0	12.3	67.5	31.2	5.2	90.6	21.4	2.9
01/30	05:00	25.6	27.8	1.7	---	12.0	15.0	38.0	2.0	60.0	43.0	12.1	62.3	33.7	2.6	92.0	20.6	1.4
01/30	07:00	24.5	27.1	1.7	---	11.5	15.0	50.0	2.0	60.0	43.0	12.0	60.6	34.6	1.7	90.6	19.7	2.8
01/30	09:00	23.3	26.5	1.7	---	11.0	6.0	48.0	2.0	65.0	48.0	12.4	61.0	33.7	1.3	93.5	18.9	-0.0
01/30	11:00	22.1	25.7	1.9	---	11.0	55.0	51.0	2.0	60.0	47.0	11.9	61.3	35.3	3.1	92.0	18.9	1.5
01/30	13:00	20.8	25.1	2.3	86.3	12.0	48.0	60.0	2.0	75.0	42.5	12.0	62.3	34.6	5.6	86.3	20.6	5.0
01/18	15:00																	
01/18	17:00																	
01/18	19:00																	
01/18	21:00																	

AVERAGES 12.1 62.3 34.6 5.6 90.8 20.0 0.5

 FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

606 3.1 1.7

CCIX RAW DATA FILE

RUN # (07)

DATE: 1-31-89

 Determine optimum operating conditions of a CCIX unit using to
 process H2O. The unit employs a Dowex Cation Exchange Resin to
 selectively remove Sr and Ca from process wastewater streams.
 The scrub solutions are 5M NaCl and 1M NaCl respectively. The
 programmable controller is set for 30 min. cycles.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	SCRUB RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
01/31	09:00	14.1	18.2	5.5	5.5	13.0	37.0	45.0	2.5	70.0	46.0	11.3	51.9	36.3	46.7	61.5	20.6	20.0
01/31	11:00	13.1	17.5	6.4	61.5	12.0	36.0	58.0	2.5	70.0	49.0	10.7	54.5	36.3	44.1	75.0	17.2	28.3
01/31	13:00	12.0	16.8	7.2		10.0	39.0	62.0	2.5	70.0	51.0	11.7	57.1	34.6	45.0	87.3	24.0	40.6
01/31	15:00	10.8	16.2	8.1	87.3	14.0	39.0	62.0	2.5	80.0	53.0	11.1	57.1	35.0	44.1	74.2	25.8	26.2
01/31	17:00	9.7	15.5	8.9	75.0	15.0	42.0	53.0	2.5	75.0	65.0	12.5	58.1	36.3	44.6	75.0	20.6	25.2
01/31	19:00	8.5	14.7	9.8		12.0	40.0	56.0	2.5									
01/31	21:00																	

AVERAGES 11.4 58.1 36.3 44.6 74.6 21.7 24.8
 FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

525 2.7 1.7

CCIX RAW DATA FILE

RUN # (08)

DATE: 2-2-89

 Determine optimum operating conditions of a CCIX unit using
 process H2O. The unit employs a Dowex Cation Exchange Resin to
 selectively remove Sr and Ca from process wastewater streams.
 The scrub solutions are 5M NaCl and 1M NaCl respectively. The
 programmable controller is set for 30 min. cycles.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
02/02	08:30	28.6	33.2	20.6	71.7	11.0	22.0	49.0	3.0	90.0	67.0	11.6	---	---	---	---	---	---
02/02	09:30	27.9	32.9	21.1	71.7	11.0	24.0	50.0	3.0	100.0	62.0	11.1	72.7	31.2	57.1	71.7	18.9	25.0
02/02	10:30	---	---	---	---	---	10.0	51.0	3.0	90.0	62.0	11.4	---	---	---	---	---	---
02/02	11:30	26.7	32.2	22.0	71.7	12.0	23.0	53.0	3.0	90.0	62.0	11.6	65.8	34.6	50.2	71.7	20.6	21.5
02/02	12:30	---	---	---	---	---	24.0	55.0	3.0	90.0	60.0	11.4	---	---	---	---	---	---
02/02	13:30	25.7	31.8	22.7	67.7	14.0	22.0	56.0	3.0	90.0	60.0	11.8	60.2	29.1	44.6	67.7	24.0	23.1
02/02	14:30	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

AVERAGES 11.5 60.2 29.1 44.6 70.4 21.2 25.7

 FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R
 542 2.8 1.4

CCIX RAW DATA FILE

RUN # (09) --- HOT # 1

DATE: 2-3-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively
remove Sr and Ca from process wastewater streams. The strip and
scrub solutions are 5M and 1M NaCl respectively. The programmable
controller is set for 30 min. cycles. The feed is process
wastewater from the PWWP.

DATE	TIME	STRIP RATE (Inches)	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BEEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	STRIP RATE (ml/min)	RINSE RATE (ml/min)
02/03	13:30	15.1	25.6	1.6	71.7	14.0	22.0	52.0	3.0	80.0	65.0	11.1	---	---	---	---	---	---
02/03	15:30	13.9	24.9	2.8	71.7	14.0	23.0	53.0	3.0	75.0	78.0	11.4	62.3	36.3	59.7	71.7	24.0	32.8
02/03	17:30	12.8	24.2	3.8	71.7	14.0	22.0	51.0	3.0	80.0	67.0	12.6	64.2	36.3	57.1	71.7	24.0	32.8
02/03	19:30	11.6	23.6	4.8	71.7	14.0	22.0	49.0	3.1	75.0	85.0	12.0	62.3	31.1	54.5	71.7	24.0	32.8
02/03	21:30	10.3	22.9	5.8	67.7	14.0	23.0	51.0	3.0	80.0	80.0	10.8	67.5	36.3	54.5	67.7	24.0	16.4
02/03	23:30	9.2	22.3	6.6	67.7	14.0	22.0	50.0	5.0	75.0	80.0	11.1	72.1	31.1	51.9	67.7	24.0	16.4
02/04	03:30	6.9	21.0	7.7	67.7	14.0	22.0	49.0	5.0	75.0	80.0	11.1	59.7	33.7	45.2	67.7	24.0	16.4
02/04	07:30	4.8	19.6	8.7	67.7	14.0	22.0	49.0	5.0	75.0	79.0	11.1	57.1	36.3	58.6	67.7	24.0	16.4
02/04	10:10																	

AVERAGES 11.4 63.6 34.5 54.5 70.4 24.0 26.8

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R S/R SC/R

476 2.6 1.4

CCIX DATA FILE

RUN # (10) --- HOT # 2

DATE: 2-22-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5N and 1M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PUP.

DATE	TIME	STRIP RATE (Inches)	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RATE (Inches)	SCRUB RECYCLE RATE (Inches)	COND. RTWSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFED RATE (LPM)	STRIP RATE (mL/min)	SCRUB RATE (mL/min)	STRIP WASTE (mL/min)	SCRUB RECYCLE RATE (mL/min)	STRIP WASTE (mL/min)	SCRUB RECYCLE RATE (mL/min)	RINSE RATE (mL/min)
02/22	08:30	19.0	10.9	2.0	14.0	82.7	22.0	51.0	3.0	75.0	23.0	11.7	62.3	36.3	59.2	82.7	24.0	43.3	---
02/22	10:30	17.8	10.2	2.9	14.0	82.7	22.0	52.0	3.0	75.0	22.0	11.4	62.3	36.3	49.3	82.7	24.0	43.3	---
02/22	12:30	16.6	9.5	3.9	14.0	82.7	22.0	54.0	3.0	75.0	22.0	11.8	62.3	36.3	49.3	82.7	24.0	43.3	---
02/22	14:30	15.3	8.8	5.0	14.0	82.7	22.0	54.0	4.0	75.0	23.0	11.9	67.5	36.3	51.9	82.7	20.6	30.8	---
02/22	16:30	14.2	8.1	5.8	13.0	82.7	22.0	52.0	4.0	75.0	22.0	11.2	65.6	36.3	49.3	82.7	22.3	22.3	---
02/22	18:30	13.0	7.4	6.8	14.0	82.7	22.0	51.0	4.0	75.0	22.0	11.6	62.3	36.3	49.8	82.7	24.0	33.9	---

AVERAGES 11.6 64.0 36.3 51.9 82.7 23.0 34.3
FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R SI/R SC/R

504 2.8 1.6

CCIX RAW DATA FILE

RUN # (11) --- HOT # 3

DATE: 2-23-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 1M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the Pulp.

DATE	TIME	STRIP RATE (Inches)	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RATE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
02/23	08:15	13.0	30.8	5.5	12.0	83.1	---	22.0	48.0	4.0	70.0	23.0	12.2	62.3	20.8	41.8	83.1	20.6	41.8
02/23	10:15	11.8	30.4	6.1	12.0	83.1	---	22.0	46.0	4.0	70.0	22.0	11.7	64.2	20.8	41.5	83.1	20.6	41.8
02/23	12:15	10.8	30.0	7.1	12.0	83.1	---	22.0	50.0	4.0	70.0	22.0	11.6	57.1	20.8	39.8	83.1	23.1	45.0
02/23	14:15	9.7	29.6	8.5	12.0	82.7	---	22.0	54.0	4.0	70.0	22.0	11.8	57.1	20.8	38.9	82.7	20.6	45.3
02/23	16:15	8.6	29.2	9.4	12.0	82.7	---	22.0	55.0	4.0	70.0	22.0	11.5	62.3	15.6	40.5	82.7	20.6	45.3
02/23	18:15	7.4	28.9	9.4	12.0	82.7	---	22.0	55.0	4.0	70.0	22.0	11.9	62.3	15.6	40.5	82.7	20.6	45.3

AVERAGES

11.8 60.6 19.7 40.5 83.0 21.1 43.1

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

559 2.9 0.9

RUN # (12) --- HOT # 4

DATE: 2-28-89

Scouting test to determine optimum operating conditions. The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 1M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PWT. NO SAMPLES TAKEN!

[illegible]

AVERAGES 11.8 60.2 18.7 40.1 70.2 20.2 31.4

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R	ST/R	SC/R
584	3.0	0.9

CCIX RAW DATA FILE

RUN # (13) --- HOT # 5

DATE: 3-1-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 1M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PWT.

DATE	TIME	STRIP RATE (inches)	SCRUB RATE (inches)	STRIP WASTE (inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (inches)	COND. CIC-1	COND. CIC-2	DELTA P (psig)	FILTER (psig)	PULSE (psig)	COLUMN PRESSURE (psig)	BEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	STRIP RATE (ml/min)	RINSE RATE (ml/min)
03/01	13:10	16.7	23.8	8.0	106.7	11.0	25.0	56.0	5.0	75.0	24.0	24.0	11.5	46.7	41.5	36.3	106.7	18.9	54.8
03/01	15:10	15.8	23.0	8.7	106.7	11.0	24.0	61.0	5.0	75.0	24.0	24.0	11.9	46.7	41.5	36.3	106.7	18.9	54.8
03/01	17:10	14.8	22.0	9.1	106.7	12.0	24.0	58.0	5.0	75.0	24.0	24.0	11.6	51.9	41.5	28.6	106.7	20.6	53.1
03/01	19:10	14.0	21.2	9.7	106.7	10.0	25.0	58.0	10.0	75.0	24.0	24.0	11.8	41.5	41.5	29.4	106.7	17.2	53.1
03/01	STOP																		
03/01																			

AVERAGES 11.7 46.7 45.0 31.4 107 18.9 46.4
FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R
619 2.5 2.4

CCIX RAW DATA FILE

RUN # (14) --- HOT # 6

DATE: 3-2-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively
remove Sr and Ca from process wastewater streams. The strip and
scrub solutions are 5M and 1M NaCl respectively. The programmable
controller is set for 30 min. cycles. The feed is process
wastewater from the PUMP.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE P PRESSURE (psig)	COLUMN PRESSURE (psig)	BEEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
03/02	08:10	14.0	21.2	9.7			22.0	46.0	11.0	70.0	23.0	11.4						
03/02	11:10	12.7	19.8	10.5	12.0	12.0	23.0	56.0	11.0	70.0	23.0	11.5	45.0	48.5	31.1	105.6	20.6	39.8
03/02	13:10	11.8	18.8	11.2	12.0	12.0	26.0	59.0	11.0	75.0	23.0	12.0	46.7	51.9	31.1	105.6	18.9	39.4
03/02	16:10	10.5	17.4	12.0	12.0	12.0	23.0	61.0	11.0	75.0	23.0	11.8	45.0	48.5	29.9	105.6	15.5	43.4
03/02	18:40	9.2	16.2	12.8	12.0	12.0	24.0	59.0	11.0	75.0	23.0	11.8	54.0	49.8	30.7		20.6	35.0
03/02	19:00																	

AVERAGES 11.7 47.7 49.7 106 18.9 39.4
FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R
619 2.5 2.6

CCIX RAW DATA FILE

RUN # (15) --- HOT # 7

DATE: 3-3-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively
remove Sr and Ca from process wastewater streams. The strip and
scrub solutions are 5M and 1M NaCl respectively. The programmable
controller is set for 30 min. cycles. The feed is process
wastewater from the PWT.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
03/03	08:25	31.1	34.0	1.7	133.1	11.0	24.0	50.0	11.0	70.0	23.0	11.6	116.3	45.7	43.8	133.1	18.9	50.2
03/03	10:25	31.1	34.0	1.7	133.1	11.0	21.0	50.0	11.0	70.0	23.0	11.6	116.3	45.7	43.8	133.1	17.2	50.8
03/03	12:55	28.3	32.9	3.6	133.1	10.0	24.0	58.0	11.0	75.0	23.0	11.7	112.1	46.9	57.8	133.1	20.6	58.4
03/03	15:25	25.6	31.8	5.6	133.1	12.0	25.0	65.0	11.0	75.0	23.0	11.8	114.2	46.7	60.0	133.1	18.9	50.2
03/03	17:25	23.4	30.9	6.9	133.1	11.0	24.0	58.0	11.0	75.0	23.0	11.8	103.8	41.5	60.3	133.1	18.9	42.3
03/03	18:55	21.9	30.3	7.8	133.1	10.0	25.0	59.0	11.0	75.0	23.0	11.8	103.8	41.5	60.3	133.1	18.9	42.3
03/03	19:10																	

AVERAGES 11.7 112 45.2 55.5 133 18.9 50.4

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

622 5.9 2.4

CCIX RAW DATA FILE

RUN # (16) --- HOT # 8

DATE: 3-16-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 1M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PUP.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
03/16	10:45	17.1	35.8	1.9	127.9	10.0	22.0	56.0	1.0	75.0	20.0	11.6	77.9	31.1	51.9	127.9	17.2	70.7
03/16	12:45	15.6	35.2	2.9	127.9	14.0	25.0	60.0	1.5	75.0	20.0	11.8	67.5	31.2	64.9	127.9	24.7	80.8
03/16	14:45	16.3	34.6	4.4	127.9	14.0	20.0	40.0	1.5	75.0	18.0	11.7	67.5	31.2	43.3	127.9	20.6	68.1
03/16	16:45	13.0	34.0	4.4	127.9	12.0	70.0	39.0	1.5	75.0	20.0	11.2	72.7	31.2	55.8	127.9	20.6	103.6
03/16	18:45	11.6	33.4	6.2	127.9	12.0	24.0	52.0	1.5	75.0	20.0	9.7	83.1	31.1	56.2	127.9	19.9	80.8
03/16	19:15	11.2	33.3	6.5	127.9	11.0	24.0	53.0	1.5	75.0	20.0							
03/16	19:30																	

AVERAGES 11.2 72.7 31.1 55.0 127.9 20.6 80.8

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

544 3.5 1.5

CCIX RAW DATA FILE

RUN # (17) --- HOT # 9

DATE: 3-18-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively
remove Sr and Ca from process wastewater streams. The strip and
scrub solutions are 5M and 0.5M NaCl respectively. The program-
able controller is set for 30 min. cycles. The feed is process
wastewater from the PWP.

DATE	TIME	STRIP RATE (Inches)	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BEEP RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
03/18	08:10	32.1	32.3	1.8	69.5	11.0	22.0	53.0	---	---	19.0	---	---	---	---	---	---	---
03/18	10:10	30.7	31.8	2.8	69.5	11.0	21.0	51.0	4.0	70.0	19.0	11.3	72.7	26.0	51.9	69.5	18.9	22.7
03/18	12:10	29.5	31.2	3.8	69.5	12.0	24.0	52.0	4.0	70.0	19.0	11.3	74.6	31.2	51.9	69.5	20.6	22.7
03/18	14:10	28.1	30.6	4.7	69.5	12.0	23.0	52.0	4.0	70.0	20.0	11.1	72.7	31.1	50.2	69.5	20.6	12.3
03/18	16:10	26.7	30.0	5.7	69.5	11.0	22.0	54.0	4.0	70.0	20.0	11.5	72.7	31.2	53.2	69.5	15.3	12.3
03/18	18:10	25.3	29.3	6.8	69.5	12.0	23.0	57.0	4.0	70.0	20.0	11.7	75.3	36.3	51.9	69.5	20.6	15.0
03/18	18:55																	

AVERAGES 11.4 73.6 31.1 51.8 69.5 19.2 16.7

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

594 3.8 1.6

CCIX RAW DATA FILE

RUN # (18) --- HOT # 10

DATE: 3-22-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 0.5M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PWP.

DATE	TIME	STRIP RATE (Inches)	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE C1C-1	COND. SCRUB C1C-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BPEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
03/22	08:50	25.0	27.7	1.8	70.4	12.0	22.0	48.0	---	---	20.0	11.4	38.9	5.2	10.4	70.4	20.6	22.1
03/22	10:50	24.3	27.6	2.0	70.4	12.0	23.0	58.0	4.0	70.0	22.0	11.4	51.9	18.2	13.0	70.4	20.6	22.1
03/22	12:50	23.3	27.3	2.5	70.4	12.0	23.0	62.0	4.0	70.0	22.0	11.4	51.9	18.2	13.0	70.4	20.6	22.1
03/22	14:50	22.8	26.8	2.9	70.4	12.0	23.0	64.0	4.0	70.0	22.0	12.0	23.4	23.4	6.9	84.4	20.6	55.0
03/22	16:50	22.0	26.2	3.1	70.4	12.0	23.0	63.0	4.0	70.0	22.0	11.2	41.5	31.2	2.6	76.4	20.6	55.0
03/22	18:45	21.0	25.5	3.8	70.4	12.0	23.0	62.0	4.0	70.0	22.0	12.0	54.2	37.9	7.3	76.4	20.6	22.1

AVERAGES 11.6 41.9 23.0 20.9 77.1 20.6 33.1

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

562 2.0 1.1

CCIX RAW DATA FILE

RUN # (19) --- HOT # 11

DATE: 3-29-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M NaCl and water respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PWP.

DATE	TIME	STRIP RATE (Inches)	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RATE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE P (psig)	COLUMN PRESSURE (psig)	BEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
03/29	08:15	21.4	10.2	1.8	12.0	96.5	12.0	20.0	51.0	6.0	70.0	21.0	11.4	31.1	31.1	31.2	96.5	20.6	60.2
03/29	10:15	20.7	9.6	2.4	12.0	96.5	12.0	24.0	39.0	6.0	70.0	20.0	11.5	31.1	31.1	31.2	96.5	20.6	60.2
03/29	12:15	20.0	9.0	2.7	12.0	96.5	12.0	23.0	60.0	6.0	70.0	20.0	11.6	31.1	31.1	31.2	96.5	20.6	60.2
03/29	14:15	19.2	8.3	2.9	12.0	96.5	12.0	22.0	64.0	6.0	70.0	20.0	11.6	31.1	31.1	31.2	96.5	20.6	60.2
03/29	16:15	18.5	7.7	3.3	12.0	96.5	12.0	23.0	63.0	6.0	70.0	20.0	11.9	31.1	31.1	31.2	96.5	20.6	60.2
03/29	18:15	17.8	7.1	3.8	12.0	96.5	12.0	19.0	56.0	7.0	70.0	20.0	11.7	31.1	31.1	31.2	96.5	20.6	60.2
03/29	18:15																		

AVERAGES 11.6 37.4 32.2 20.8 85.8 20.6 36.2
FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

564 1.8 1.6

CCIX RAW DATA FILE

RUN # (20) --- HOT # 12

DATE: 4-5-89

 Scouting test to determine optimum operating conditions.
 The unit employs a Dowex Cation Exchange Resin to selectively
 remove Sr and Ca from process wastewater streams. The strip and
 scrub solutions are 5M NaCl and water respectively. The program-
 able controller is set for 30 min. cycles. The feed is process
 wastewater from the PWP.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BPEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
04/05	09:30	12.9	25.8	2.4	96.5	12.0	23.0	47.0	---	---	20.0	---	---	---	---	---	---	---
04/05	10:30	12.5	25.5	2.8	96.5	12.0	22.0	50.0	2.0	70.0	20.0	11.4	41.5	31.2	41.5	24.2	96.5	20.6
04/05	12:30	11.8	24.9	3.5	80.4	12.0	21.0	53.0	2.0	70.0	20.0	11.5	36.3	31.2	24.2	24.2	20.6	60.2
04/05	14:30	11.0	24.4	4.0	80.4	12.0	22.0	61.0	2.0	70.0	20.0	11.6	41.5	26.0	10.4	80.4	20.6	13.0
04/05	16:30	10.0	23.8	4.1	80.4	12.0	21.0	60.0	2.0	70.0	20.0	11.9	31.6	36.3	1.5	80.4	20.6	35.3
04/05	18:30	9.0	23.4	4.5	80.4	12.0	20.0	60.0	2.0	70.0	20.0	11.7	36.1	40.3	4.6	80.4	20.6	35.3
04/05	19:00																	

AVERAGES 11.6 37.4 33.0 24.2 85.8 20.6 36.2

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

564 1.8 1.6

CCIX RAW DATA FILE

RUN # (21) --- HOT # 13

DATE: 4-11-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Cs from process wastewater streams. The strip and scrub solutions are 5M and 0.5M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PWIP.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTR DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BREED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
04/11	08:00	29.9	34.0	2.0	74.4	11.0	22.0	42.0	2.0	80.0	20.0	11.2	36.3	31.2	26.0	74.4	18.9	32.9
04/11	10:00	29.2	33.4	2.5	74.4	11.0	22.0	45.0	2.0	80.0	20.0	11.2	36.3	31.2	26.0	74.4	18.9	32.9
04/11	12:00	28.3	32.6	3.3	59.3	11.0	22.0	53.0	2.0	80.0	21.0	11.6	46.7	41.5	20.8	59.3	18.9	38.5
04/11	14:00	27.5	32.1	4.2	5.0	12.0	20.0	57.0	2.0	80.0	21.0	10.9	41.5	26.0	15.6	59.3	18.9	38.5
04/11	16:00	26.6	31.4	5.0	60.3	12.0	20.0	56.0	2.0	80.0	21.0	11.3	46.7	36.3	10.4	60.3	20.6	44.7
04/11	18:00	25.8	30.8	6.1	58.2	11.0	22.0	50.0	2.0	80.0	21.0	10.9	41.5	31.1	11.4	60.3	20.6	44.7
04/12	02:00	22.5	28.3	9.2	58.2	11.0	22.0	39.0	2.0	80.0	23.0	11.2	42.8	32.4	40.2	58.2	18.9	16.7
04/12	06:00	21.3	27.0	10.6	59.3	11.0	22.0	39.0	2.0	80.0	23.0	11.6	31.1	33.7	12.1	59.3	18.9	16.7
04/12	08:00	20.4	26.5	11.5	39.4	12.0	23.0	41.0	5.0	80.0	27.0	11.3	41.5	31.1	9.8	39.4	20.6	15.4
04/12	12:00	18.8	25.3	13.2	39.4	12.0	23.0	54.0	5.0	80.0	27.0	10.0	41.5	31.2	4.7	39.4	20.6	15.4
04/12	14:00	18.0	24.7	14.1														
04/12	14:12	Stop Run																

147

Restart a

AVERAGES 11.0 40.8 30.9 14.7 52.3 19.5 22.8

F/R ST/R SC/R

563 2.1 1.6

CCIX RAW DATA FILE

RUN # (22) --- HOT # 14

DATE: 4-12-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 0.5M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PWP.

DATE	TIME	STRIP RATE (Inches)	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RATE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BPEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
04/12	14:25	18.0	24.7	1.8	---	---	---	22.0	53.0	---	---	30.0	---	---	---	---	---	---	---
04/12	16:25	17.1	24.1	2.8	---	---	---	22.0	38.0	---	---	30.0	---	---	---	---	---	---	---
04/12	18:25	16.2	23.5	3.6	---	---	---	22.0	56.0	6.0	80.0	30.0	11.7	46.7	31.1	51.9	64.3	18.9	33.2
04/13	04:00	11.5	20.5	8.0	---	---	---	22.0	39.0	6.0	80.0	30.0	11.2	46.7	31.2	20.8	---	---	---
04/13	08:25	9.8	19.4	10.0	---	---	---	22.0	39.0	6.0	80.0	31.0	10.1	50.9	32.5	33.6	64.3	18.9	34.6
04/13	10:25	8.9	18.8	10.9	---	---	---	22.0	43.0	7.0	80.0	32.0	9.6	40.0	25.9	11.5	---	---	---
04/13	Restart	8.9	18.8	10.9	---	---	---	22.0	46.0	---	---	37.0	12.1	46.7	31.1	4.7	64.3	18.9	33.6
04/13	14:30	6.9	17.4	12.9	---	---	---	23.0	38.0	7.0	70.0	34.0	12.1	50.9	35.6	---	---	---	---
04/13	16:55	5.8	16.7	14.2	---	---	---	23.0	38.0	7.0	70.0	34.0	11.2	47.3	30.1	50.9	64.3	18.9	33.2
04/13	18:25	28.0	16.2	14.2	---	---	---	23.0	38.0	7.0	75.0	34.0	11.6	---	---	55.9	---	18.9	---
04/13	20:15	26.5	15.0	---	---	---	---	23.0	43.0	7.0	75.0	35.0	11.6	---	---	---	64.3	18.9	34.6
04/14	04:00	23.5	13.5	19.5	---	---	---	23.0	42.0	8.5	75.0	35.0	10.9	85.0	68.0	55.4	---	18.9	---
04/14	07:50	22.1	12.5	21.3	---	---	---	22.0	40.0	2.0	75.0	35.0	10.4	40.2	20.1	40.2	64.3	18.9	33.6
04/14	09:25	21.4	12.0	21.8	---	---	---	23.0	39.0	2.0	75.0	37.0	9.4	37.9	27.1	48.8	---	18.9	---
04/14	09:37 Stop	---	---	---	64.3	---	---	---	45.0	2.0	75.0	35.0	10.7	45.9	32.8	32.8	64.3	18.9	---

AVERAGES

10.9 47.2 30.6 47.2 64.3 18.9 33.8
 FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

579 2.5 1.6

CCIX RAW DATA FILE

RUN # (23) --- HOT # 15

DATE: 4-14-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 0.75M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PMP.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (Inches)	RESIN RATE (Inches)	COND. CIC-1	COND. CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPM)	STRIP RATE (mL/min)	SCRUB RATE (mL/min)	STRIP WASTE (mL/min)	SCRUB RECYCLE (mL/min)	RESIN RATE (mL/min)	RINSE RATE (mL/min)
04/14	11:00	34.0	34.0	2.0	---	---	23.0	40.0	---	4.0	80.0	16.0	11.3	51.9	31.2	41.5	---	---
04/14	13:00	33.0	33.4	2.8	---	---	21.0	55.0	4.0	80.0	16.0	11.3	51.9	31.2	46.7	60.3	18.9	34.8
04/14	15:00	32.0	32.8	3.7	60.3	---	23.0	55.0	4.0	80.0	16.0	11.4	51.9	31.2	46.7	60.3	18.9	34.3
04/15	08:00	25.0	27.5	11.3	---	---	22.0	40.0	11.0	80.0	17.0	9.9	42.8	32.4	46.4	---	---	---
04/15	11:00	23.5	26.5	12.5	67.0	---	23.0	44.0	14.0	80.0	21.0	11.9	51.9	34.6	41.5	67.0	18.9	35.0
04/15	15:00	21.8	25.3	14.7	---	---	22.0	39.0	1.0	80.0	22.0	12.1	44.1	31.1	57.1	---	---	---
04/16	08:00	13.7	20.3	23.0	64.3	---	22.0	39.0	5.0	80.0	26.0	10.8	49.5	30.5	50.7	64.3	20.6	---
04/16	08:30	13.7	20.3	8.0	---	---	22.0	39.0	5.0	80.0	26.0	12.0	---	---	---	---	20.6	---
04/16	14:30	10.8	18.4	11.3	---	---	22.0	50.0	7.0	80.0	24.0	10.8	46.8	31.5	57.1	---	20.6	---
04/17	08:30	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

AVERAGES 10.8 46.8 31.5 49.0 64.3 19.7 34.7

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

547 2.5 1.6

CCIX RAW DATA FILE

RUN # (24) --- HOT # 16

DATE: 4-18-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 0.5M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PUP.

DATE	TIME	STRIP RATE (Inches)	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	SCRUB RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	SCRUB RATE (ml/min)	RINSE RATE (ml/min)	
04/18	08:50	29.4	32.3	1.5	----	----	22.0	46.0	----	----	19.0	11.6	----	----	----	----	----	33.4	
04/18	11:20	28.2	31.3	2.8	----	----	21.0	56.0	5.0	80.0	19.0	12.4	49.8	41.5	54.0	66.3	41.5	20.6	
04/18	12:50	27.5	30.7	3.7	66.3	----	22.0	56.0	5.0	80.0	19.0	12.6	48.5	41.5	62.3	72.0	41.5	20.6	
04/18	14:50	26.4	29.7	4.5	72.0	----	22.0	63.0	5.0	80.0	18.0	12.3	57.1	51.9	41.5	----	20.6	38.6	
04/18	16:50	25.5	29.2	5.5	----	----	22.0	63.0	8.0	80.0	18.0	12.2	46.7	26.0	51.9	----	20.6	43.8	
04/18	18:50	24.5	28.4	6.4	----	----	22.0	62.0	8.0	80.0	18.0	12.7	51.9	41.5	46.7	----	20.6	----	
04/19	07:50	18.8	23.5	16.7	55.9	----	23.0	29.0	12.0	80.0	20.0	11.3	45.5	39.1	82.3	55.9	39.1	20.6	
04/19	11:20	Stop Restart on 4/20	----	----	----	----	22.0	29.0	----	----	20.0	11.5	----	----	----	----	----	----	
04/20	09:00	34.5	34.2	1.5	----	----	22.0	54.0	12.0	80.0	20.0	10.7	46.7	41.5	51.9	69.7	41.5	20.6	
04/20	11:00	33.6	33.4	2.5	69.7	----	22.0	51.9	13.0	80.0	20.0	10.7	51.9	38.9	62.3	69.7	38.9	20.6	
04/20	15:00	31.6	31.9	4.9	69.7	----	22.0	60.0	15.0	80.0	24.0	11.8	40.4	43.0	18.5	69.7	25.2	38.6	
04/20	17:00	30.6	31.3	5.9	----	----	22.0	61.0	15.0	80.0	24.0	11.6	46.7	41.5	83.1	69.7	27.5	43.8	
04/20	19:00	29.7	30.5	7.5	69.7	----	22.0	49.0	15.0	80.0	24.0	11.2	58.8	34.6	72.7	69.7	20.6	43.8	
04/20	22:00	28.0	29.5	9.6	----	----	22.0	45.0	15.0	80.0	24.0	11.2	58.8	34.6	72.7	69.7	20.6	43.8	
04/21	04:00	Stop and Sample	----	----	----	----	22.0	45.0	15.0	80.0	24.0	11.2	58.8	34.6	72.7	69.7	20.6	43.8	
AVERAGES																			
													11.2	48.9	39.9	57.7	69.7	22.9	38.6

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.																			

													F/R	ST/R	SC/R				
													489	2.1	1.7				

CCIX RAW DATA FILE

RUN # (25) --- NOT # 17

DATE: 5-11-89

 Scouting test to determine optimum operating conditions.
 The unit employs a Dowex Cation Exchange Resin to selectively
 remove Sr and Ca from process wastewater streams. The strip and
 scrub solutions are 5M and 0.5M NaCl respectively. The program-
 able controller is set for 30 min. cycles. The feed is process
 wastewater from the PAIP.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. CIC-1	COND. CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
05/11	09:15	33.1	33.8	2.2	---	---	22.0	29.0	14.0	---	22.0	11.5	---	---	---	---	---	---
05/11	11:15	32.0	33.0	3.2	---	13.0	22.0	49.0	16.0	80.0	22.0	11.4	57.1	41.5	51.9	104.2	22.3	57.5
05/11	13:15	31.0	32.2	5.0	---	12.0	22.0	50.0	18.0	80.0	22.0	11.1	51.9	41.5	93.4	---	20.6	---
05/11	15:15	30.1	31.5	6.6	---	13.0	23.0	49.0	20.0	80.0	22.0	9.5	46.7	36.3	83.1	104.2	22.3	88.6
05/11	17:15	29.3	30.8	7.6	---	12.0	22.0	54.0	25.0	80.0	27.0	12.3	53.7	36.3	40.5	---	20.6	---
05/11	19:15	28.2	30.0	8.7	108.3	13.0	22.0	48.0	1.0	80.0	27.0	12.0	57.1	45.6	57.1	108.3	22.3	85.4
05/11	19:30	Stop																

AVERAGES 11.3 53.3 40.3 65.2 105.6 21.6 77.2

F/R ST/R SC/R
 522 2.5 1.9

CCIX RAW DATA FILE

RUN # (26) ---- NOT # 18

DATE: 5-12-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 1M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PUIP.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. CIC-1	COND. CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
05/12	09:20	28.2	30.3	1.7	---	---	20.0	35.0	1.0	---	26.0	12.1	---	---	---	---	---	---
05/12	11:20	27.3	29.4	2.5	125.0	13.0	18.0	45.0	1.0	80.0	26.0	11.8	46.7	46.7	41.5	125.0	22.3	78.3
05/12	13:20	26.2	28.5	3.9	---	13.0	22.0	60.0	1.0	80.0	29.0	12.2	57.1	46.7	72.7	---	22.3	---
05/12	15:20	25.2	27.8	5.3	---	13.0	23.0	50.0	1.5	80.0	30.0	11.6	51.9	36.3	72.7	---	22.3	---
05/12	17:20	24.5	27.0	6.4	---	14.0	22.0	48.0	1.5	80.0	35.0	11.9	36.3	41.5	57.1	---	24.0	---
05/12	19:20	23.6	26.3	8.5	141.7	10.0	22.0	50.0	1.5	80.0	35.0	10.9	46.7	36.3	109.0	141.7	17.2	130.0
05/13	08:00	18.0	21.5	18.0	129.2	13.0	22.0	33.0	6.0	80.0	37.0	10.0	45.9	39.3	77.9	129.2	22.3	150.7

AVERAGES 11.5 46.7 40.3 74.7 132 21.7 120

F/R ST/R SC/R
529 2.1 1.9

CCIX RAW DATA FILE

RUN # (27) --- HOT # 19

DATE: 5-13-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 1M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PUMP.

DATE	TIME	STRIP RATE (Inches)	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
05/13	09:15	33.8	21.5	1.7	104.2	13.0	22.0	43.0	6.0	80.0	17.0	11.6	---	---	---	---	---	---
05/13	11:15	32.8	20.9	2.3	---	---	22.0	52.0	6.0	80.0	17.0	11.8	---	---	---	104.2	22.3	53.6
05/13	13:15	31.9	20.2	2.8	---	12.0	22.0	60.0	6.0	80.0	17.0	11.5	46.7	36.3	26.0	---	20.6	---
05/13	15:15	31.0	19.5	3.5	97.90	13.0	22.0	47.0	8.0	80.0	17.0	11.3	46.7	36.3	36.3	97.9	23.8	46.00
05/13	17:15	30.1	18.9	4.2	---	12.0	22.0	55.0	8.0	80.0	17.0	12.2	46.7	31.2	36.3	---	20.6	---
05/13	19:15	29.3	18.3	4.6	101.2	13.0	22.0	53.0	8.0	80.0	17.0	11.4	41.5	31.1	20.8	101.2	22.3	78.6
05/14	07:55	23.2	14.8	9.9	---	12.0	22.0	38.0	12.0	80.0	18.0	10.7	50.0	28.7	43.4	---	20.6	---

AVERAGES 11.5 48.6 30.7 37.6 101 21.7 59.4

F/R ST/R SC/R
530 2.2 1.4

CCIX RAW DATA FILE

RUN # (28) --- HOT # 20

DATE: 5-14-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 1M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PWP.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFED RATE (LPM)	STRIP RATE (mL/min)	SCRUB RATE (mL/min)	STRIP WASTE (mL/min)	SCRUB RECYCLE (mL/min)	RESIN RATE (mL/min)	RINSE RATE (mL/min)
05/14	08:35	23.0	34.0	1.7	---	---	22.0	46.0	12.0	80.0	20.0	11.2	---	---	---	---	---	---
05/14	10:35	22.0	33.0	2.2	129	12.0	22.0	48.0	14.0	80.0	21.0	11.5	51.9	51.9	26.0	129	20.6	31.6
05/14	12:35	21.1	32.0	3.8	---	13.0	19.0	47.0	---	80.0	21.0	11.4	46.7	51.9	83.1	---	22.3	---
05/14	14:35	20.2	31.0	4.8	142	12.0	19.0	48.0	---	80.0	21.0	10.9	46.7	51.9	51.9	142	20.6	---
05/14	16:35	19.3	30.0	6.0	---	12.0	22.0	46.0	---	80.0	26.0	11.4	46.7	51.9	62.3	---	22.1	---
05/14	18:35	18.4	29.0	6.5	133	13.0	20.0	39.0	17.0	80.0	32.0	11.3	46.7	51.9	26.0	133	22.3	149
05/15	07:35	12.7	23.0	17.4	---	13.0	21.0	45.0	2.0	80.0	35.0	10.4	45.5	47.9	87.1	---	22.3	148

AVERAGES 11.1 46.5 49.7 70.9 135 21.7 109

F/R ST/R SC/R

509 2.1 2.3

CCIX RAW DATA FILE

RUN # (29) ---- NOT # 21

DATE: 5-15-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 1M NaCl respectively. The programmable controller is set for 30 min. cycles. The feed is process wastewater from the PWP.

DATE	TIME	STRIP RATE (Inches)	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	SCRUB RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BPEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	SCRUB RATE (ml/min)	RINSE RATE (ml/min)
05/15	18:40	31.7	30.9	3.0	14.0	23.0	37.0	3.0	80.0	16.0	11.4	20.8	41.5	120.8	10.4	120.8	20.6	53.4
05/15	19:40	31.5	30.5	3.1	12.0	22.0	41.0	3.0	80.0	16.0	11.2	20.8	41.5	120.8	10.4	120.8	20.6	53.4
05/16	07:40	25.7	26.0	5.4	12.0	22.0	51.0	7.0	80.0	17.0	10.8	50.2	38.9	120.8	10.4	120.8	20.6	53.4
05/16	09:40	24.7	25.2	5.6	12.0	22.0	53.0	7.0	70.0	17.0	11.8	51.9	41.5	120.8	10.4	120.8	20.6	53.4
05/16	11:40	23.7	24.4	5.8	12.0	21.0	62.0	8.0	70.0	19.0	11.9	51.9	41.5	120.8	10.4	120.8	20.6	53.4
05/16	13:40	22.8	23.7	6.3	10.0	23.0	57.0	8.0	85.0	19.0	11.7	46.7	36.3	132.7	26.0	132.7	17.2	55.5
05/16	15:40	21.9	23.0	6.6	14.0	22.0	59.0	8.0	80.0	19.0	11.5	46.7	36.3	132.7	15.6	132.7	24.0	56.00

AVERAGES 11.5 48.5 39.1 17.8 124.8 21.1 55.0

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

543 2.3 1.9

CCIX RAW DATA FILE

RUN # (30) --- HOT # 22

DATE: 6-6-89

 Scouting test to determine optimum operating conditions.
 The unit employs a Dowex Cation Exchange Resin to selectively
 remove Sr and Ca from process wastewater streams. The strip and
 scrub solutions are 5M and 1M NaCl respectively. The program-
 able controller is set for 30 min. cycles. The feed is process
 wastewater from the PUP.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
06/06	07:55	14.3	17.9	1.8	---	11.0	23.0	54.0	3.0	85.0	16.0	11.8	---	---	---	---	---	---
06/06	09:55	13.4	17.3	1.9	100	11.0	21.0	55.0	4.0	90.0	16.0	11.8	46.7	31.1	5.2	100	18.9	27.3
06/06	11:55	12.7	16.8	2.0	100	11.0	22.0	57.0	6.0	90.0	17.0	11.8	36.3	26.0	5.2	100	18.9	37.9
06/06	13:55	12.0	16.2	2.2	100	11.0	22.0	54.0	12.0	100	17.0	11.8	36.3	31.2	10.4	100	18.9	39.00
06/06	15:55	11.3	15.7	2.4	100	11.0	22.0	57.0	12.0	100	19.0	11.8	36.3	26.0	10.4	100	18.9	---

AVERAGES 11.8 38.9 28.6 7.8 100 18.9 34.7

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

625 2.1 1.5

CCIX RAW DATA FILE

RUN # (31) --- HOT # 23

DATE: 6-14-89

 Scouting test to determine optimum operating conditions.
 The unit employs a Dowex Cation Exchange Resin to selectively
 remove Sr and Ca from process wastewater streams. The strip and
 scrub solutions are 5N and 1M NaCl respectively. The program-
 able controller is set for 60 min. cycles. The feed is process
 wastewater from the Pulp.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
06/14	08:00	32.0	29.0	1.7	---	---	23.0	33.0	1.0	---	20.0	11.6	---	---	---	---	---	---
06/14	10:00	31.6	28.8	2.1	100	14.0	23.0	42.0	1.0	100	20.0	11.6	20.8	10.4	20.8	100	12.0	89.6
06/14	12:00	31.2	28.5	2.6	100	14.0	22.0	48.0	2.0	100	20.0	11.8	20.8	15.6	26.0	100	12.0	113
06/14	14:00	30.8	28.3	3.3	100	8.0	22.0	57.0	2.0	100	20.0	11.3	20.8	10.4	36.3	100	6.9	138
06/14	16:00	30.2	27.9	4.5	100	8.0	20.0	53.0	3.0	75.0	20.0	11.7	31.2	20.8	62.3	100	6.9	---
06/15	08:00	25.8	25.3	12.5	100	14.0	22.0	51.0	---	---	20.0	11.5	28.6	16.9	51.9	100	12.0	---
06/15	10:00	25.3	25.0	13.9	100	16.0	21.0	46.0	---	---	20.0	11.5	26.0	15.6	72.7	100	13.7	---
06/15	12:00	24.8	24.7	15.6	100	11.0	22.0	47.0	32.0	---	20.0	11.1	26.0	15.6	88.3	100	9.4	---
06/15	14:00	23.9	23.9	18.8	100	10.0	22.0	48.0	1.0	---	21.0	11.4	46.7	41.5	168	100	8.6	---

AVERAGES 11.5 28.0 17.7 59.3 100 10.3 114
 FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R ST/R SC/R

 1119 2.8 1.7

CCIX RAW DATA FILE

RUN # (32) --- NOT # 24

DATE: 6-21-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 1M NaCl respectively. The programmable controller is set for 40.6 min. cycles. The feed is process wastewater from the PWIP.

DATE	TIME	STRIP RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BPEED RATE (LPM)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
06/21	10:00	24.2	24.2	1.7	---	23.0	40.0	1.0	---	22.0	11.5	---	---	---	---	---	---
06/21	12:00	23.2	23.5	3.0	85.0	12.0	57.0	1.0	100	22.0	11.5	54.5	36.3	67.5	85.0	12.7	61.7
06/21	14:00	22.2	23.0	5.2	---	15.0	57.0	2.0	95.0	23.0	10.6	49.3	26.0	114	---	10.1	---
06/21	16:00	21.2	22.4	6.8	85.0	15.0	49.0	2.0	95.0	22.0	11.6	51.9	31.2	83.1	85.0	12.7	90.2
06/22	08:00	13.8	18.9	19.5	---	14.0	46.0	4.0	95.0	24.0	10.1	48.0	22.7	82.4	91.7	10.8	102
06/22	12:00	11.2	16.5	21.7	8.5	12.0	42.0	6.0	95.0	28.0	11.6	67.5	62.6	57.1	---	10.8	---

AVERAGES 11.1 51.9 30.8 79.9 87.2 11.4 84.5

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R S1/R SC/R

977 4.6 2.7

CCIX RAW DATA FILE

RUN # (33) --- HOT # 25

DATE: 6-26-89

Scouting test to determine optimum operating conditions.
The unit employs a Dowex Cation Exchange Resin to selectively remove Sr and Ca from process wastewater streams. The strip and scrub solutions are 5M and 1M NaCl respectively. The programmable controller is set for 40.6 min. cycles. The feed is process wastewater from the PWIP.

DATE	TIME	STRIP RATE (Inches)	SCRUB RATE (Inches)	STRIP WASTE (Inches)	SCRUB RECYCLE (ml/min)	RESIN RATE (Inches)	COND. RINSE CIC-1	COND. SCRUB CIC-2	FILTER DELTA P (psig)	PULSE PRESSURE (psig)	COLUMN PRESSURE (psig)	BFEED RATE (LPH)	STRIP RATE (ml/min)	SCRUB RATE (ml/min)	STRIP WASTE (ml/min)	SCRUB RECYCLE (ml/min)	RESIN RATE (ml/min)	RINSE RATE (ml/min)
06/26	08:20	27.9	12.8	8.3	75.0	10.0	23.0	44.0	10.0	100.0	14.5	11.6	46.7	26.0	51.9	75.0	12.7	54.2
06/26	10:20	27.0	12.3	9.3	75.0	10.0	22.0	54.0	10.0	100.0	16.0	11.5	57.1	26.0	51.9	75.0	10.8	42.10
06/26	12:20	25.9	11.8	9.9	75.0	10.0	20.0	66.0	12.0	100.0	16.0	11.1	51.9	26.0	51.9	75.0	7.6	46.90
06/26	14:20	24.9	11.3	10.9	75.0	10.0	21.0	58.0	15.0	100.0	17.0	12.0	51.9	31.2	67.5	75.0	6.3	46.90
06/26	16:20	23.9	10.7	12.2	75.0	10.0	21.0	62.0	16.0	100.0	17.0	11.2	44.8	22.5	45.5	75.0	7.1	
06/26	18:20	23.0	10.3	13.1			22.0	57.0										

AVERAGES 11.5 50.5 26.3 49.6 75.0 8.9 47.7

FINAL AVERAGES BASED ON STARTING LEVEL AND FINAL LEVEL IN TANKS.

F/R S1/R SC/R
1289 5.7 3.0

APPENDIX B

EXAMPLES OF INPUT-OUTPUT DATA SETS

TYPICAL INPUT FILE (NLIN.DAT)

The following data represents the information that is required in the nonlinear parameter estimation computer program NLIN.FOR. The independent variables are the liquid phase concentrations obtained from the multicomponent equilibrium isotherm. The observed values are solid phase concentrations divided by Q' given in Eq. 1. A convergence tolerance must be set. Scaling factors for dependent and independent variables are optional (default value set at 1.0). Initial parameter estimates are required to initiate the linearization routine.

NUMBER OF OBSERVATIONS = 32
 NUMBER OF PARAMETERS = 4
 NO. OF INDEPENDENT VARIABLES = 4
 CONVERGENCE TOLERANCE = 1.0E-10

SCALING FACTORS FOR INDEPENDENT VARIABLES
 1.0000 1.0000 1.0000 1.0000

SCALING FACTORS FOR INDEPENDENT VARIABLES
 1.0000 1.0000 1.0000 1.0000

INITIAL ESTIMATES OF PARAMETERS
 100.0000 1.0000 1.0000 1.0000

NUMBER OF OBSERVATIONS = 40
 NUMBER OF PARAMETERS = 4

NO. OF INDEPENDENT VARIABLES = 4
 CONVERGENCE TOLERANCE = 1.0E-10

SCALING FACTORS FOR INDEPENDENT VARIABLES
 1.0000 1.0000 1.0000 1.0000

SCALING FACTORS FOR INDEPENDENT VARIABLES
 1.0000 1.0000 1.0000 1.0000

INITIAL ESTIMATES OF PARAMETERS
 100.0000 1.0000 1.0000 1.0000

K	Yi	C1	C2	C3	C4
1	0.2043	0.0106	0.0305	0.0926	10.6764
1	0.2813	0.3183	0.7009	1.5593	7.4354
1	0.2949	0.5717	1.1324	1.6384	8.3583
1	0.4232	1.4734	2.4663	2.9233	4.4537
1	0.1764	0.0065	0.0154	3.2778	8.8197
1	0.3518	0.8015	1.5117	1.7321	6.6545
1	0.2371	0.0301	0.0815	0.0729	10.7519
1	0.1922	0.0100	0.0292	0.0771	11.4109
2	0.2987	0.0106	0.0305	0.0926	10.6764
2	0.3818	0.3183	0.7009	1.5593	7.4354
2	0.3863	0.5717	1.1324	1.6384	8.3583
2	0.4869	1.4734	2.4663	2.9233	4.4537
2	0.2585	0.0065	0.0154	3.2778	8.8197
2	0.4440	0.8015	1.5117	1.7321	6.6545
2	0.3443	0.0301	0.0815	0.0729	10.7519
2	0.2810	0.0100	0.0292	0.0771	11.4109
3	0.2805	0.0106	0.0305	0.0926	10.6764
3	0.2469	0.3183	0.7009	1.5593	7.4354
3	0.2816	0.5717	1.1324	1.6384	8.3583
3	0.2163	1.4734	2.4663	2.9233	4.4537
3	0.0097	0.0065	0.0154	3.2778	8.8197
3	0.3631	0.8015	1.5117	1.7321	6.6545
3	0.3300	0.0301	0.0815	0.0729	10.7519
3	0.2650	0.0100	0.0292	0.0771	11.4109
4	0.2704	0.0106	0.0305	0.0926	10.6764
4	0.2811	0.3183	0.7009	1.5593	7.4354
4	0.0000	0.5717	1.1324	1.6384	8.3583
4	0.0016	1.4734	2.4663	2.9233	4.4537

4	0.5065	0.0065	0.0154	3.2778	8.8197
4	0.0028	0.8015	1.5117	1.7321	6.6545
4	0.1391	0.0301	0.0815	0.0729	10.7519
4	0.2554	0.0100	0.0292	0.0771	11.4109

TYPICAL OUTPUT FILE FROM NLIN.FOR

The following printout is a typical output file generated by NLIN.FOR. The information status indicates that the relative error in the sum of squares is at most the tolerance value. Values for the parameter estimates are determined in the subroutine. A comparison of the observed and calculated values is given. Finally, statistical analysis data is estimated for the nonlinear model fit.

```
run nlin
info = 1
```

```
K(1) = 9.08150E+01
K(2) = 5.91824E+01
K(3) = 2.03313E+01
K(4) = 2.06816E-01
```

comparison of observed and calculated values

i	obs.	calc.	residuals	independent variables			
1	0.2043	0.1225	-8.18025E-02	0.0106	0.0305	0.0926	10.6764
2	0.2813	0.2763	-5.02138E-03	0.3183	0.7009	1.5593	7.4354
3	0.2949	0.3350	4.01115E-02	0.5717	1.1324	1.6384	8.3583
4	0.0902	0.0137	-7.64987E-02	0.0006	0.0043	0.0119	11.7303
5	0.1764	0.0083	-1.68082E-01	0.0065	0.0154	3.2778	8.8197
6	0.3518	0.3642	1.24208E-02	0.8015	1.5117	1.7321	6.6545
7	0.2371	0.2229	-1.41860E-02	0.0301	0.0815	0.0729	10.7519
8	0.1922	0.1201	-7.21344E-02	0.0100	0.0292	0.0771	11.4109
9	0.2987	0.2297	-6.90026E-02	0.0106	0.0305	0.0926	10.6764
10	0.3818	0.3965	1.46620E-02	0.3183	0.7009	1.5593	7.4354
11	0.3863	0.4324	4.61404E-02	0.5717	1.1324	1.6384	8.3583
12	0.4869	0.4279	-5.90160E-02	1.4734	2.4663	2.9233	4.4537
13	0.2585	0.0128	-2.45657E-01	0.0065	0.0154	3.2778	8.8197
14	0.4440	0.4477	3.67382E-03	0.8015	1.5117	1.7321	6.6545
15	0.3443	0.3933	4.90357E-02	0.0301	0.0815	0.0729	10.7519
16	0.2810	0.2285	-5.25262E-02	0.0100	0.0292	0.0771	11.4109
17	0.2805	0.2396	-4.09253E-02	0.0106	0.0305	0.0926	10.6764
18	0.2469	0.3030	5.61043E-02	0.3183	0.7009	1.5593	7.4354
19	0.2816	0.2149	-6.66587E-02	0.5717	1.1324	1.6384	8.3583
20	0.1263	0.0608	-6.54634E-02	0.0006	0.0043	0.0119	11.7303
21	0.0097	0.9390	9.29346E-01	0.0065	0.0154	3.2778	8.8197
22	0.3631	0.1762	-1.86885E-01	0.8015	1.5117	1.7321	6.6545
23	0.3300	0.1209	-2.09133E-01	0.0301	0.0815	0.0729	10.7519
24	0.2650	0.2072	-5.77562E-02	0.0100	0.0292	0.0771	11.4109
25	0.2704	0.2810	1.05786E-02	0.0106	0.0305	0.0926	10.6764
26	0.2811	0.0147	-2.66403E-01	0.3183	0.7009	1.5593	7.4354
27	0.0000	0.0112	1.11361E-02	0.5717	1.1324	1.6384	8.3583
28	0.6401	0.6100	-3.00841E-02	0.0006	0.0043	0.0119	11.7300
29	0.5065	0.0257	-4.80797E-01	0.0065	0.0154	3.2778	8.8197
30	0.0028	0.0069	4.08658E-03	0.8015	1.5117	1.7321	6.6545
31	0.1391	0.1813	4.22356E-02	0.0301	0.0815	0.0729	10.7519
32	0.2554	0.3120	5.66079E-02	0.0100	0.0292	0.0771	11.4109

COVARIANCE MATRIX

1.85503E+04	1.12602E+04	3.81713E+03	3.12218E+01
1.12602E+04	7.37505E+03	2.45528E+03	2.00844E+01
3.81713E+03	2.45528E+03	9.10526E+02	6.96940E+00
3.12218E+01	2.00844E+01	6.96940E+00	6.64706E-02

regression coefficient (R2) = 2.0756

sum error squared = 1.3916

TYPICAL OUTPUT FILE FROM IXNEW.FOR

The following printout is a typical output file generated by IXNEW.FOR. The input data. NMAX is the number of operating cycles for a Continuous Countercurrent Ion eXchange (CCIX) system. ISY1-4 is the order sequence that each column in the series is advanced. SN, R, CAD, BVM, and ACT are Thomas model parameters (N, R, K_s, T) and the relative radioactivity on the ion exchange column, respectively. Instantaneous fractional breakthrough and cumulative fractional breakthrough are calculated in the program for each of the four columns in series.

RUN IXNEW
INPUT NMAX IN I3 FORMAT
123
40
INPUT ISY1-4 IN 4I4 FORMAT, FOLLOWED BY ISX1-4
1234123412341234
2 3 4 0
2 3 4 0

INPUT SN, R, CAD, BVM, AND ACT IN 5F10.3 FORMAT
12345678901234567890123456789012345678901234567890
4.0 1.0 24.3 30.0 2.4

N= 4.00

R= 1.00

KD= 24.3

BED VOLUMES= 30.

INPUT ACTIVITY= 2.CURIES

NUMBER OF CYCLES= 40

Y SWITCH VECTOR 2 3 4 0

X SWITCH VECTOR 2 3 4 0

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 1

2.0	4.443E-02	1.596E-03	5.135E-05	1.541E-06
4.0	7.891E-02	4.108E-03	1.775E-04	6.855E-06
6.0	1.193E-01	8.162E-03	4.396E-04	2.053E-05
8.0	1.642E-01	1.407E-02	9.103E-04	4.979E-05
10.0	2.126E-01	2.211E-02	1.677E-03	1.054E-04
12.0	2.633E-01	3.249E-02	2.842E-03	2.021E-04
14.0	3.151E-01	4.536E-02	4.518E-03	3.600E-04
16.0	3.671E-01	6.081E-02	6.827E-03	6.041E-04
18.0	4.185E-01	7.886E-02	9.895E-03	9.657E-04
20.0	4.685E-01	9.947E-02	1.385E-02	1.482E-03
22.0	5.168E-01	1.225E-01	1.881E-02	2.197E-03
24.0	5.628E-01	1.479E-01	2.391E-02	3.159E-03
26.0	6.062E-01	1.753E-01	3.223E-02	4.424E-03
28.0	6.468E-01	2.046E-01	4.089E-02	6.051E-03
30.0	6.845E-01	2.355E-01	5.096E-02	8.105E-03

CYCLE NUMBER= 2

2.0	2.806E-01	6.296E-02	1.066E-02	4.389E-04
4.0	3.226E-01	7.668E-02	1.381E-02	8.958E-04
6.0	3.661E-01	9.231E-02	1.762E-02	1.536E-03
8.0	4.102E-01	1.099E-01	2.219E-02	2.390E-03
10.0	4.544E-01	1.294E-01	2.760E-02	3.492E-03
12.0	4.979E-01	1.508E-01	3.394E-02	4.880E-03
14.0	5.404E-01	1.741E-01	4.128E-02	6.593E-03
16.0	5.813E-01	1.990E-01	4.969E-02	8.676E-03
18.0	6.204E-01	2.256E-01	5.926E-02	1.118E-02
20.0	6.573E-01	2.535E-01	7.002E-02	1.414E-02
22.0	6.919E-01	2.826E-01	8.202E-02	1.762E-02
24.0	7.242E-01	3.128E-01	9.530E-02	2.168E-02
26.0	7.540E-01	3.437E-01	1.099E-01	2.635E-02
28.0	7.815E-01	3.751E-01	1.257E-01	3.169E-02
30.0	8.065E-01	4.068E-01	1.428E-01	3.776E-02

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 3

2.0	4.465E-01	1.614E-01	4.457E-02	1.889E-03
4.0	4.836E-01	1.813E-01	5.226E-02	3.644E-03
6.0	5.207E-01	2.026E-01	6.081E-02	5.932E-03
8.0	5.575E-01	2.252E-01	7.028E-02	8.777E-03
10.0	5.934E-01	2.490E-01	8.070E-02	1.220E-02
12.0	6.283E-01	2.739E-01	9.211E-02	1.622E-02
14.0	6.617E-01	2.999E-01	1.045E-01	2.085E-02
16.0	6.935E-01	3.267E-01	1.180E-01	2.612E-02
18.0	7.235E-01	3.543E-01	1.325E-01	3.205E-02
20.0	7.515E-01	3.825E-01	1.480E-01	3.865E-02
22.0	7.776E-01	4.111E-01	1.646E-01	4.595E-02
24.0	8.017E-01	4.399E-01	1.821E-01	5.396E-02
26.0	8.238E-01	4.688E-01	2.007E-01	6.271E-02
28.0	8.440E-01	4.976E-01	2.201E-01	7.221E-02
30.0	8.623E-01	5.262E-01	2.404E-01	8.248E-02

CYCLE NUMBER= 4

2.0	5.600E-01	2.618E-01	9.345E-02	4.005E-03
4.0	5.914E-01	2.840E-01	1.053E-01	7.565E-03
6.0	6.224E-01	3.070E-01	1.180E-01	1.208E-02
8.0	6.528E-01	3.307E-01	1.315E-01	1.753E-02
10.0	6.822E-01	3.551E-01	1.458E-01	2.389E-02
12.0	7.104E-01	3.801E-01	1.609E-01	3.115E-02
14.0	7.373E-01	4.056E-01	1.768E-01	3.926E-02
16.0	7.626E-01	4.315E-01	1.936E-01	4.820E-02
18.0	7.864E-01	4.576E-01	2.111E-01	5.795E-02
20.0	8.086E-01	4.838E-01	2.293E-01	6.846E-02
22.0	8.291E-01	5.100E-01	2.482E-01	7.972E-02
24.0	8.479E-01	5.361E-01	2.679E-01	9.170E-02
26.0	8.651E-01	5.620E-01	2.881E-01	1.044E-01
28.0	8.808E-01	5.875E-01	3.090E-01	1.177E-01
30.0	8.950E-01	6.125E-01	3.303E-01	1.318E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES	COLUMN 1	COLUMN 2	COLUMN 3	COLUMN 4
-------------	----------	----------	----------	----------

CYCLE NUMBER= 5

2.0	6.412E-01	3.523E-01	1.463E-01	6.306E-03
4.0	6.678E-01	3.747E-01	1.617E-01	1.179E-02
6.0	6.939E-01	3.975E-01	1.776E-01	1.864E-02
8.0	7.192E-01	4.207E-01	1.942E-01	2.679E-02
10.0	7.436E-01	4.442E-01	2.113E-01	3.617E-02
12.0	7.668E-01	4.680E-01	2.290E-01	4.669E-02
14.0	7.889E-01	4.919E-01	2.472E-01	5.825E-02
16.0	8.096E-01	5.158E-01	2.659E-01	7.079E-02
18.0	8.290E-01	5.397E-01	2.852E-01	8.419E-02
20.0	8.469E-01	5.635E-01	3.048E-01	9.840E-02
22.0	8.635E-01	5.870E-01	3.249E-01	1.133E-01
24.0	8.787E-01	6.102E-01	3.454E-01	1.289E-01
26.0	8.926E-01	6.331E-01	3.661E-01	1.451E-01
28.0	9.052E-01	6.554E-01	3.872E-01	1.618E-01
30.0	9.165E-01	6.772E-01	4.085E-01	1.791E-01

CYCLE NUMBER= 6

2.0	7.017E-01	4.301E-01	1.966E-01	8.499E-03
4.0	7.244E-01	4.518E-01	2.147E-01	1.579E-02
6.0	7.465E-01	4.737E-01	2.333E-01	2.483E-02
8.0	7.679E-01	4.957E-01	2.521E-01	3.550E-02
10.0	7.884E-01	5.178E-01	2.713E-01	4.766E-02
12.0	8.078E-01	5.398E-01	2.908E-01	6.118E-02
14.0	8.262E-01	5.618E-01	3.106E-01	7.589E-02
16.0	8.435E-01	5.837E-01	3.306E-01	9.166E-02
18.0	8.596E-01	6.053E-01	3.508E-01	1.084E-01
20.0	8.744E-01	6.267E-01	3.712E-01	1.258E-01
22.0	8.882E-01	6.477E-01	3.917E-01	1.440E-01
24.0	9.007E-01	6.683E-01	4.124E-01	1.627E-01
26.0	9.121E-01	6.884E-01	4.331E-01	1.819E-01
28.0	9.225E-01	7.080E-01	4.539E-01	2.015E-01
30.0	9.318E-01	7.270E-01	4.746E-01	2.214E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 7

2.0	7.481E-01	4.954E-01	2.413E-01	1.045E-02
4.0	7.677E-01	5.162E-01	2.617E-01	1.936E-02
6.0	7.866E-01	5.370E-01	2.823E-01	3.033E-02
8.0	8.048E-01	5.576E-01	3.030E-01	4.321E-02
10.0	8.223E-01	5.781E-01	3.237E-01	5.782E-02
12.0	8.388E-01	5.985E-01	3.445E-01	7.395E-02
14.0	8.544E-01	6.186E-01	3.654E-01	9.140E-02
16.0	8.690E-01	6.385E-01	3.862E-01	1.100E-01
18.0	8.825E-01	6.581E-01	4.070E-01	1.295E-01
20.0	8.951E-01	6.773E-01	4.277E-01	1.498E-01
22.0	9.066E-01	6.960E-01	4.484E-01	1.707E-01
24.0	9.171E-01	7.144E-01	4.689E-01	1.920E-01
26.0	9.267E-01	7.322E-01	4.894E-01	2.138E-01
28.0	9.354E-01	7.495E-01	5.097E-01	2.357E-01
30.0	9.432E-01	7.662E-01	5.298E-01	2.578E-01

CYCLE NUMBER= 8

2.0	7.845E-01	5.497E-01	2.797E-01	1.214E-02
4.0	8.015E-01	5.695E-01	3.020E-01	2.241E-02
6.0	8.179E-01	5.891E-01	3.242E-01	3.504E-02
8.0	8.336E-01	6.084E-01	3.463E-01	4.981E-02
10.0	8.487E-01	6.275E-01	3.682E-01	6.650E-02
12.0	8.629E-01	6.463E-01	3.900E-01	8.485E-02
14.0	8.762E-01	6.648E-01	4.116E-01	1.046E-01
16.0	8.887E-01	6.829E-01	4.330E-01	1.256E-01
18.0	9.003E-01	7.007E-01	4.542E-01	1.475E-01
20.0	9.110E-01	7.180E-01	4.751E-01	1.701E-01
22.0	9.208E-01	7.349E-01	4.957E-01	1.933E-01
24.0	9.298E-01	7.513E-01	5.161E-01	2.169E-01
26.0	9.379E-01	7.672E-01	5.362E-01	2.407E-01
28.0	9.453E-01	7.826E-01	5.559E-01	2.646E-01
30.0	9.519E-01	7.974E-01	5.754E-01	2.885E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 9

2.0	8.135E-01	5.945E-01	3.120E-01	1.355E-02
4.0	8.284E-01	6.134E-01	3.358E-01	2.499E-02
6.0	8.427E-01	6.319E-01	3.593E-01	3.900E-02
8.0	8.564E-01	6.500E-01	3.825E-01	5.536E-02
10.0	8.695E-01	6.679E-01	4.054E-01	7.379E-02
12.0	8.818E-01	6.853E-01	4.280E-01	9.400E-02
14.0	8.934E-01	7.024E-01	4.502E-01	1.157E-01
16.0	9.042E-01	7.190E-01	4.720E-01	1.386E-01
18.0	9.143E-01	7.353E-01	4.934E-01	1.625E-01
20.0	9.235E-01	7.511E-01	5.143E-01	1.871E-01
22.0	9.320E-01	7.664E-01	5.349E-01	2.122E-01
24.0	9.397E-01	7.812E-01	5.551E-01	2.376E-01
26.0	9.467E-01	7.955E-01	5.748E-01	2.632E-01
28.0	9.531E-01	8.092E-01	5.940E-01	2.887E-01
30.0	9.588E-01	8.224E-01	6.129E-01	3.141E-01

CYCLE NUMBER= 10

2.0	8.367E-01	6.313E-01	3.389E-01	1.473E-02
4.0	8.499E-01	6.493E-01	3.639E-01	2.712E-02
6.0	8.626E-01	6.669E-01	3.885E-01	4.229E-02
8.0	8.747E-01	6.841E-01	4.126E-01	5.996E-02
10.0	8.862E-01	7.008E-01	4.362E-01	7.984E-02
12.0	8.970E-01	7.171E-01	4.594E-01	1.016E-01
14.0	9.072E-01	7.330E-01	4.820E-01	1.249E-01
16.0	9.166E-01	7.484E-01	5.041E-01	1.495E-01
18.0	9.254E-01	7.634E-01	5.257E-01	1.750E-01
20.0	9.335E-01	7.779E-01	5.467E-01	2.012E-01
22.0	9.409E-01	7.918E-01	5.672E-01	2.279E-01
24.0	9.476E-01	8.053E-01	5.871E-01	2.548E-01
26.0	9.537E-01	8.183E-01	6.065E-01	2.817E-01
28.0	9.593E-01	8.308E-01	6.253E-01	3.086E-01
30.0	9.642E-01	8.427E-01	6.436E-01	3.352E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 11

2.0	8.555E-01	6.614E-01	3.611E-01	1.570E-02
4.0	8.673E-01	6.787E-01	3.871E-01	2.889E-02
6.0	8.786E-01	6.955E-01	4.125E-01	4.501E-02
8.0	8.894E-01	7.119E-01	4.374E-01	6.376E-02
10.0	8.996E-01	7.277E-01	4.616E-01	8.482E-02
12.0	9.092E-01	7.431E-01	4.852E-01	1.078E-01
14.0	9.182E-01	7.579E-01	5.082E-01	1.325E-01
16.0	9.266E-01	7.723E-01	5.305E-01	1.584E-01
18.0	9.344E-01	7.862E-01	5.522E-01	1.852E-01
20.0	9.415E-01	7.996E-01	5.732E-01	2.128E-01
22.0	9.480E-01	8.126E-01	5.936E-01	2.407E-01
24.0	9.540E-01	8.250E-01	6.133E-01	2.689E-01
26.0	9.594E-01	8.368E-01	6.324E-01	2.970E-01
28.0	9.642E-01	8.482E-01	6.509E-01	3.249E-01
30.0	9.686E-01	8.591E-01	6.688E-01	3.526E-01

CYCLE NUMBER= 12

2.0	8.707E-01	6.861E-01	3.793E-01	1.650E-02
4.0	8.814E-01	7.028E-01	4.061E-01	3.034E-02
6.0	8.916E-01	7.189E-01	4.322E-01	4.724E-02
8.0	9.013E-01	7.346E-01	4.577E-01	6.688E-02
10.0	9.105E-01	7.497E-01	4.824E-01	8.892E-02
12.0	9.191E-01	7.642E-01	5.064E-01	1.130E-01
14.0	9.272E-01	7.783E-01	5.297E-01	1.387E-01
16.0	9.347E-01	7.918E-01	5.522E-01	1.657E-01
18.0	9.416E-01	8.049E-01	5.740E-01	1.937E-01
20.0	9.480E-01	8.174E-01	5.950E-01	2.223E-01
22.0	9.538E-01	8.294E-01	6.153E-01	2.513E-01
24.0	9.591E-01	8.409E-01	6.348E-01	2.804E-01
26.0	9.639E-01	8.519E-01	6.537E-01	3.095E-01
28.0	9.683E-01	8.624E-01	6.719E-01	3.383E-01
30.0	9.722E-01	8.724E-01	6.893E-01	3.668E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 13

2.0	8.830E-01	7.062E-01	3.943E-01	1.715E-02
4.0	8.928E-01	7.224E-01	4.217E-01	3.152E-02
6.0	9.021E-01	7.381E-01	4.484E-01	4.906E-02
8.0	9.109E-01	7.531E-01	4.743E-01	6.944E-02
10.0	9.193E-01	7.676E-01	4.995E-01	9.227E-02
12.0	9.271E-01	7.815E-01	5.238E-01	1.172E-01
14.0	9.344E-01	7.949E-01	5.473E-01	1.438E-01
16.0	9.412E-01	8.077E-01	5.699E-01	1.717E-01
18.0	9.475E-01	8.201E-01	5.917E-01	2.006E-01
20.0	9.532E-01	8.319E-01	6.128E-01	2.301E-01
22.0	9.585E-01	8.431E-01	6.330E-01	2.599E-01
24.0	9.633E-01	8.539E-01	6.524E-01	2.899E-01
26.0	9.676E-01	8.642E-01	6.711E-01	3.198E-01
28.0	9.715E-01	8.740E-01	6.890E-01	3.493E-01
30.0	9.750E-01	8.833E-01	7.061E-01	3.784E-01

CYCLE NUMBER= 14

2.0	8.931E-01	7.226E-01	4.065E-01	1.769E-02
4.0	9.021E-01	7.385E-01	4.344E-01	3.250E-02
6.0	9.107E-01	7.537E-01	4.616E-01	5.056E-02
8.0	9.188E-01	7.682E-01	4.879E-01	7.153E-02
10.0	9.265E-01	7.822E-01	5.134E-01	9.502E-02
12.0	9.337E-01	7.956E-01	5.379E-01	1.206E-01
14.0	9.403E-01	8.084E-01	5.616E-01	1.479E-01
16.0	9.465E-01	8.207E-01	5.844E-01	1.766E-01
18.0	9.523E-01	8.324E-01	6.063E-01	2.062E-01
20.0	9.575E-01	8.436E-01	6.273E-01	2.364E-01
22.0	9.623E-01	8.543E-01	6.474E-01	2.670E-01
24.0	9.667E-01	8.645E-01	6.667E-01	2.977E-01
26.0	9.706E-01	8.742E-01	6.852E-01	3.281E-01
28.0	9.742E-01	8.834E-01	7.029E-01	3.583E-01
30.0	9.773E-01	8.921E-01	7.198E-01	3.879E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 15

2.0	9.013E-01	7.360E-01	4.165E-01	1.812E-02
4.0	9.097E-01	7.516E-01	4.449E-01	3.329E-02
6.0	9.177E-01	7.664E-01	4.724E-01	5.178E-02
8.0	9.252E-01	7.806E-01	4.990E-01	7.323E-02
10.0	9.323E-01	7.941E-01	5.248E-01	9.726E-02
12.0	9.390E-01	8.071E-01	5.495E-01	1.234E-01
14.0	9.451E-01	8.194E-01	5.733E-01	1.513E-01
16.0	9.509E-01	8.313E-01	5.962E-01	1.806E-01
18.0	9.562E-01	8.425E-01	6.181E-01	2.108E-01
20.0	9.610E-01	8.532E-01	6.391E-01	2.416E-01
22.0	9.654E-01	8.635E-01	6.592E-01	2.728E-01
24.0	9.694E-01	8.732E-01	6.784E-01	3.040E-01
26.0	9.730E-01	8.824E-01	6.968E-01	3.350E-01
28.0	9.763E-01	8.911E-01	7.143E-01	3.656E-01
30.0	9.792E-01	8.993E-01	7.310E-01	3.957E-01

CYCLE NUMBER= 16

2.0	9.080E-01	7.470E-01	4.246E-01	1.848E-02
4.0	9.158E-01	7.622E-01	4.534E-01	3.394E-02
6.0	9.233E-01	7.768E-01	4.812E-01	5.278E-02
8.0	9.304E-01	7.906E-01	5.081E-01	7.463E-02
10.0	9.371E-01	8.038E-01	5.340E-01	9.909E-02
12.0	9.433E-01	8.164E-01	5.590E-01	1.257E-01
14.0	9.491E-01	8.284E-01	5.829E-01	1.541E-01
16.0	9.544E-01	8.399E-01	6.059E-01	1.839E-01
18.0	9.593E-01	8.508E-01	6.278E-01	2.146E-01
20.0	9.638E-01	8.611E-01	6.488E-01	2.459E-01
22.0	9.679E-01	8.709E-01	6.689E-01	2.775E-01
24.0	9.717E-01	8.802E-01	6.880E-01	3.091E-01
26.0	9.750E-01	8.890E-01	7.062E-01	3.406E-01
28.0	9.781E-01	8.973E-01	7.236E-01	3.716E-01
30.0	9.808E-01	9.052E-01	7.402E-01	4.020E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER = 17

2.0	9.134E-01	7.559E-01	4.313E-01	1.877E-02
4.0	9.209E-01	7.709E-01	4.603E-01	3.447E-02
6.0	9.280E-01	7.852E-01	4.884E-01	5.359E-02
8.0	9.347E-01	7.988E-01	5.155E-01	7.577E-02
10.0	9.409E-01	8.118E-01	5.416E-01	1.006E-01
12.0	9.468E-01	8.241E-01	5.667E-01	1.276E-01
14.0	9.523E-01	8.358E-01	5.907E-01	1.564E-01
16.0	9.573E-01	8.469E-01	6.137E-01	1.865E-01
18.0	9.619E-01	8.575E-01	6.357E-01	2.176E-01
20.0	9.661E-01	8.675E-01	6.567E-01	2.493E-01
22.0	9.700E-01	8.770E-01	6.767E-01	2.813E-01
24.0	9.735E-01	8.859E-01	6.958E-01	3.133E-01
26.0	9.767E-01	8.944E-01	7.139E-01	3.451E-01
28.0	9.795E-01	9.024E-01	7.312E-01	3.765E-01
30.0	9.820E-01	9.100E-01	7.476E-01	4.072E-01

CYCLE NUMBER = 18

2.0	9.178E-01	7.632E-01	4.367E-01	1.901E-02
4.0	9.250E-01	7.781E-01	4.660E-01	3.490E-02
6.0	9.318E-01	7.921E-01	4.943E-01	5.425E-02
8.0	9.381E-01	8.055E-01	5.216E-01	7.670E-02
10.0	9.441E-01	8.182E-01	5.478E-01	1.018E-01
12.0	9.497E-01	8.303E-01	5.730E-01	1.291E-01
14.0	9.549E-01	8.418E-01	5.971E-01	1.582E-01
16.0	9.596E-01	8.526E-01	6.202E-01	1.887E-01
18.0	9.640E-01	8.629E-01	6.422E-01	2.201E-01
20.0	9.680E-01	8.727E-01	6.632E-01	2.522E-01
22.0	9.717E-01	8.819E-01	6.831E-01	2.845E-01
24.0	9.750E-01	8.906E-01	7.022E-01	3.168E-01
26.0	9.780E-01	8.989E-01	7.202E-01	3.488E-01
28.0	9.807E-01	9.066E-01	7.374E-01	3.804E-01
30.0	9.831E-01	9.139E-01	7.537E-01	4.114E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 19

2.0	9.214E-01	7.692E-01	4.411E-01	1.920E-02
4.0	9.283E-01	7.839E-01	4.706E-01	3.525E-02
6.0	9.348E-01	7.978E-01	4.991E-01	5.480E-02
8.0	9.410E-01	8.110E-01	5.265E-01	7.745E-02
10.0	9.467E-01	8.235E-01	5.529E-01	1.028E-01
12.0	9.520E-01	8.354E-01	5.781E-01	1.304E-01
14.0	9.570E-01	8.467E-01	6.023E-01	1.597E-01
16.0	9.615E-01	8.573E-01	6.254E-01	1.905E-01
18.0	9.657E-01	8.674E-01	6.474E-01	2.222E-01
20.0	9.696E-01	8.769E-01	6.684E-01	2.545E-01
22.0	9.730E-01	8.860E-01	6.884E-01	2.870E-01
24.0	9.762E-01	8.945E-01	7.074E-01	3.196E-01
26.0	9.790E-01	9.025E-01	7.254E-01	3.519E-01
28.0	9.816E-01	9.100E-01	7.424E-01	3.837E-01
30.0	9.839E-01	9.171E-01	7.586E-01	4.148E-01

CYCLE NUMBER= 20

2.0	9.244E-01	7.740E-01	4.447E-01	1.936E-02
4.0	9.311E-01	7.886E-01	4.744E-01	3.554E-02
6.0	9.373E-01	8.024E-01	5.030E-01	5.524E-02
8.0	9.433E-01	8.155E-01	5.305E-01	7.807E-02
10.0	9.488E-01	8.278E-01	5.570E-01	1.036E-01
12.0	9.539E-01	8.396E-01	5.823E-01	1.314E-01
14.0	9.587E-01	8.506E-01	6.066E-01	1.610E-01
16.0	9.631E-01	8.611E-01	6.297E-01	1.919E-01
18.0	9.671E-01	8.710E-01	6.517E-01	2.238E-01
20.0	9.708E-01	8.804E-01	6.727E-01	2.564E-01
22.0	9.742E-01	8.892E-01	6.927E-01	2.891E-01
24.0	9.772E-01	8.976E-01	7.116E-01	3.219E-01
26.0	9.799E-01	9.054E-01	7.295E-01	3.543E-01
28.0	9.824E-01	9.128E-01	7.466E-01	3.863E-01
30.0	9.846E-01	9.197E-01	7.627E-01	4.177E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 21

2.0	9.268E-01	7.780E-01	4.477E-01	1.949E-02
4.0	9.333E-01	7.924E-01	4.774E-01	3.577E-02
6.0	9.394E-01	8.061E-01	5.062E-01	5.560E-02
8.0	9.451E-01	8.191E-01	5.338E-01	7.858E-02
10.0	9.505E-01	8.313E-01	5.603E-01	1.043E-01
12.0	9.555E-01	8.429E-01	5.857E-01	1.322E-01
14.0	9.601E-01	8.539E-01	6.100E-01	1.620E-01
16.0	9.644E-01	8.642E-01	6.332E-01	1.931E-01
18.0	9.683E-01	8.740E-01	6.552E-01	2.252E-01
20.0	9.718E-01	8.832E-01	6.762E-01	2.579E-01
22.0	9.751E-01	8.919E-01	6.961E-01	2.908E-01
24.0	9.780E-01	9.001E-01	7.150E-01	3.237E-01
26.0	9.806E-01	9.078E-01	7.330E-01	3.564E-01
28.0	9.830E-01	9.150E-01	7.499E-01	3.885E-01
30.0	9.851E-01	9.218E-01	7.660E-01	4.199E-01

CYCLE NUMBER= 22

2.0	9.288E-01	7.812E-01	4.501E-01	1.960E-02
4.0	9.351E-01	7.956E-01	4.800E-01	3.596E-02
6.0	9.411E-01	8.092E-01	5.088E-01	5.589E-02
8.0	9.467E-01	8.221E-01	5.365E-01	7.899E-02
10.0	9.519E-01	8.342E-01	5.631E-01	1.048E-01
12.0	9.568E-01	8.457E-01	5.885E-01	1.329E-01
14.0	9.613E-01	8.565E-01	6.128E-01	1.628E-01
16.0	9.654E-01	8.668E-01	6.360E-01	1.941E-01
18.0	9.692E-01	8.764E-01	6.581E-01	2.263E-01
20.0	9.727E-01	8.855E-01	6.791E-01	2.591E-01
22.0	9.758E-01	8.941E-01	6.990E-01	2.922E-01
24.0	9.787E-01	9.022E-01	7.179E-01	3.253E-01
26.0	9.812E-01	9.098E-01	7.357E-01	3.580E-01
28.0	9.835E-01	9.169E-01	7.527E-01	3.903E-01
30.0	9.856E-01	9.235E-01	7.687E-01	4.218E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER = 23

2.0	9.304E-01	7.838E-01	4.521E-01	1.968E-02
4.0	9.366E-01	7.982E-01	4.820E-01	3.612E-02
6.0	9.424E-01	8.117E-01	5.109E-01	5.613E-02
8.0	9.479E-01	8.245E-01	5.387E-01	7.932E-02
10.0	9.530E-01	8.366E-01	5.653E-01	1.053E-01
12.0	9.578E-01	8.480E-01	5.908E-01	1.335E-01
14.0	9.622E-01	8.587E-01	6.151E-01	1.635E-01
16.0	9.663E-01	8.689E-01	6.383E-01	1.949E-01
18.0	9.700E-01	8.784E-01	6.604E-01	2.272E-01
20.0	9.733E-01	8.874E-01	6.814E-01	2.602E-01
22.0	9.764E-01	8.959E-01	7.013E-01	2.934E-01
24.0	9.792E-01	9.039E-01	7.202E-01	3.265E-01
26.0	9.817E-01	9.114E-01	7.380E-01	3.594E-01
28.0	9.839E-01	9.184E-01	7.549E-01	3.917E-01
30.0	9.860E-01	9.249E-01	7.709E-01	4.233E-01

CYCLE NUMBER = 24

2.0	9.317E-01	7.860E-01	4.537E-01	1.975E-02
4.0	9.378E-01	8.003E-01	4.837E-01	3.625E-02
6.0	9.435E-01	8.137E-01	5.126E-01	5.633E-02
8.0	9.489E-01	8.265E-01	5.404E-01	7.960E-02
10.0	9.540E-01	8.385E-01	5.671E-01	1.056E-01
12.0	9.586E-01	8.498E-01	5.927E-01	1.339E-01
14.0	9.630E-01	8.605E-01	6.170E-01	1.640E-01
16.0	9.669E-01	8.705E-01	6.402E-01	1.955E-01
18.0	9.706E-01	8.800E-01	6.623E-01	2.280E-01
20.0	9.739E-01	8.890E-01	6.833E-01	2.610E-01
22.0	9.769E-01	8.974E-01	7.032E-01	2.943E-01
24.0	9.796E-01	9.053E-01	7.220E-01	3.275E-01
26.0	9.821E-01	9.127E-01	7.399E-01	3.605E-01
28.0	9.843E-01	9.196E-01	7.567E-01	3.929E-01
30.0	9.863E-01	9.261E-01	7.727E-01	4.246E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES	COLUMN 1	COLUMN 2	COLUMN 3	COLUMN 4
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CYCLE NUMBER= 25

2.0	9.327E-01	7.877E-01	4.550E-01	1.981E-02
4.0	9.388E-01	8.020E-01	4.850E-01	3.635E-02
6.0	9.445E-01	8.154E-01	5.140E-01	5.649E-02
8.0	9.498E-01	8.281E-01	5.419E-01	7.982E-02
10.0	9.547E-01	8.400E-01	5.686E-01	1.059E-01
12.0	9.593E-01	8.513E-01	5.942E-01	1.343E-01
14.0	9.636E-01	8.619E-01	6.186E-01	1.645E-01
16.0	9.675E-01	8.719E-01	6.418E-01	1.960E-01
18.0	9.711E-01	8.814E-01	6.639E-01	2.286E-01
20.0	9.743E-01	8.902E-01	6.848E-01	2.617E-01
22.0	9.773E-01	8.986E-01	7.047E-01	2.950E-01
24.0	9.800E-01	9.064E-01	7.236E-01	3.283E-01
26.0	9.824E-01	9.137E-01	7.414E-01	3.613E-01
28.0	9.846E-01	9.206E-01	7.582E-01	3.938E-01
30.0	9.865E-01	9.270E-01	7.741E-01	4.256E-01

CYCLE NUMBER= 26

2.0	9.336E-01	7.892E-01	4.560E-01	1.986E-02
4.0	9.396E-01	8.034E-01	4.861E-01	3.644E-02
6.0	9.452E-01	8.167E-01	5.152E-01	5.662E-02
8.0	9.505E-01	8.294E-01	5.431E-01	8.000E-02
10.0	9.554E-01	8.413E-01	5.698E-01	1.061E-01
12.0	9.599E-01	8.525E-01	5.954E-01	1.346E-01
14.0	9.641E-01	8.631E-01	6.198E-01	1.648E-01
16.0	9.680E-01	8.731E-01	6.430E-01	1.965E-01
18.0	9.715E-01	8.824E-01	6.651E-01	2.291E-01
20.0	9.747E-01	8.912E-01	6.861E-01	2.622E-01
22.0	9.776E-01	8.995E-01	7.060E-01	2.957E-01
24.0	9.803E-01	9.073E-01	7.248E-01	3.290E-01
26.0	9.827E-01	9.146E-01	7.426E-01	3.621E-01
28.0	9.848E-01	9.214E-01	7.594E-01	3.946E-01
30.0	9.867E-01	9.278E-01	7.753E-01	4.264E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 27

2.0	9.343E-01	7.903E-01	4.569E-01	1.989E-02
4.0	9.402E-01	8.045E-01	4.871E-01	3.651E-02
6.0	9.458E-01	8.178E-01	5.161E-01	5.673E-02
8.0	9.510E-01	8.304E-01	5.441E-01	8.015E-02
10.0	9.559E-01	8.423E-01	5.708E-01	1.063E-01
12.0	9.604E-01	8.535E-01	5.964E-01	1.348E-01
14.0	9.645E-01	8.640E-01	6.208E-01	1.651E-01
16.0	9.683E-01	8.740E-01	6.441E-01	1.968E-01
18.0	9.718E-01	8.833E-01	6.662E-01	2.295E-01
20.0	9.750E-01	8.921E-01	6.871E-01	2.627E-01
22.0	9.779E-01	9.003E-01	7.070E-01	2.962E-01
24.0	9.805E-01	9.080E-01	7.258E-01	3.296E-01
26.0	9.829E-01	9.153E-01	7.436E-01	3.627E-01
28.0	9.850E-01	9.221E-01	7.604E-01	3.952E-01
30.0	9.869E-01	9.284E-01	7.763E-01	4.271E-01

CYCLE NUMBER= 28

2.0	9.349E-01	7.913E-01	4.576E-01	1.992E-02
4.0	9.408E-01	8.054E-01	4.878E-01	3.656E-02
6.0	9.463E-01	8.187E-01	5.169E-01	5.681E-02
8.0	9.515E-01	8.313E-01	5.448E-01	8.027E-02
10.0	9.563E-01	8.432E-01	5.716E-01	1.065E-01
12.0	9.607E-01	8.543E-01	5.972E-01	1.350E-01
14.0	9.649E-01	8.648E-01	6.217E-01	1.654E-01
16.0	9.686E-01	8.747E-01	6.449E-01	1.971E-01
18.0	9.721E-01	8.840E-01	6.670E-01	2.298E-01
20.0	9.753E-01	8.928E-01	6.880E-01	2.631E-01
22.0	9.781E-01	9.010E-01	7.078E-01	2.966E-01
24.0	9.807E-01	9.087E-01	7.267E-01	3.300E-01
26.0	9.830E-01	9.159E-01	7.444E-01	3.632E-01
28.0	9.851E-01	9.226E-01	7.612E-01	3.958E-01
30.0	9.870E-01	9.289E-01	7.771E-01	4.276E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 29

2.0	9.354E-01	7.921E-01	4.582E-01	1.995E-02
4.0	9.412E-01	8.062E-01	4.884E-01	3.661E-02
6.0	9.467E-01	8.195E-01	5.175E-01	5.688E-02
8.0	9.518E-01	8.320E-01	5.455E-01	8.037E-02
10.0	9.566E-01	8.439E-01	5.723E-01	1.066E-01
12.0	9.610E-01	8.550E-01	5.979E-01	1.352E-01
14.0	9.651E-01	8.655E-01	6.223E-01	1.656E-01
16.0	9.689E-01	8.753E-01	6.456E-01	1.973E-01
18.0	9.723E-01	8.846E-01	6.677E-01	2.300E-01
20.0	9.755E-01	8.933E-01	6.887E-01	2.634E-01
22.0	9.783E-01	9.015E-01	7.085E-01	2.969E-01
24.0	9.809E-01	9.092E-01	7.273E-01	3.304E-01
26.0	9.832E-01	9.163E-01	7.451E-01	3.636E-01
28.0	9.853E-01	9.231E-01	7.619E-01	3.962E-01
30.0	9.871E-01	9.294E-01	7.777E-01	4.281E-01

CYCLE NUMBER= 30

2.0	9.357E-01	7.927E-01	4.587E-01	1.997E-02
4.0	9.416E-01	8.068E-01	4.889E-01	3.664E-02
6.0	9.470E-01	8.201E-01	5.180E-01	5.694E-02
8.0	9.521E-01	8.326E-01	5.460E-01	8.045E-02
10.0	9.569E-01	8.444E-01	5.728E-01	1.067E-01
12.0	9.613E-01	8.555E-01	5.985E-01	1.353E-01
14.0	9.654E-01	8.660E-01	6.229E-01	1.657E-01
16.0	9.691E-01	8.758E-01	6.462E-01	1.975E-01
18.0	9.725E-01	8.851E-01	6.683E-01	2.303E-01
20.0	9.756E-01	8.938E-01	6.892E-01	2.636E-01
22.0	9.785E-01	9.019E-01	7.091E-01	2.972E-01
24.0	9.810E-01	9.096E-01	7.279E-01	3.307E-01
26.0	9.833E-01	9.167E-01	7.457E-01	3.639E-01
28.0	9.854E-01	9.234E-01	7.624E-01	3.965E-01
30.0	9.872E-01	9.297E-01	7.783E-01	4.285E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER = 31

2.0	9.361E-01	7.932E-01	4.591E-01	1.999E-02
4.0	9.418E-01	8.073E-01	4.893E-01	3.668E-02
6.0	9.473E-01	8.206E-01	5.184E-01	5.699E-02
8.0	9.524E-01	8.331E-01	5.464E-01	8.052E-02
10.0	9.571E-01	8.449E-01	5.733E-01	1.068E-01
12.0	9.615E-01	8.560E-01	5.989E-01	1.354E-01
14.0	9.655E-01	8.664E-01	6.233E-01	1.659E-01
16.0	9.693E-01	8.762E-01	6.466E-01	1.977E-01
18.0	9.727E-01	8.855E-01	6.687E-01	2.304E-01
20.0	9.758E-01	8.941E-01	6.897E-01	2.638E-01
22.0	9.786E-01	9.023E-01	7.095E-01	2.974E-01
24.0	9.811E-01	9.099E-01	7.283E-01	3.309E-01
26.0	9.834E-01	9.170E-01	7.461E-01	3.641E-01
28.0	9.854E-01	9.237E-01	7.629E-01	3.968E-01
30.0	9.873E-01	9.300E-01	7.787E-01	4.288E-01

CYCLE NUMBER = 32

2.0	9.363E-01	7.936E-01	4.594E-01	2.000E-02
4.0	9.421E-01	8.077E-01	4.896E-01	3.670E-02
6.0	9.475E-01	8.210E-01	5.188E-01	5.703E-02
8.0	9.526E-01	8.335E-01	5.468E-01	8.057E-02
10.0	9.573E-01	8.452E-01	5.736E-01	1.069E-01
12.0	9.617E-01	8.563E-01	5.993E-01	1.355E-01
14.0	9.657E-01	8.668E-01	6.237E-01	1.660E-01
16.0	9.694E-01	8.766E-01	6.470E-01	1.978E-01
18.0	9.728E-01	8.858E-01	6.691E-01	2.306E-01
20.0	9.759E-01	8.944E-01	6.901E-01	2.640E-01
22.0	9.787E-01	9.026E-01	7.099E-01	2.976E-01
24.0	9.812E-01	9.102E-01	7.287E-01	3.311E-01
26.0	9.835E-01	9.173E-01	7.465E-01	3.644E-01
28.0	9.855E-01	9.240E-01	7.632E-01	3.970E-01
30.0	9.873E-01	9.302E-01	7.790E-01	4.290E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 33

2.0	9.365E-01	7.940E-01	4.596E-01	2.001E-02
4.0	9.423E-01	8.080E-01	4.899E-01	3.672E-02
6.0	9.477E-01	8.213E-01	5.191E-01	5.706E-02
8.0	9.527E-01	8.338E-01	5.471E-01	8.062E-02
10.0	9.574E-01	8.456E-01	5.739E-01	1.069E-01
12.0	9.618E-01	8.566E-01	5.996E-01	1.356E-01
14.0	9.658E-01	8.670E-01	6.240E-01	1.660E-01
16.0	9.695E-01	8.768E-01	6.473E-01	1.979E-01
18.0	9.729E-01	8.860E-01	6.694E-01	2.307E-01
20.0	9.760E-01	8.947E-01	6.904E-01	2.641E-01
22.0	9.787E-01	9.028E-01	7.102E-01	2.977E-01
24.0	9.813E-01	9.104E-01	7.290E-01	3.313E-01
26.0	9.835E-01	9.175E-01	7.468E-01	3.645E-01
28.0	9.856E-01	9.242E-01	7.635E-01	3.972E-01
30.0	9.874E-01	9.304E-01	7.793E-01	4.292E-01

CYCLE NUMBER= 34

2.0	9.367E-01	7.943E-01	4.598E-01	2.002E-02
4.0	9.424E-01	8.083E-01	4.901E-01	3.674E-02
6.0	9.478E-01	8.216E-01	5.193E-01	5.708E-02
8.0	9.529E-01	8.340E-01	5.473E-01	8.065E-02
10.0	9.576E-01	8.458E-01	5.741E-01	1.070E-01
12.0	9.619E-01	8.569E-01	5.998E-01	1.356E-01
14.0	9.659E-01	8.673E-01	6.243E-01	1.661E-01
16.0	9.696E-01	8.771E-01	6.475E-01	1.980E-01
18.0	9.730E-01	8.862E-01	6.696E-01	2.308E-01
20.0	9.760E-01	8.949E-01	6.906E-01	2.642E-01
22.0	9.788E-01	9.030E-01	7.105E-01	2.978E-01
24.0	9.813E-01	9.106E-01	7.292E-01	3.314E-01
26.0	9.836E-01	9.177E-01	7.470E-01	3.647E-01
28.0	9.856E-01	9.243E-01	7.638E-01	3.974E-01
30.0	9.874E-01	9.305E-01	7.796E-01	4.294E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 35

2.0	9.368E-01	7.945E-01	4.600E-01	2.003E-02
4.0	9.426E-01	8.085E-01	4.903E-01	3.675E-02
6.0	9.479E-01	8.218E-01	5.195E-01	5.710E-02
8.0	9.530E-01	8.343E-01	5.475E-01	8.068E-02
10.0	9.577E-01	8.460E-01	5.743E-01	1.070E-01
12.0	9.620E-01	8.571E-01	6.000E-01	1.357E-01
14.0	9.660E-01	8.675E-01	6.245E-01	1.662E-01
16.0	9.697E-01	8.772E-01	6.477E-01	1.980E-01
18.0	9.730E-01	8.864E-01	6.698E-01	2.309E-01
20.0	9.761E-01	8.950E-01	6.908E-01	2.643E-01
22.0	9.789E-01	9.031E-01	7.107E-01	2.979E-01
24.0	9.814E-01	9.107E-01	7.294E-01	3.315E-01
26.0	9.836E-01	9.178E-01	7.472E-01	3.648E-01
28.0	9.856E-01	9.245E-01	7.640E-01	3.975E-01
30.0	9.874E-01	9.307E-01	7.798E-01	4.295E-01

CYCLE NUMBER= 36

2.0	9.369E-01	7.947E-01	4.601E-01	2.003E-02
4.0	9.427E-01	8.087E-01	4.904E-01	3.676E-02
6.0	9.480E-01	8.220E-01	5.196E-01	5.712E-02
8.0	9.531E-01	8.344E-01	5.476E-01	8.070E-02
10.0	9.577E-01	8.462E-01	5.745E-01	1.071E-01
12.0	9.621E-01	8.572E-01	6.002E-01	1.357E-01
14.0	9.661E-01	8.676E-01	6.246E-01	1.662E-01
16.0	9.697E-01	8.774E-01	6.479E-01	1.981E-01
18.0	9.731E-01	8.866E-01	6.700E-01	2.309E-01
20.0	9.761E-01	8.952E-01	6.910E-01	2.644E-01
22.0	9.789E-01	9.033E-01	7.108E-01	2.980E-01
24.0	9.814E-01	9.108E-01	7.296E-01	3.316E-01
26.0	9.837E-01	9.179E-01	7.474E-01	3.649E-01
28.0	9.857E-01	9.246E-01	7.641E-01	3.976E-01
30.0	9.875E-01	9.308E-01	7.799E-01	4.296E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 37

2.0	9.370E-01	7.948E-01	4.603E-01	2.004E-02
4.0	9.428E-01	8.089E-01	4.905E-01	3.677E-02
6.0	9.481E-01	8.221E-01	5.197E-01	5.713E-02
8.0	9.531E-01	8.346E-01	5.478E-01	8.072E-02
10.0	9.578E-01	8.463E-01	5.746E-01	1.071E-01
12.0	9.621E-01	8.573E-01	6.003E-01	1.358E-01
14.0	9.661E-01	8.677E-01	6.248E-01	1.663E-01
16.0	9.698E-01	8.775E-01	6.480E-01	1.981E-01
18.0	9.731E-01	8.867E-01	6.701E-01	2.310E-01
20.0	9.762E-01	8.953E-01	6.911E-01	2.644E-01
22.0	9.789E-01	9.034E-01	7.110E-01	2.981E-01
24.0	9.814E-01	9.109E-01	7.297E-01	3.317E-01
26.0	9.837E-01	9.180E-01	7.475E-01	3.650E-01
28.0	9.857E-01	9.246E-01	7.642E-01	3.977E-01
30.0	9.875E-01	9.308E-01	7.800E-01	4.297E-01

CYCLE NUMBER= 38

2.0	9.371E-01	7.949E-01	4.603E-01	2.004E-02
4.0	9.428E-01	8.090E-01	4.906E-01	3.678E-02
6.0	9.482E-01	8.222E-01	5.198E-01	5.715E-02
8.0	9.532E-01	8.347E-01	5.479E-01	8.074E-02
10.0	9.579E-01	8.464E-01	5.747E-01	1.071E-01
12.0	9.622E-01	8.575E-01	6.004E-01	1.358E-01
14.0	9.662E-01	8.678E-01	6.249E-01	1.663E-01
16.0	9.698E-01	8.776E-01	6.481E-01	1.982E-01
18.0	9.732E-01	8.868E-01	6.702E-01	2.310E-01
20.0	9.762E-01	8.954E-01	6.912E-01	2.645E-01
22.0	9.790E-01	9.034E-01	7.111E-01	2.981E-01
24.0	9.815E-01	9.110E-01	7.299E-01	3.317E-01
26.0	9.837E-01	9.181E-01	7.476E-01	3.650E-01
28.0	9.857E-01	9.247E-01	7.643E-01	3.978E-01
30.0	9.875E-01	9.309E-01	7.801E-01	4.298E-01

INSTANTANEOUS FRACTIONAL BREAKTHROUGH

BED VOLUMES COLUMN 1 COLUMN 2 COLUMN 3 COLUMN 4

CYCLE NUMBER= 39

2.0	9.372E-01	7.950E-01	4.604E-01	2.005E-02
4.0	9.429E-01	8.091E-01	4.907E-01	3.678E-02
6.0	9.482E-01	8.223E-01	5.199E-01	5.716E-02
8.0	9.532E-01	8.348E-01	5.480E-01	8.075E-02
10.0	9.579E-01	8.465E-01	5.748E-01	1.071E-01
12.0	9.622E-01	8.575E-01	6.005E-01	1.358E-01
14.0	9.662E-01	8.679E-01	6.250E-01	1.663E-01
16.0	9.699E-01	8.777E-01	6.482E-01	1.982E-01
18.0	9.732E-01	8.868E-01	6.703E-01	2.311E-01
20.0	9.762E-01	8.954E-01	6.913E-01	2.645E-01
22.0	9.790E-01	9.035E-01	7.112E-01	2.982E-01
24.0	9.815E-01	9.111E-01	7.299E-01	3.318E-01
26.0	9.837E-01	9.182E-01	7.477E-01	3.651E-01
28.0	9.857E-01	9.248E-01	7.644E-01	3.978E-01
30.0	9.875E-01	9.310E-01	7.802E-01	4.298E-01

CYCLE NUMBER= 40

2.0	9.372E-01	7.951E-01	4.605E-01	2.005E-02
4.0	9.429E-01	8.092E-01	4.908E-01	3.679E-02
6.0	9.483E-01	8.224E-01	5.200E-01	5.716E-02
8.0	9.533E-01	8.349E-01	5.480E-01	8.076E-02
10.0	9.579E-01	8.466E-01	5.749E-01	1.071E-01
12.0	9.622E-01	8.576E-01	6.006E-01	1.358E-01
14.0	9.662E-01	8.680E-01	6.250E-01	1.663E-01
16.0	9.699E-01	8.777E-01	6.483E-01	1.982E-01
18.0	9.732E-01	8.869E-01	6.704E-01	2.311E-01
20.0	9.763E-01	8.955E-01	6.914E-01	2.645E-01
22.0	9.790E-01	9.036E-01	7.112E-01	2.982E-01
24.0	9.815E-01	9.111E-01	7.300E-01	3.318E-01
26.0	9.837E-01	9.182E-01	7.478E-01	3.651E-01
28.0	9.857E-01	9.248E-01	7.645E-01	3.979E-01
30.0	9.875E-01	9.310E-01	7.803E-01	4.299E-01

INTEGRAL XD(NT)/NT

CUMULATIVE FRACTIONAL BREAKTHROUGH

CYCLE	COL 1	COL 2	COL 3	COL 4
1	3.445E-01	7.630E-02	1.234E-02	1.593E-03
2	5.491E-01	2.022E-01	5.599E-02	1.146E-02
3	6.645E-01	3.218E-01	1.213E-01	2.973E-02
4	7.379E-01	4.225E-01	1.931E-01	5.171E-02
5	7.886E-01	5.050E-01	2.620E-01	7.370E-02
6	8.255E-01	5.722E-01	3.236E-01	9.381E-02
7	8.535E-01	6.268E-01	3.767E-01	1.113E-01
8	8.753E-01	6.714E-01	4.214E-01	1.262E-01
9	8.924E-01	7.076E-01	4.586E-01	1.387E-01
10	9.062E-01	7.372E-01	4.893E-01	1.489E-01
11	9.173E-01	7.613E-01	5.146E-01	1.574E-01
12	9.262E-01	7.810E-01	5.353E-01	1.644E-01
13	9.335E-01	7.970E-01	5.522E-01	1.701E-01
14	9.394E-01	8.101E-01	5.660E-01	1.747E-01
15	9.442E-01	8.208E-01	5.773E-01	1.785E-01
16	9.481E-01	8.295E-01	5.866E-01	1.816E-01
17	9.513E-01	8.366E-01	5.941E-01	1.841E-01
18	9.539E-01	8.424E-01	6.002E-01	1.862E-01
19	9.561E-01	8.471E-01	6.052E-01	1.879E-01
20	9.578E-01	8.509E-01	6.093E-01	1.893E-01
21	9.592E-01	8.541E-01	6.127E-01	1.904E-01
22	9.604E-01	8.566E-01	6.154E-01	1.913E-01
23	9.613E-01	8.587E-01	6.176E-01	1.921E-01
24	9.621E-01	8.604E-01	6.194E-01	1.927E-01
25	9.627E-01	8.618E-01	6.209E-01	1.932E-01
26	9.632E-01	8.630E-01	6.221E-01	1.936E-01
27	9.636E-01	8.639E-01	6.231E-01	1.939E-01
28	9.640E-01	8.646E-01	6.239E-01	1.942E-01
29	9.642E-01	8.653E-01	6.245E-01	1.944E-01
30	9.645E-01	8.658E-01	6.251E-01	1.946E-01
31	9.646E-01	8.662E-01	6.255E-01	1.947E-01
32	9.648E-01	8.665E-01	6.259E-01	1.948E-01
33	9.649E-01	8.668E-01	6.262E-01	1.949E-01
34	9.650E-01	8.670E-01	6.264E-01	1.950E-01
35	9.651E-01	8.672E-01	6.266E-01	1.951E-01
36	9.652E-01	8.673E-01	6.267E-01	1.951E-01
37	9.652E-01	8.675E-01	6.269E-01	1.952E-01
38	9.653E-01	8.676E-01	6.270E-01	1.952E-01
39	9.653E-01	8.676E-01	6.271E-01	1.952E-01
40	9.653E-01	8.677E-01	6.271E-01	1.953E-01

INTEGRAL YD(N)/NT
FRACTIONAL LOADING

CYCLE	COL 1	COL 2	COL 3	COL 4
1	6.545E-01	2.667E-01	9.536E-02	1.718E-02
2	7.185E-01	4.095E-01	2.064E-01	6.273E-02
3	7.458E-01	4.986E-01	3.006E-01	1.208E-01
4	7.614E-01	5.595E-01	3.768E-01	1.798E-01
5	7.716E-01	6.037E-01	4.382E-01	2.339E-01
6	7.787E-01	6.370E-01	4.878E-01	2.812E-01
7	7.840E-01	6.629E-01	5.279E-01	3.213E-01
8	7.881E-01	6.833E-01	5.605E-01	3.549E-01
9	7.912E-01	6.996E-01	5.871E-01	3.827E-01
10	7.937E-01	7.127E-01	6.087E-01	4.056E-01
11	7.957E-01	7.233E-01	6.263E-01	4.244E-01
12	7.974E-01	7.319E-01	6.406E-01	4.397E-01
13	7.987E-01	7.389E-01	6.523E-01	4.523E-01
14	7.997E-01	7.446E-01	6.618E-01	4.626E-01
15	8.006E-01	7.493E-01	6.696E-01	4.710E-01
16	8.013E-01	7.530E-01	6.759E-01	4.778E-01
17	8.019E-01	7.561E-01	6.811E-01	4.834E-01
18	8.024E-01	7.586E-01	6.853E-01	4.879E-01
19	8.028E-01	7.607E-01	6.888E-01	4.917E-01
20	8.031E-01	7.624E-01	6.916E-01	4.947E-01
21	8.033E-01	7.637E-01	6.939E-01	4.972E-01
22	8.035E-01	7.648E-01	6.957E-01	4.992E-01
23	8.037E-01	7.658E-01	6.973E-01	5.008E-01
24	8.038E-01	7.665E-01	6.985E-01	5.022E-01
25	8.040E-01	7.671E-01	6.995E-01	5.033E-01
26	8.040E-01	7.676E-01	7.004E-01	5.042E-01
27	8.041E-01	7.680E-01	7.010E-01	5.049E-01
28	8.042E-01	7.683E-01	7.016E-01	5.055E-01
29	8.042E-01	7.686E-01	7.020E-01	5.060E-01
30	8.043E-01	7.688E-01	7.024E-01	5.064E-01
31	8.043E-01	7.690E-01	7.027E-01	5.067E-01
32	8.043E-01	7.691E-01	7.029E-01	5.069E-01
33	8.044E-01	7.693E-01	7.031E-01	5.072E-01
34	8.044E-01	7.693E-01	7.033E-01	5.073E-01
35	8.044E-01	7.694E-01	7.034E-01	5.075E-01
36	8.044E-01	7.695E-01	7.035E-01	5.076E-01
37	8.044E-01	7.695E-01	7.036E-01	5.077E-01
38	8.044E-01	7.696E-01	7.037E-01	5.078E-01
39	8.044E-01	7.696E-01	7.038E-01	5.078E-01
40	8.044E-01	7.697E-01	7.038E-01	5.079E-01

CURIE LOADING ON COLUMNS

CYCLE	COL 1	COL 2	COL 3	COL 4
1	1.571E+00	6.401E-01	2.289E-01	4.122E-02
2	1.724E+00	9.827E-01	4.954E-01	1.506E-01
3	1.790E+00	1.197E+00	7.214E-01	2.900E-01
4	1.827E+00	1.343E+00	9.044E-01	4.314E-01
5	1.852E+00	1.449E+00	1.052E+00	5.613E-01
6	1.869E+00	1.529E+00	1.171E+00	6.748E-01
7	1.882E+00	1.591E+00	1.267E+00	7.711E-01
8	1.891E+00	1.640E+00	1.345E+00	8.517E-01
9	1.899E+00	1.679E+00	1.409E+00	9.185E-01
10	1.905E+00	1.710E+00	1.461E+00	9.734E-01
11	1.910E+00	1.736E+00	1.503E+00	1.018E+00
12	1.914E+00	1.757E+00	1.537E+00	1.055E+00
13	1.917E+00	1.773E+00	1.565E+00	1.086E+00
14	1.919E+00	1.787E+00	1.588E+00	1.110E+00
15	1.921E+00	1.798E+00	1.607E+00	1.130E+00
16	1.923E+00	1.807E+00	1.622E+00	1.147E+00
17	1.925E+00	1.815E+00	1.635E+00	1.160E+00
18	1.926E+00	1.821E+00	1.645E+00	1.171E+00
19	1.927E+00	1.826E+00	1.653E+00	1.180E+00
20	1.927E+00	1.830E+00	1.660E+00	1.187E+00
21	1.928E+00	1.833E+00	1.665E+00	1.193E+00
22	1.928E+00	1.836E+00	1.670E+00	1.198E+00
23	1.929E+00	1.838E+00	1.673E+00	1.202E+00
24	1.929E+00	1.840E+00	1.676E+00	1.205E+00
25	1.929E+00	1.841E+00	1.679E+00	1.208E+00
26	1.930E+00	1.842E+00	1.681E+00	1.210E+00
27	1.930E+00	1.843E+00	1.682E+00	1.212E+00
28	1.930E+00	1.844E+00	1.684E+00	1.213E+00
29	1.930E+00	1.845E+00	1.685E+00	1.214E+00
30	1.930E+00	1.845E+00	1.686E+00	1.215E+00
31	1.930E+00	1.846E+00	1.686E+00	1.216E+00
32	1.930E+00	1.846E+00	1.687E+00	1.217E+00
33	1.930E+00	1.846E+00	1.688E+00	1.217E+00
34	1.931E+00	1.846E+00	1.688E+00	1.218E+00
35	1.931E+00	1.847E+00	1.688E+00	1.218E+00
36	1.931E+00	1.847E+00	1.689E+00	1.218E+00
37	1.931E+00	1.847E+00	1.689E+00	1.218E+00
38	1.931E+00	1.847E+00	1.689E+00	1.219E+00
39	1.931E+00	1.847E+00	1.689E+00	1.219E+00
40	1.931E+00	1.847E+00	1.689E+00	1.219E+00

APPENDIX C
COMPUTER PROGRAMS

NLIN.FOR A FORTRAN COMPUTER PROGRAM
(Written for the STC-VAX Computer)

This program uses nonlinear parameter estimation algorithms to curvefit experimental data to nonlinear models. This program (listed as LMDER1) is contained in the Core Library of numerical software at ORNL. Details of the program can be accessed by typing @NUM CORLIB on the STC-VAX computer system. The user must provide a subroutine which calculates the model function and its Jacobian matrix. The original input subroutine was written by Richard L. Cox. The program was modified and adapted by Reginald Hall for curvefitting nonlinear equilibrium isotherm data.

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C NLIN.FOR
C PROGRAM TO ILLUSTRATE THE USE OF LMDER1.
C PROGRAM CAN BE USED TO FIND COEFFICIENTS FOR LEAST SQUARES FIT
C OF NONLINEAR PARAMETER MODELS
C
C REVISED BY: REGINALD HALL, ORNL, BLDG. 3017, MS-6044, OAK RIDGE, TN 37830
C REVISION DATE: NOVEMBER 8, 1989
C
C ORIGINAL AUTHOR: RICHARD L. COX
C VERSION OF NOVEMBER 6, 1989
C
C INPUT DATA REQUIRED BY PROGRAM :
C (SEE HELP FILE FOR LMDER1 FOR MORE DETAILED INFORMATION)
C
C M  = NUMBER OF DATA OBSERVATIONS
C N  = NUMBER OF PARAMETERS
C NIV = NUMBER OF INDEPENDENT VARIABLES
C TOL = NONNEGATIVE CONVERGENCE TOLERANCE
C C  = MATRIX OF SIZE (M,NIV) OF INDEPENDENT VARIABLE VALUES
C OBS = VECTOR OF LENGTH M OF OBSERVED DEPENDENT VARIABLE VALUES
C X  = VECTOR OF LENGTH N OF INITIAL GUESSES FOR COEFFICIENTS
C      OF LEAST SQUARES FUNCTION
C
C DIMENSION ARRAYS IN DIMENSION STATEMENT BELOW AT LEAST :
C   DIMENSION X(N),FVEC(M),FJAC(M,N),WA(5*N+M),IWA(N)
C   DIMENSION C(M,NIV),OBS(M),CALC(M),WEIGHT(M),COVMAT(N,N)
C
C FURTHER, VALUES OF MMAX, NMAX, AND LWA MUST BE EXPLICITLY
C DECLARED IN FORTRAN STATEMENTS BELOW WHERE
C
C MMAX = POSITIVE INTEGER NOT LESS THAN M WHICH SPECIFIES THE
C   LEADING DIMENSION OF THE ARRAYS C AND FJAC
C NMAX = POSITIVE INTEGER NOT LESS THAN N WHICH SPECIFIES THE
C   LEADING DIMENSION OF THE ARRAY COVMAT
C LWA  = POSITIVE INTEGER WHICH SPECIFIES DIMENSION OF WA
C
C FOLLOWING DIMENSIONING IS FOR A MAXIMUM OF SIX PARAMETERS,
C FOUR INDEPENDENT VARIABLES, AND 100 DATA POINTS
C   IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C   DIMENSION X(6),FVEC(100),FJAC(100,6),WA(130),IWA(6)
C   DIMENSION C(100,4),OBS(100),CALC(100),WEIGHT(100),COVMAT(6,6)
C   DIMENSION SD(4),SI(4)
C   COMMON/AA/ KOBS(100)
C   EXTERNAL FCN
C
C FOLLOWING STATEMENT IS FOR USE ON VAX COMPUTER
C   OPEN (UNIT=5,FILE='NLIN.DAT',STATUS='OLD')
C
C   MMAX=100

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      NMAX=6
      LWA=130
C
C INPUT NO. OF OBSERVATIONS, NO. OF PARAMETERS, NO. OF INDEP. VARIABLES
      READ (5,101) M,N,NIV
C INPUT CONVERGENCE TOLERANCE
      READ (5,102) TOL
C INPUT SCALING FACTORS FOR DEPENDENT VARIABLES
      READ (5,105)
      READ (5,103) (SD(J),J=1,NIV)
C INPUT SCALING FACTORS FOR INDEPENDENT VARIABLES
      READ (5,105)
      READ (5,103) (SI(J),J=1,NIV)
C INPUT INITIAL ESTIMATES FOR PARAMETERS
      READ (5,105)
      READ (5,103) (X(I),I=1,N)
C INPUT OBSERVED VALUES OF DEPENDENT AND INDEPENDENT VARIABLES
      READ (5,105)
      DO 5 I=1,M
        5 READ (5,104) KOBS(I),OBS(I),(C(I,J),J=1,NIV)
C
C ASSIGN EQUAL WEIGHTS TO THE DATA POINTS. NOTE THAT ONE COULD
C ALTERNATIVELY ASSIGN DIFFERING WEIGHT TO EACH DATA POINT IN
C WHICH CASE VECTOR OF WEIGHTS SHOULD BE MADE PART OF INPUT DATA.
      DO 10 I=1,M
        10 WEIGHT(I)=1.0
C
C SCALE OBSERVED DEPENDENT VALUES
      DO 11 I=1,M
        K=KOBS(I)
        11 OBS(I)=OBS(I)/SD(K)
C
C SCALE INDEPENDENT VARIABLES
      DO 12 J=1,NIV
        SCALE=SI(J)
        DO 12 I=1,M
          12 C(I,J)=C(I,J)/SCALE
C
C DETERMINE LEAST SQUARES POLYNOMIAL FIT TO DATA
      CALL LMDER1 (FCN,M,N,NIV,C,OBS,WEIGHT,X,FVEC,FJAC,
        > MMAX,NMAX,TOL,INFO,FNORM,COVMAT,IWA,WALWA)
C
C UNSCALE DEPENDENT VARIABLE VALUES AND RESIDUAL VALUES. AND
C DETERMINE VECTOR OF CALCULATED DEPENDENT VARIABLE VALUES
C USING THE LEAST SQUARES FIT
      DO 21 I=1,M
        K = KOBS(I)
        OBS(I) = OBS(I)*SD(K)
        FVEC(I) = FVEC(I)*SD(K)

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21 CALC(I) = OBS(I) + FVEC(I)
C
C UNSCALE INDEPENDENT VALUES
  DO 22 J=1,NIV
    SCALE = SI(J)
    DO 22 I=1,M
      22 C(I,J) = C(I,J)*SCALE
C
C UNSCALE PARAMETER VALUES
  DO 23 I=1,N
    23 X(I) = X(I)/SI(I)
C
C PRINT INFORMATION FLAG, SOLUTION VECTOR FOR PARAMETERS.
C VECTORS OF OBSERVATIONS, CALCULATED VALUES, AND RESIDUALS
  WRITE (6,200) INFO
  WRITE (6,202) (I,X(I),I=1,N)
  WRITE (6,203)
  DO 30 I=1,M
    30 WRITE (6,204) (I,OBS(I),CALC(I),FVEC(I),(C(I,J),J=1,NIV))
C WRITE OUT COVARIANCE MATRIX
  WRITE (6,205)
  DO 31 I=1,N
    31 WRITE (6,206) (COVMAT(I,J), J=1,N)
C
C COMPUTE REGRESSION COEFFICIENT (R2) FOR MODEL
C REFERENCE: N. R. DRAPER AND H. SMITH, APPLIED REGRESSION ANALYSIS.
C YOBSM = MEAN Y OF OBSERVED VALUES
C SUMOBS, SUMCAL = SQUARED DIFFERENCE BETWEEN YOBS-MEAN AND
YCALC-MEAN
C REG = REGRESSION COEFFICIENT (R2)
  SUM=0.0
  DO 32 J=1,M
    32 SUM=OBS(J)+SUM
    RM=M
    YOBSM=SUM/RM
C
  SUMOBS = 0.0
  SUMCAL = 0.0
  DO 33 I=1,M
    SUMOBS = SUMOBS + (OBS(I)-YOBSM)**2.
    33 SUMCAL = SUMCAL + (CALC(I)-YOBSM)**2.
    REG = SUMCAL/SUMOBS
C
C WRITE REGRESSION COEFFICIENT
  WRITE(6,207)REG
C
C WRITE ERROR SUMMED SQUARE FOR MODEL
C ERSS = ERROR SUMMED SQUARED FOR RESIDUALS
C

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```

    ERSS = 0.0
    DO 34 I=1,M
34 ERSS = FVEC(I)**2 + ERSS
C
    WRITE(6,208)ERSS
C
50 CONTINUE
C
    STOP
C
101 FORMAT(30X,I10)
102 FORMAT(30X,F10.0)
103 FORMAT(8F10.0)
104 FORMAT(I5,7F10.0)
105 FORMAT(1H0)
200 FORMAT(' INFO =',I5,/)
202 FORMAT(1X,'X('I1.') =',1PE15.5)
203 FORMAT('0COMPARISON OF OBSERVED AND CALCULATED VALUES',/,
> '0 I OBS. CALC. DIFF. INDEPENDENT VARIABLES ',/)
204 FORMAT(1X,I3,2F8.4,1PE15.5,0P4F8.4)
205 FORMAT(/,X, ' COVARIANCE MATRIX ',/)
206 FORMAT(1X,1P4E15.5)
207 FORMAT(/,X, ' REGRESSION COEFFICIENT (R2) = ', F10.4,/)
208 FORMAT(X, ' SUM ERROR SQUARED = ', F10.4,/)
    END
    SUBROUTINE FCN (M,N,NIV,C,X,FVEC,FJAC,MMAX,IFLAG)
    IMPLICIT DOUBLE PRECISION (A-H,O-Z)
    DIMENSION C(MMAX,NIV),X(N),FVEC(M),FJAC(MMAX,N)
    COMMON/AA/ KOBS(1)
C
    GO TO (10,20),IFLAG
C
C FUNCTION VALUES
10 DO 12 I=1,M
    K = KOBS(I)
C
    DENOM = 1.D0
    DO 11 J=1,NIV
11 DENOM = DENOM + X(J)*C(I,J)
C
12 FVEC(I)=X(K)*C(I,K)/DENOM
C
    RETURN
C
C JACOBIAN CALCULATION
20 DO 25 I=1,M
    K = KOBS(I)
C
    DENOM = 1.D0

```

```

      DO 21 J=1,NIV
21  DENOM = DENOM + X(J)*C(I,J)
C
      DO 22 L=1,NIV
      IF (L .EQ. K) THEN
        FJAC(I,K) = C(I,K)/DENOM*(1.D0-X(K)*C(I,K)/DENOM)
      ELSE
        FJAC(I,L) = -X(K)*C(I,K)*C(I,L)/(DENOM*DENOM)
      END IF
22  CONTINUE
C
25  CONTINUE
C
      RETURN
      END

```

IXNEW.FOR A FORTRAN COMPUTER PROGRAM
(Written for the STC-VAX Computer)

This program uses the Wallace Model "merry-go-round" technique to model a Continuous Countercurrent Ion eXchange (CCIX) system loading section. The CCIX loading section is modeled as four columns in series. The user must provide the Thomas model parameters (N , R , K_d , T). The throughput parameter, T , is the number of bed volumes processed through each column per loading cycle. ISY1-4 is the order sequence that each column in the series is advanced. ACT is the relative radioactivity loaded on the ion exchange resin per cycle.

```

C IXNEW.FOR
  DIMENSION X(2,4001,2),Y(2,4001,2),ISX(4),ISY(4),YP(4001)
  DIMENSION SX1D(50),SX2D(50),SX3D(50),SX4D(50),SXT1D(50),
&SXT2D(50),SXT3D(50),SXT4D(50),A1D(50),A2D(50),A3D(50),A4D(50),
&ACT1(50),ACT2(50),ACT3(50),ACT4(50)
  WRITE(*,99999)
99999 FORMAT(' INPUT NMAX IN I3 FORMAT',/ 123')
  READ (*,1) NMAX
  1 FORMAT (I3)
  IMAX=100
  IMAX=150
  WRITE(*,99998)
99998 FORMAT(' INPUT ISY1-4 IN 4I4 FORMAT, FOLLOWED BY ISX1-4',/
  2,' 1234123412341234')
  READ(*,30)ISY(1),ISY(2),ISY(3),ISY(4)
  READ(*,30)ISX(1),ISX(2),ISX(3),ISX(4)
  30 FORMAT(4I4)
  333 WRITE(*,99997)
99997 FORMAT(' ',/,' INPUT SN, R, CAD, BVM, AND ACT IN 5F10.3 FORMAT',
  2,' 12345678901234567890123456789012345678901234567890')
  READ(*,205,END=999)SN,R,CAD,BVM,ACT
  205 FORMAT(5F10.3)
  WRITE(*,335)
  335 FORMAT('1',/ )
  WRITE(*,70)SN
  WRITE(*,71)R
  WRITE(*,72)CAD
  WRITE(*,73)BVM
  WRITE(*,74)ACT
  70 FORMAT(30X,'N= ',F6.2,/ )
  71 FORMAT(30X,'R= ',F6.2,/ )
  72 FORMAT(30X,'KD= ',F6.1,/ )
  73 FORMAT(30X,'BED VOLUMES= ',F6.0,/ )
  74 FORMAT(30X,'INPUT ACTIVITY= ',F6.0,'CURIES',/ )
  WRITE(*,32)NMAX
  WRITE(*,33)ISY
  WRITE(*,34)ISX
  32 FORMAT(30X,'NUMBER OF CYCLES= ',I4,/ )
  33 FORMAT(30X,'Y SWITCH VECTOR',4I4,/ )
  34 FORMAT(30X,'X SWITCH VECTOR',4I4,/// )
  WRITE(*,38)
  WRITE(*,35)
  38 FORMAT(20X,'INSTANTANEOUS FRACTIONAL BREAKTHROUGH',/ )

  35 FORMAT(6X,'BED VOLUMES',5X,'COLUMN 1',6X,'COLUMN 2',6X,'COLUMN 3',
  16X,'COLUMN 4',/ )
  TM=BVM/CAD
  SNT=SN*TM

```

```

DEL1=SN/1000
DEL2=SNT/IMAX
M=0
N=0
SX1=0.0
SX2=0.0
SX3=0.0
SX4=0.0
SXT1=0.0
SXT2=0.0
SXT3=0.0
SXT4=0.0
DO 4 J=2,4001
4 X(1,J,1) = 0.0
  X(1,1,1)=1.0
  X(2,1,1) = 1.0
  DO 5 J=1,4001
5 Y(1,J,1)=0.0
  Y0=0
6 N=N+1
  WRITE(*,1080)
  WRITE(*,37)N
37 FORMAT(30X,'CYCLE NUMBER=',I3,/)
  IF ( N.GT.NMAX ) GO TO 100
  L=0
  MOUT=0
8 L=L+1
  MOUT=MOUT+1
  CNT=L*DEL2
  Y(2,1,1)=1.-(1.-Y0)*EXP(-CNT)
  M=M+1
  CRIT=1.0E-30
  DO 9 J = 1,4000
  G1=X(2,J,1)*(1.-Y(2,J,1))-R*Y(2,J,1)*(1.-X(2,J,1))
  H1=X(1,J+1,1)*(1.-Y(1,J+1,1))-R*Y(1,J+1,1)*(1.-X(1,J+1,1))
  X(2,J+1,2)=X(2,J,1)-G1*DELI
  IF(X(2,J+1,2).LT.CRIT) X(2,J+1,2)=0.0
  Y(2,J+1,2)=Y(1,J+1,1)+H1*DEL2
  G2=X(2,J+1,2)*(1.-Y(2,J+1,2))-R*Y(2,J+1,2)*(1.-X(2,J+1,2))
  X(2,J+1,1)=X(2,J,1)-(G1+G2)*DEL1/2.0
  IF(X(2,J+1,1).LT.CRIT) X(2,J+1,1)=0.0
  Y(2,J+1,1)=Y(1,J+1,1)+(H1+G2)*DEL2/2.0
9 CONTINUE
  DO 60 J=2,4001
  X(1,J,1)=X(2,J,1)
60 Y(1,J,1)=Y(2,J,1)
  SX1=SX1+X(1,1001,1)*DEL2
  SX2=SX2+X(1,2001,1)*DEL2
  SX3=SX3+X(1,3001,1)*DEL2

```

```

SX4= SX4+X(1,4001,1)*DEL2
SXT1= SXT1+X(1,1001,1)*DEL2
SXT2= SXT2+X(1,2001,1)*DEL2
SXT3= SXT3+X(1,3001,1)*DEL2
SXT4= SXT4+X(1,4001,1)*DEL2
IT=10
IF((MOUT/IT)*IT.NE.MOUT)GOTO 40
BV=L*BVM/IMAX
WRITE(*,36)BV,X(1,1001,1),X(1,2001,1),X(1,3001,1),X(1,4001,1)
40 CONTINUE
IF(L/IMAX*IMAX.NE.L) GOTO 8
36 FORMAT(6X,F10.1,5X,4(1PE10.3,4X))
A1=0
A2=0
A3=0
A4=0
DO 200 J=1,1000
A1=A1+(Y(2,J,1)+Y(2,J+1,1))*0.5*DEL1
A2=A2+(Y(2,J+1000,1)+Y(2,J+1001,1 ))*0.5*DEL1
A3=A3+ (Y(2,J+2000,1)+Y(2,2001,1))*DEL1*0.5
A4=A4+(Y(2,J+3000,1)+Y(2,3001,1))*0.5*DEL1
200 CONTINUE
IF(L.LT.IMAX) GOTO 8
SX1D(N)=SX1/SNT
SX2D(N)=SX2/SNT
SX3D(N)=SX3/SNT
SX4D(N)=SX4/SNT
SXT1D(N)=SXT1/SNT
SXT2D(N)=SXT2/SNT
SXT3D(N)=SXT3/SNT
SXT4D(N)=SXT4/SNT
A1D(N)=A1/SNT
A2D(N)=A2/SNT
A3D(N)=A3/SNT
A4D(N)=A4/SNT
ACT1(N)=A1D(N)*ACT
ACT2(N)=A2D(N)*ACT
ACT3(N)=A3D(N)*ACT
ACT4(N)=A4D(N)*ACT
DO 61 J=1,4001
61 YP(J)=Y(1,J,1)
CALL SWITCH(ISY,YP)
DO 62 J=1,4001
62 Y(1,J,1)=YP(J)
DO 63 J=1,4001
63 YP(J)=X(1,J,1)
CALL SWITCH(ISX,YP)
DO 64 J=1,4001
64 X(1,J,1)=YP(J)

```

```

Y0=Y(1,1,1)
X(1,1,1)=1.0
X(2,1,1)=1.0
SX1=0.0
SX2=0.0
SX3=0.0
SX4=0.0
GO TO 6
100 WRITE(*,101)
101 FORMAT(2X,'CALC COMPLETE')
WRITE(*,331)
331 FORMAT(2X,' * * * * *')
&* * * * *',//)
WRITE(*,1000)
1000 FORMAT(22X,'INTEGRAL XD(NT)/NT',/)
1010 FORMAT(12X,'CUMULATIVE FRACTIONAL BREAKTHROUGH',//)

WRITE(*,1010)
WRITE(*,1020)
1020 FORMAT(5X,'CYCLE COL 1 COL 2 COL 3 COL 4',/)
DO 1022 J=1,NMAX
WRITE(*,1030)J,SX1D(J),SX2D(J),SX3D(J),SX4D(J)
1022 CONTINUE
1030 FORMAT(4X,I3,3X,4(1PE12.3))
WRITE(*,1080)
WRITE(*,1040)
WRITE(*,1041)
WRITE(*,1020)
1040 FORMAT(22X,'INTEGRAL YD(N)/NT')
1041 FORMAT(22X,'FRACTIONAL LOADING',//)
DO 1052 J=1,NMAX
WRITE(*,1030)J,A1D(J),A2D(J),A3D(J),A4D(J)
1052 CONTINUE
WRITE(*,1080)
WRITE(*,1090)
1090 FORMAT(12X,'CURIE LOADING ON COLUMNS',//)
WRITE(*,1020)
DO 1062 J=1,NMAX
WRITE(*,1030)J,ACT1(J),ACT2(J),ACT3(J),ACT4(J)
1062 CONTINUE
1080 FORMAT(2X,////)
GOTO 333
999 CONTINUE
STOP
END
SUBROUTINE SWITCH(IS,Y)
DIMENSION IS(4),Y(4001),TEMP(4,1000)
DO 700 J=1,4
DO 699 K=1,1000

```

```
      I=1000*(J-1)+K
      TEMP(J,K)=Y(I)
699  CONTINUE
700  CONTINUE
      DO 710 J=1,4
      IF(IS(J).NE.0) GOTO 705
      DO 704 K=1,1000
      I=1000*(J-1)+K
      Y(I)=0.0
704  CONTINUE
      GOTO 710
705  CONTINUE
      DO 709 K=1,1000
      I=1000*(J-1)+K
      JJ=IS(J)
      Y(I)=TEMP(JJ,K)
709  CONTINUE
710  CONTINUE
      Y(4001)=Y(4000)
11  RETURN
      END
```

APPENDIX D
FORMULAS FOR ECONOMIC ANALYSIS

The following formulas were used to evaluate the cost comparisons for the alternative projects listed in this report.

$$S = P \frac{e^r - 1}{r}$$

where

S represents discrete lump-sum payments as future worth,
P represents present principal (or present worth),
r represents inflation rate percentage, and
n represents number of years money is invested.

Future value of capital investment costs were determined using the following formula:

$$FV = Pe^{rn}$$

where

FV represents future value costs,
P represents present worth,
r represents inflation rate percentage, and
n represents number of years money is invested.

VITA

Mr. Hall has six years of industrial experience at the Oak Ridge National Laboratory. He is currently working on alternative methods for minimization of secondary waste generated in treatment of low-level radioactively contaminated wastewaters prior to discharge into the environment. He has held positions primarily in the Radiochemical Processing Plant for recovery of multi-kilogram quantities of enriched uranium from highly radioactive solutions using industrial scale ion exchange, solvent extraction, and extraction chromatography techniques. Mr. Hall and his coworkers received the 1987 Outstanding Engineering Achievement Award from the Tennessee Society of Professional Engineers for the successful completion of the multimillion dollar Consolidated Edison Enriched Uranium Solidification Project.

Mr. Hall is a registered Engineer-in-Training in the State of Tennessee. He is a member of the American Institute of Chemical Engineers. He received a B.S. Degree in Chemical Engineering at the Tennessee Technological University in 1983 where he was a member of the Tau Beta Pi Scholastic Honor Engineering Society. Mr. Hall is also a 1978 scholastic graduate of the Lincoln County High School in Fayetteville, Tennessee.