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Evaluation of Alternative Flow Sheets for Upgrade of the Process Waste Treatment Plant

S. M. Robinson

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Chemical Technology Division

EVALUATION OF ALTERNATIVE FLOW SHEETS FOR UPGRADE OF THE PROCESS WASTE TREATMENT PLANT

S. M. Robinson

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SYMBOLS

C = concentration of solute in effluent, g-mol/cm^3.

C_o = concentration of solute in feed, g-mol/cm^3.

f = flow rate through column, cm^3/s.

K_a = mass-transfer coefficient, 1/s.

K_d = distribution coefficient, dimensionless.

K'_d = distribution coefficient, cm^3/g.

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_v = concentration of solute per unit volume of sorbent bed, g-mol/g.

R = separation factor, dimensionless.

T = throughput parameter, dimensionless.

V = effluent volume, cm^3.

v = sorbent bed volume, cm^3.

X = concentration of solute in fluid phase, dimensionless.

Y = concentration of solute in solid phase, dimensionless.

Greek Letters

ρ_b = bulk density of sorbent, g/cm^3.

EVALUATION OF ALTERNATIVE FLOW SHEETS FOR UPGRADE OF THE PROCESS WASTE TREATMENT PLANT

S. M. Robinson

ABSTRACT

Improved chemical precipitation and/or ion-exchange (IX) methods are being developed at the Oak Ridge National Laboratory (ORNL) in an effort to reduce waste generation at the Process Waste Treatment Plant (PWTP). A wide variety of screening tests were performed on potential precipitation techniques and IX materials on a laboratory scale. Two of the more promising flow sheets have been tested on pilot and full scales. The data were modeled to determine the operating conditions and waste generation at plant-scale and used to develop potential flow sheets for use at the PWTP. Each flow sheet was evaluated using future-value economic analyses and performance ratings (where numerical values were assigned to costs, process flexibility and simplicity, stage of development, waste reduction, environmental and occupational safety, post-processing requirements, and final waste form). The results of this study indicated that several potential flow sheets should be considered for further development, and more detailed cost estimates should be made before a final selection is made for upgrade of the PWTP.

1. INTRODUCTION

Beginning in 1985, a major effort was made to develop a decontamination process that would minimize the waste generated during the treatment of slightly contaminated process wastewaters at the PWTP. Previous experience[1] has shown that cesium is effectively removed from untreated wastewaters by IX processes. However, it was anticipated that strontium removal would not be effectively accomplished by a simple, one-step operation because Ca, Na, and Mg ions in the water compete with strontium for sites on the exchange resin. Therefore, extensive laboratory-scale studies[1] were conducted to determine the most effective IX processes using both fresh wastewater and water softened by chemical precipitation to remove the competing calcium and magnesium ions. The results from the experimental tests were used to develop five potential flow sheets for use at the PWTP. Each flow sheet has been evaluated using economic analyses and

performance ratings to determine the most effective processes to be considered for further development. This report summarizes the results of the experimental tests, modeling of the experimental data for full-scale applications, calculations of the waste generation, and flow sheet analyses.

1.1 BACKGROUND

From March 1976 to August 1981, ORNL process wastewater was treated by the scavenging precipitation ion-exchange (SPIX)[2] process. SPIX involves chemically softening the water by the scavenging precipitation process which adjusts the pH to 11.9 with sodium hydroxide (NaOH), followed by the addition of 5 ppm iron ferrous sulfate ($FeSO_4$) and a polymer to act as flocculating agents to precipitate calcium carbonate ($CaCO_3$) and magnesium hydroxide [$Mg(OH)_2$]. The radionuclide was removed from the supernate by Duolite CS-100 resin, a bifunctional phenolic-carboxylate resin that was regenerated with 0.5 *M* HNO_3 after processing ~2000 bed volumes (bv).[2] This process was abandoned because the weak-acid resin degraded easily, and sludge disposal became a problem.

From 1981 to 1986, ORNL treated process wastewaters that contained low levels of beta and gamma activity by IX at the PWTP. The ^{90}Sr and ^{137}Cs were loaded onto Nalcite HCR-S, a strong-acid cation resin, that had to be regenerated with 2.7 *M* HNO_3 after a throughput of ~400 bv. The low-level waste (LLW) produced by regeneration was concentrated by evaporation and treated for permanent in-situ disposal at the ORNL Hydrofracture Facility.[3] Although this treatment method generated a large volume of concentrated liquid waste, it was an easily operated process that accommodated fluctuations in the feed. The waste volume was easily handled by the hydrofracture facility until 1985 when new regulations disallowed the use of hydrofracture for radioactive waste disposal.

In 1985, a major effort was made to develop a decontamination process that would minimize the waste generated by the PWTP. An extensive laboratory- and pilot-scale study[1] was undertaken to develop alternative process flow sheets that would minimize waste generation while producing a nonhazardous solid waste form for safe storage with a

minimum of surveillance. This study was based on the data obtained from previous processing experience of slightly contaminated wastewater at ORNL and development of decontamination processes for high-activity-level water at Three Mile Island.[4] The results from this study have been described previously and, thus, are only summarized below.

2.0 EXPERIMENTAL TESTS[1]

Four types of precipitation processes (needed to remove calcium and magnesium ions compete with the radionuclides for adsorption sites on the sorbents) and 17 IX materials (including organic weak-acid and strong-acid cation resins and synthetic and natural zeolites) have been tested in laboratory-scale screening tests using actual wastewater. Initial scouting tests resulted in the selection of two water softening processes (listed in Table 1) to be tested in conjunction with IX materials in the proposed flow sheets based on softening ability, minimization of chemical additions, and properties of the resulting sludge. The caustic-soda-ash (CSA) process involves precipitating $CaCO_3$ and $Mg(OH)_2$ with sodium carbonate (Na_2CO_3), NaOH, and a polymer coagulant while the scavenging-precipitation (SP) process eliminates the Na_2CO_3 and adds ferrous sulfate ($FeSO_4$). Each softening process reduces the Ca ion concentration (the major ion that competes with the predominant radionuclides, ^{137}Cs and ^{90}Sr, for adsorption sites on IX materials) in the process wastewater from ~ 50 mg/L Ca to <10 mg/L. The SP process operates in the pH range of >11 where magnesium is also precipitated, and its concentration is reduced from 10 mg/L Mg to <5 mg/L. Lower hardness values should be obtained in continuously operated full-scale equipment.

The CSA process has the advantage of minimizing the sodium concentration in the softened water, while the other process has the advantage of accommodating fluctuations in the feed stream more easily. The SP process improves precipitation when inhibitors, such as detergents, are present, but the iron makes the sludge harder to dewater and produces more sludge. The iron can often be eliminated from the process to reduce sludge generation without affecting the degree of softening. Since the iron has no effect

Table 1. Water softening processes tested in the Process Waste Treatment Plant flow sheets

Parameters	Caustic-soda-ash process	Scavenging precipitation process
Chemical requirements		
Sodium carbonate	95	0
Sodium hydroxide	70	500
Iron	0	5
Betz 1100 polymer	0.6	0.3
Effluent characteristics[a]		
Total hardness[b]	49	10
Calcium hardness[b]	8	4
Sodium	80	290
Final pH	10.5	11.9
% solids in filter cake	60[c]	25
Total hardness[b]	498	10
Calcium hardness[b]	880	4
Sodium	80	290
Final pH	10.5	11.9
% solids in filter cake	60[c]	25[c] - 50[d]

[a]Based on bench-scale results.

[b]Measured in mg/L as calcium carbonate.

[c]No filter aid added to filter-press feed.

[d]15 g/L diatomaceous earth filter aid added to filter-press feed.

on IX processes, only the SP and caustic processes were used to pretreat the water for use in column tests. Economic analyses were made assuming that the iron could be eliminated to reduce the total waste generation.

Experimental, small-scale columns containing 6.5 to 20 mL of IX material were tested to determine distribution coefficients of 16 commercially available zeolites and organic cation-exchange resins (listed in Table 2) as a function of the Ca, Mg, and Na concentrations in the feed stream. Two pilot-scale tests were made to the PWTP prior to the flow sheet evaluations. In the first test, a series of two 3.7-m^3 (130-ft^3) columns and a 0.43-m^3 (15-ft^3) column were operated at full scale using IE-95 as the sorbent. A total of 6700 m^3 or 1810 bv (1,770,000 gal) were treated at a residence time of 13 min per column until strontium breakthrough occurred. In the second test, a train of 4 columns was tested using 0.57-m^3 (20-ft^3) equipment (0.1 plant scale) filled with PDZ-300 that has a 10-min residence time per column. These columns were operated using the merry-go-round technique; that is, removing the first column in the series when the effluent from the last column reached the ^{90}Sr limit, moving the remaining columns forward one position, and placing a new column in the last position. Data from these tests were used in flow sheet development rather than the laboratory-scale tests, when available.

Experimental breakthrough curves were obtained by plotting the mean throughput vs fractional breakthrough (i.e., effluent/feed concentration) based on the mean feed concentration for each run. The volume-based distribution coefficients (K_d) listed in Tables 3 and 4 were approximated as the throughput in bed volumes at the 50% breakthrough point. In many column tests, ^{137}Cs had not begun to break through at the time of shutdown. In these cases, K_ds are listed as greater than the total number of bed volumes which had passed through the column at a particular point.

Results from these tests indicated that most of the zeolites have high cesium distribution coefficients (up to 23,000) for unsoftened process water. However, the zeolites were found to have lower distribution coefficients of 2,000 to 6,500 for strontium when column residence times of 10 min were used. Several zeolites and resins are good sorbents (^{90}Sr distribution coefficients of 10,000 to 36,000) when the feed was pretreated by either of the softening processes.

The data for the CH zeolite tend to be questionable. Since the experimental data for softened water only went through 20% breakthrough, distribution coefficients were

Table 2. Sorption and ion-exchange materials tested in the Process Waste Treatment Plant flow sheets

Material	Supplier	Costs, $\$/m^3$	Description
Zeolon 400	Norton Chemicals	5300	clinoptilolite
Zeolon 500	Norton Chemicals	5300	natural chabazite-erionite mixture
Zeolon 700	Norton Chemicals	5300	ferriorite
Zeolon 900	Norton Chemicals	5300	synthetic mordenite
Linde 4A	Union Carbide	5300	inorganic zeolite
Linde A-51	Union Carbide	6000	inorganic zeolite
Ionsiv IE-95	Union Carbide	5800	synthetic chabazite
PDZ-140	Tenneco Specialty Minerals	530	natural Na^+-rich clinoptilolite
PDZ-300	Tenneco Specialty	530	natural chabazite
CH	Chem Nuclear	180	natural clinoptilolite
HCR-S	Dow Chemicals	2100	strong-acid resin
Amberlite IRC-84	Rohm & Haas	5800	weak-acid cation resin
Duolite CS-100	Diamond Shamrock	8100	weak-acid cation resin
Dowex C12	Dow Chemicals	----	strong-acid cation resin
Dowex XFS-43230	Dow Chemicals	----	radium-selective resin

Table 3. Experimentally determined ^{137}Cs distribution coefficients[a]

Ion-exchange material	^{137}Cs distribution coefficient		
	Unsoftened water[b]	Caustic-soda-ash softened water[c]	Scavenging-precipitation softened water
Zeolon 400	21,000	NT[d]	NT
Zeolon 500	>15,000[e]	NT	NT
Zeolon 700	> 8,500	NT	NT
Zeolon 900	>14,000	NT	NT
Ionsiv IE-95	>15,000	>18,000	13,000[f]
PDZ-300-AL	> 9,000	NT	NT
PDZ-300-D	> 4,000	NT	NT
PDZ-300-17	23,000	NT	NT
PDZ-140-D	> 8,000	19,000	14,000[g]
PDZ-150-D	NT	NT	NT
CH	> 2,000	15,000	10,500[g]
Linde 4A	NT	8,400	3,400[f]
Linde A-51	3,600	NT	NT
TG-650-C12	1,000	NT	NT
XFS-43230	470	NT	NT
HCR-S	NT	430	100[f]
IRC-84	NT	400	160[g]
CS-100	NT	500	3,600[f]

[a]Based on laboratory-scale data unless otherwise specified.

[b]Average cation concentrations of 50 ppm Ca, 12 ppm Mg, and 30 ppm Na and total hardness of 150 ppm as $CaCO_3$.

[c]Average cation concentrations of 5 ppm Ca, 3 ppm Mg, and 150 ppm Na and total hardness of 27 ppm as $CaCO_3$.

[d]Not tested.

[e]Greater than indicates no breakthrough at the maximum throughput measured in bed volumes of water processed at shutdown.

[f]Average cation concentrations of 5 ppm Ca, 1 ppm Mg, and 270 ppm Na and total hardness of 18 ppm as $CaCO_3$.

[g]Average cation concentrations of 1 ppm Ca, 0.05 ppm Mg, and 300 ppm Na and total hardness of 4 ppm as $CaCO_3$.

Table 4. Experimentally determined ^{85}Sr or ^{90}Sr distribution coefficients[a]

Ion-exchange material	Distribution coefficients		
	Unsoftened water[b]	Caustic-soda-ash softened water[c]	Scavenging-precipitation softened water
Zeolon 400	370	NT[d]	NT
Zeolon 500	2,000	NT	NT
Zeolon 700	320	NT	NT
Zeolon 900	300	NT	NT
Ionsiv IE-95	2,200	3,800	1,400[e]
Ionsiv IE-95[f]	1,700		
PDZ-300-AL	2,000	NT	NT
PDZ-300-D	3,000	NT	NT
PDZ-300-17	3,100	NT	NT
PDZ-300[f]	6,500		
PDZ-140-D	800	15,000	10,500[g]
PDZ-150-D	NT	NT	NT
CH[h]	350	13,000	30,000[g]
Linde 4A	NT	13,000	12,000[e]
Linde A-51	800	NT	NT
TG-650-C12	1,500	NT	NT
XFS-43230	540	NT	NT
HCR-S	NT	7,000	6,800[e]
IRC-84	NT	15,000	31,000[g]
CS-100	NT	500	3,800[e]

[a]Based on laboratory-scale data unless otherwise specified.

[b]Average cation concentrations of 50 ppm Ca, 12 ppm Mg, and 30 ppm Na and total hardness of 150 ppm as $CaCO_3$.

[c]Average cation concentrations of 5 ppm Ca, 3 ppm Mg, and 150 ppm Na and total hardness of 27 ppm as $CaCO_3$.

[d]Not tested.

[e]Average cation concentrations of 5 ppm Ca, 1 ppm Mg, and 270 ppm Na and total hardness of 18 ppm as $CaCO_3$.

[f]Based on pilot-scale data.

[g]Average cation concentrations of 1 ppm Ca, 0.05 ppm Mg, and 300 ppm Na and total hardness of 4 ppm as $CaCO_3$.

[h]The distribution coefficient for Sr using scavenging-precipitation softened water does not follow the trends in the literature or other experimental data. The value is therefore considered somewhat questionable.

determined by extrapolation. The resulting increase in Sr capacity for the CH zeolite with SP softened water over CSA processed water does not agree with literature values or experimental data for similar materials and is therefore highly suspect.[1] Amberlite IRC-84 resin is more sensitive to variations in hardness and bicarbonate alkalinity than most of the materials tested, and, therefore, it needs to be tested under actual plant conditions.

3.0 POTENTIAL FLOW SHEETS

The data obtained in the above scouting tests indicated that several materials have the potential to remove ^{90}Sr and/or ^{137}Cs. The alternative process flow sheets shown in Figs. 1-5 were proposed for potential development based on these results. The first four flow sheets utilize fixed-bed IX columns and are similar to the configuration of the present PWTP. The fifth flow sheet includes a continuous countercurrent ion-exchange (CCIX) column not previously used at ORNL. Each flow sheet was designed to completely replace the existing plant, but they all have the potential for being run in parallel with the existing system or for stepwise upgrading of the present facilities.

The simplest proposed flow sheet (Fig. 1) consists of a series of columns loaded with a chabazite zeolite, such as PDZ-300, that would be operated by the merry-go-round technique to remove both cesium and strontium. The zeolite would be disposed of as solid LLW. Although the chabazite has a much lower distribution coefficient for ^{90}Sr in untreated wastewater compared to other materials using softened water, this process has the advantage of being a simple decontamination method that would produce only one type of solid waste.

The flow sheet in Fig. 2 utilizes the materials with the maximum sorption capacities for cesium and strontium, respectively (assuming the ^{90}Sr distribution coefficient for CH zeolite using SP softened water is too high). It includes chabazite columns in series for cesium removal, followed by a caustic water softener for magnesium and calcium removal, and columns containing IRC-84 (a regenerable weak acid resin) for strontium removal. The loaded zeolites would be disposed of as solid LLW. Two treatment options were considered for the loaded resin: regeneration and direct LLW disposal. The columns

ORNL DWG 86-1032R

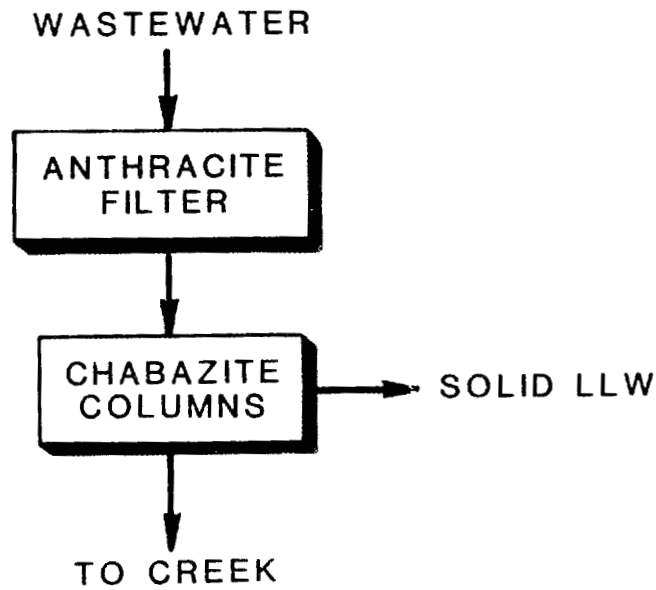


Fig. 1. Proposed chabazite flow sheet.

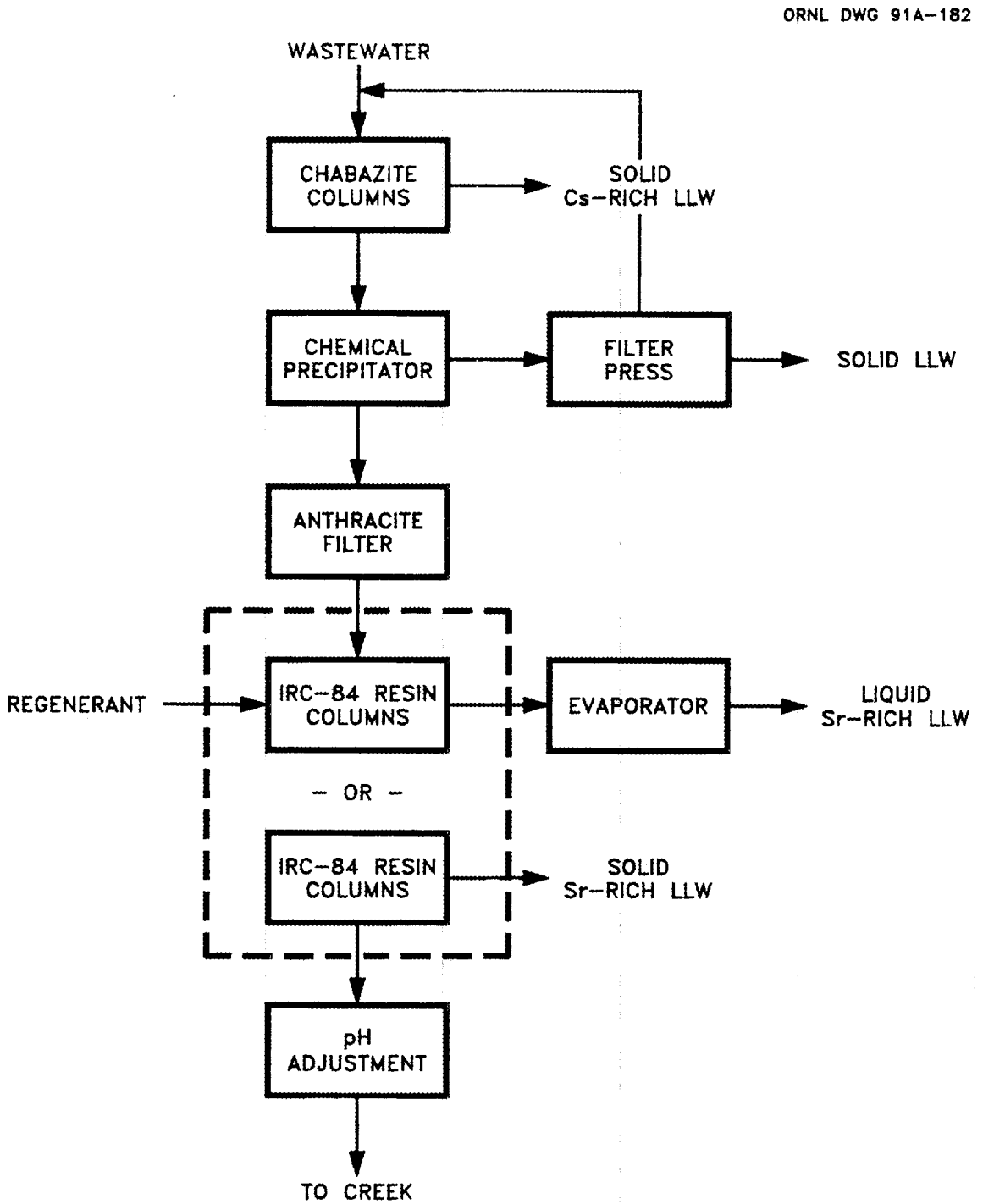


Fig. 2. Proposed IRC-84 weak-acid resin flow sheet.

ORNL DWG 86-1029R

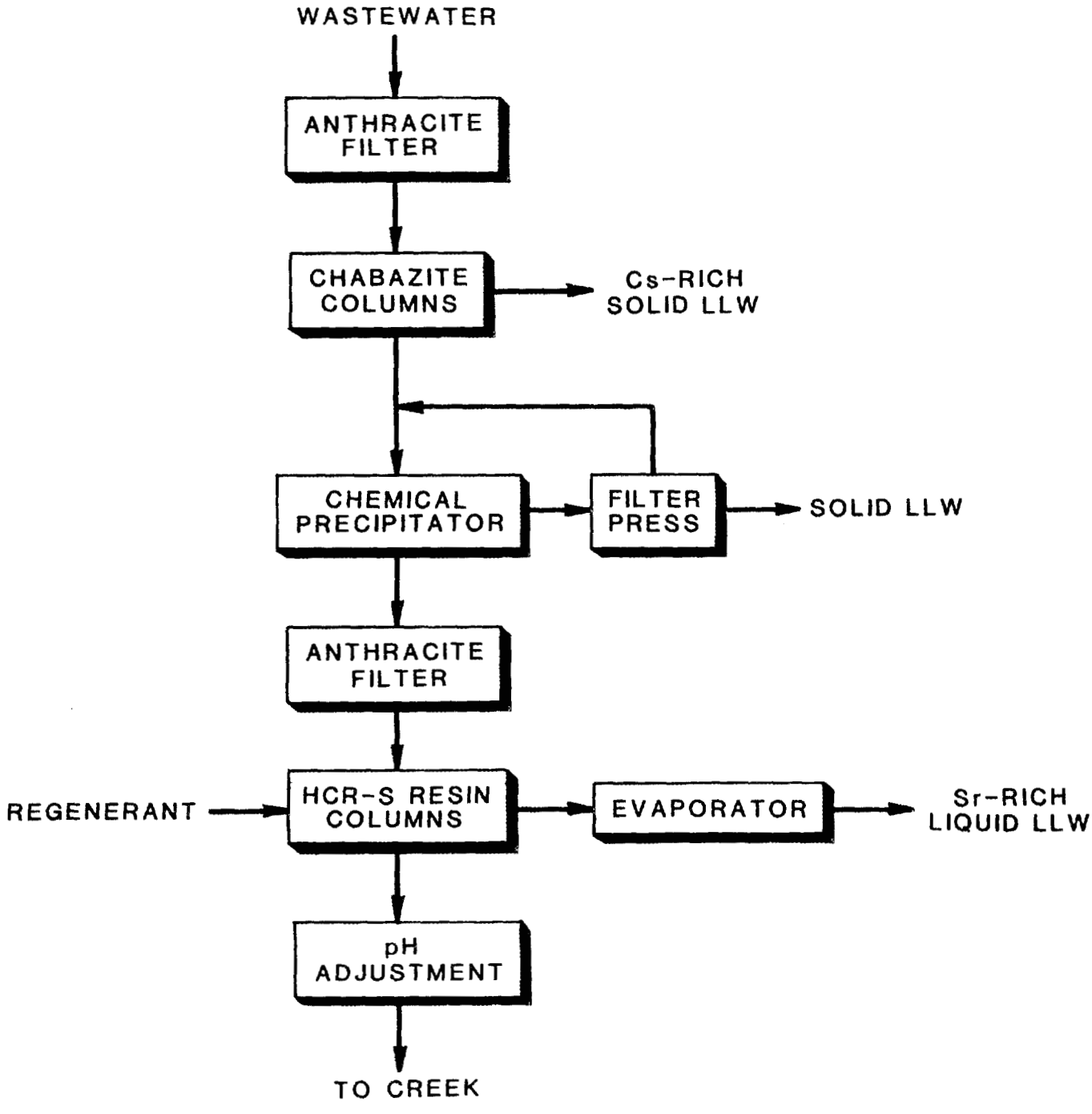


Fig. 3. Proposed HCR-S strong-acid resin flow sheet.

ORNL DWG 86-1031R

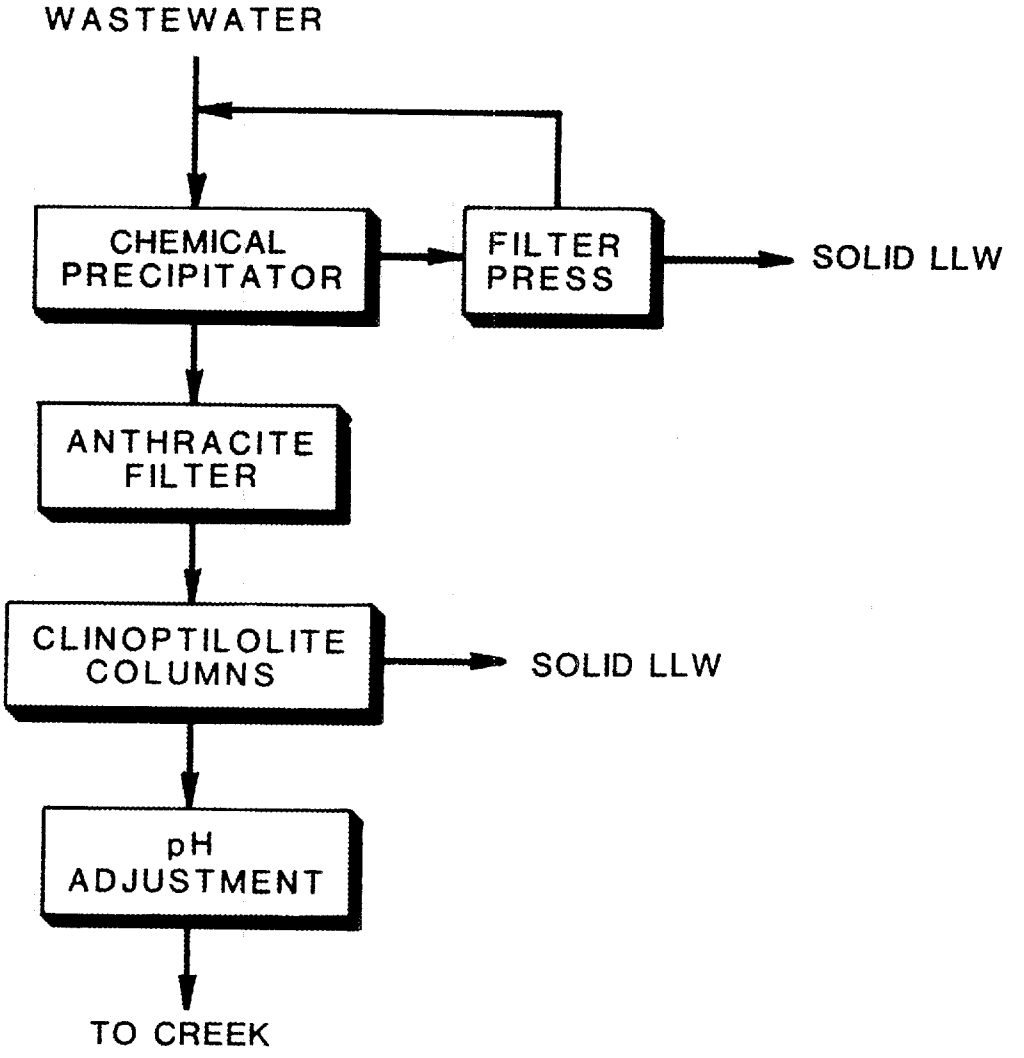


Fig. 4. Proposed clinoptilolite flow sheet.

ORNL-DWG 86-1228

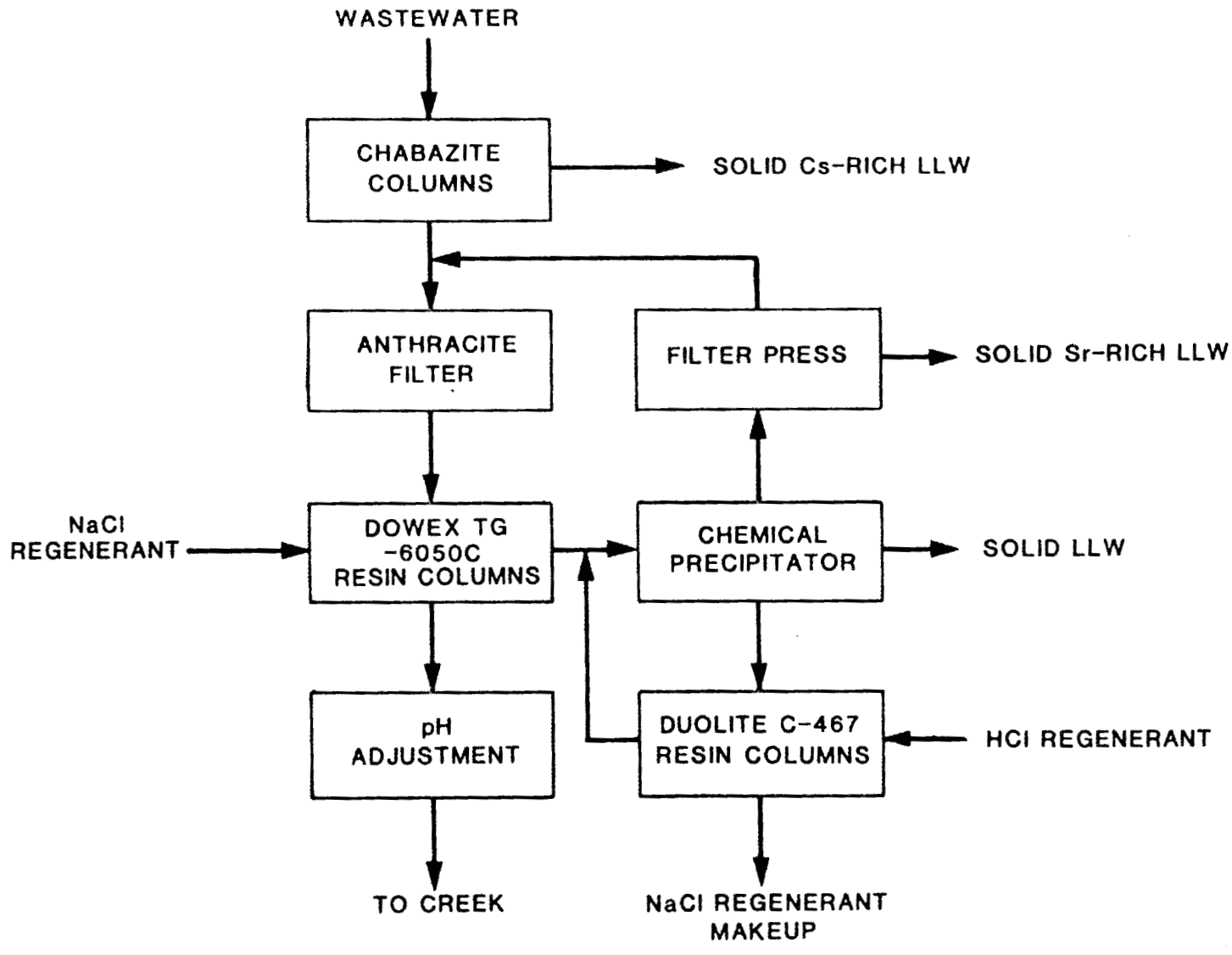


Fig. 5. Proposed continuous countercurrent ion-exchange flow sheet developed by CSA, Inc.

would be operated in the merry-go-round fashion when nonregenerated sorbents were used. Otherwise, columns similar to those in the existing plant could be utilized.

Since laboratory tests have indicated that the use of IRC-84 may result in operational problems typically associated with weak-acid resins (i.e., swelling, degassing, and degrading), a similar flow sheet (Fig. 3) was developed in which IRC-84 was replaced with HCR-S, a more forgiving strong acid resin with a lower strontium loading capacity. The PWTP is presently being operated using this regenerable flow sheet with the SP softening process. A chabazite column for ^{137}Cs removal was installed at the head end of the process in February 1987. Three levels of upgrade of the existing plant were considered in this evaluation as described in Sect. 5.

An alternative flow sheet (Fig. 4) proposes the PDZ-140, a clinoptilolite, be used to remove both Cs and Sr after Ca and Mg have been removed from the feed by chemical precipitation. Although the cesium and strontium distribution coefficients for PDZ-140 are lower than those of the materials selected for use in Fig. 2, the flow sheet eliminates the first set of sorption columns. The columns located after the precipitator would be operated using the merry-go-round technique. This flow sheet eliminates liquid low level wastes (LLLW) and only generates two solid wastes: sludge and zeolite.

The final flow sheet (Fig. 5) to be considered for the PWTP includes a fixed-bed zeolite column (with prefilter) for cesium removal and a CCIX column containing Dowes TG-650-C12, a strong-acid resin, for strontium removal.[5] Although the data from the small-scale fixed-bed column tests indicate that the resin does not have large enough strontium loading capacities from unsoftened water to warrant consideration for potential use in fixed-bed columns, the increased efficiency of the continuous column allows strontium removal without the use of a water softener. Since the resin has a higher sorption capacity for divalent ions than for monovalent ions, the calcium and strontium ions will replace the competing ions as the feed moves through the CCIX column. Therefore, the resin will be loaded to near capacity with calcium and strontium ions when it exits the loading section. The ions can then be stripped off the resin separately using different concentrations of NaCl regenerant solutions. The strontium can be precipitated by the traditional processes in higher concentrations than is possible using fixed-bed columns. The process produces three types of solid wastes: spent zeolite, resin, and sludge. This flow sheet is denoted as the CSA flow sheet in the remainder of this report.

4. MODELING OF FULL-SCALE FIXED-BED ION-EXCHANGE COLUMNS

The above flow sheets were modeled for a plant throughput of 150 gal/min (9.45 L/s), assuming the feed contains an average of 4000 Bq/L ^{90}Sr and 400 Bq/L ^{137}Cs. Maximum effluent concentrations were limited to 10 Bq/L for ^{90}Sr and 40 Bq/L for ^{137}Cs based on the respective 10 CFR 20 limits of 11.1 and 740 Bq/L for individual ions. In anticipation of changes in the limits to 37 for ^{90}Sr and 11 Bq/L for ^{137}Cs, the flow sheets were re-evaluated assuming the maximum effluent concentrations will be 32 and 15 Bq/L respectively. In both cases, the summation of the fractional releases were less than or equal to one.

The flow sheets were developed for a train of two to four 3.7-m^3 (130-ft^3) columns in series for the nonregenerable sorbents. This configuration was selected since it is presently being tested at the PWTP on a pilot scale at a flow rate of 6.30 L/s (100 gal/min). (Since the PWTP needs a maximum throughput of 9.45 L/s (150 gal/min), this single train of columns may need to be replaced with two parallel trains of smaller columns to eliminate high pressure drops.) Two 1.34-m^3 (47.5-ft^3) columns in parallel (as presently exist in the PWTP) were assumed for resins that would be regenerated. The mean residence time through each column would be 6.5 min for the 3.7-m^3 columns and 4.7 min for the 1.34-m^3 columns.

The experimental breakthrough data for fixed-bed IX columns were fitted by means of a model developed by Thomas[6] in order to predict the performance of these full-scale columns. According to the model (as derived in Appendix A), IX data can be fit by a mathematical J-function, using three basic parameters: the separation factor, R; the column length measured in number of transfer units, N; and a throughput parameter, T. If the data are linear when plotted on logarithmic-probability graphs, $T = 1$ and T is independent of R and N. The separation factor, R, is also equal to one when the concentration of the ion of interest is small relative to the concentration of the replaceable ions in the feed. Under these conditions, the distribution coefficient can be approximated as the throughput measured in bv at the 50% breakthrough point. The experimental data can be modeled to determine the value of N for the experimental system. These values can then be used to estimate performance at increased residence times and for columns in series.

The data from the most promising small-scale IX tests were plotted on logarithmic-probability graphs as shown in Appendix B. The values for R and T in the Thomas model were assumed to be 1, and values for N at the experimental conditions were determined for each set of data by iteration.[7] These values are shown in Table 5, and the model-predicted performances are compared to the experimental data on the plots in Appendix B. Most of the data is approximately linear, and the models fit the data well. The models for IRC-84 and CH using SP softened water and CH using CSA softened water are the most questionable since the experimental data only went through 10% percent breakthrough. These experiments should be rerun before final flow sheets are developed using these transfer units.

A linear relationship between column length and residence time was then used to predict the values of N for full-scale columns (summarized in Table 6). Breakthrough curves generated by these new N values were used to predict the frequency of column regeneration and subsequent calculations for nonregenerable columns.

In order to maximize resin usage, nonregenerable columns would need to be operated using the merry-go-round technique. Since partially loaded IX material would be used in this method of operation, additional calculations were needed to determine the replacement rate of the nonregenerable columns. This type of operation has been modeled using a numerical analysis solution of the Thomas equation by R. M. Wallace.[4]

Calculations using Wallace's model indicated that the minimum amount of IX waste would be generated if the merry-go-round were operated such that the steady-state effluent concentration from the last column in the series would equal the discharge limit of the limiting ion.

An example of one such set of calculations is shown in Table 7 for a series of four 0.57-m^3 columns containing PDZ-300 using model parameters of $K_d = 6500$, $R = 1.0$, and $N = 10$ for ^{90}Sr based on experimental data obtained in pilot tests at the PWTP. The instantaneous fractional breakthroughs were obtained assuming the first column was replaced after 600 bv. Table 7 indicates that an additional 2 to 4 columns would need to be replaced after six cycles in order to keep the effluent from the fourth column below the limiting fractional breakthrough of 0.0025 as determined in Sect. 2. If all four columns were replaced, the overall operation would produce nine columns of zeolite per six cycles.

Table 5. Calculated transfer units for experimental ion-exchange data[a]

Resin	Distribution coefficient		Residence	Transfer units (N)	
	^{90}Sr	^{137}Sr	Time, min	^{90}Sr	^{137}Sr
Fresh water					
IE-95[b]	1,700	NT[c]	13	9.5	NT
PDZ-300[d]	6,500	NT	10	10.5	NT
PDZ-300	3,100	23,000	3.3	NT	8.5
Scavenging-precipitation softened water					
IRC-84	31,000	160	1.4	9.5	NT
CH	36,000	10,500	1.4	3.8	6.0
PDZ-140	10,500	14,000	1.4	4.0	6.0
HCR-S	6,800	160	1.2	4.0	NT
CS-100	3,800	3,600	1.2	6.5	4.5
Caustic-soda-ash softened water					
CH	13,000	15,000	1.1	3.0	5.0
PDZ-140	15,000	19,000	1.0	2.5	4.0

[a]Based on laboratory-scale tests.

[b]Based on full-scale test at PWTP.

[c]Not tested.

[d]Based on 0.1 pilot-scale test at PWTP.

Table 6. Calculated transfer units for full-scale ion-exchange columns[a]

Resin	Distribution coefficient		Transfer units (N)			
			3.7 m^3[b]		1.3 m^3[c]	
	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
Fresh water						
IE-95[d]	1,700	NT[e]	4.8	NT	NT	NT
PDZ-300[f]	6,500	NT	6.5	NT	NT	NT
PDZ-300	3,100	23,000	NT	16.7	NT	NT
Scavenging-precipitation softened water						
IRC-84	31,000	160	44.0	NT	32.0	NT
CH	36,000	10,500	17.6	27.9	12.8	20.3
PDZ-140	10,500	14,000	18.6	28.7	13.5	20.3
HCR-S	6,800	160	21.7	NT	NT	NT
CS-100	3,800	3,600	35.2	24.4	NT	NT
Caustic-soda-ash softened water						
CH	13,000	15,000	17.7	29.5	12.9	21.5
PDZ-140	15,000	19,000	16.3	26.0	11.8	18.9

[a]Based on laboratory-scale tests.

[b]6.5 min mean residence time per column.

[c]4.7 min mean residence time per column.

[d]Based on full-scale test at PWTP.

[e]Not tested.

[f]Based on 0.1 pilot-scale test at PWTP.

Table 7. Calculated ^{90}Sr breakthrough for ten cycles of operation[a]

	Instantaneous fractional breakthrough[b]			
Cycle no.	Column 1	Column 2	Column 3	Column 4
1	4.7×10^{-1}	2.6×10^{-2}	3.6×10^{-4}	2.2×10^{6}
2	5.8×10^{-1}	6.4×10^{-2}	2.6×10^{-3}	5.43×10^{-5}
3	6.3×10^{-1}	1.0×10^{-1}	7.1×10^{-3}	2.63×10^{-4}
4	6.6×10^{-1}	1.3×10^{-1}	1.3×10^{-2}	7.6×10^{-4}
5	6.8×10^{-1}	1.6×10^{-1}	2.0×10^{-2}	1.5×10^{-2}
6	6.93×10^{-1}	1.8×10^{-1}	2.73×10^{-2}	2.5×10^{-3}
7	7.1×10^{-1}	2.0×10^{-1}	3.5×10^{-2}	3.6×10^{-3}
8	7.2×10^{-1}	2.1×10^{-1}	4.2×10^{-2}	4.8×10^{-3}
9	7.2×10^{-1}	2.1×10^{-1}	4.8×10^{-2}	6.0×10^{-3}
10	7.3×10^{-1}	2.4×10^{-1}	5.5×10^{-2}	7.2×10^{-3}

[a]Parameters used in the calculation were: $K_d = 5400$, $N = 10$, $R + 1.0$.

[b]Based on concentration of 4000 Bg/L ^{90}Sr in the feed water.

Similarly, seven columns of waste would be generated after the first six cycles if two columns were replaced. Two columns would have to be replaced after five to six cycles thereafter, since the first two columns would be partially loaded at the beginning of the new cycle.

A series of calculations were made to determine the point at which the first column should be replaced in order to minimize the total solid waste generated. The instantaneous fractional breakthroughs for ^{90}Sr were calculated assuming one column would be replaced at 4000 to 8000 bv under the above conditions. When the breakthrough limit was reached in the effluent from the fourth column, calculations were made assuming that (a) the first two columns and (b) all four columns would be replaced. The amount of zeolite waste generated under these operating conditions are shown in Fig. 6, assuming 6.3 L/s (100 gal/min) are processed.

The minimum volume generation occurred when the first column was changed every 5250 bv. Under these conditions, the effluent from the fourth column reached a steady-state value just below the limiting value, and additional column replacement was not needed. When the first column was replaced more frequently than 5250 bv, the limiting concentration was never reached, and the zeolites were under utilized. Similar calculations for other sorption materials resulted in the same conclusion.

The placement frequency of the first column in the series required to maintain the maximum effluent concentration equal to the limiting ^{90}Sr concentration was determined by iterative calculations for each flow sheet. The resulting frequencies and steady-state fractional breakthroughs are listed in Table 8 for all nonregenerable materials considered in the flow sheets. Results for both the present and anticipated release limits are included.

5. WASTE GENERATION CALCULATIONS

The volume of three types of waste were calculated for use in the flow sheet comparisons: solid sorbents loaded with ^{90}Sr and ^{137}Cs, LLLW produced by regeneration of sorbent materials, and dewatered sludge generated in the water softening processes. The total volumes generated for many different variations of each flow sheet are given in

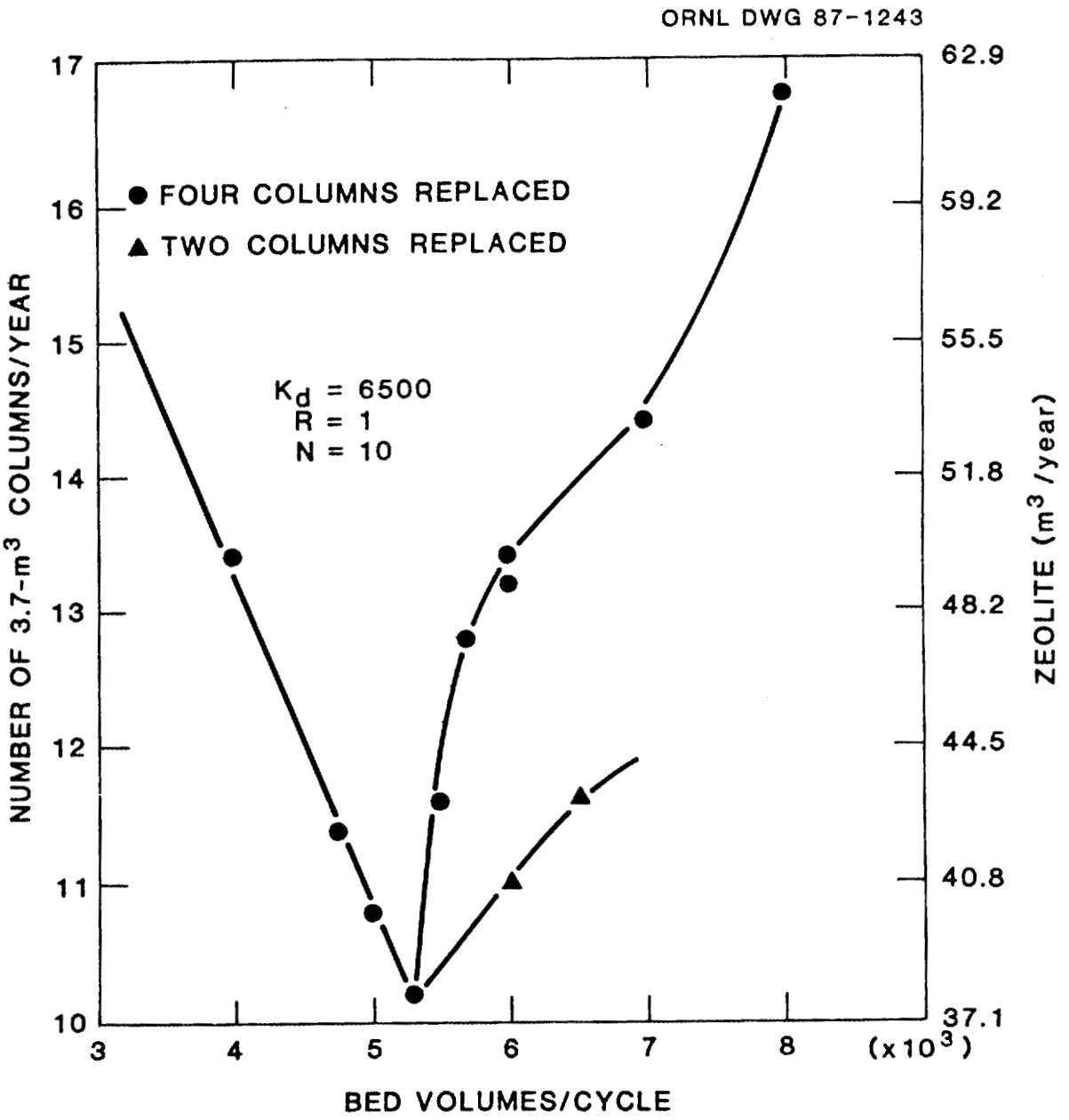


Fig. 6. Effect of cycle rate on volume of waste generated from four PDZ-300 chabazite columns run in series.

Table 8. Calculated instantaneous breakthroughs for ion-exchange columns operated in series

Sorbent	Softening process[a]	Ion	Column configuration	Column changeout rate, bv	Limiting ion for dual adsorption[b]	Instantaneous fractional breakthrough			
						Column 1	Column 2	Column 3	Column 4
1986 Release limits									
PDZ-300	None	^{90}Sr	Four 3.7-m^3	4,850.00		5.40×10^{-1}	1.20×10^{-1}	2.10×10^{-2}	2.60×10^{-3}
PDZ-300	None	^{137}Cs	Four 3.7-m^3	23,800.00		9.50×10^{-1}	6.70×10^{-1}	3.60×10^{-1}	8.60×10^{-2}
IE-95	None	^{90}Sr	Four 3.7-m^3	1,100.00		4.50×10^{-1}	1.00×10^{-1}	1.90×10^{-2}	2.40×10^{-3}
PDZ-140	Scav. Prec.	^{90}Sr	Two 1.34-m^3	6,750.00		2.10×10^{-1}	2.50×10^{-3}		
PDZ-140	Scav. Prec.	^{137}Cs	Two 1.34-m^3	6,750.00	^{90}Sr	3.00×10^{-1}	2.50×10^{-3}		
PDZ-140	Scav. Prec.	^{90}Sr	Four 3.7-m^3	9,800.00		7.30×10^{-1}	1.70×10^{-1}	3.00×10^{-2}	2.40×10^{-3}
PDZ-140	Scav. Prec.	^{137}Cs	Four 3.7-m^3	9,800.00	^{90}Sr	1.40×10^{-1}	4.50×10^{-6}	7.20×10^{-9}	1.00×10^{-12}
PDZ-140	Caus. Soda	^{90}Sr	Two 1.34-m^3	9,000.00		1.90×10^{-1}	2.50×10^{-3}		
CH	Scav. Prec.	^{137}Cs	Two 1.34-m^3	10,100.00		7.60×10^{-1}	1.00×10^{-1}		
CH	Scav. Prec.	^{90}Sr	Two 1.34-m^3	10,100.00	^{137}Cs	1.20×10^{-2}	6.10×10^{-6}		
CH	Scav. Prec.	^{90}Sr	Four 3.7-m^3	33,200.00		7.30×10^{-1}	1.80×10^{-1}	3.20×10^{-2}	2.50×10^{-3}
CH	Scav. Prec.	^{137}Cs	Four 3.7-m^3	11,000.00		9.70×10^{-1}	7.00×10^{-1}	3.60×10^{-1}	7.20×10^{-2}
CH	Scav. Prec.	^{90}Sr	Four 3.7-m^3	11,000.00	^{137}Cs	5.30×10^{-3}	2.30×10^{-7}	2.10×10^{-12}	9.80×10^{-18}
CH	Caus. Soda	^{90}Sr	Two 1.34-m^3	8,200.00		2.10×10^{-1}	2.50×10^{-3}		
CH	Caus. Soda	^{137}Cs	Two 1.34-m^3	8,200.00	^{90}Sr	5.40×10^{-2}	9.88×10^{-6}		
CH	Caus. Soda	^{137}Cs	Four 3.7-m^3	15,900.00		9.80×10^{-1}	7.50×10^{-1}	4.20×10^{-1}	1.00×10^{-1}
CH	Caus. Soda	^{90}Sr	Four 3.7-m^3	11,750.00		7.10×10^{-1}	1.70×10^{-1}	3.00×10^{-2}	2.50×10^{-3}
CH	Caus. Soda	^{137}Cs	Four 3.7-m^3	11,750.00	^{90}Sr	2.60×10^{-1}	6.00×10^{-4}	8.80×10^{-3}	9.40×10^{-10}
PDZ-140	Caus. Soda	^{90}Sr	Four 3.7-m^3	13,750.00		7.00×10^{-1}	1.60×10^{-1}	2.80×10^{-2}	2.30×10^{-3}
PDZ-140	Caus. Soda	^{137}Cs	Four 3.7-m^3	13,750.00	^{90}Sr	1.90×10^{-1}	2.30×10^{-4}	1.60×10^{-7}	8.90×10^{-11}
IRC-84	Caustic	^{90}Sr	Two 1.34-m^3	26,300.00		3.90×10^{-1}	2.30×10^{-3}		
IRC-84	Caustic	^{90}Sr	One 1.34-m^3	12,500.00		2.50×10^{-3}			
IRC-84	Caustic	^{90}Sr	Four 3.7-m^3	30,000.00		8.00×10^{-1}	1.70×10^{-1}	2.80×10^{-2}	2.00×10^{-3}
Proposed release limits									
PDZ-300[c]	None	^{90}Sr	Four 3.7-m^3	5,250.00		6.20×10^{-1}	2.00×10^{-1}	4.90×10^{-2}	7.70×10^{-3}
PDZ-300[c]	None	^{137}Cs	Two 3.7-m^3	20,000.00		5.60×10^{-1}	3.60×10^{-2}		
PDZ-300	None	^{137}Cs	Four 3.7-m^3	22,800.00		8.90×10^{-1}	4.90×10^{-1}	2.10×10^{-1}	3.60×10^{-2}
PDZ-140[c]	Caus. Soda	^{90}Sr	Four 3.7-m^3	14,000.00		7.60×10^{-1}	2.30×10^{-1}	5.60×10^{-2}	6.20×10^{-3}
PDC-140[c]	Caus. Soda	^{137}Cs	Four 3.7-m^3	14,000.00	^{90}Sr	2.10×10^{-1}	3.40×10^{-5}	3.30×10^{-7}	2.65×10^{-10}
IRC-84	Caustic	^{90}Sr	Two 1.34-m^3	27,500.00		5.10×10^{-1}	8.10×10^{-3}		
IRC-84	Caustic	^{90}Sr	One 1.34-m^3	15,500.00		8.00×10^{-3}			
IRC-84	Caustic	^{90}Sr	Four 3.7-m^3	30,600.00		8.90×10^{-1}	3.40×10^{-1}	9.80×10^{-2}	8.30×10^{-3}
IRC-84[c]	Caustic	^{90}Sr	Two 3.7-m^3	28,500.00		5.60×10^{-1}	7.30×10^{-3}		

[a]Caus. Soda is the caustic-soda-ash process. Scav. Prec. is the scavenging precipitation process. Caustic is the scavenging precipitation process without iron. The latter two processes should produce the same breakthrough data.

[b]Column change out frequencies were based on the discharge limits for the individual ion being removed. When one material was used to remove both radionuclides, the change out frequency was based on the limiting ion noted in this column.

[c]Used in economic evaluations.

Appendix C. The variables for each flow sheet included size and number of IX columns, precipitation process, and zeolite material. Two chabazites (IE-95 and PDZ-300) and two clintoptilolites (PDZ-140 and CH) were used in these evaluations. The results indicated that the PDZ-300 and PDZ-140 will result in less waste generation. Therefore, IE-95 and CH were eliminated from further consideration. The variations for each flow sheet that warranted further consideration (based on waste generation) are listed in Table 9.

The volumes for the CCIX column/precipitator in the CSA flow sheet were estimated by the manufacturer.[5] The values for the remaining flow sheets were based on experimental data as summarized below. The actual volumes generated by the original SPIX process (assuming dewatered sludge) are included for comparison.

The volume of nonregenerable IX materials was determined using the data from Table 8 based on a throughput of 30,000 m^3/year (150 gal/min). The amounts of sludge generated by the softening processes were calculated from PWTP data. The values for the SP and caustic processes were based on the actual waste volumes processed from February to August 1986 (measured in numbers of 55-gal drums generated per volume of wastewater treated).

The clarifier operated in a steady-state mode from July 28 to August 7, 1986, using the SP process. During this time, 0.0785 m^3 (450 gal) sludge was generated per 355 m^3 (1,599,000 gal) wastewater processed. Based on these values, 50 m^3 (22,525 gal) of sludge would be generated per year by the scavenging precipitation process.

During the period between April 25 and July 27, iron was only added to the softening process when the total hardness in the effluent exceeded 10 ppm as calcium carbonate (approximately one-fourth to one-half of the time). Sludge produced during this period was thick and accumulated in the bottom of the clarifier. The unit was shut down, the sludge removed and dewatered, and the system restarted using the SP process. The total amount of dewatered sludge produced during this period (sludge continuously processed plus that removed during shutdown) was 5 m^3 (2,250 gal) for 29,350 m^3 (13,209,000 gal) of water were treated. Based on these values, 30 m^3 (13,400 gal) of sludge would be generated per year. These values were used as conservative estimates of the volumes that would be generated by the CSA processes. The actual volumes would have been lower if no iron had been present.

Table 9. Waste generated by proposed flow sheets

Flow sheet name	Flow sheet figure no.	Presoftening columns: Sorbent	Presoftening columns: Column configuration	Presoftening columns: Regenerated	Clarifier type[a]	Presoftening columns: Sorbent	Presoftening columns: Column configuration	Presoftening columns: Regenerated	Waste generation rate, m^3/year: Presoftening sorbent	Sludge	Presoftening sorbent	Evaporator product	Total solids	Total waste
Present release limits														
Chabazite	C1	PDZ-300	Four 3.7-m^3	No	None				62.0	0	0	0	62.0	62.0
IRC-84	C3	PDZ-300	Four 3.7-m^3	No	Caustic	IRC-84	2 sets 2 1.34-m^3	Yes	12.6	51.0	1.4	12.5	65.0	77.5
IRC-84	C7	PDZ-300	Four 3.7-m^3	No	Caustic	IRC-84	Four 3.7-m^3	No	12.6	51.0	9.9	0	73.5	73.5
HCR-S	C9	PDZ-300	Four 3.7-m^3	No	Caustic	HCR-S	2 sets 2 1.34-m^3	Yes	12.6	51.0	2.7	21.0	66.3	87.2
HCR-S	C10	PDZ-300	Four 3.7-m^3	No	Scav. Prec.	HCR-S	2 sets 2 1.34-m^3	Yes	12.6	85.0	2.7	21.0	100.2	121.2
Clino	C11	—	—	—	Caus. Soda	PDZ-140	Four 3.7-m^3	No	0	51.0	21.8	0	72.8	72.8
CSA	C23	PDZ-300	Four 3.7-m^3	No	Caus. Soda	TG-650c	One continuous	Yes	12.6	0.5	0.5	0	13.6	13.6
SPIX	C24	—	—	—	Scav. Prec.	CS-100	2 sets 2 1.34-m^3	Yes	0	85.0	9.6	17.0	94.6	111.6
Proposed release limits														
Chabazite[b]	C25	PDZ-300	Four 3.7-m^3	No	None				57.2	0	0	0	57.2	57.2
IRC-84	C26	PDZ-300	Four 3.7-m^3	No	Caustic	IRC-84	2 sets 2 1.34-m^3	Yes	13.3	51.0	1.4	10.2	65.7	75.9
IRC-84[b]	C27	PDZ-300	Two 3.7-m^3	No	Caustic	IRC-84	2 sets 2 1.34-m^3	Yes	15.0	51.0	1.4	10.2	67.4	77.6
IRC-84	C28	PDZ-300	Two 3.7-m^3	No	Caustic	IRC-84	Four sets 3.7-m^3	No	15.0	51.0	9.8	0	75.7	75.7
IRC-84[b]	C29	PDC-300	Two 3.7-m^3	No	Caustic	IRC-84	Two 3.7-m^3	No	15.0	51.0	10.5	0	76.5	76.5
HCR-S[b]	C30	PDZ-300	Two 3.7-m^3	No	Scav. Prec[c]	HCR-S	2 sets 2 1.34-m^3[d]	Yes	15.0	85.0	2.7	38.8	102.6	141.4
HCR-S[b]	C31	PDZ-300	Two 3.7-m^3	No	Caustic	HCR-S	2 sets 2 1.34-m^3[d]	Yes	15.0	51.0	2.7	21.0	68.7	89.6
HCR-S[b]	C32	PDZ-300	Two 3.7-m^3	No	Caustic	HCR-S	2 sets 2 1.34-m^3	Yes	15.0	51.0	2.7	5.2	68.7	73.9
Clino[b]	C33	—	—	—	Caus. Soda	PDZ-140	Four 3.7-m^3	No	0	51.0	21.5	0	72.5	72.5
Clino	C34	—	—	—	Caus. Soda	PDZ-140	Two 3.7-m^3	No	0	51.0	26.2	0	77.2	77.2
CSA[b]	C35	PDZ-300	Two 3.7-m^3	No	Caus. Soda	TG-650c	One continuous	Yes	15.0	0.5	0.5	0	16.0	16.0

[a]Scav. prec. is the scavenging precipitation softening process, caustic is scav. prec. without iron, and caus. soda is the caustic-soda-ash process.

[b]Not tested.

[c]Used in economic study.

[d]Assuming present clarifier is not replaced. All other flow sheets assume new clarifier.

[e]Assuming present columns are not replaced. All other flow sheets assume new equipment.

The volume of LLW produced by resin regeneration was calculated using previous data from the PWTP for the HCR-S and CS-100 resins. The present regeneration process for HCR-S resin, shown in Table 10, indicates that each regeneration produces 0.6 m^3 (290 gal) rinse solution, which is returned to the PWTP feed via the sump, and 2.7 m^3 (1200 gal) contaminated regenerant solution, which is concentrated to 7% of its original volume by evaporation and is sent to the LLLW storage tanks for disposal. Since the reactor/clarifier has lowered the total hardness to 10 ppm, the resin columns have been operating an average of 2440 m^3 (1,100,000 gal) before they become loaded. Based on this throughput, the columns would be regenerated a total of 72 times per year and would generate 12.2 m^3 (5500 gal) of LLLW per year. The resin in the columns are presently replaced approximately once every two years. This would generate an additional 2.7 m^3 (95 ft^3) of solid waste per year.

Past data[8] indicates that the regeneration of CS-100 resin produces 5 bv (1700 gal) of waste which can be reduced by 98% to 0.11 bv by evaporation, but the frequency of regeneration varied considerably because the resin degraded with use. The resin degraded very rapidly[9] from the initial capacity of 2000 bv per regeneration to <500 bv after 30 cycles, and the resin capacity was "significantly reduced" after 20 cycles. The PWTP data indicates that an average of 16 gal/d of concentrated unneutralized waste was generated when the plant was run at 12.6 L/s (200 gal/min), which indicates an average column cycle of 1490 bv.

To estimate the waste produced by regeneration of CS-100, a linear relationship between the above throughput and waste generation was assumed. This leads to the conclusion that a 9.45 L/s (150 gal/min) plant would produce 17 m^3/year (600 ft^3/year). Assuming the resin will be replaced after 20 1500-bv cycles, 9.6 m^3 (340 ft^3) of solid waste will be generated per year.

Similar values were determined for IRC-84 based on generation resin specifications.[10] The predicted capacity of the IRC-84 resin is 4 meq/mL (0.25 lb mol/ft^3) of sodium. The recommended regeneration procedure for the resin is to treat it with 110% of the stoichiometric amount of 4% (0.65 *N*) acid, which is equal 4450 mol HNO_3 m^3 resin or 6.7 bv 4% HNO_3 per column. Assuming the acid waste can be concentrated to 7% of its original volume (based on HCR-S performance), 0.52 bv

Table 10. Regeneration procedure for HCR-S at the Process Waste Treatment Plant

Step	Feed	Receiver	Volume		
			bv	m^3	gal
Backwash	Fresh Water	Sump	2.0	1.5	680
Water displacement	Recycle Acid	Sump	0.8	0.6	290
Regeneration	Recycle Acid	Evaporator	2.4	1.8	800
Regeneration	Fresh Acid	Evaporator	1.2	0.9	400
Regeneration	Fresh Acid	Recycle Tank	2.4	1.8	800
Rinse	Fresh Water	Recycle Tank	1.2	0.9	400
Rinse	Fresh Water	Sump	2.4	1.8	800

concentrated waste will be generated per column regeneration. It should be noted that laboratory tests indicate that the waste can be concentrated to 2 or 3 times because the regenerant from a column loaded with calcium can be treated more easily than one loaded with sodium.

The frequency of regeneration was determined from the breakthrough curve for IRC-84 (Fig. 7) using the test conditions listed in Table 6 (K_d = 31,000, R = 1, and N = 32) for two existing columns run in parallel. According to Fig. 7, the columns will have to be regenerated after each 12,500 bv, yielding 17.8 regenerations per year. This would produce 12.5 m^3 (440 ft^3) of LLLW per year. Assuming the resin will be replaced at the same rate as the CS-100 resin (each 20 regenerations), replacement will be required once per year and will generate 1.4 m^3 (50 ft^3) solid wastes per year.

The above estimates of waste generation, except for the HCR-S resin, are based on experimental data that were obtained using small-scale equipment that had better operating capabilities than the existing equipment at the PWTP. The amount of waste generated at the PWTP by the HCR-S flow sheet has rarely reached the theoretical

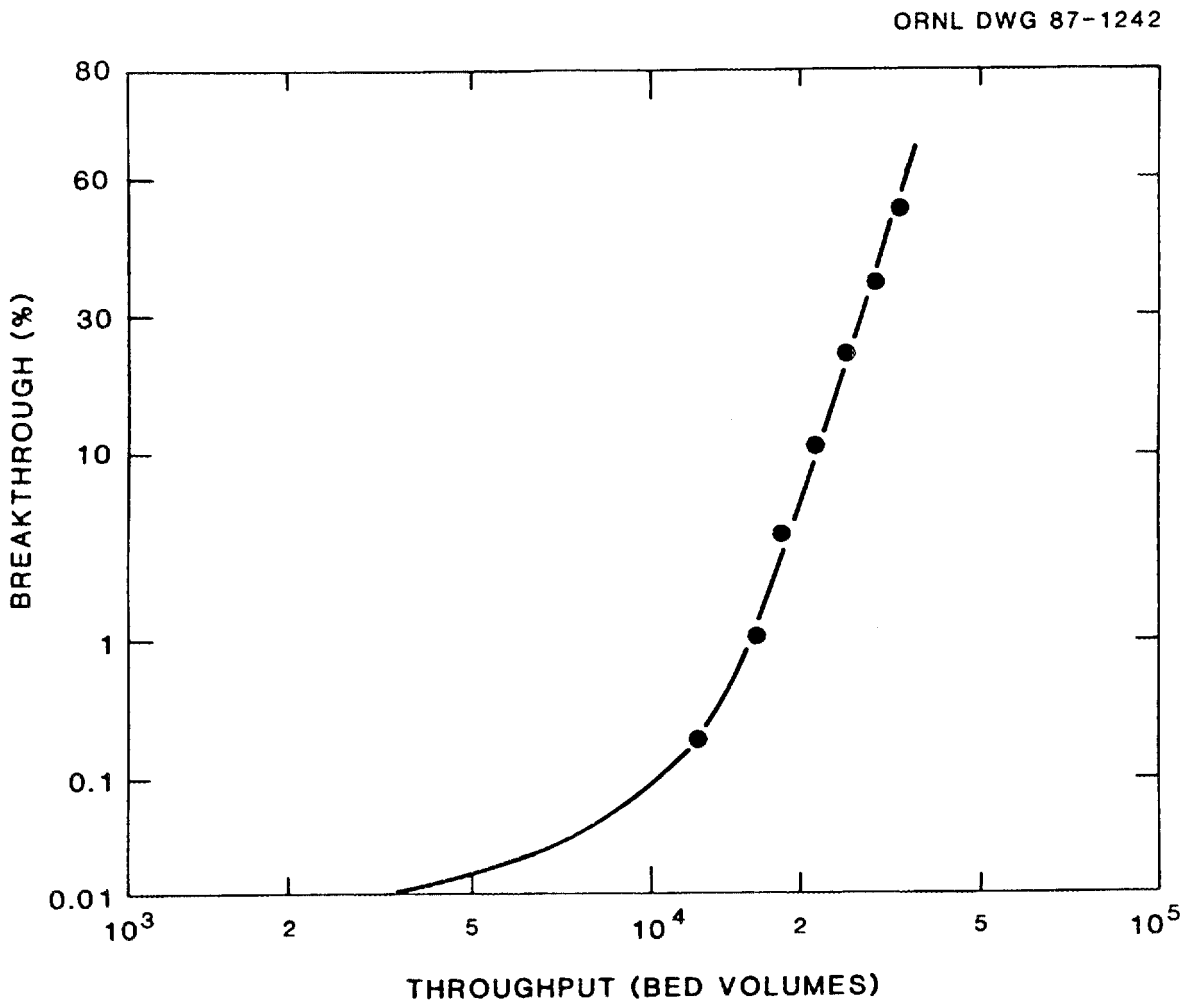


Fig. 7. Predicted breakthrough curve for IRC-84 at full-scale conditions.

minimum because of plugging of columns, mixing of resin during backwashing, etc. Since the remaining flow sheets use sorption materials with considerably longer lives than the HRC-S resin, new equipment and operating procedures will be required to significantly reduce waste generation. The existing clarifier can only be used for the SP process, but a different precipitator could accommodate either of the precipitation processes described in Table 1. New IX equipment with superior backwashing capabilities and possibly better prefilters will be required to remove solids without excessive mixing and reduction of column life.

In order to determine if these equipment upgrades would be economically effective, waste generation rates as a function of equipment are needed. Since relatively large amounts of full-scale data are available for the HCR-S flow sheet, it was evaluated as a function of equipment upgrade. The frequency of column regeneration was assumed to be a function of the equipment. For the minimum upgrade case (addition of chabazite columns for ^{137}Cs removal), the life of the HCR-S resin was assumed to be 2,600 m^3 (700,000 gal) based on the average performance of the PWTP from August through December of 1986. The generation rates of SP sludge and zeolites are described above. If a new precipitator were included in the flow sheet, the HCR-S column life was assumed to be 4,200 m^3 (1,100,000 gal). This was the average life of the HCR-S columns when the clarifier was operated using the SP process during the March to August 1986 time frame. The calculated sludge generation rate was lowered since the iron could presumably be eliminated if the new precipitator could accommodate a dense sludge. When new IX columns were included, the HCR-S column life was estimated to be 15,100 m^3 (4,000,000 gal), the maximum value obtained at the PWTP to date which is near the theoretical capacity of the resin. Since the existing filter press has performed relatively well using both the caustic and SP processes, it was not replaced in the flow sheet analyses.

It should be noted that the flow sheet which reduces the waste generation most significantly is the CSA flow sheet. The waste volumes quoted by the manufacturer are based on very limited data and are assumed to be optimistic. This type of system has never been used at ORNL and would need to be tested on a pilot scale before it is considered further.

The chabazite flow sheet generates the lowest amount of total waste of the fixed-bed-column flow sheets, even though the chabazites have relatively low distribution coefficient for ^{90}Sr. The sludge generated in the other flow sheets is 1-2 orders of magnitude greater than the sorption material and offsets gains made by increased resin efficiency. This fact also indicates that errors due to estimation of resin performance should have little bearing on the overall outcome of flow sheet analyses.

The results from the flow sheet development indicate that the CSA flow sheet has the highest potential for volume reduction. The chabazite and clinoptilolite flow sheets are significant improvements over the previously used processes, and the two resin flow sheets produce approximately the same amount of waste. Slightly less total waste would be produced by not regenerating the IRC-84 resin in the weak acid resin flow sheet. The CSA flow sheet generated the least amount of waste, but the waste generated by the remaining flow sheets are so similar that pilot-scale testing and economic analyses will be required to determine which process should ultimately be used.

The results from Table 9 indicated that the new release limits will reduce the total waste generated by the chabazite flow sheet by 4.8 m^3/year (170 ft^3/year), while the LLLW from regeneration of IRC-84 would be reduced from 12.5 to 10.2 m^3/year (440 to 360 ft^3/year). Data were not available to predict the new HCR-S and continuous-column values, but were assumed to be similar. The total waste generated for the remaining flow sheets remain essentially unchanged. Therefore, economic evaluations, unless noted, were based on the proposed limits.

Table 6 also indicates that the last two columns in the series for nonregenerable columns only reduce the waste generation by 0.7 to 1.7 m^3/year (25 to 60 ft^3/year) for all flow sheets except the chabazite and clinoptilolite flow sheets that utilize zeolites to remove both ^{90}Sr and ^{137}Cs. Since removal of these columns should reduce operational complexity and capital and capital cost, only two columns in series were used in the analyses of the IRC-84, HCR-S, and the continuous-column flow sheets. The flow sheets used in the economic analyses are indicated in Table 9.

6. COST ANALYSES

Cost comparisons for the flow sheets were made by calculating the "future value" of total capital and operating costs based on a startup date of 1989 and a plant life of 15 yrs.[11] 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. If the existing plant were kept for a backup facility, additional space requirements might be necessary. No salvage value or decommissioning costs were taken into account. 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 4% in 1986, 3% in 1987, 4% in 1988, 5% in 1989, and 5.5% through 2004.[12] The cost for each flow sheet, given in 2004 dollars, is estimated in Tables 11-18. The cost bases are summarized below.

All operating costs, except the purchase of IX materials, were based on 1986 cost estimates[13] for operation of the present PWTP plant versus the chabazite flow sheet (see Tables 19 and 20). Chemical costs not previously estimated were based on in-house stores' prices. The costs for IX sorbents were based on vendors' quotes.

The costs for fixed-bed IX columns with prefilters were estimated using standard equations based on column capacity.[14] The 1986 cost for a skid-mounted column with regeneration equipment is cost = $9000*V^{0.55}$ where V is resin volume in ft^3. The estimated cost for a column without the regeneration equipment is cost = $5000*V^{0.55}$. The prices for the continuous IX column and a new precipitator were based on manufacturer's quotes. Installation costs were calculated as a function of the purchased equipment costs using equations for fluid-processing plants.[11] Building and land costs were excluded from the cost equations.

Total disposal costs included storage of solid wastes for 10 years, heat treatment of the zeolites to reduce volume and leachability, solidification of loaded zeolites and resins and sludge in concrete, and final disposal of all wastes. Regenerated resins would be disposed of in 0.2-m^3 (55-gal) drums without additional treatment. The present cost for

Table 11. Chabazite flow sheet cost analyses[a]

	Cost	
	1986 $/year	1989 $/year
Operating costs		
Labor (O. Culberson)	33,960	
Utilities (O. Culberson)	13,080	
Analytical services (O. Culberson)	9,720	
Zeolite (57.2 m^3 @ $620/$m^3$, Tenneco)	35,350	
Total	**92,110**	102,800
Capital costs		
Four 3.7-m^3 sluicible skid-mounted columns with prefilter (R. Kunin)	290,970	
Installation costs (260% of purchased equipment costs as estimated in *Peters and Timmerhaus* for fluid-processing plants without building and land costs)	756,260	1,168,900
Total	**1,047,130**	1,168,900
Disposal costs		
10 year storage and ultimate disposal of zeolite (5.72 m^3 @ $1060/$m^3$ in 1989, J. Berry)	54,300	
Heat treatment of zeolite to reduce leachability (57.2 m^2 @ $706/$m^3$ based on solidification costs)	40,400	
Solidification of zeolite in concrete (57.2 m^3 @ $530/$m^3$ not including handling, transport, and ultimate disposal, M. Gilliam)	30,000	
Total	**125,000**	139,500

[a]Future value in 2004 assuming startup in 1989 and 15-plant life—$8.3 M.

Table 12. IRC-84 flow sheet with direct disposal of resin cost analyses[a]

	Cost	
	1986 $/year	1989 $/year
Operating Costs		
Labor (O. Culberson's costs for SPIX process)	254,400	
Chemicals (O. Culberson's costs for SPIX process)		
NaOH ($450/m^3)	57,000	
H_2SO_4 ($0.518/gal) ($233/m^3)	6,040	
IX materials		
IRC-84 resin (10.5 m^3 @ $5830/m^3, Rohm & Haas)	61,060	
PDZ-300 zeolite (15 m^3 @ $620/m^3, Tenneco)	9,280	
Utilities (O. Culberson's costs for electricity in SPIX process)	26,160	
Analytical services (O. Culberson's costs for SPIX + 1/2 of chabazite processes)	43,680	
Total	**456,610**	510,800
Capital Costs		
Two trains of 2 2.8-m^3 sluicible skid-mounted columns with prefilters (R. Kunin)	290,870	
18-ft diam precipitator with rake and bottom drain including equipment and driver (Permutit Co.)	90,000	
Total installation costs (260% of purchased equipment costs as estimated in *Peters and Timmerhaus* for fluid-processing plants without building and land costs)	990,260	
Total	**1,371,130**	1,530,600
Disposal Costs		
10-year storage and ultimate disposal of zeolite, resin, and sludge (76.5 m^3 @ $1060/m^3 in 1989, J. Berry)	72,560	
Heat treatment of zeolite to reduce leachability (15 m^3 @ $706/m^3 based on solidification cost)	10,600	
Solidification of zeolite, resin, and sludge in concrete (76.5 m^3 @ $530/m^3 not including handling, transport, and ultimate disposal, M. Gilliam)	40,500	
Total	**123,660**	138,400

[a]Future value in 2004 assuming startup in 1989 and 15-plant life—$18.6 M.

Table 13. IRC-84 flow sheet with regeneration of resin cost analyses

	Cost	
	1986 $/year	1989 $/year
Operating Costs		
Labor (O. Culberson's 1986 for SPIX + 1/2 of chabazite processes)	254,400	
Chemicals (O. Culberson's costs for SPIX process)		
NaOH ($450/m^3)	57,000	
HNO_3 ($287/m^3)	1,200	
H_2SO_4 ($233/m^3)	6,040	
IX materials		
IRC-84 resin (1.4 m^3 @ $5830/m^3, Dow Chemicals)	8,250	
PDZ-300 zeolite (15 m^3 @ $620/m^3, Tenneco)	9,280	
Utilities (O. Culberson's costs SPIX and chabazite processes)	48,630	
Analytical services (O. Culberson's costs for SPIX + 1/2 of chabazite processes)	43,680	
Total	**445,460**	497,300
Capital Costs		
2 3.7-m^3 sluicible skid-mounted columns with prefilter (R. Kunin)	145,430	
18-ft diam precipitator with rake and bottom drain including equipment and driver (Permutit Co.)	90,000	
Four 1.34-m^3 skid-mounted columns with regeneration equipment (R. Kunin)	300,800	
Total installation costs (260% of purchased equipment costs as estimated in *Peters and Timmerhaus* for fluid-processing plants without building and land costs)	1,394,210	
Total	**1,930,440**	2,154,900
Disposal Costs		
10-year storage and ultimate disposal of zeolite and sludge (66 m^3 @ $1060/m^3 in 1989, J. Berry)	62,620	
Heat treatment of zeolite to reduce leachability (15 m^3 @ $706/m^3 based on solidification cost)	10,600	
Solidification of zeolite and sludge in concrete (66 m^3 @ $530/m^3 not including handling, transport, and ultimate disposal, M. Gilliam)	34,950	
Direct burial of regenerated resin (1.4 m^3 @ present costs of $220/55-gal drum, J. Van Cleve)	1,650	
Disposal of liquid LLW (10.2 m^3 @ $900/m^3, J. Berry)	54,000	
Total	**123,660**	182,900

[a]Future value in 2004 assuming startup in 1989 and 15-plant life—$20.8 M.

Table 14. HCR-S flow sheet cost analyses with new zeolite columns[a]

	Cost	
	1986 $/year	1989 $/year
Operating Costs		
Labor (O. Culberson's costs for SPIX + 1/2 of chabazite processes)	271,380	
Chemicals (O. Culberson's costs for SPIX process)		
NaOH ($450/m^3)	57,000	
HNO_3 ($287/m^3)	3,980	
H_2SO_4 ($233/m^3)	6,040	
$FeSO_4$ ($0.26/kg)	400	
IX materials		
HCR-S resin (2.7 m^3 @ $2120/m^3, Dow Chemicals)	5,700	
PDZ-300 zeolite (15 m^3 @ $620/m^3, Tenneco)	9,280	
Utilities (O. Culberson's costs SPIX and chabazite processes)	48,630	
Analytical services (O. Culberson's costs for SPIX + 1/2 of chabazite processes)	43,680	
Total	**446,090**	498,000
Capital Costs		
Two 3.7-m^3 sluicible skid-mounted columns with prefilter (R. Kunin)	145,430	
Installation and startup costs (260% of purchased equipment costs as estimated in *Peters and Timmerhaus* for fluid-processing plants without building and land costs)	378,130	
Total	**523,550**	584,400
Disposal Costs		
10-year storage and ultimate disposal of zeolite and sludge (100 m^3 @ $1060/m^3 in 1989, J. Berry)	94,870	
Heat treatment of zeolite to reduce leachability (15 m^3 @ $706/m^3 based on solidification cost)	10,600	
Solidification of zeolite and sludge in concrete (100 m^3 @ $530/m^3 not including handling, transport, and ultimate disposal, M. Gilliam)	52,950	
Direct burial of regenerated resin (2.7 m^3 @ present costs of $220/55-gal drum, J. Van Cleve)	3,130	
Disposal of liquid LLW (22.7 m^3 @ $900/m^3, J. Berry)	204,600	
Total	**366,150**	408,700

[a]Future value in 2004 assuming startup in 1989 and 15-plant life—$22.5 M.

Table 15. HCR-S flow sheet cost analyses with new zeolite clarifier and zeolite columns[a]

	Cost	
	1986 $/year	1989 $/year
Operating Costs		
Labor (O. Culberson's costs for SPIX + 1/2 of chabazite processes)	271,380	
Chemicals (O. Culberson's costs for SPIX process)		
NaOH ($450/m^3)	57,000	
HNO_3 ($287/m^3)	2,530	
H_2SO_4 ($233/m^3)	6,040	
IX materials		
HCR-S resin (2.7 m^3 @ $2120/m^3, Dow Chemicals)	5,700	
PDZ-300 zeolite (15 m^3 @ $620/m^3, Tenneco)	9,280	
Utilities (O. Culberson's costs SPIX and chabazite processes)	48,630	
Analytical services (O. Culberson's costs for SPIX + 1/2 of chabazite processes)	43,680	
Total	**444,240**	495,900
Capital Costs		
Two 3.7-m^3 sluicible skid-mounted columns with prefilter (R. Kunin)	145,400	
18-ft diam precipitator with rake and bottom drain including equipment and driver (Permutit Co.)	90,000	
Installation costs (260% of purchased equipment costs as estimated in *Peters and Timmerhaus* for fluid-processing plants without building and land costs)	512,200	
Total	**847,600**	946,100
Disposal Costs		
10-year storage and ultimate disposal of zeolite and sludge (66 m^3 @ $1060/m^3 in 1989, J. Berry)	62,620	
Heat treatment of zeolite to reduce leachability (15 m^3 @ $706/m^3 based on solidification cost)	10,600	
Solidification of zeolite and sludge in concrete (66 m^3 @ $530/m^3 not including handling, transport, and ultimate disposal, M. Gilliam)	34,950	
Direct burial of regenerated resin (2.7 m^3 @ present costs of $220/55-gal drum, J. Van Cleve)	3,130	
Disposal of liquid LLW (12.2 m^3 @ $900/m^3, J. Berry)	111,000	
Total	**222,300**	248,200

[a]Future value in 2004 assuming startup in 1989 and 15-plant life—$19.5 M.

Table 16. HCR-S flow sheet cost analyses with new precipitator and zeolite and ion-exchange columns*

	Cost	
	1986 $/year	1989 $/year
Operating Costs		
Labor (O. Culberson's costs for SPIX + 1/2 of chabazite processes)	271,380	
Chemicals (O. Culberson's costs for SPIX process)		
NaOH ($450/m^3)	57,000	
HNO_3 ($287/m^3)	1,260	
H_2SO_4 ($233/m^3)	6,040	
IX materials		
IRC-84 resin (2.7 m^3 @ $2120/m^3, Dow Chemicals)	5,700	
PDZ-300 zeolite (15 m^3 @ $620/m^3, Tenneco)	9,280	
Utilities (O. Culberson's costs SPIX and chabazite processes)	48,630	
Analytical services (O. Culberson's costs for SPIX + 1/2 of chabazite processes)	43,680	
Total	**442,970**	494,500
Capital Costs		
Two 3.7-m^3 sluicible skid-mounted columns with prefilter (R. Kunin)	145,430	
18-ft diam precipitator with rake and bottom drain including equipment and driver (Permutit Co.)	90,000	
Four 1.34-m^3 skid-mounted columns with regeneration equipment (R. Kunin)	300,800	
Total installation costs (260% of purchased equipment costs as estimated in *Peters and Timmerhaus* for fluid-processing plants without building and land costs)	1,394,210	
Total	**1,930,440**	2,154,900
Disposal Costs		
10-year storage and ultimate disposal of zeolite and sludge (66 m^3 @ $1060/m^3 in 1989, J. Berry)	62,620	
Heat treatment of zeolite to reduce leachability (15 m^3 @ $706/m^3 relative to solidification)	10,600	
Solidification of zeolite and sludge in concrete (66 m^3 @ $530/m^3 not including handling, transport, and ultimate disposal, M. Gilliam)	34,950	
Direct burial of regenerated resin (2.7 m^3 @ present costs of $220/55-gal drum, J. Van Cleve)	3,130	
Disposal of liquid LLW (3.1 m^3 @ $900/m^3, J. Berry)	27,600	
Total	**138,900**	155,100

*Future value in 2004 assuming startup in 1989 and 15-plant life—$20.1 M.

Table 17. Clinoptilolite flow sheet cost analyses[a]

	Cost	
	1986 $/year	1989 $/year
Operating Costs		
Labor (O. Culberson's costs for SPIX processes)	254,400	
Chemicals (O. Culberson's costs for SPIX process)		
NaOH ($450/m^3)	57,000	
H_2SO_4 ($233/m^3)	6,040	
IX materials		
PDZ-140 zeolite (21.5 m^3 @ $620/m^3, Tenneco)	13,300	
Utilities (O. Culberson's costs for electricity in SPIX process)	26,160	
Analytical services (1.5 times O. Culberson's costs for chabazite processes)	14,400	
Total	**371,300**	414,500
Capital Costs		
Four 3.7-m^3 sluicible skid-mounted columns with prefilter (R. Kunin)	290,870	
18-ft diam precipitator with rake and bottom drain including equipment and driver (Permutit Co.)	90,000	
Total installation costs (260% of purchased equipment costs as estimated in *Peters and Timmerhaus* for fluid-processing plants without building and land costs)	990,260	
Total	**1,371,130**	1,530,600
Disposal Costs		
10-year storage and ultimate disposal of zeolite and sludge (72.5 m^3 @ $1060/m^3 in 1989, J. Berry)	76,800	
Heat treatment of zeolite to reduce leachability (21.5 m^3 @ $706/m^3 relative to solidification)	15,200	
Solidification of zeolite and sludge in concrete (72.5 m^3 @ $530/m^3 not including handling, transport, and ultimate disposal, M. Gilliam)	38,400	
Total	**130,400**	145,600

[a]Future value in 2004 assuming startup in 1989 and 15-plant life—$16.6 M.

Table 18. CSA flow sheet cost analyses[a]

	Cost	
	1968 $/year	1989 $/year
Operating Costs		
Labor (O. Culberson's costs for 1/2 of SPIX + 1/2 of chabazite processes)	144,180	
Chemicals (based on ORNL stores' costs)		
Na_2CO_3 ($0.17/kg)	260	
NaCl ($0.08/kg)	5,350	
HCl ($373/$m^3$)	180	
IX materials		
Duolite TG-650C resin (0.34 m^3 @ $3530/$ft^3$)	1,200	
Duolite C-467 resin (0.14 m^3 @ $3530/$m^3$)	500	
PDZ-300 zeolite (15 m^3 @ $620/$m^3$, Tenneco)	9,280	
Utilities (O. Culberson's costs SPIX and chabazite processes)	43,680	
Total	**253,260**	282,600
Capital Costs		
Two 3.7-m^3 sluicible skid-mounted columns with prefilter (R. Kunin)	145,430	
Precipitator (calculated from costs of 18-ft dia unit using capacity ratio equation from *Peters and Timmerhaus*	2,000	
One 0.3-m^3 skid-mounted columns with regeneration equipment (R. Kunin)	32,000	
One 30-cm continuously-operated countercurrent ion-exchange column (I. Higgins)	260,000	
Total installation costs (260% of purchased equipment costs as estimated in *Peters and Timmerhaus for fluid-processing* plants without building and land costs)	1,142,400	
Total	**1,541,840**	1,765,300
Disposal Costs		
10-year storage and ultimate disposal of zeolite and sludge (15.6 m^3 @ $1060/$m^3$ in 1989, J. Berry)	14,780	
Heat treatment of zeolite to reduce leachability (15 m^3 @ $706/$m^3$ based on solidification cost)	10,600	
Solidification of zeolite and sludge in concrete (15.6 m^3 @ $530/$m^3$ not including handling, transport, and ultimate disposal, M. Gilliam)	8,220	
Direct burial of regenerated resin (0.5 m^3 @ present costs of $220/55-gal drum, J. Van Cleve)	560	
Total	**34,160**	155,100

[a]Future value in 2004 assuming startup in 1989 and 15-plant life—$11.5 M.

Table 19. Process Waste Treatment Plant operating cost using sludge and units

Item		$/month
Labor		21,200
Chemicals		
NaOH ($450/m^3)	4750	
HNO_3 ($287/m^3)	331	
H_2SO_4 ($233/m^3)	503	
$FeSO_4$ (0.26/kg)	33	
Cs-100 Resin ($7420/m^3)	3270	
		8,887
Utilities		
Electricity	2180	
Steam and Water	382	
		2,962
Analytical Services		3,240
Subtotal		**$36,289**
Drums for Sludge (1.43/d @ $30 each)		1,290
Total		**$37,579**

[a]These calculations are based on one month of operation at 9.45 L/s through drumming of sludge but does not include removal, temporary storage and permanent disposal of drummed sludge, or storage and permanent disposal of concentrate.

[b]Must dispose of 5.24 m^3/month of drummed sludge and 1.78 m^3/month of concentrate.

Table 20. Process Waste Treatment Plant operating cost using once-through zeolite units[a,b]

Item	$/month[c]
Purchase of 4.98 zeolite-filled vessels @ $12,000 each.	59,800
Labor	2,830
Electricity	1,090
Analytical services	810
Total	**$64,530**

[a]These calculations are based on one month of operation at 9.45 L/s through loading of a 2.22 m^3 vessel of zeolite but does not include the disposal of the loaded zeolite.

[b]Must dispose of 11.1 m^3/month of spent zeolite.

[c]Will also require capital to house four-vessel train.

such disposal is $1,100/m^3 ($220/drum).[15] Liquid wastes would be disposed of as LLLW at an estimated cost of $5,300/m^3 ($20/gal).[16] Storage and final disposal without additional processing of solid LLW was estimated to cost $1,100/m^3 ($30/ft^3) in 1989.[16] It was assumed that the solid LLW would be solidified in concrete before final disposal at a cost of $500/m^3 ($15/ft^3).[17] Costs for heat treating the zeolites to reduce volume and leachability was estimated to be $700/m^3 ($20/ft^3) based on the costs for solidification. This heat-treating step may not be used. All cost estimates were based on the as-generated waste volumes.

These cost analyses indicate that the chabazite flow sheet will cost significantly less than the remaining flow sheets. The CSA and clinoptilolite flow sheets are the second and third least expensive, respectively. The most expensive alternative will be to continue operating the plant in the present manner. The IRC-84 and HCR-S flow sheets that utilize new equipment are similar in costs.

7. FLOW SHEET EVALUATIONS

Since many factors other than costs will influence the flow sheet selection, flow sheet evaluations attempted to numerically rate the processes on plant operability, interim waste generation, postprocessing requirements, and ultimate disposal. The procedure is similar to that used to rate treatment processes and waste forms for the Centralized Waste Disposal Facility (CWDF).[18]

Each flow sheet was rated from 1 to 10 (from worst to best, respectively) for each criteria listed in Table 21. These individual ratings were multiplied by the respective weighting factors listed in Table 21 to obtain scores for each criteria. The scores for each criteria were summed to obtain an overall score for each flow sheet.

The criteria categories were based on those used to evaluate liquid treatment processes in the CWDF study. The weighting factors were selected to emphasize the criteria that are better known, such as costs, operability, and waste generation. Since postprocessing and ultimate disposal methods are to be determined at a later date, these criteria were given low weighting factors.

Table 21. Process Waste Treatment Plant flow sheet evaluations

Criteria	Individual rating (1-10)[a]								Weighting factor	Score (individual rating x weighting factor)							
	Chabazite	HCR-S-1[b]	HCR-S-2[b]	HCR-S-3[b]	RIRC-84[c]	NRIC-84[c]	Clino	CSA		Chabazite	HCR-S-1[b]	HCR-S-2[b]	HCR-S-3[b]	RIRC-84[c]	NRIC-84[c]	Clino	CSA
									(20)								
PROCESSING COSTS	5	10	6	1	1	4	4	2	10	50	100	60	10	10	40	40	20
Capital costs	10	2	2	2	2	1	3	5	10	100	20	20	20	20	10	30	50
Operational costs																	
PLANT OPERATION									(35)								
Process flexibility	1	7	8	9	8	8	6	3	15	15	105	120	135	120	120	90	45
Process simplicity	10	1	3	5	5	5	5	6	10	100	10	30	50	50	50	50	60
Stage of development	4	9	8	7	3	3	3	1	5	20	45	40	35	15	15	15	5
Occupational safety	7	1	2	4	4	5	5	4	5	35	5	10	20	20	25	25	20
INTERIM WASTE FORM									(30)								
Environmental safety	8	2	2	2	2	6	6	7	15	120	30	30	30	30	90	90	105
Solid Waste reduction	7	1	4	4	5	2	3	10	5	35	5	20	20	25	10	15	50
Liquid Waste reduction	10	1	5	7	7	10	10	10	10	100	10	50	70	70	100	100	100
POSTPROCESSING									(7)								
Costs	8	1	3	7	6	8	8	10	2	16	2	6	14	12	16	16	20
Waste from flexibility	2	9	8	7	7	5	4	4	1	2	9	8	7	7	5	4	4
Nonrad plant compatible	1	7	8	8	8	8	4	2	1	1	7	8	8	8	8	4	2
Stage of development	1	5	5	5	5	4	2	5	2	2	10	10	10	10	8	4	10
Occupational safety	3	5	5	5	5	4	4	5	1	3	5	5	5	5	5	5	5
FINAL WASTE FORM						3			(8)								
Environmental safety	7	3	3	3	3	8	5	6	4	28	12	12	12	12	12	20	24
Waste reduction	8	1	3	7	8		6	10	4	32	4	12	28	32	32	24	40
TOTAL	87	55	69	82	78	80	74	88	100	659	379	441	474	446	545	531	560

[a] Ranges from a minimum rating of 1 to 1 maximum of 10.

[b] HCR-S-1 includes minimal upgrade: chabazite columns for Cs removal. HCR-S-2 includes new chabazite columns and clarifier. HCR-S-3 includes new HCR-S columns in addition to HCR-S-2 equipment.

[c] RIRC-84 involves regeneration of resin. NRIC-84 involves direct disposal of resin without regeneration.

disposal methods are to be determined at a later date, these criteria were given low weighting factors.

The bases of the individual ratings are described below. The processing costs were rated from 1 to 10 for each flow sheet according to the 1989 capital and operating costs listed in Tables 11-18. The process flexibility indicates the capability of a flow sheet to accommodate fluctuations in the feed composition and flow rate, as well as its capability to remove potential radionuclides other than ^{90}Sr and ^{137}Cs. The present plant has operated over a wide range of feed compositions and throughputs. The clarifier has removed both ^{60}Co and ^{152}Eu in the past.[1] Both the HCR-S and IRC-84 resins should remove divalent cations. The zeolites, on the other hand, should not remove other radionuclides. It is anticipated that the CCIX column will not perform well unless it is run in a steady-state mode; that is, it could not accommodate composition or flow rate changes well. The column has the potential of removing other radionuclides, but those with lower affinities than strontium would be discharged in the column effluent.

The number and complexity of the processing steps and labor intensity of the processes were considered under process simplicity. The simplest process is the chabazite flow sheet. The HCR-S flow sheets without equipment upgrades were rated low because of the labor intensity involved in clarifier operation and column regenerations. The remaining flow sheets were considered to be similar in complexity. The stage of development rating reflects the PWTP's experience with both the equipment and materials. The chabazite process is presently being tested at the PWTP on a pilot scale. Although the equipment for the IRC-84 and clinoptilolite materials have been tested, the sorbents have only been tested on a lab scale. The CCIX columns have never been tested. Occupational safety ratings were based on the potential for exposure of personnel to radiation and hazardous chemicals.

The interim waste form ratings were based on the waste generated at the PWTP without posttreatment. The flow sheets generating only solids were rated higher than those generating liquid wastes for environmental safety. The waste reduction ratings were determined using the generation rates listed in Table 9.

The postprocessing costs were based on the disposal costs listed in Tables 11-18. Liquids and sludges were rated high for their flexibility for further processing, while loaded

zeolites and resins were rated low. The only probable treatment for these latter materials is solidification. (Although it is possible that the zeolites could be heat treated to reduce leachability.). The nonradiological plant compatibility ratings were determined by each flow sheet's potential to remove heavy metals. Their capabilities for removing metal ions would be similar to that for removing additional radionuclides. The zeolites were rated low for the stage of development for postprocessing methods, while those for the remaining waste forms were considered to be similar. Occupational safety ratings were again based on potential personnel exposure to high levels of radiation.

The ultimate safety of the final waste forms were rated assuming that heat treated zeolites would be the most stable waste form. Monoliths containing solidified sludges and liquid wastes were assumed to have higher potentials for leachability. The final waste reduction was rated according to the total wastes generated in Table 9.

The results from the flow sheet evaluations are summarized in Table 21 under total score. They indicate that the chabazite flow sheet is the best process for further consideration. The clinoptilolite, IRC-84 without regeneration, and the continuous-column flow sheets are closely grouped for second place. There was little difference between the scores for the HCR-S flow sheet with upgraded facilities and the regenerated IRC-84 flow sheet. The existing process was rated the lowest by a significant amount.

It should be noted that these criteria, weighting factors, and ratings were all determined by one person. Although an evaluation by one individual makes the process subjective, the procedure was designed to make sure that areas of concern are not overlooked in the final flow sheet selection.

8. SUMMARY

The results from the plant-scale modeling, economic evaluations, and performance ratings are summarized in Table 22. The waste generation calculations indicate that the CSA flow sheet has the best potential for waste volume reduction. The calculations for this flow sheet were based on much less data than the other flow sheets. Pilot-scale tests are therefore needed to substantiate these results. The chabazite flow sheet generates the

Table 22. Summary of alternative flow sheet evaluations for Process Waste Treatment Plant upgrade

Flow sheet name	Flow sheet figure number	Waste generation m^3/year	Future value $M in 2004	Numerical rating (0-1000)
Chabazite	1	57.2	8.3	659
CSA	5	16.0	11.5	560
Clinoptilolite	4	72.5	16.6	531
IRC-84[a]	2	76.5	18.6	545
HCR-S[b]	3	73.9	20.1	474
IRC-84[b]	2	77.6	20.8	446
HCR-S[c]	3	89.6	19.5	441
HCR-S[d]	3	141.4	22.5	379

[a]Assuming direct disposal of resin and completely upgraded equipment.
[b]Assuming regeneration of resin and completely upgraded equipment.
[c]Assuming the clarifier is replaced and zeolite columns are added.
[d]Assuming minimum plant upgrade, (i.e., only zeolite columns are added).

lowest amount of total waste of the fixed-bed-column flow sheets, even though the chabazites have relatively low sorption capacity for ^{90}Sr. The sludge generated in the other flow sheets is 1 to 2 orders of magnitude greater in volume than the volume of sorption material that offsets gains made by increased resin efficiency. Regeneration of the IRC-84 resin is not needed, but upgraded equipment is needed to significantly reduce waste generation.

The cost analyses indicate that the chabazite flow sheet will cost significantly less than the remaining flow sheets. The CSA and clinoptilolite flow sheets are the second and third least expensive, respectively. The most expensive alternative will be to continue operating the plant in the present manner. The IRC-84 and HCR-5 flow sheets that utilize identical equipment are similar in cost.

The results from the flow sheet ratings indicate that the chabazite flow sheet is the best process for further consideration. The clinoptilolite, IRC-84 without regeneration, and the continuous-column flow sheets are closely grouped for second place. There was little difference between the scores for the HCR-S flow sheet with upgraded facilities and

the regenerated IRC-84 flow sheet. The existing process was rated the lowest by a significant amount.

The economic analyses and flow sheet evaluations both lead to the same conclusions—the chabazite flow sheet is the most attractive process for use at the PWTP. The clinoptilolite, IRC-84 without regeneration, and the CSA flow sheets fall close behind as the next best alternatives. The results from this study indicate that each of these processes warrant closer evaluation. A more detailed economic study should be made to determine the costs more precisely. Additional pilot-scale tests are needed to obtain data under actual operating conditions. The major advantages and disadvantages of each process are listed below, along with suggested laboratory- and pilot-scale tests.

The chabazite flow sheet offers the simplest and cheapest alternative for removal of ^{90}Sr and ^{137}Cs for ORNL process wastewater. It also has the advantage of producing a relatively small amount of LLW that could possibly be heat treated to produce a leach-resistant waste form for ultimate disposal. The major disadvantage in the process is that it lacks the flexibility to remove other radionuclides such as cobalt and europium. If the HCR-S columns from the existing plant were used in parallel with this flow sheet, this disadvantage could be eliminated. A monitoring system would need to be installed to determine when the resin backup system should be used.

Testing of the merry-go-round operation using the chabazite zeolites should be continued. The effects of heat treating the zeolites should also be determined. If heat treatment is unnecessary, treating the wastewater with zeolites in large concrete trenches rather than tanks could also be investigated. The loaded zeolites could potentially be solidified in situ, reducing both capital and labor costs.[13]

The incorporation of a chemical precipitator in the flow sheet significantly increases the flexibility of the process for removing additional radionuclides and heavy metals. The clinoptilolite and IRC-84 flow sheets were ranked closely together because they are of similar complexity and the sludge generation is the major factor influencing waste volumes. The clinoptilolite flow sheet is the simplest since it eliminates one set of sorption columns. The nonregenerable IRC-84 flow sheet is an attractive alternative because the resin has the capability to remove other radionuclides. However, it is very sensitive to the

efficiency of the softening process. Testing of these flow sheets on a pilot scale in the Ion Exchange Process Facility is suggested.

The CSA flow sheet has the distinct advantage of producing significantly less waste than the other processes. This process has the disadvantage of being complex, because although the equipment has been developed for several years, it has never been demonstrated for the application. A pilot-scale demonstration is needed to determine if the process could maintain steady-state operation (and continually produce these predicted low waste volumes) with feed variations typical of the PWTP.

The results from this study indicate that the chabazite flow sheet is the most promising alternative for upgrade of the PWTP. However, the study also shows that each flow sheet has potential advantages. The waste generation, economic evaluations, and process ratings results were fairly close for several alternatives. Therefore, each of these processes warrants closer evaluation before a final selection is made. Additional pilot-scale tests are recommended to obtain data under actual operating conditions. A more detailed economic study should then be made to determine the costs more precisely.

9. REFERENCES

1. S. M. Robinson and J. M. Begovich, *Treatment Studies at the Process Waste Treatment Plant at Oak Ridge National Laboratory*, ORNL/TM-10352, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, in publication.

2. J. M. Chilton and L. C. Lasher, "Decontamination of Low-Level Liquid Waste at Oak Ridge National Laboratory Using a Scavenging-Precipitation, Ion Exchange Process," presented at the Waste Management Conference, Tucson, AZ, March 8, 1982, published in *Waste Isolation in the US and Elsewhere, Technical Programs and Public Communications, Vol. 2 Low-Level Waste*, University of Tucson, 1982.

3. T. Tamura and H. O. Weeren, "Disposal of Waste by Hydraulic Fracturing," presented at the 2nd Hazardous Materials Conf., Philadelphia, June 6-8, 1984, published in *Proc. 2nd Hazardous Materials Conf.*, pp. 483-97.

4. E. D. Collins, D. O. Campbell, L. J. King, J. B. Knauer, and R. M. Wallace, "Development of the Flowsheet Used for Decontaminating High-Activity-Level Water," *The Three Mile Island Accident, Diagnosis and Prognosis*, ACS Symposium Series, 293, American Chemical Society, Washington, D.C. (1986), pp 212-227.

5. I. R. Higgins, *Treatment of ORNL Low-Level Waste Water for Selective Removal of Strontium-90*, Progress Reports #1 and #2, CSA, Inc., Oak Ridge, Tennessee, 1986.

6. N. K. Hiester, T. Vermeulen, and G. Klein, G. *Chemical Engineers' Handbook*, 4th ed. (J. J. Perry, et al., Eds.) McGraw-Hill, New York, 1963, p. 16-22.

7. H. K. S. Tan, *Chem Engr*, 91 (26), 57 (1984).

8. F. E. Harrington and J. M. Holmes, *Design Study—New ORNL Process Waste Treatment Plant*, ORNL-TM-3522, 1972.

9. J. M. Chilton, *The use of a Phenolic-Carboxylic Acid Cation Resin in the Treatment of Low-Level Liquid Waste at Oak Ridge National Laboratory*, ORNL/TM-7524, 1981.

10. Rohm and Haas Company, *Amberlite IRC-84*, Technical Bulletin Fluid Process Chemicals, Philadelphia, 1981.

11. M. E. Peter and K. D. Timmerhaus, *Plant Design and Economics for Chemical Engineers*, 2nd Ed., McGraw-Hill, St. Louis, 1968.

12. M. Lasiter, Personal Communication, Engineering Division, Oak Ridge National Laboratory, March 1986.

13. O. L. Culberson, Personal Communication, Chemical Technology Division, Oak Ridge National Laboratory, March 1986.

14. R. Kunin, *Ion Exchange: Theory and Practices*, AIChE Continuing Education Short Course, Miami Beach, Florida, October 30-November 2, 1986.

15. J. E. Van Cleve, Personal Communication, Operations Division, Oak Ridge National Laboratory, December 1986.

16. J. B. Berry, Personal Communication, Operations Division, Oak Ridge National Laboratory, December 1986.

17. T. M. Gilliam, Personal Communication, Chemical Technology Division, Oak Ridge National Laboratory, December 1986.

18. W. W. Pitt, S. M. Robinson, and E. S. Harrington, *Screening Evaluation of Alternatives for Treatment and Disposal of Low-Level Wastes*, ORNL/TM-9825, in publication.

19. N. K. Heister and T. Vermeulen, *Chem. Eng. Prog.*, 48, 505 (1952).

Appendix A. MATHEMATICAL ION-EXCHANGE MODEL

Appendix A. MATHEMATICAL ION-EXCHANGE MODEL

The experimental breakthrough data were fitted by means of the mathematical J-function,[6] using a constant separation factor model developed by Thomas, in order to predict the performance of longer columns, columns in series, and different flow rates. The general Thomas equation for the reaction kinetics of fixed-bed ion exchange is as follows:

$$-\frac{\partial X}{\partial N}_{NT} = \frac{\partial Y}{\partial NT}_{N} = X(1 - Y) - RY(1 - X), \tag{1}$$

where X and Y are the dimensionless concentration of the solute ion in the fluid and solid phases, respectively, and R is the separation factor. The variable X is defined as C/C_o, where C and C_o are the concentrations of the solute ion of interest in the effluent and feed, respectively. The variable Y is defined as q/q^* where q is the actual concentration in the solid phase, and q^* is the concentration in the solid phase when it is in equilibrium with fluid at the inlet (feed) concentration, C_o. When the concentration of the solute ion is small relative to the concentration of the replaceable ion in the feed, R approaches unity, and the isotherm is linear.

The variable N represents the length of the exchange column in transfer units and is defined by the expression

$$N = K_d' \rho_B K_a / (f/v), \tag{2}$$

in which K_d' is the distribution coefficient when $X = 1$, ρ_b is the bulk density of the ion exchanger, K_a is the mass-transfer coefficient characteristic of the system, f is the rate of flow of solution through the volume, and v denotes the overall volume of the sorbent bed, including the void spaces. The throughput parameter, T, is defined to be:

$$T = (V/v)/K_d' \rho B, \tag{3}$$

where V is the volume of solution processed through the column and V/v is the number of bed volumes (bv) of solution that has passed through the bed.

When ρ_b is constant, the volume-based distribution coefficient is defined as $K_d = q_v/C_o$, where q_v is the concentration of the solute ion per unit volume of sorbent bed and C_o is the concentration in the feed. Eqs. (2) and (3) can then be expressed as

$$N = K_d K_a/(f/v), \tag{4}$$

and

$$T = (V/v)/K_d. \tag{5}$$

When Eq. (1) is integrated for ion-exchange beds assuming reversible second-order reaction kinetics[19], the solution is:

$$X = C/C_o =$$

$$\frac{J(RN, NT)}{J(RN, NT) + [1 - J(N, RNT)] \exp[(R-1)N(T-1)]}, \tag{6}$$

where J is a mathematical function related to the Bessel function.

For the large values of RN obtained for small-scale resin columns, $C/C_o = \sim 0.5$ when $T = 1$ and is independent of RN. Therefore, K_d is approximately equal to V/v at the point where $C/C_o = 0.5$. This characteristic implies that plots of experimental data on logarithmic-probability graphs will be linear. Therefore, K_d can be approximated by obtaining the 50% point on experimental breakthrough curves or by extrapolating experimental data on logarithmic-probability plots of C/C_o vs V/v. Values of R and N can then be obtained from the experimental data by iterating around Eqs. (5) and (6) and used to estimate performance at increased residence times and for columns in series.

Appendix B. EXPERIMENTAL AND MODEL-PREDICTED BREAKTHROUGH CURVES FOR LABORATORY-SCALE ION-EXCHANGE COLUMNS

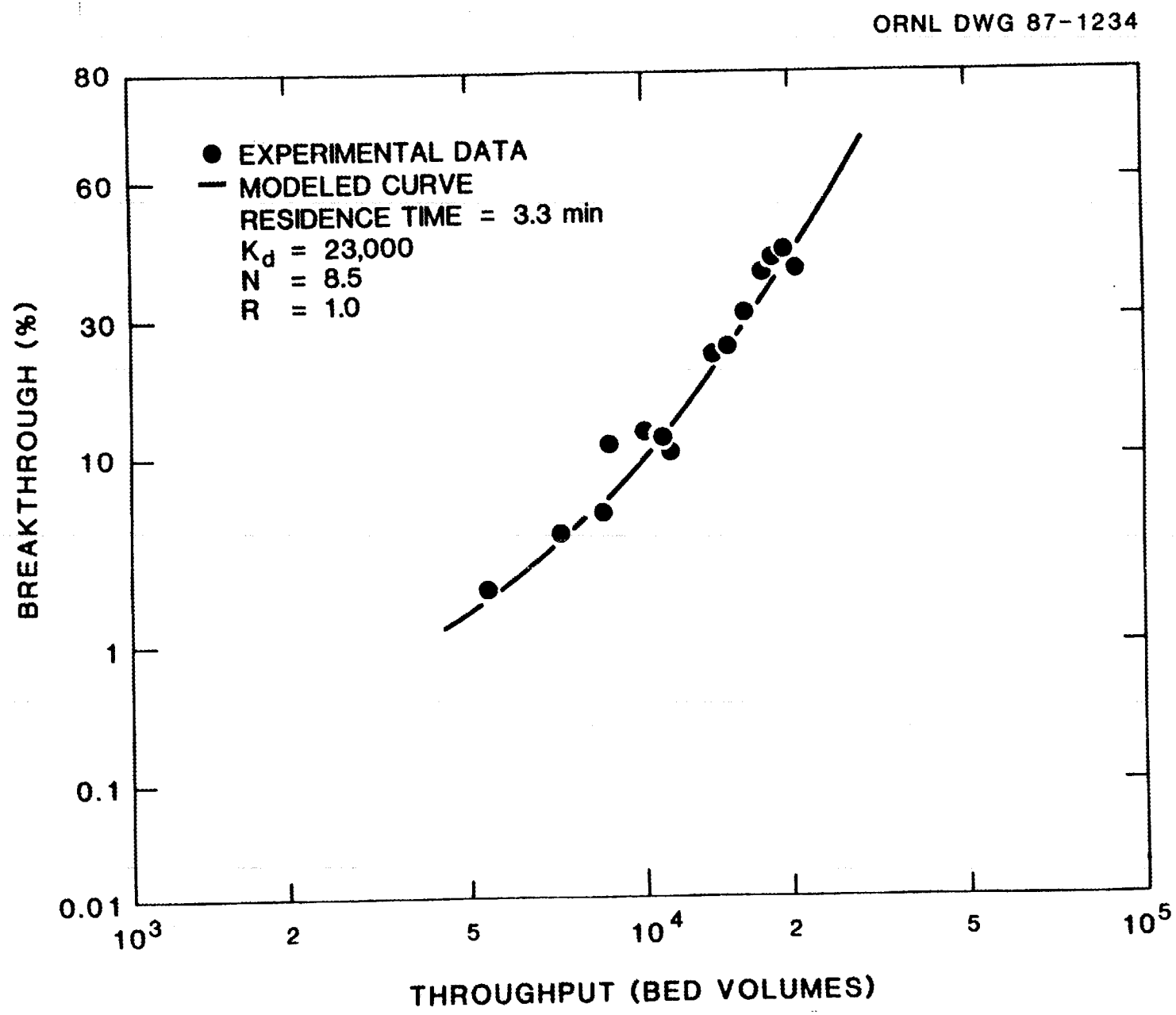


Fig. 8. ^{137}Cs breakthrough curve of PDZ-300 using unsoftened wastewater.

ORNL DWG 87-1236

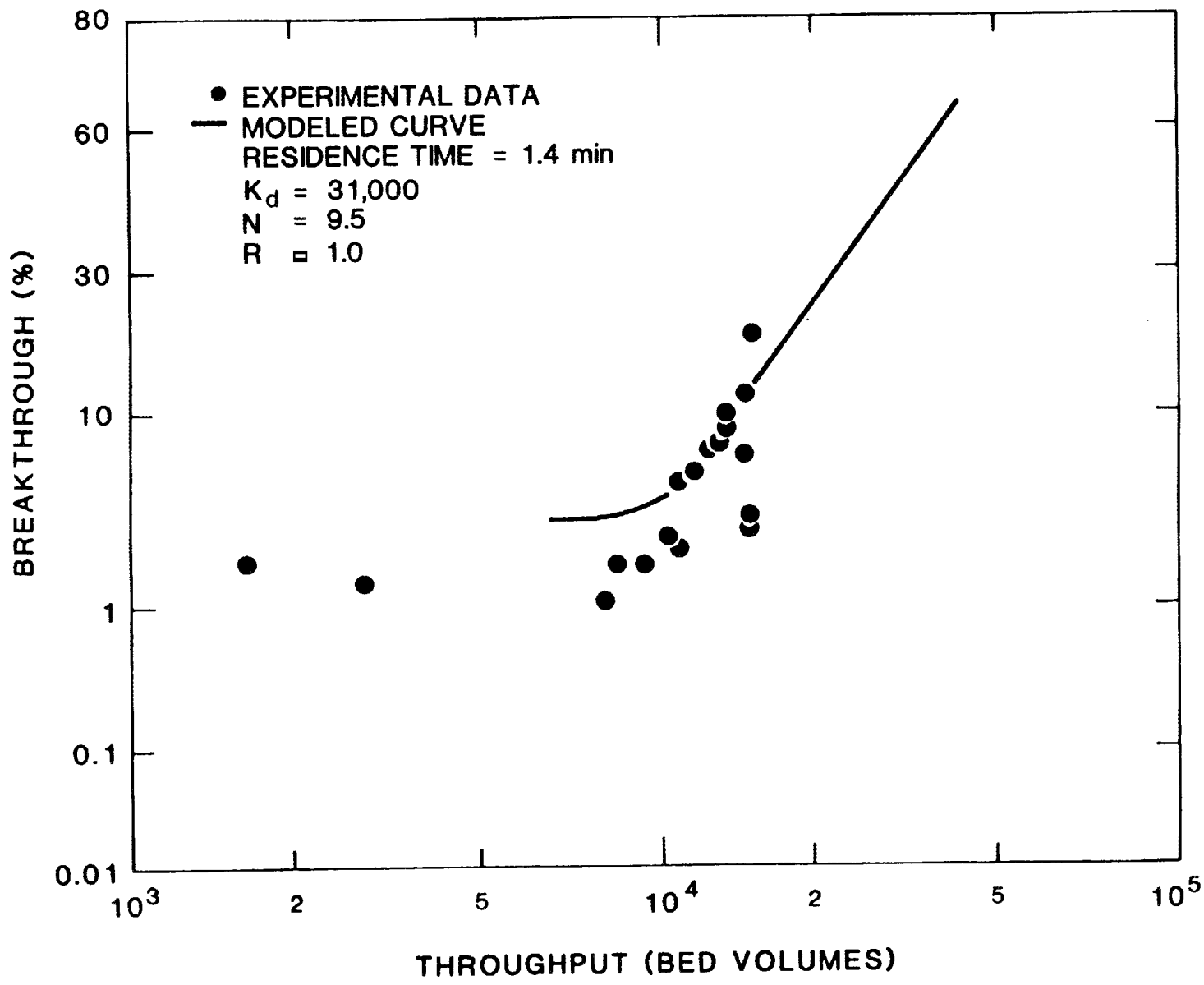


Fig. 9. ^{85}Sr breakthrough curve for IRC-84 resin using scavenging-precipitation softened wastewater.

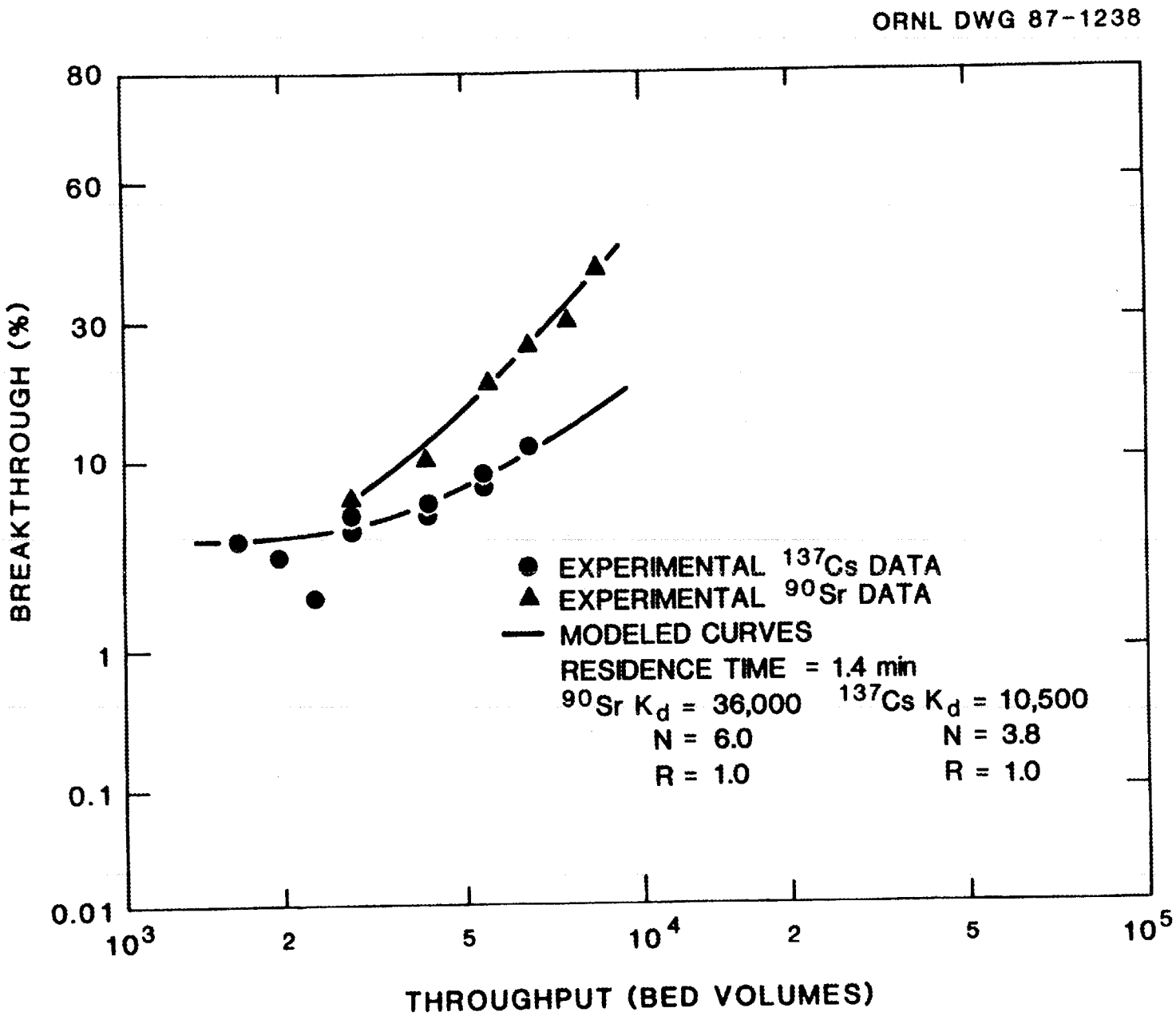


Fig. 10. Breakthrough curve for CH clinoptilolite using scavenging-precipitation softened wastewater.

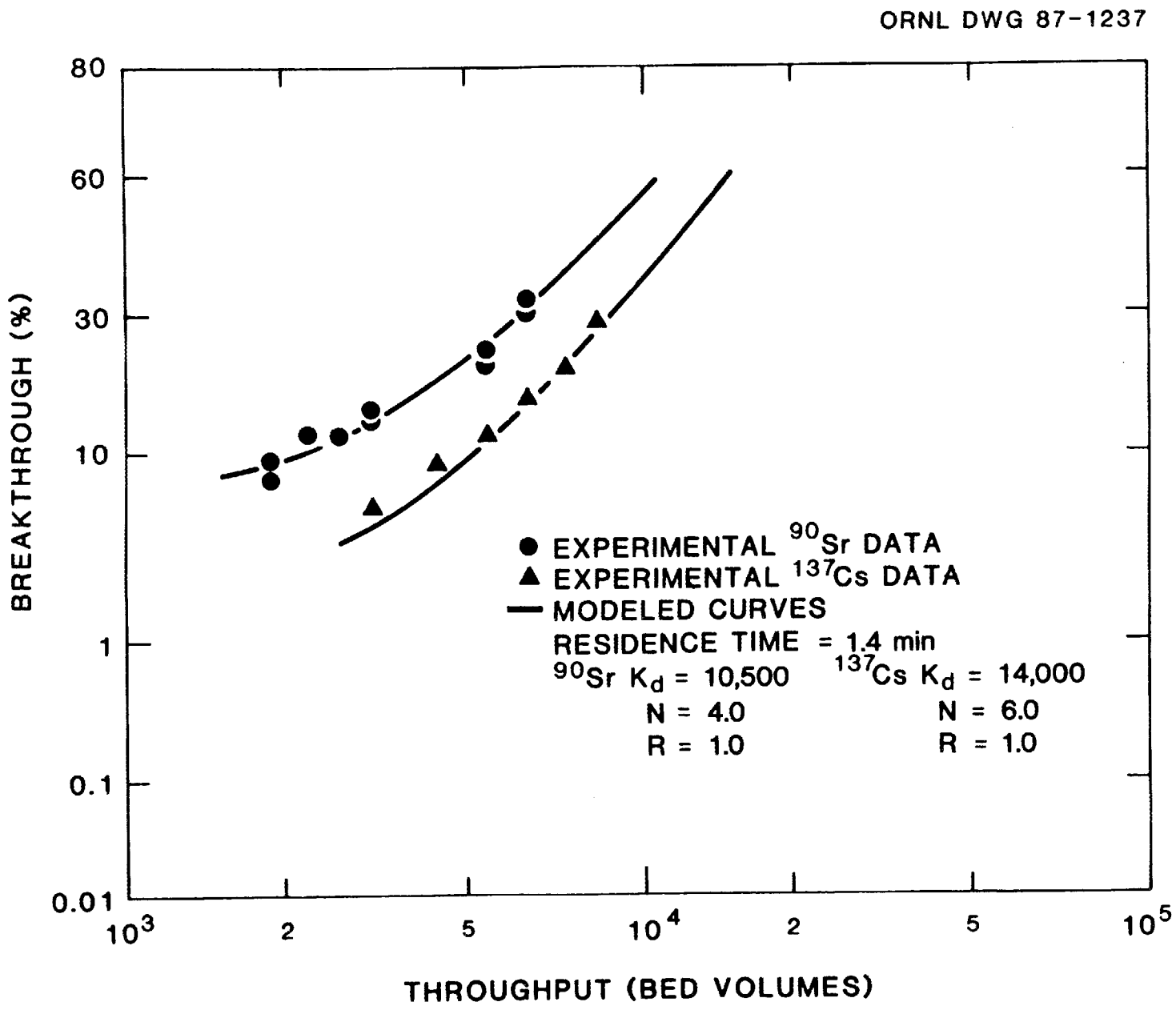


Fig. 11. Breakthrough curve for PDZ-140 using scavenging-precipitation softened wastewater.

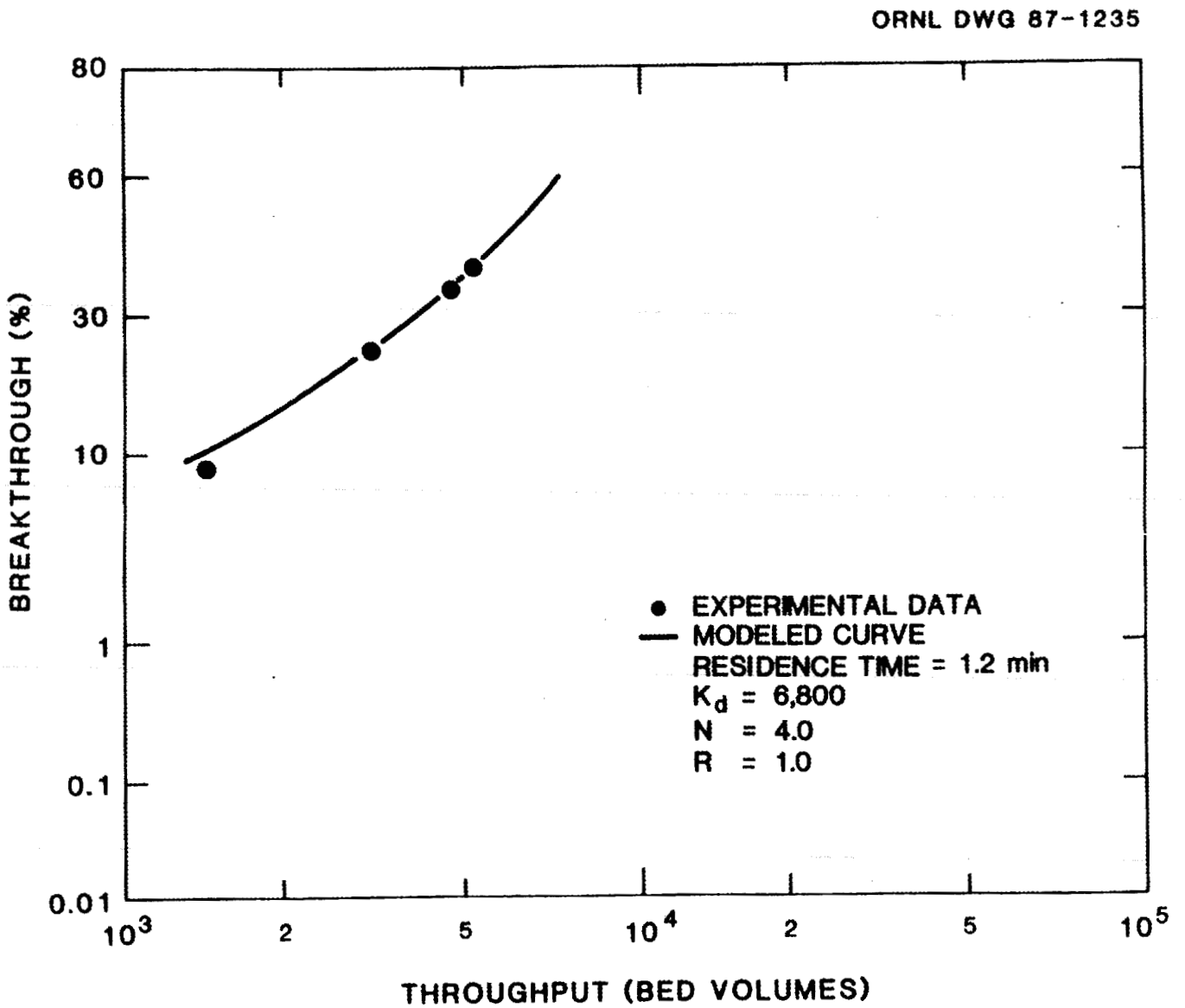


Fig. 12. ^{90}Sr breakthrough curve for HCR-S resin using scavenging-precipitation softened wastewater.

ORNL DWG 87-1241

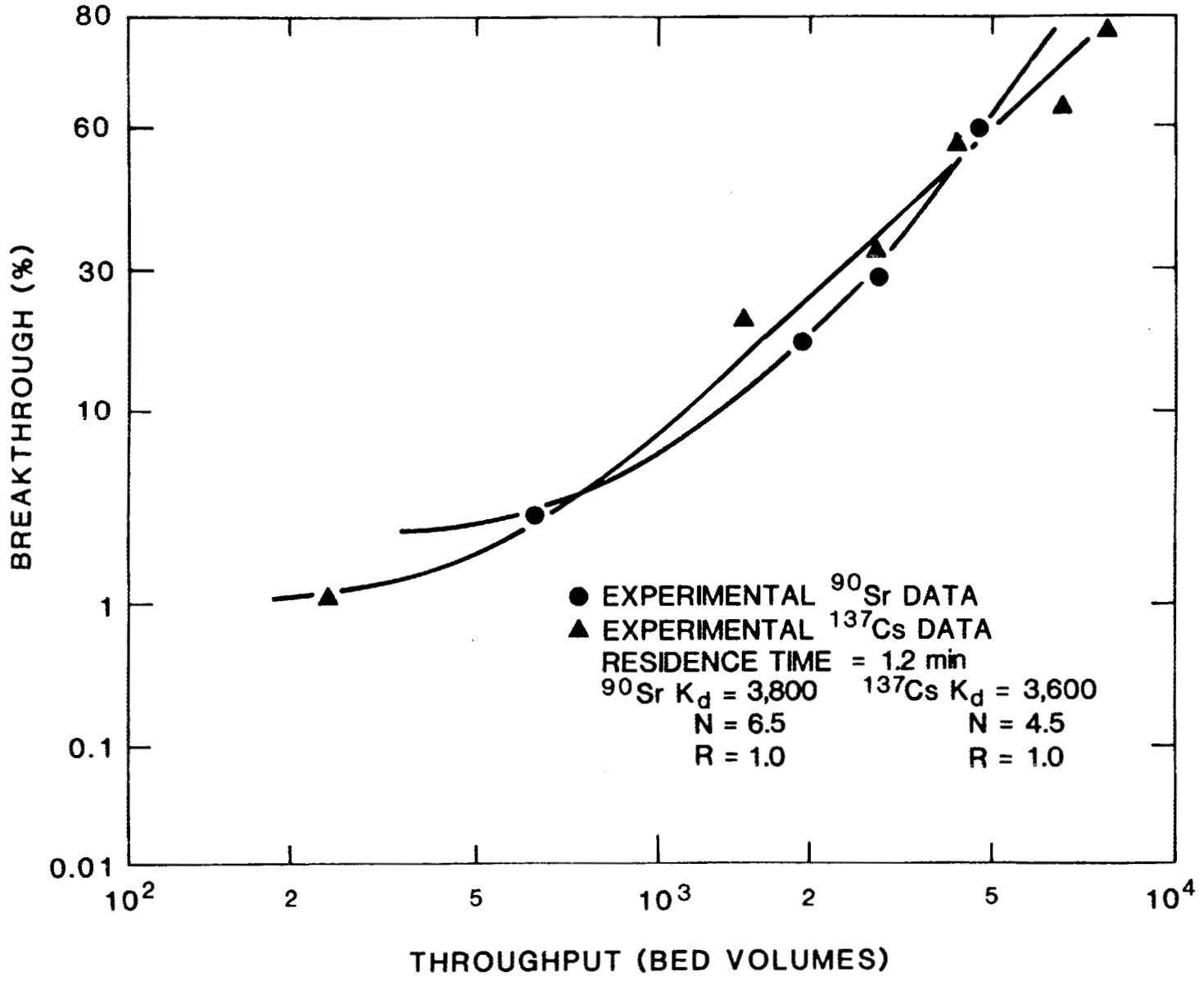


Fig. 13. Breakthrough curve for CS-100 resin using scavenging-precipitation softened wastewater.

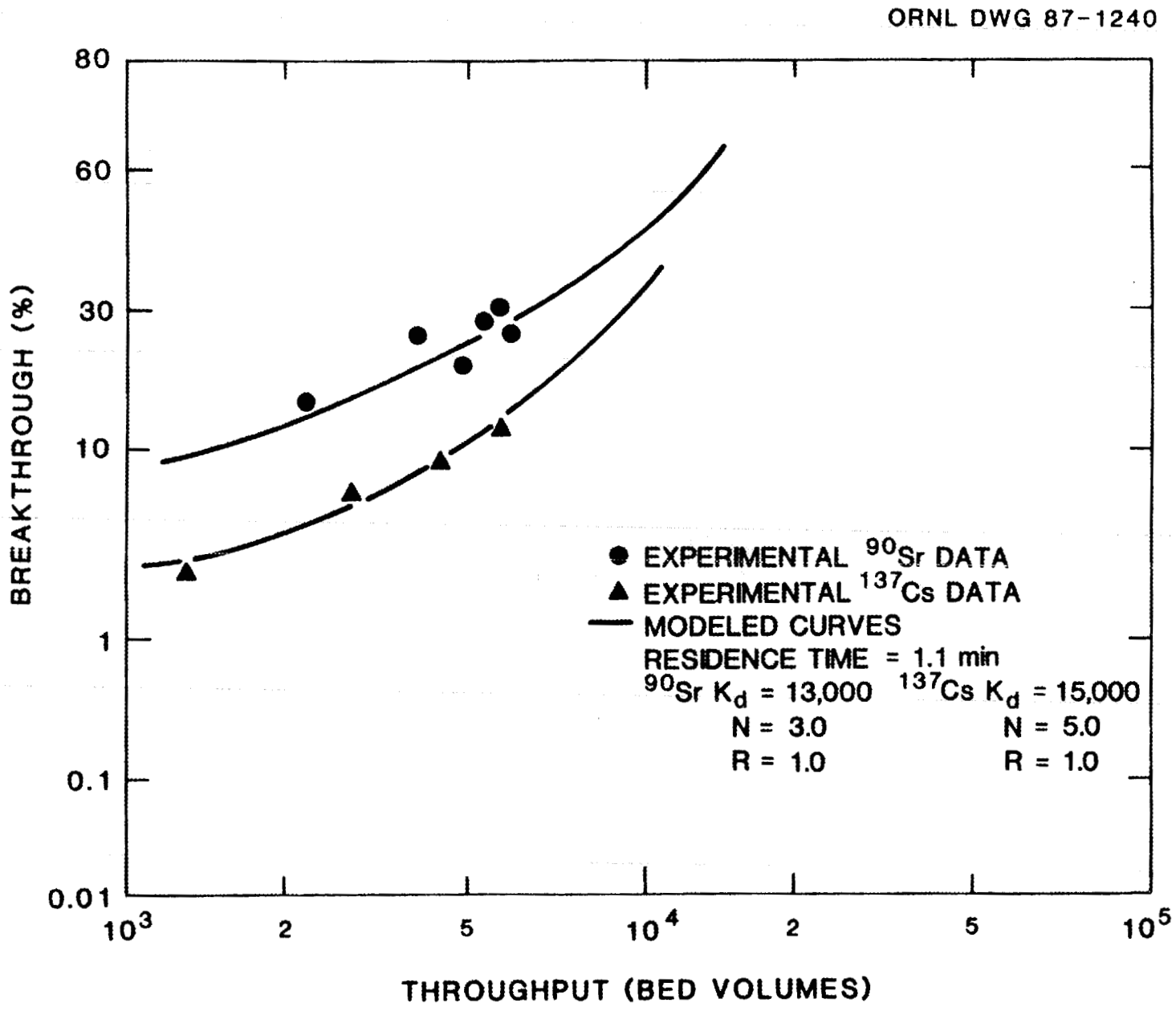


Fig. 14. Breakthrough curve for CH clinoptilolite using caustic-soda-ash softened wastewater.

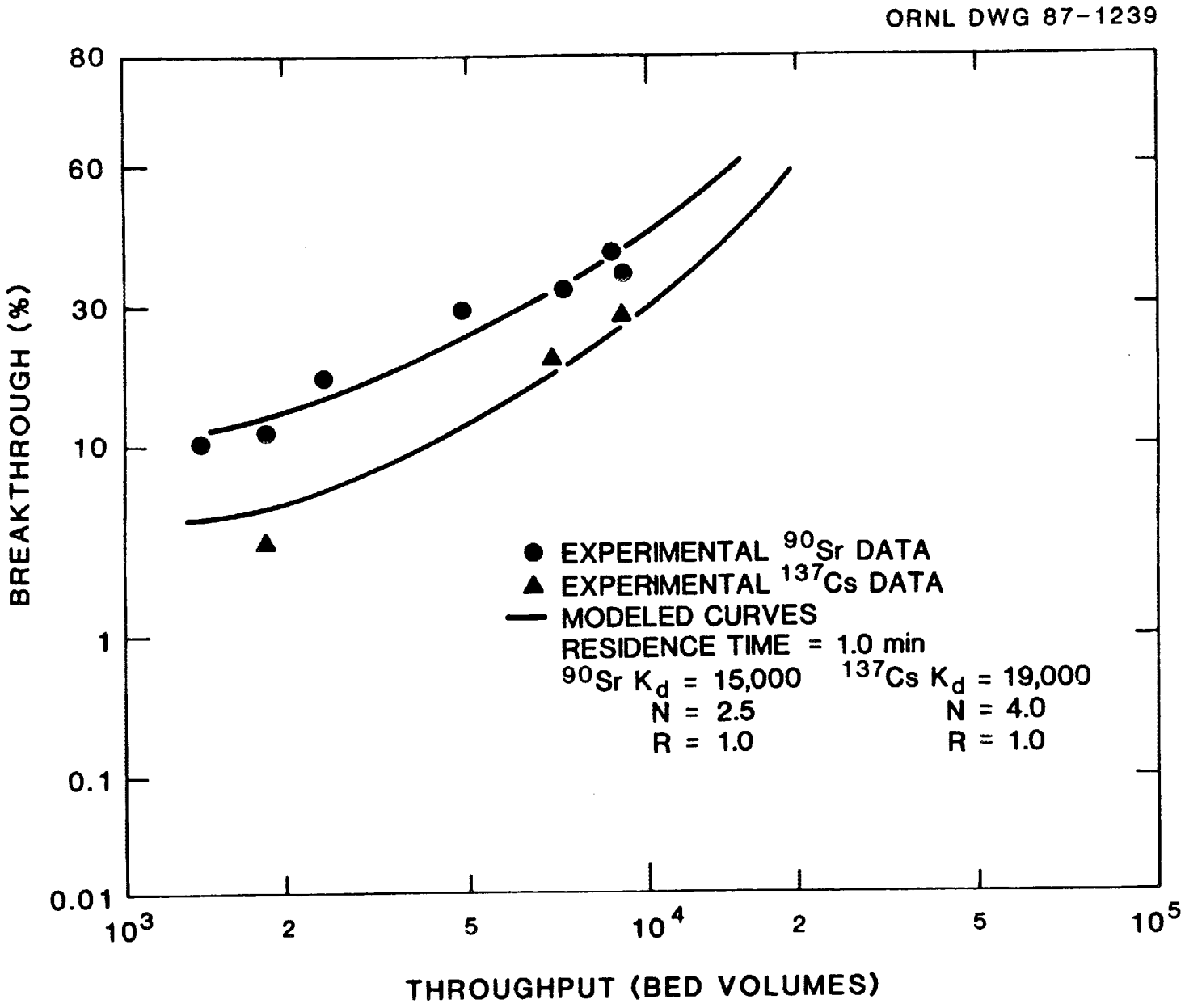


Fig. 15. Breakthrough curve for PDZ-140 using caustic-soda-ash softened wastewater.

Appendix C. WASTE GENERATION CALCULATIONS FOR POSSIBLE FLOW SHEETS FOR THE PROCESS WASTE TREATMENT PLANT UPGRADE

Appendix C. WASTE GENERATION CALCULATIONS FOR POSSIBLE FLOW SHEETS FOR THE PROCESS WASTE TREATMENT PLANT UPGRADE

Figures 16-40 meet the present 10CRF20 effluent limits of 11.1 and 740 Bq/L for ^{90}Sr and ^{137}Cs, respectively. Figures 41-52 met the proposed limits of 37 and 111 Bq/L for ^{90}Sr and ^{137}Cs, respectively. Figures 41, 43, 45, 46, 47, 48, 49, 51 and 52 were used in economic analyses as indicated in Table 9.

ORNL DWG 87-1310

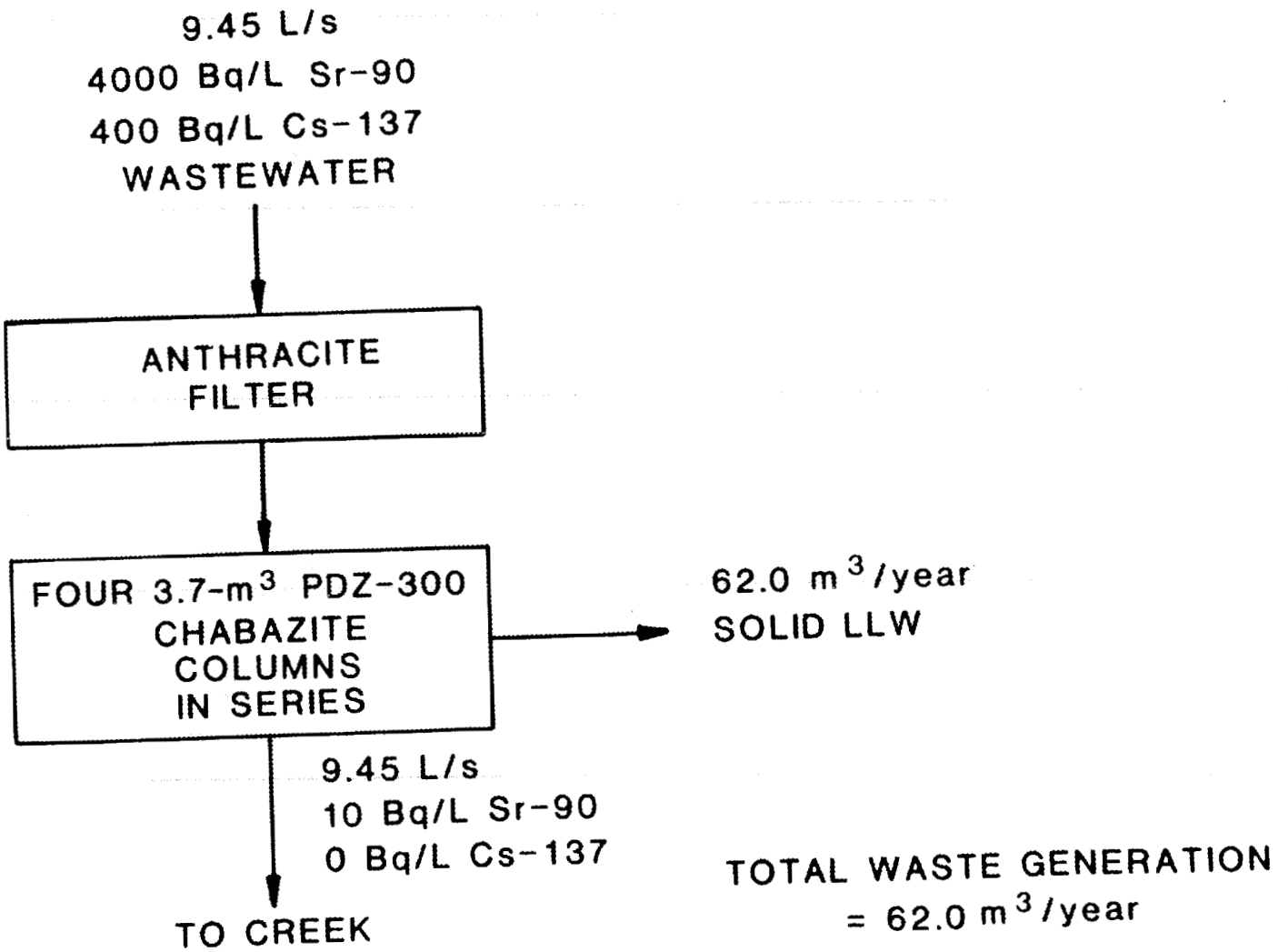


Fig. 16. Chabazite flow sheet using PDZ-300 zeolite.

ORNL DWG 87-1309

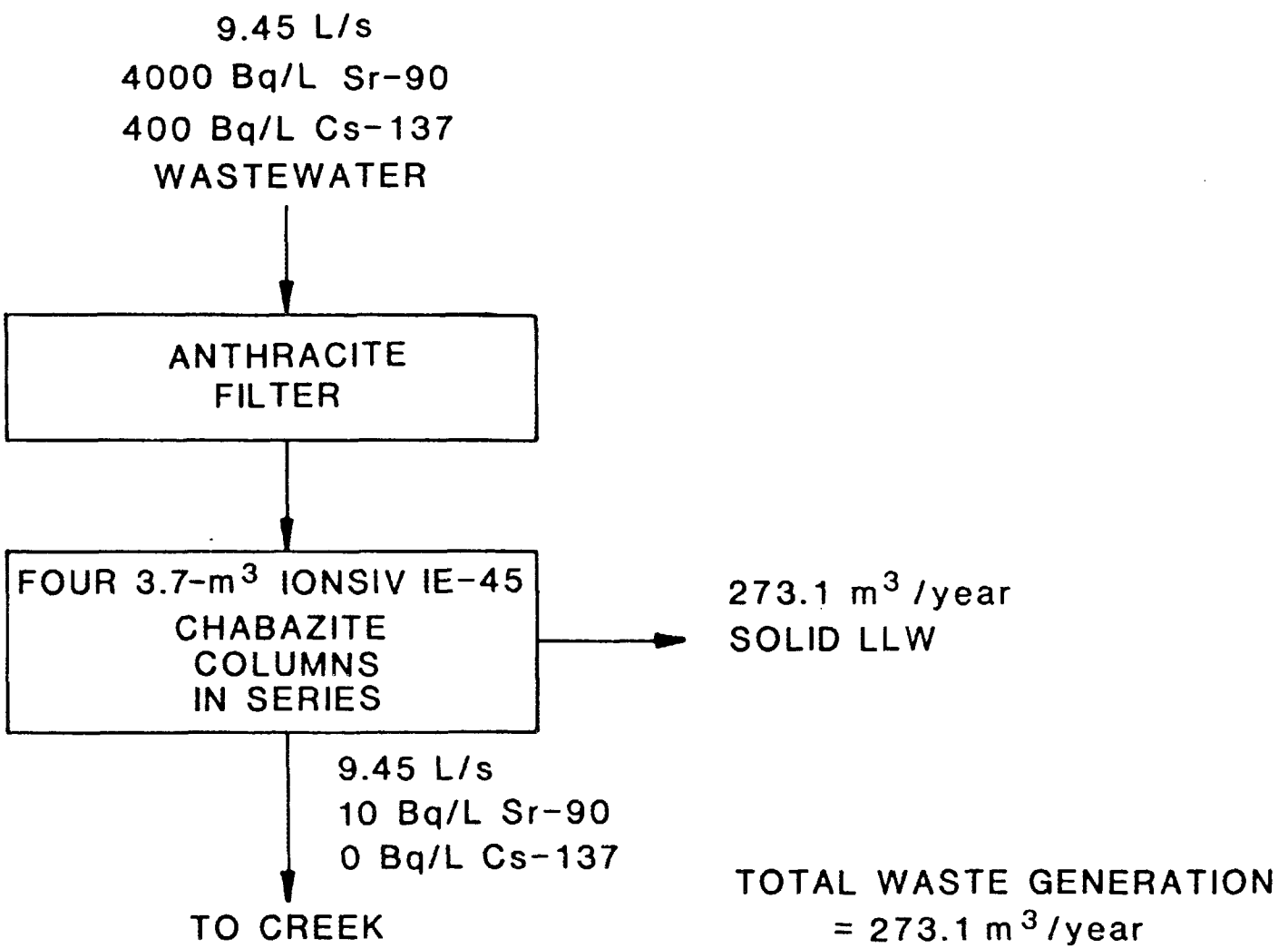


Fig. 17. Chabazite flow sheet using Ionsiv IE-95 zeolite.

ORNL DWG 87-1322

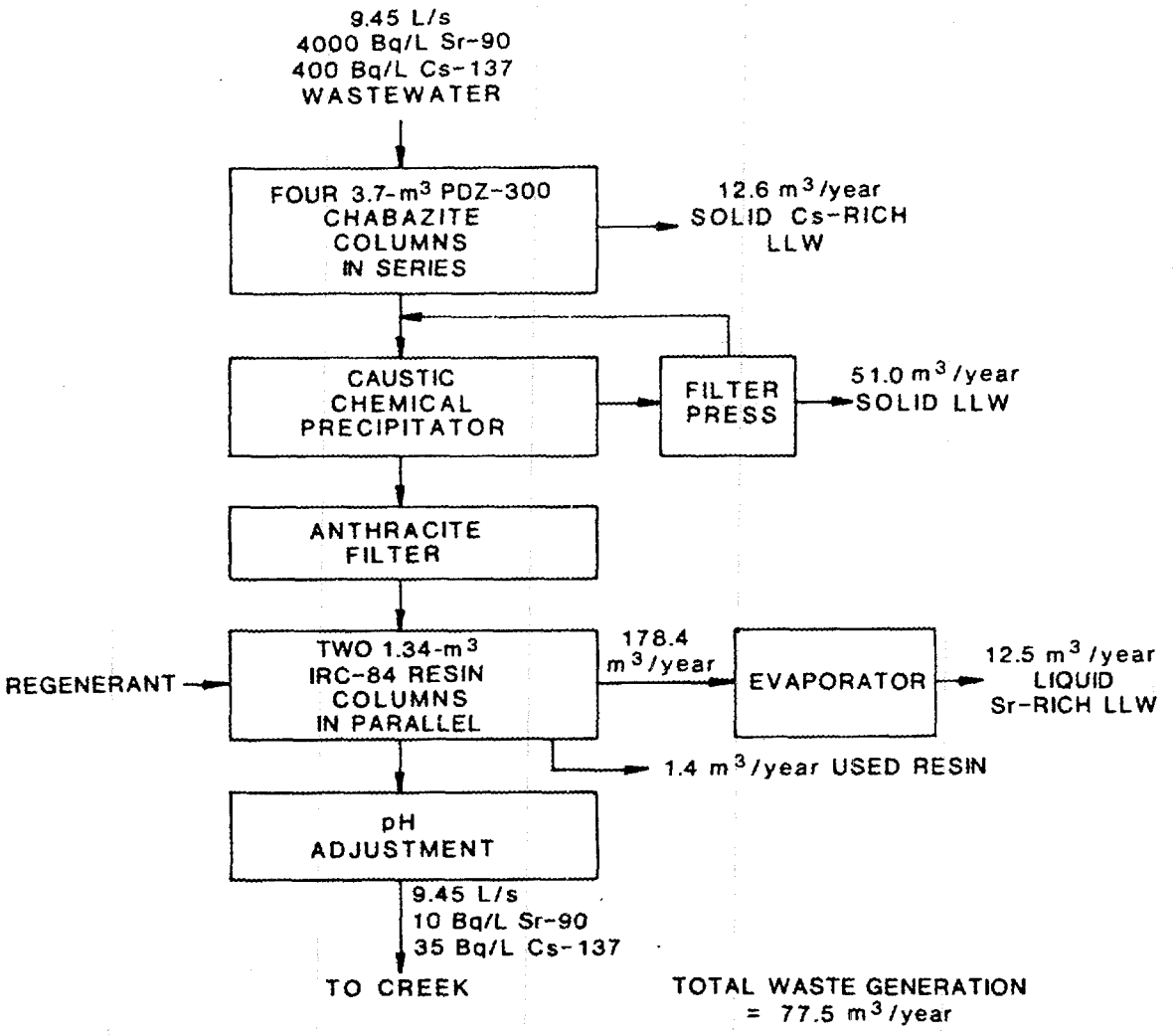


Fig. 18. IRC-84 flow sheet with caustic precipitation and regeneration of resin.

ORNL DWG 87-1321

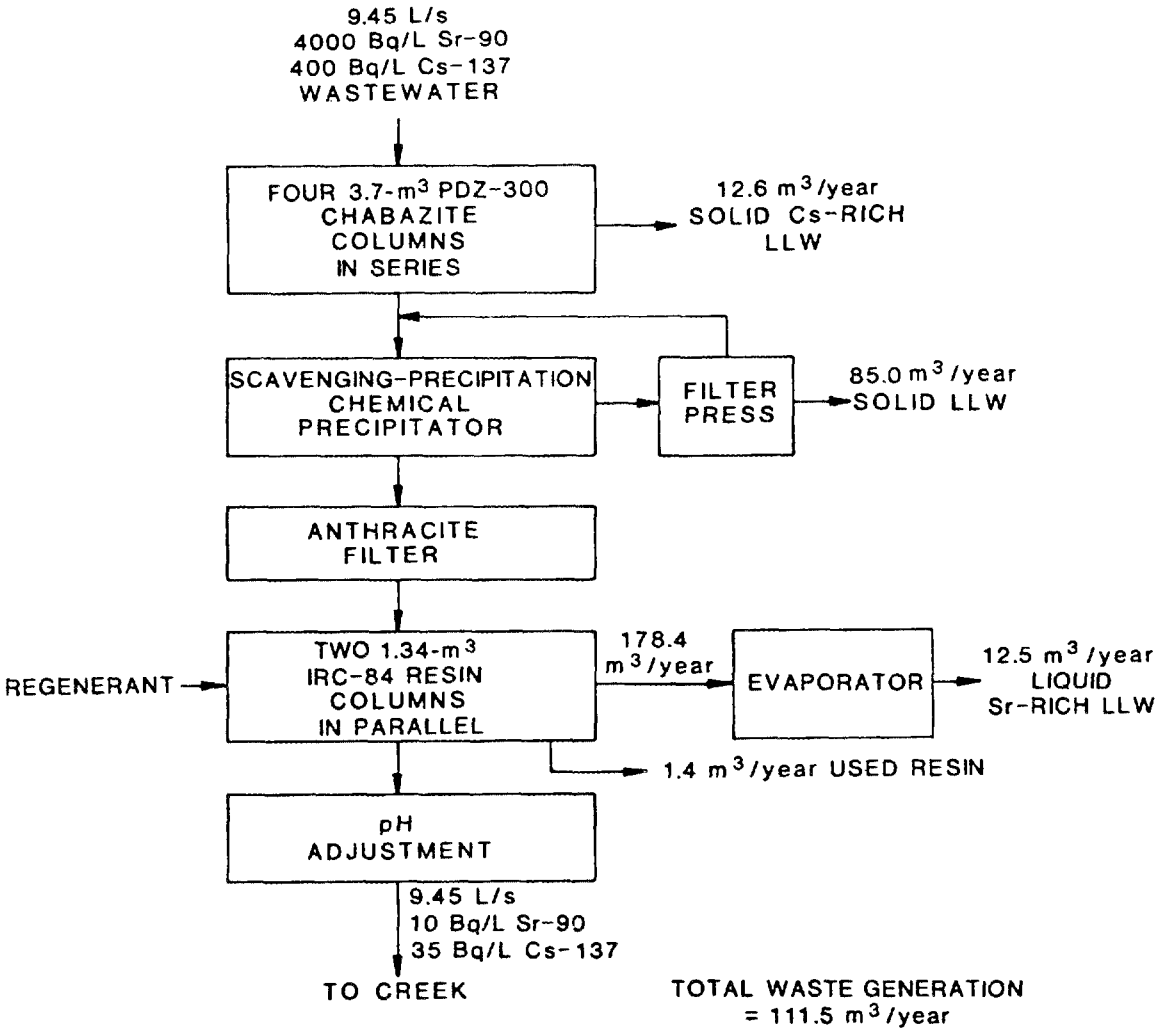


Fig. 19. IRC-84 flow sheet with scavenging precipitation and regeneration of resin.

ORNL DWG 87-1313

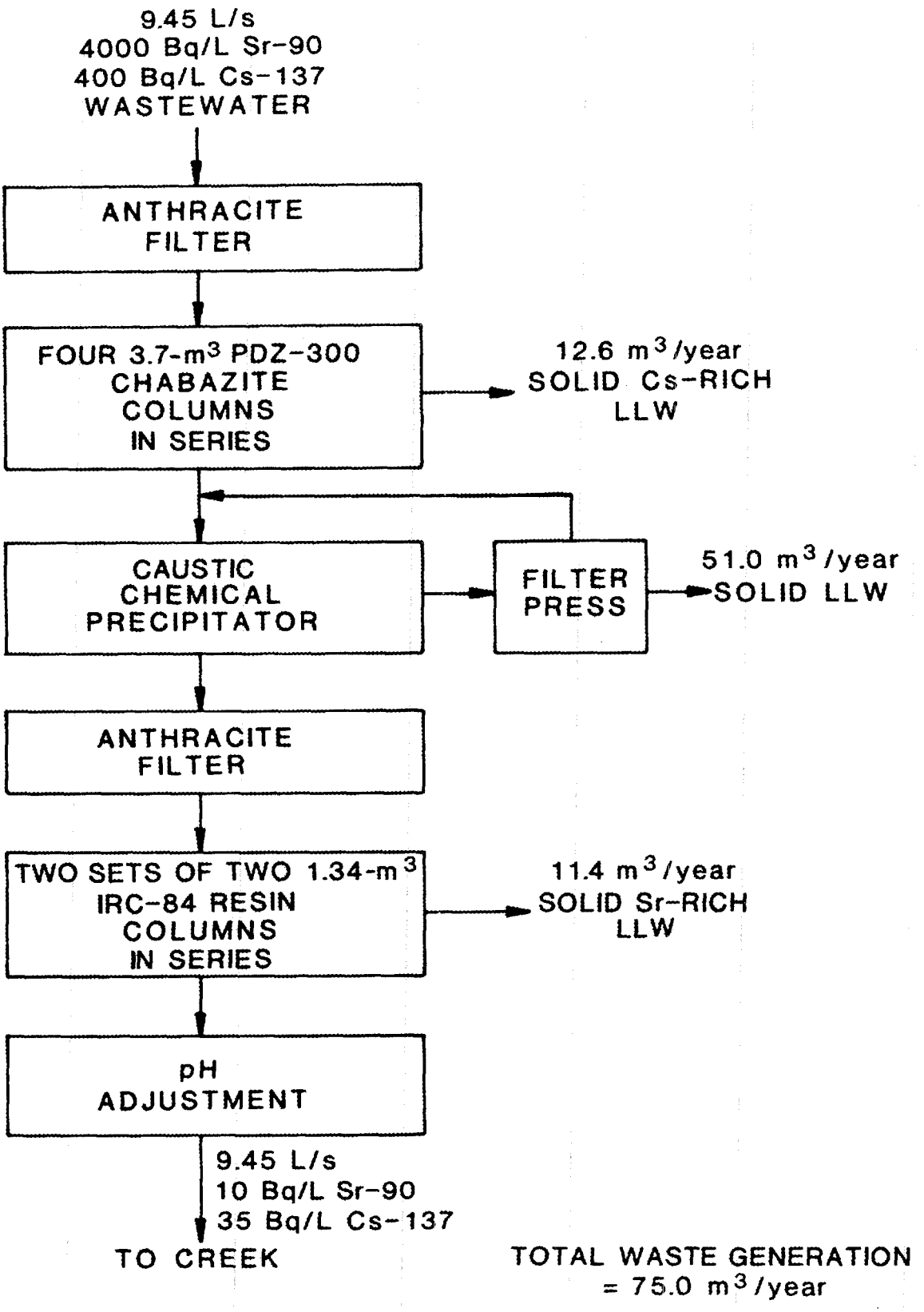


Fig. 20. IRC-84 flow sheet with caustic precipitation and direct disposal of resin from 1.34-m^3 columns.

ORNL DWG 87-1315

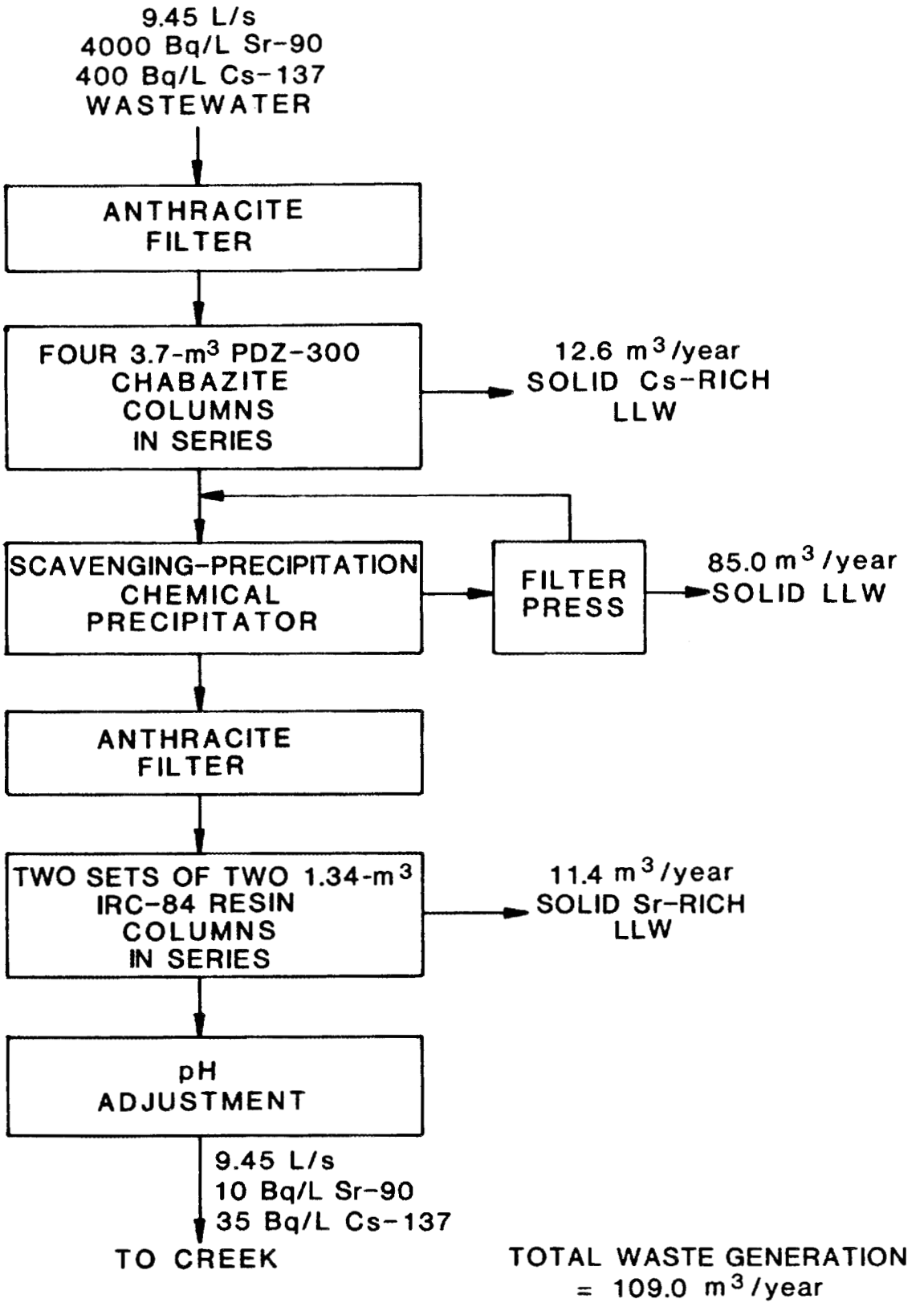


Fig. 21. IRC-84 flow sheet with scavenging precipitation and direct disposal of resin from 1.34-m^3 columns.

ORNL DWG 87-1314

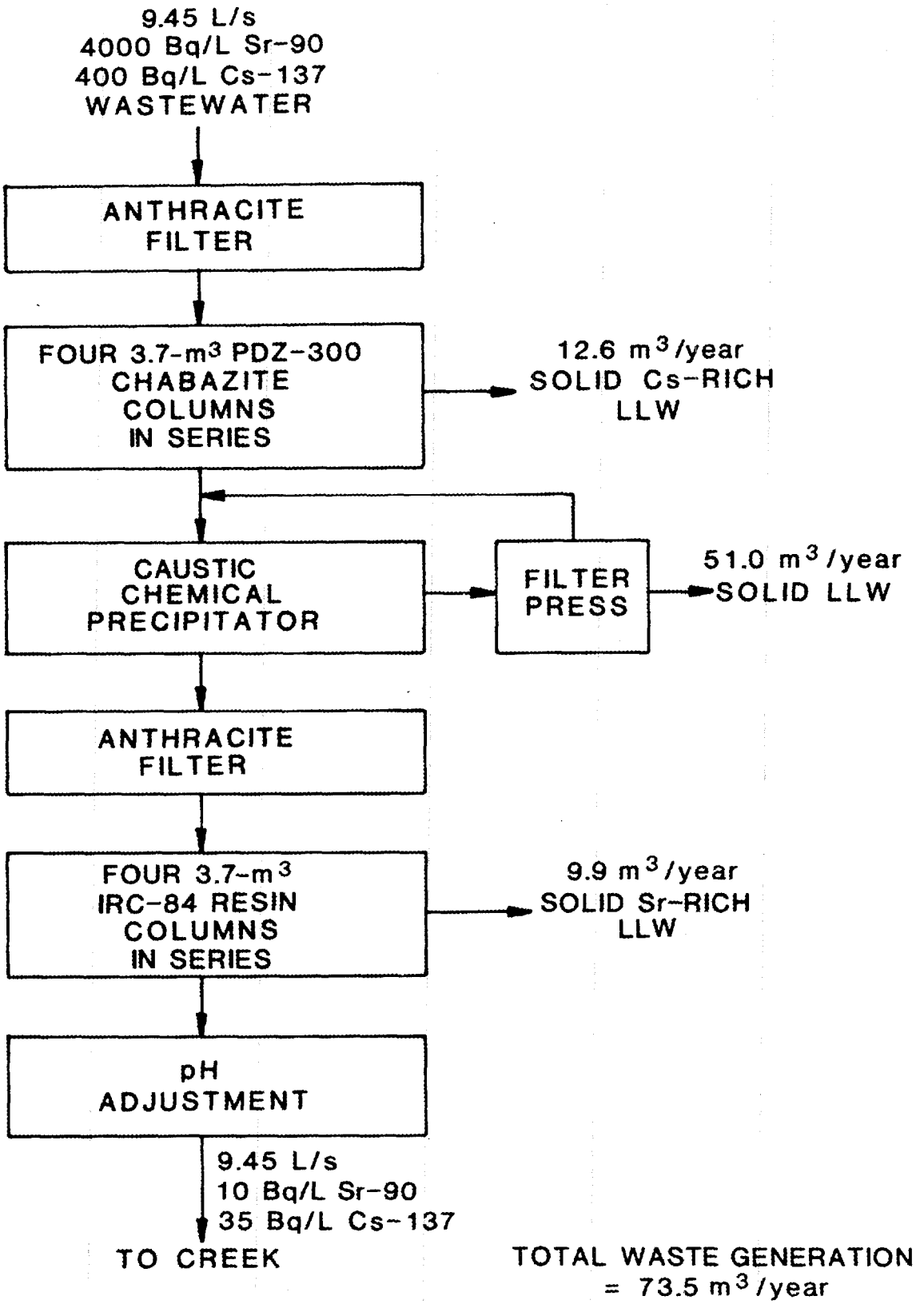


Fig. 22. IRC-84 flow sheet with caustic precipitation and direct disposal of resin from 3.7-m^3 columns.

ORNL DWG 87-1316

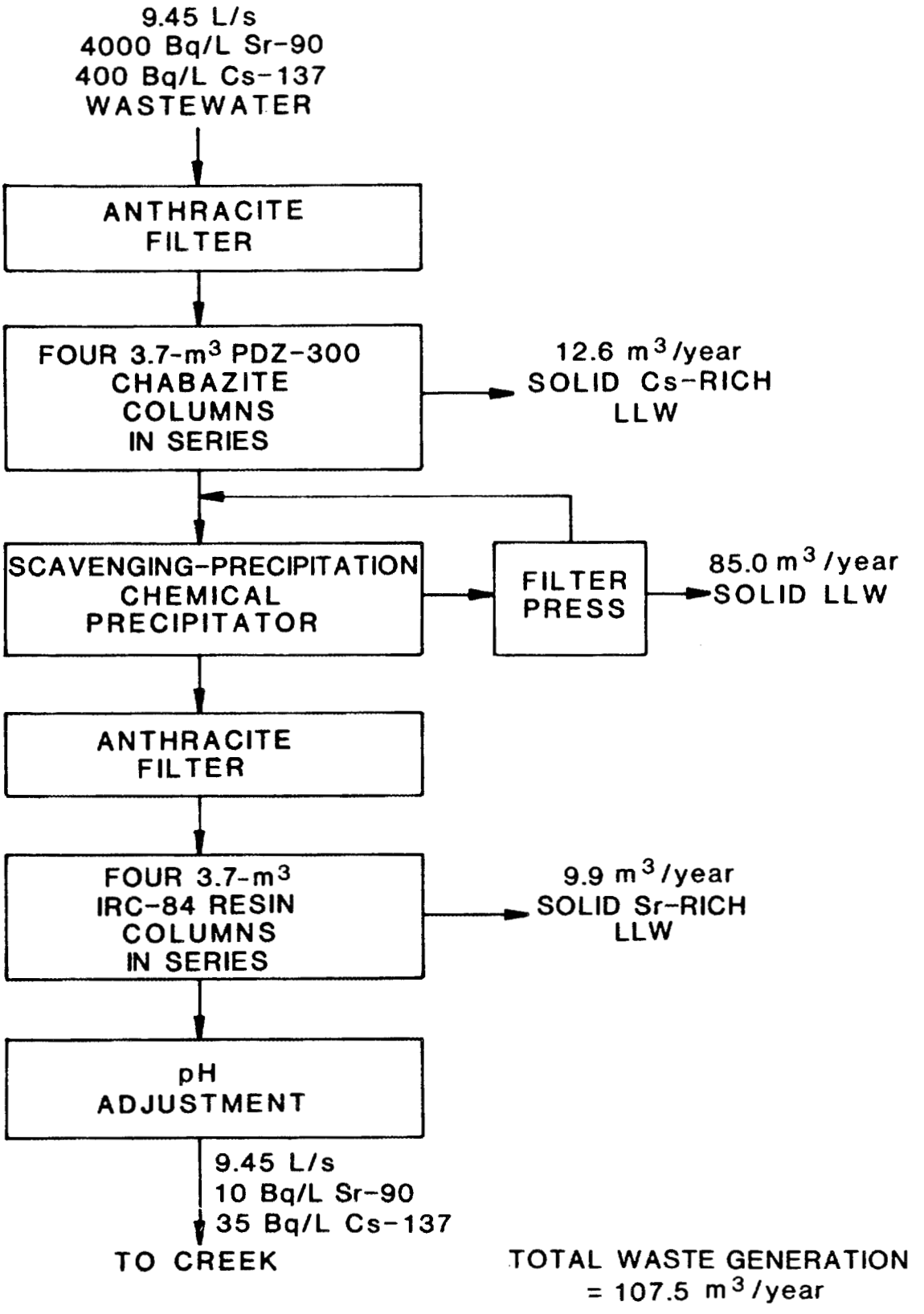


Fig. 23. IRC-84 flow sheet with scavenging precipitation and direct disposal of resin from 3.7-m^3 columns.

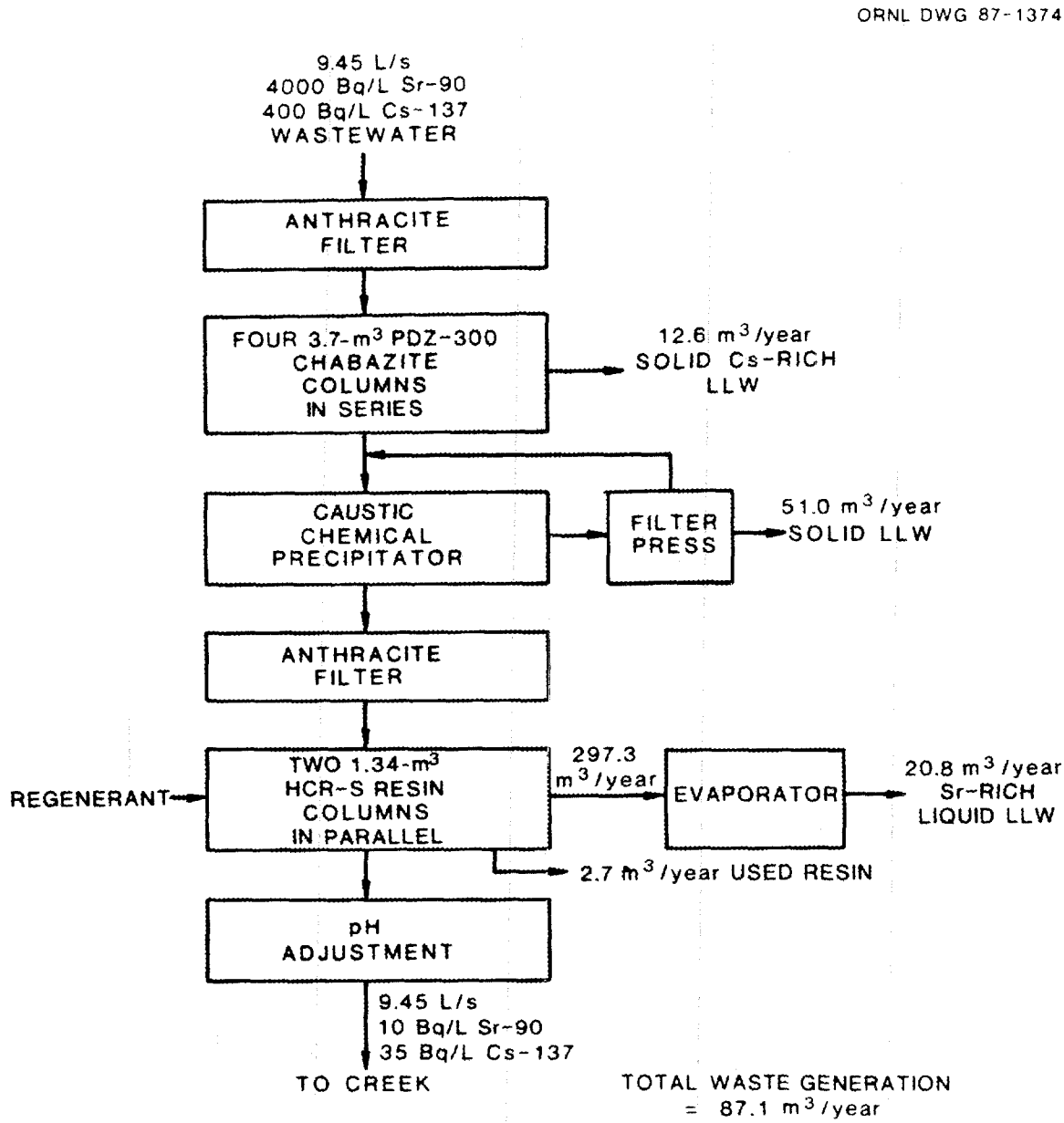


Fig. 24. HRC-S flow sheet with caustic precipitation.

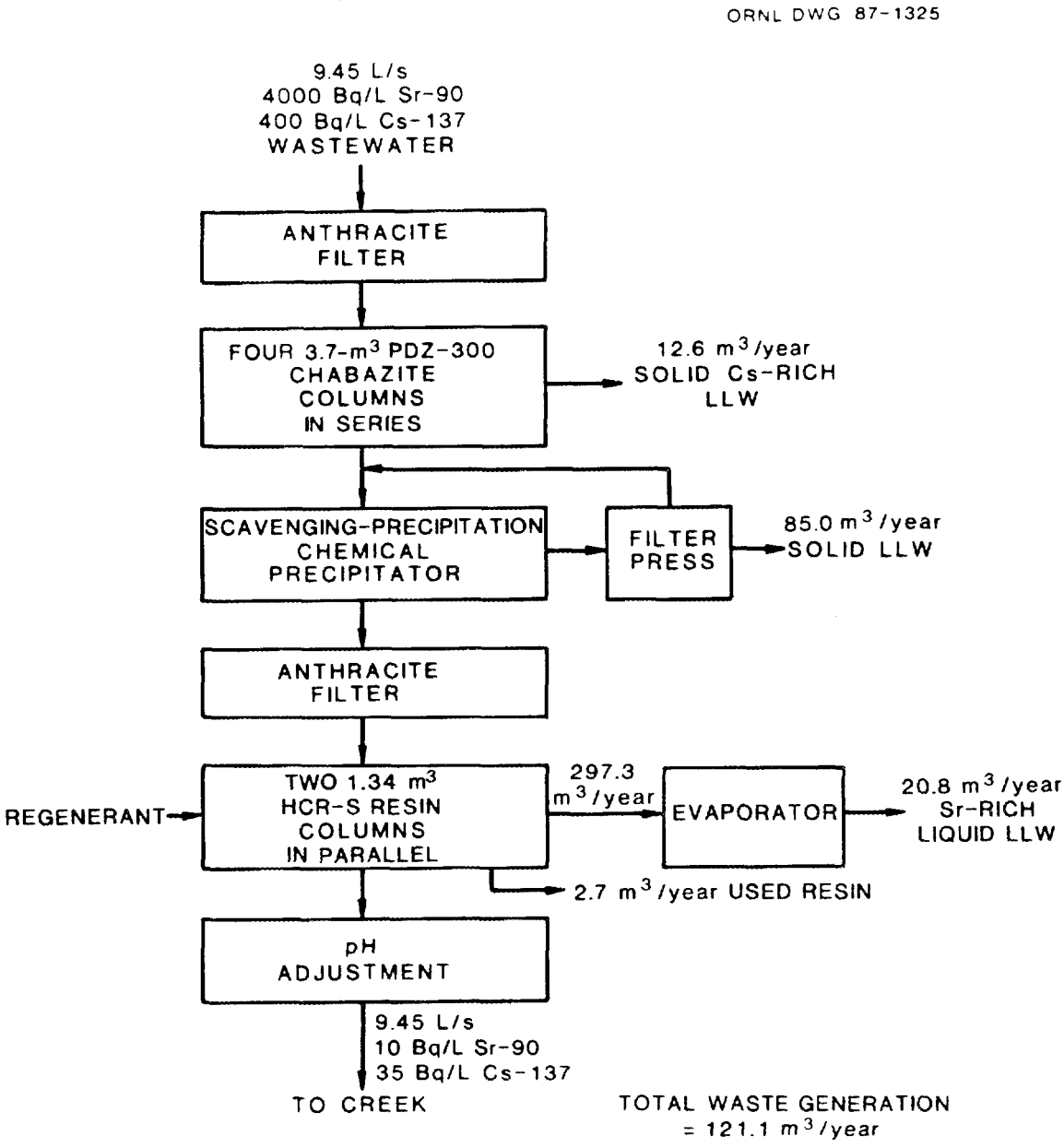


Fig. 25. HRC-S flow sheet with scavenging precipitation.

ORNL DWG 87-1298

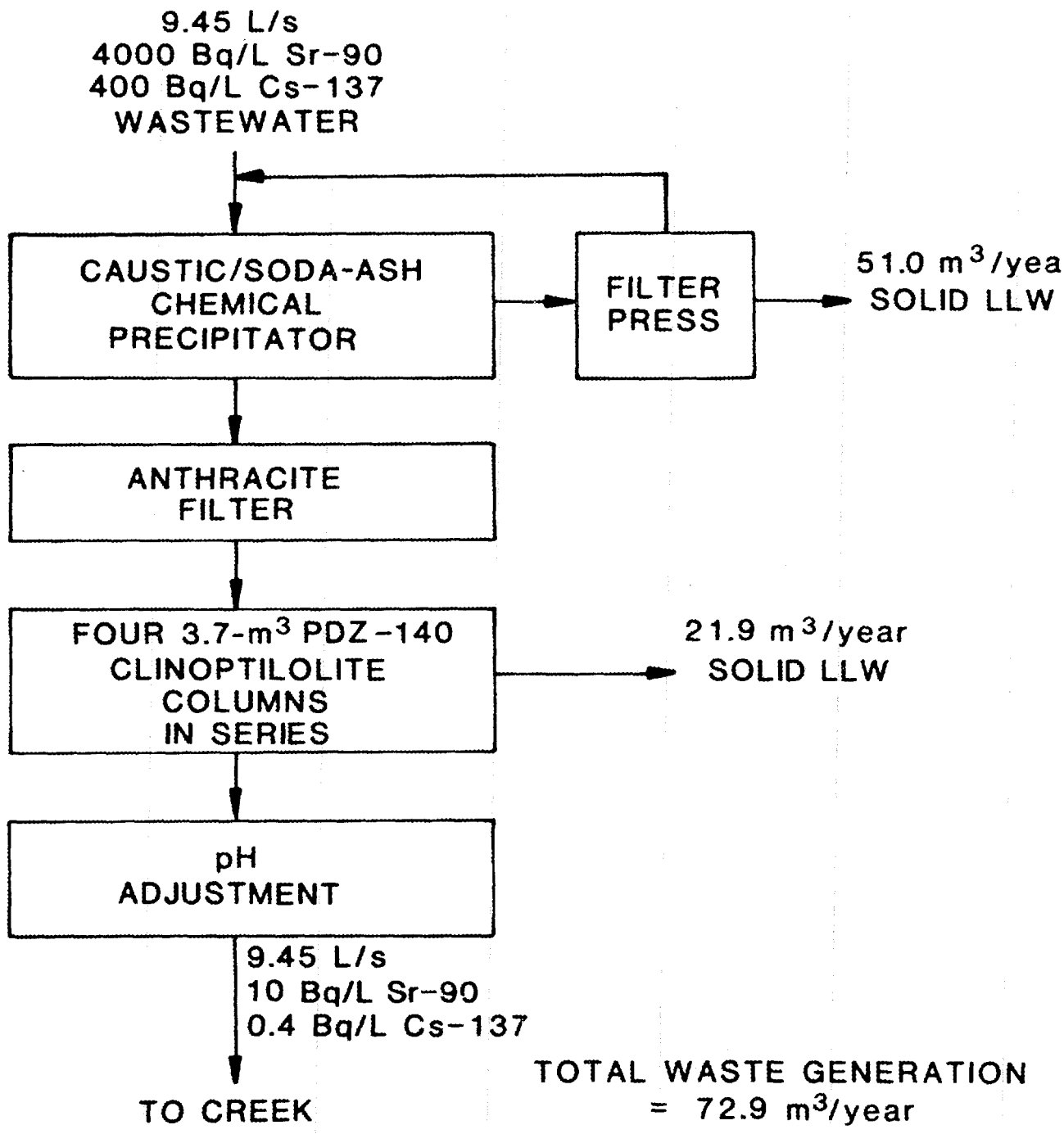


Fig. 26. Clinoptilolite flow sheet with caustic-soda-ash precipitation and PDZ-140 zeolite in 3.7-m^3 columns.

ORNL DWG 87-1299

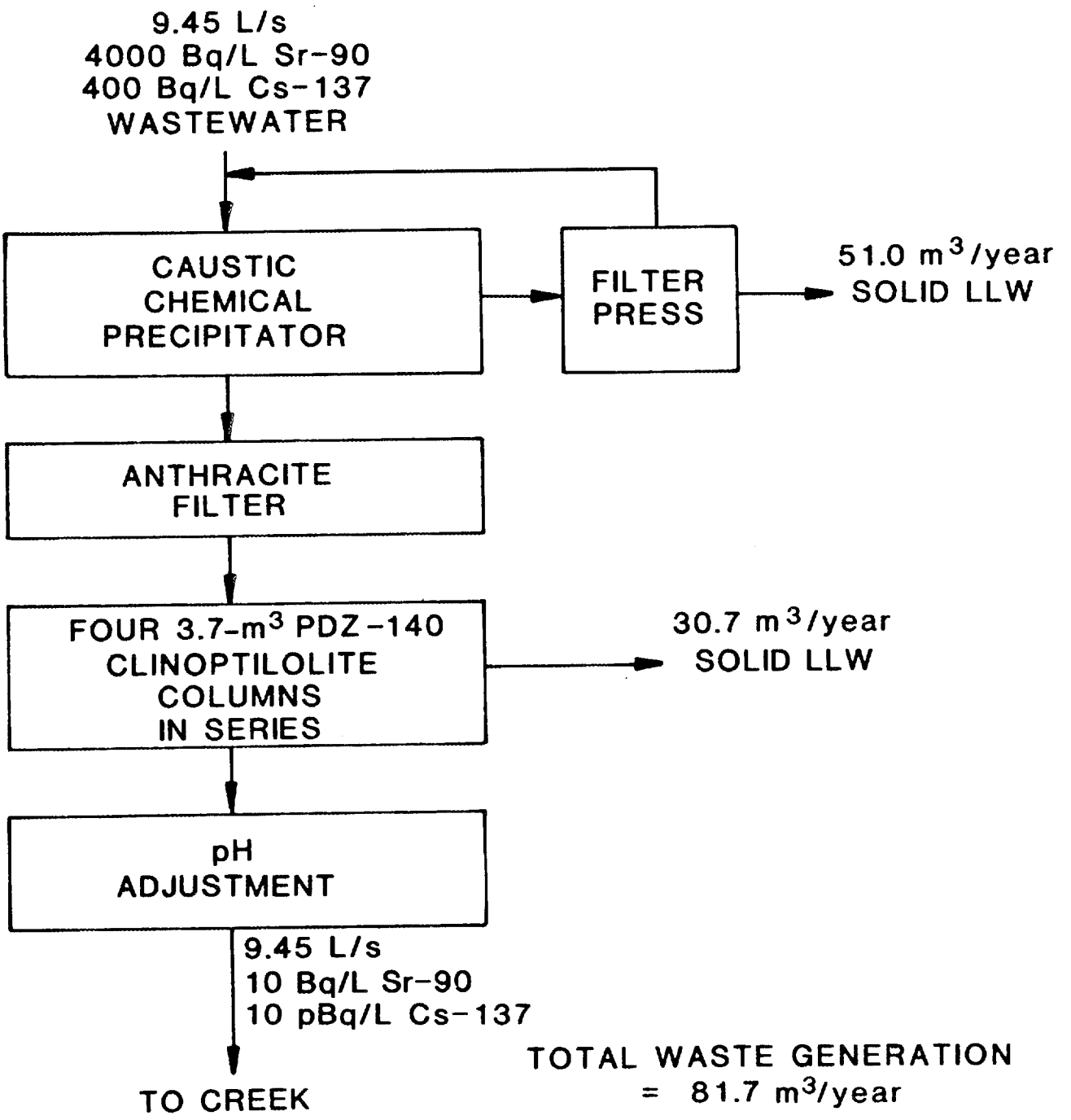


Fig. 27. Clinoptilolite flow sheet with caustic precipitation and PDZ-140 zeolite in 3.7-m^3 columns.

ORNL DWG 87-1300

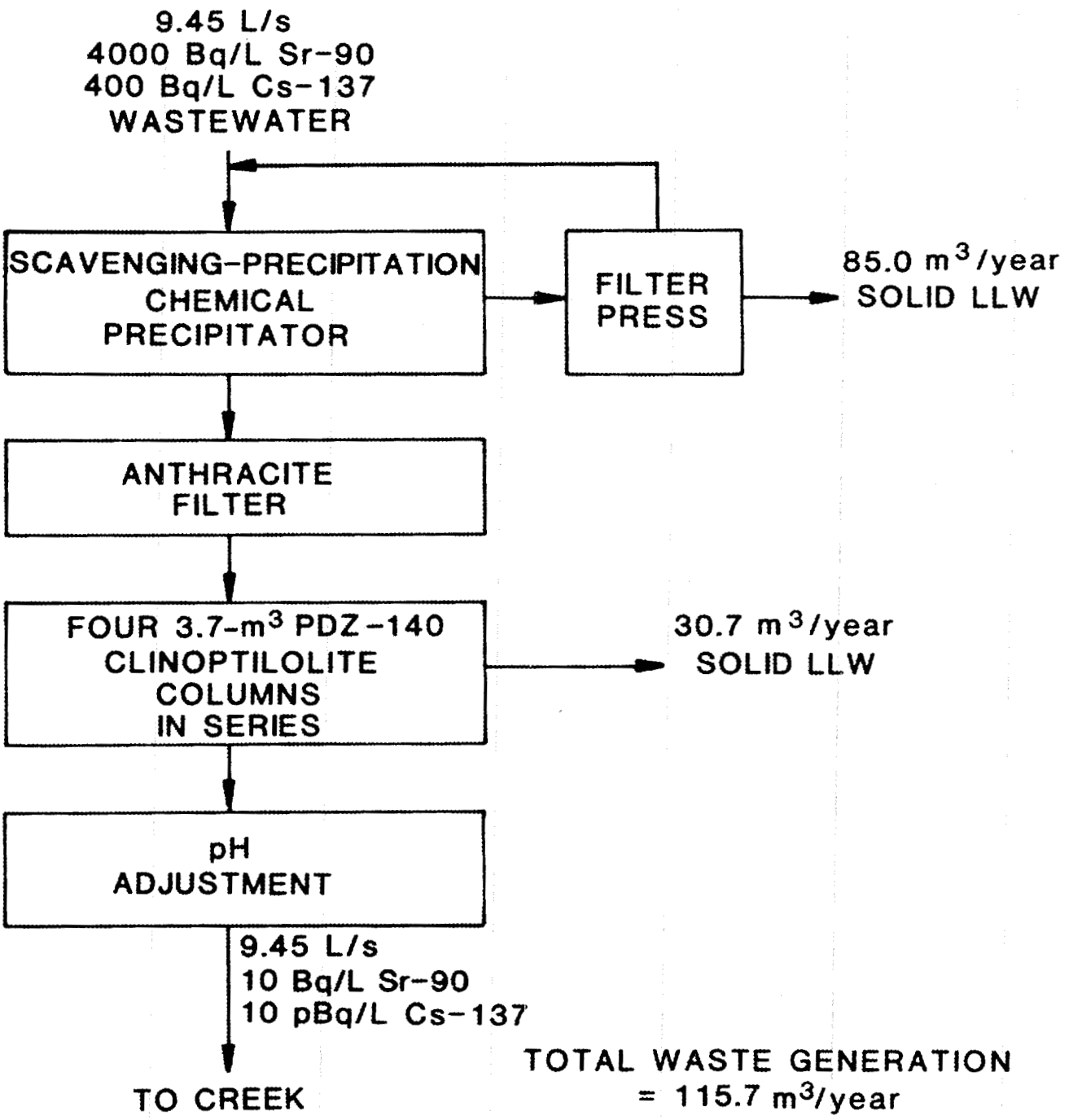


Fig. 28. Clinoptilolite flow sheet with scavenging-precipitation and PDZ-140 zeolite in 3.7-m^3 columns.

ORNL DWG 87-1301

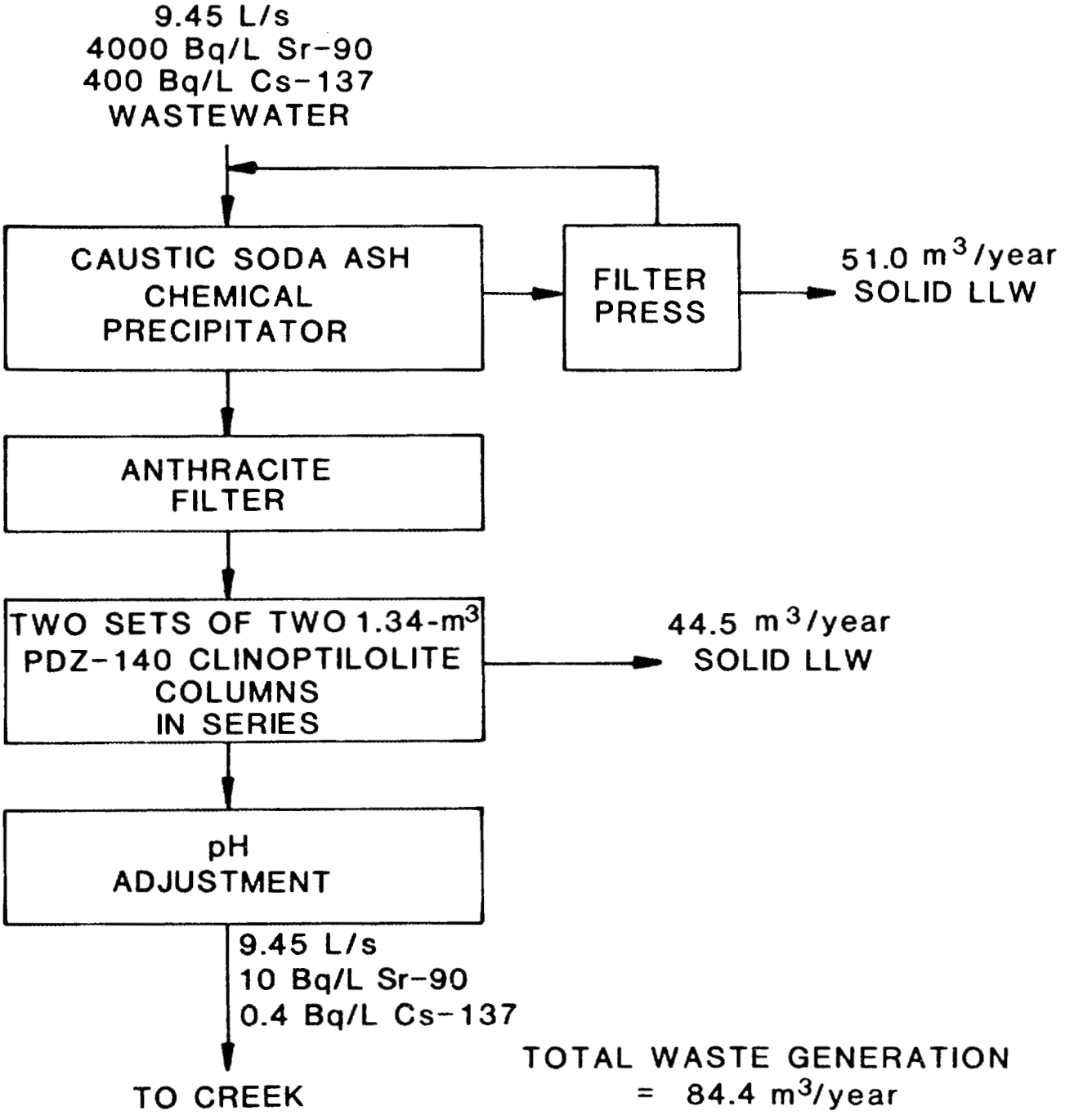


Fig. 29. Clinoptilolite flow sheet with caustic-soda-ash precipitation and PDZ-140 zeolite in 1.34-m^3 columns.

ORNL DWG 87-1302

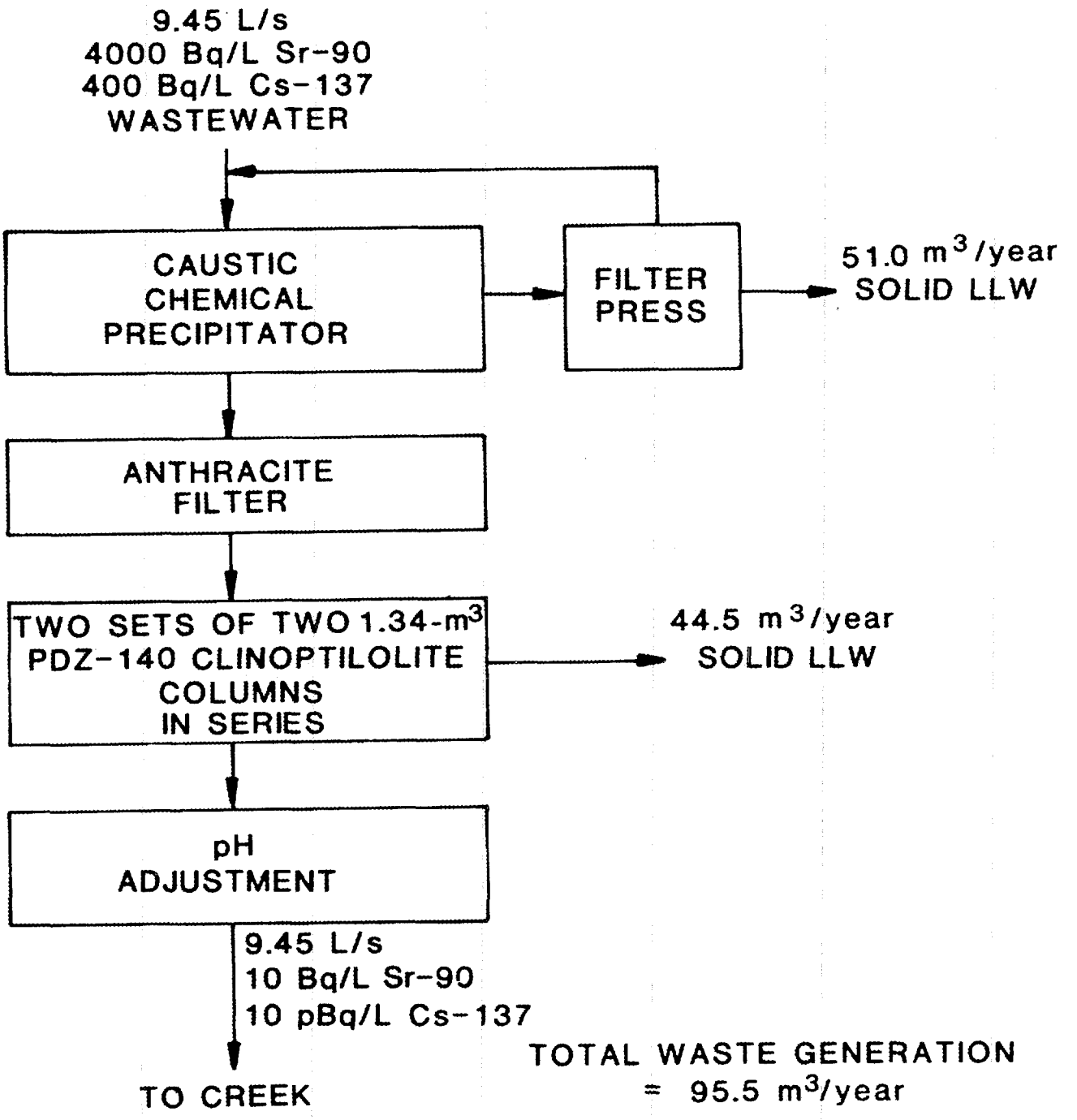


Fig. 30. Clinoptilolite flow sheet with caustic precipitation and PDZ-140 zeolite in 1.34-m^3 columns.

ORNL DWG 87-1303

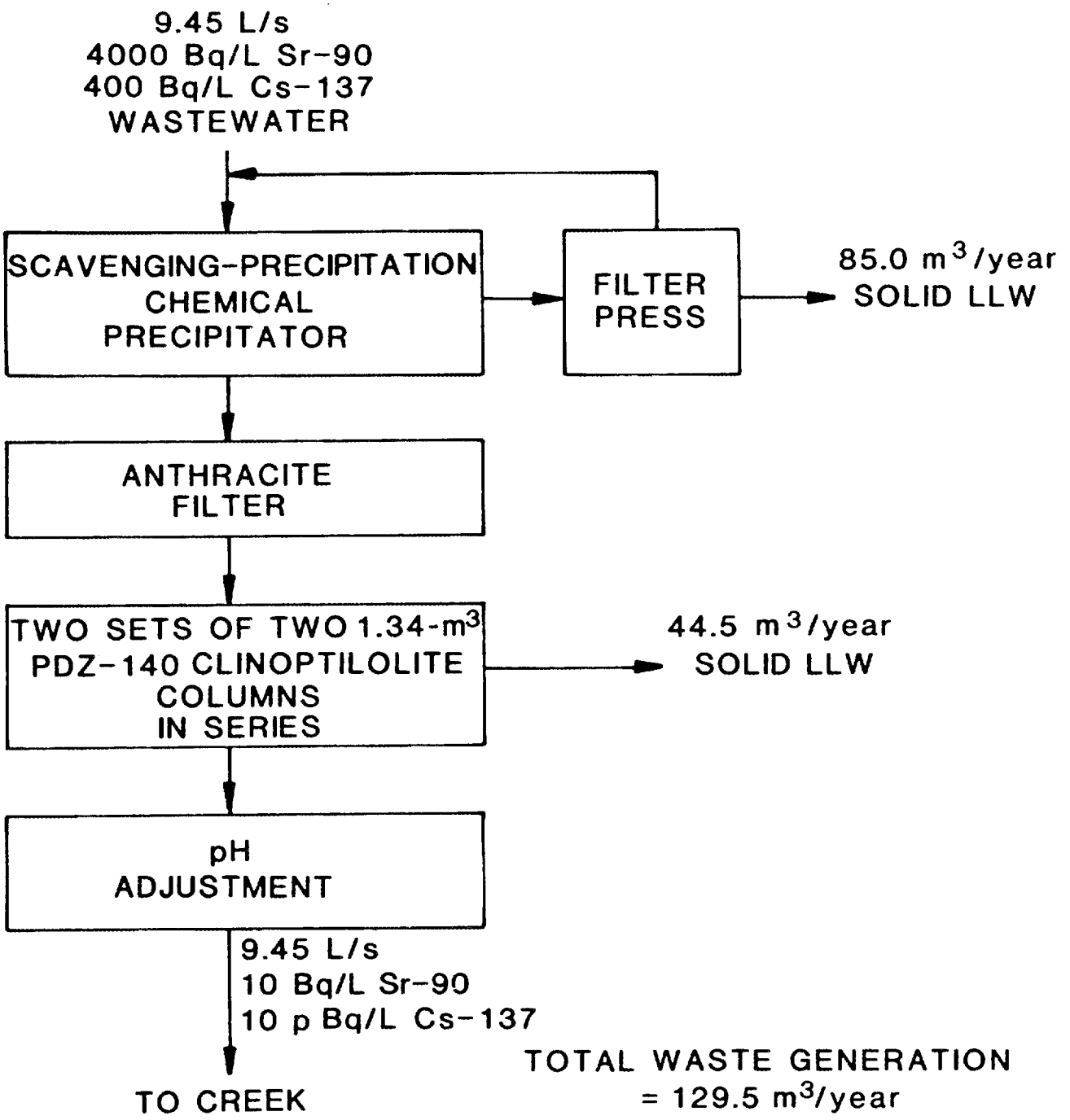


Fig. 31. Clinoptilolite flow sheet with scavenging-precipitation and PDZ-140 zeolite in 1.34-m^3 columns.

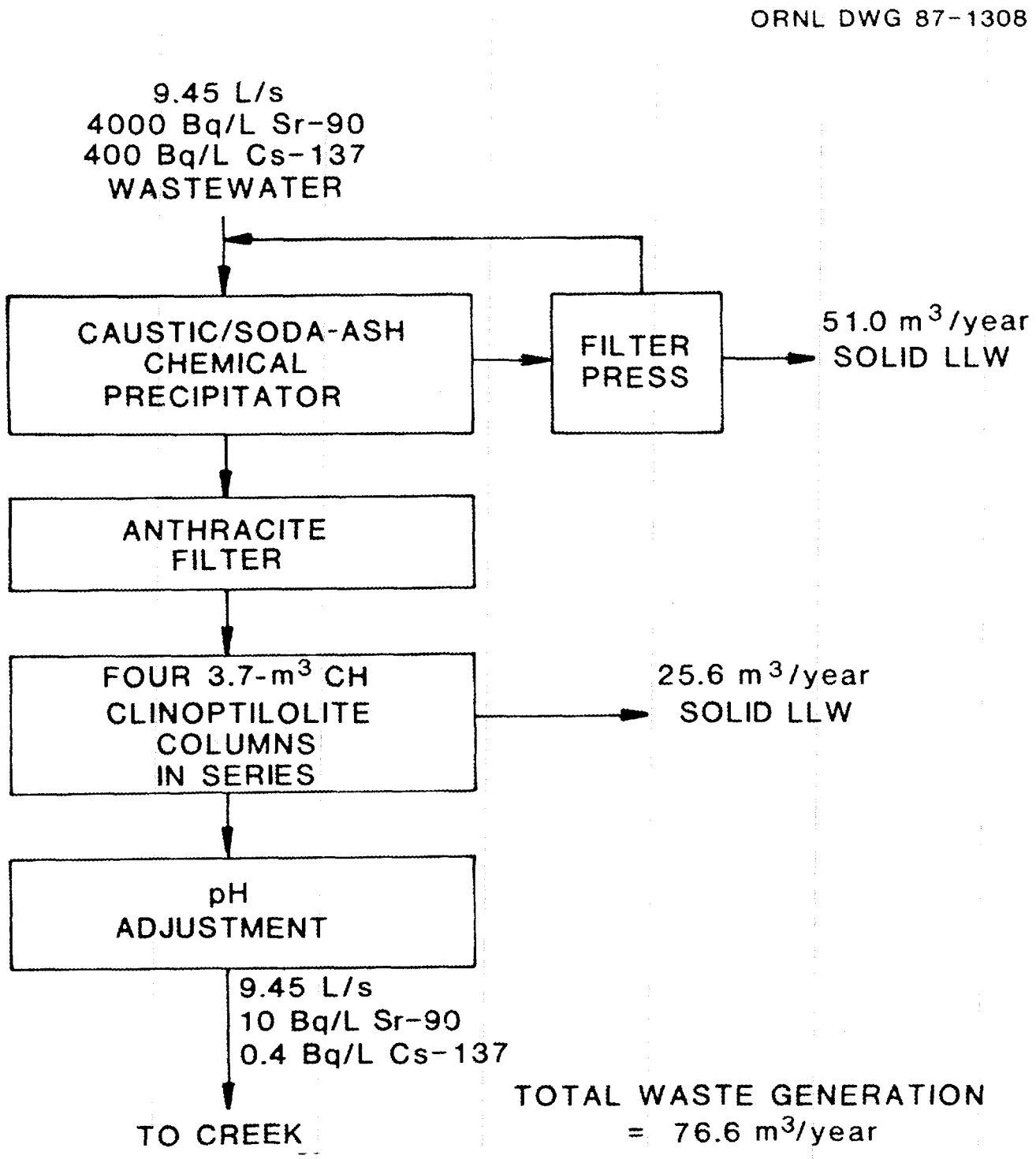


Fig. 32. Clinoptilolite flow sheet with caustic-soda-ash precipitation and CH zeolite in 3.7-m^3 columns.

ORNL DWG 87-1324

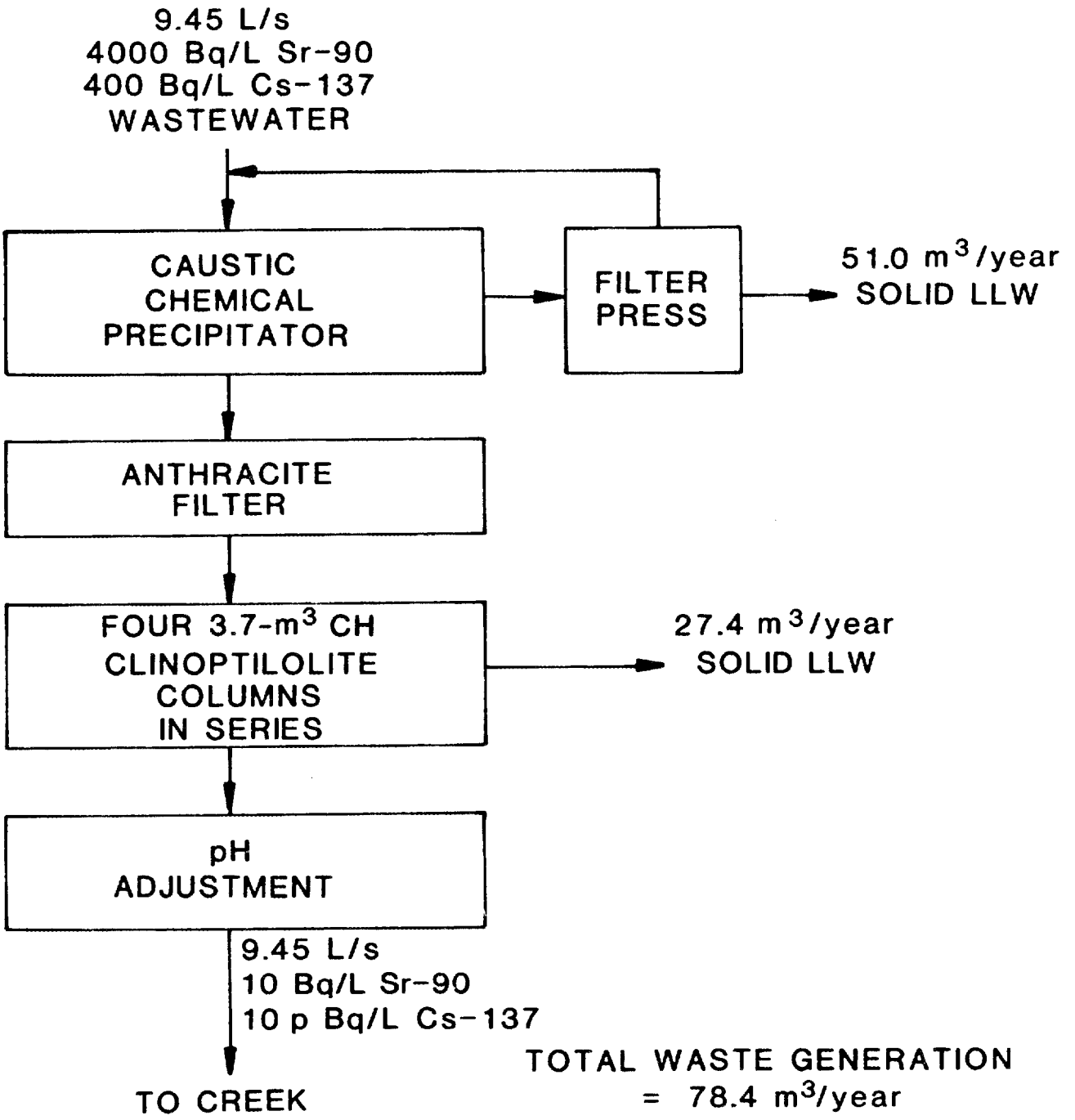


Fig. 33. Clinoptilolite flow sheet with caustic precipitation and CH zeolite in 3.7-m^3 columns.

ORNL DWG 87-1312

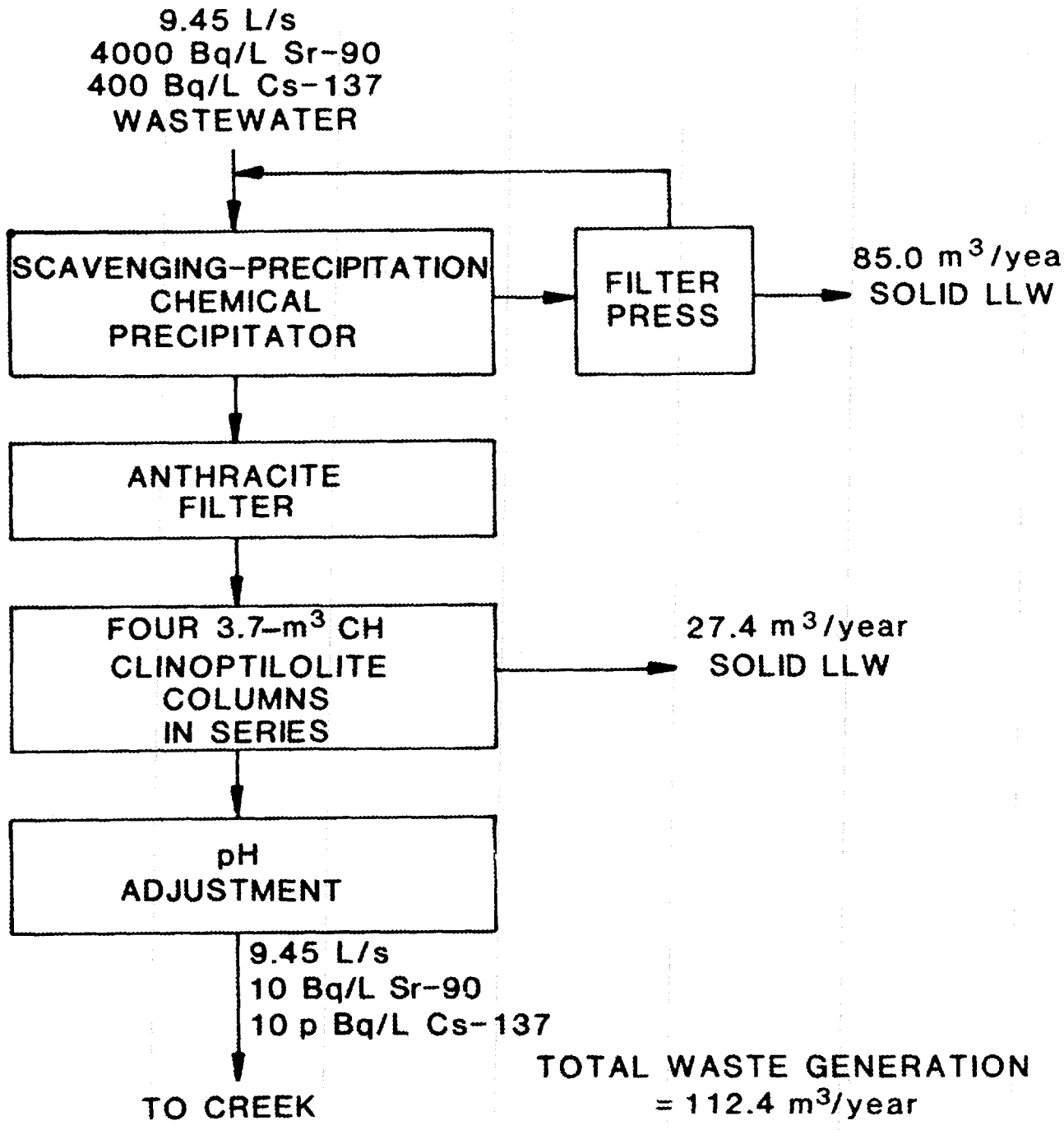


Fig. 34. Clinoptilolite flow sheet with scavenging-precipitation and CH zeolite in 3.7-m^3 columns.

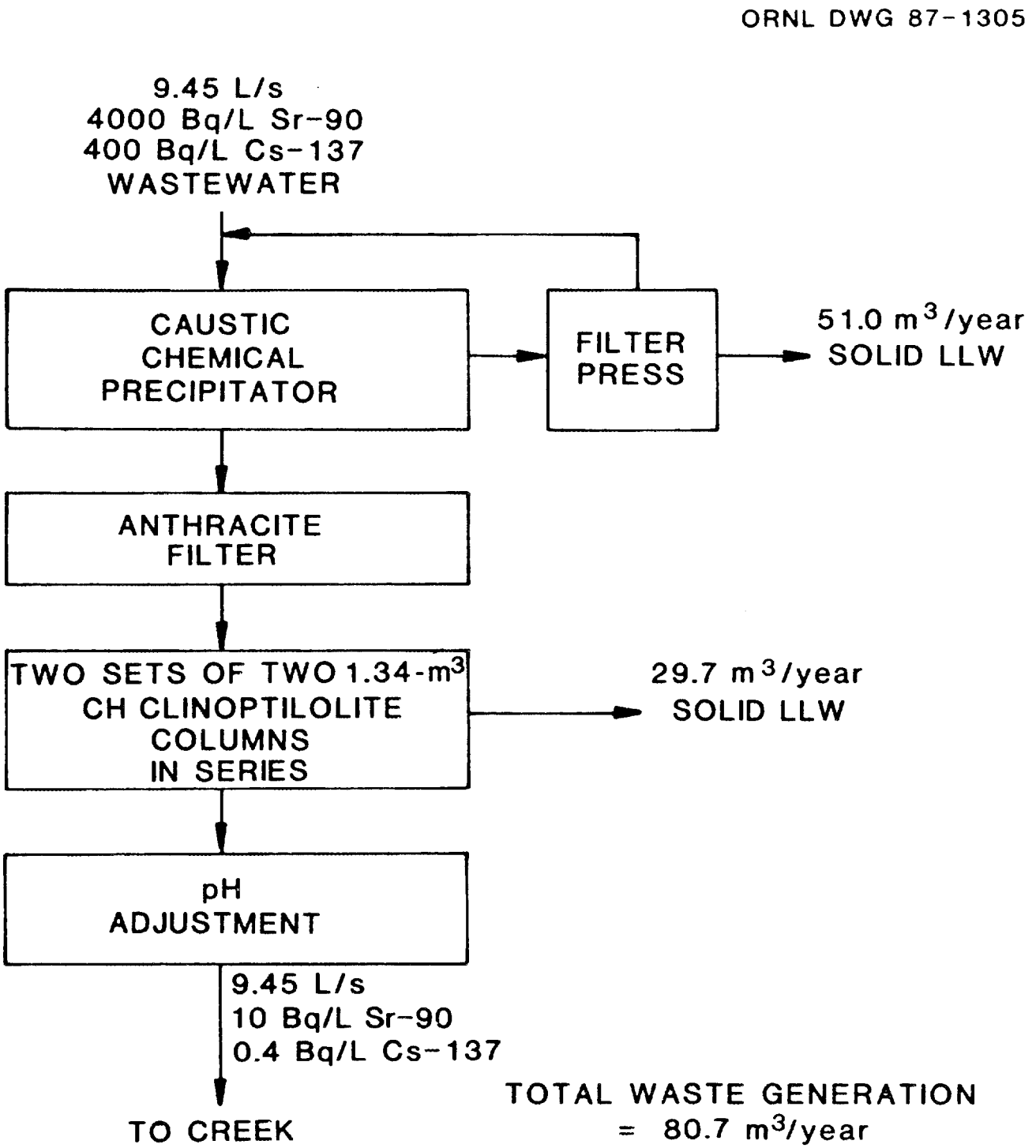


Fig. 35. Clinoptilolite flow sheet with caustic precipitation and CH zeolite in 1.34-m^3 columns.

ORNL DWG 87-1306

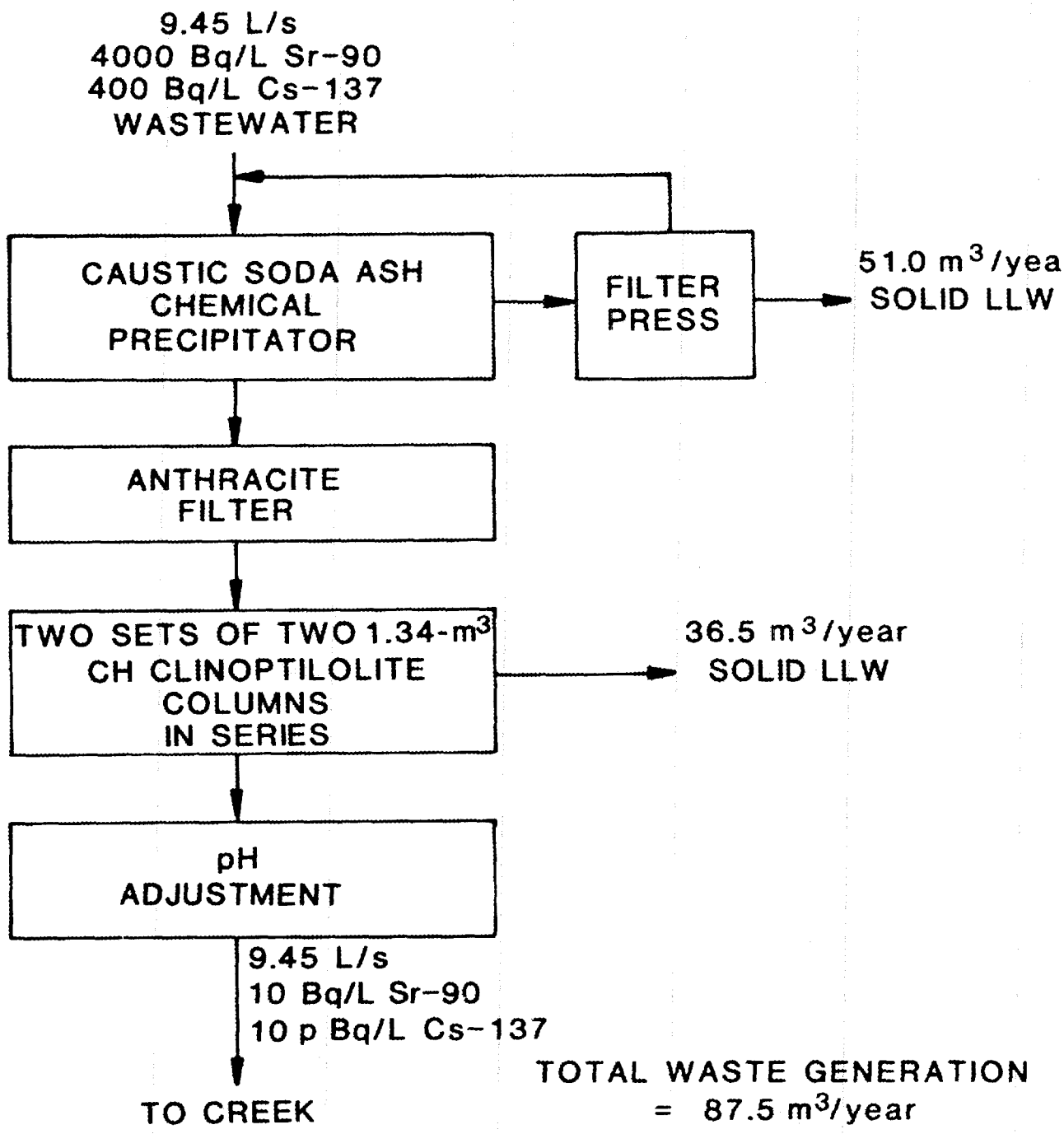


Fig. 36. Clinoptilolite flow sheet with caustic-soda-ash precipitation and CH zeolite in 1.34-m^3 columns.

ORNL DWG 87-1304

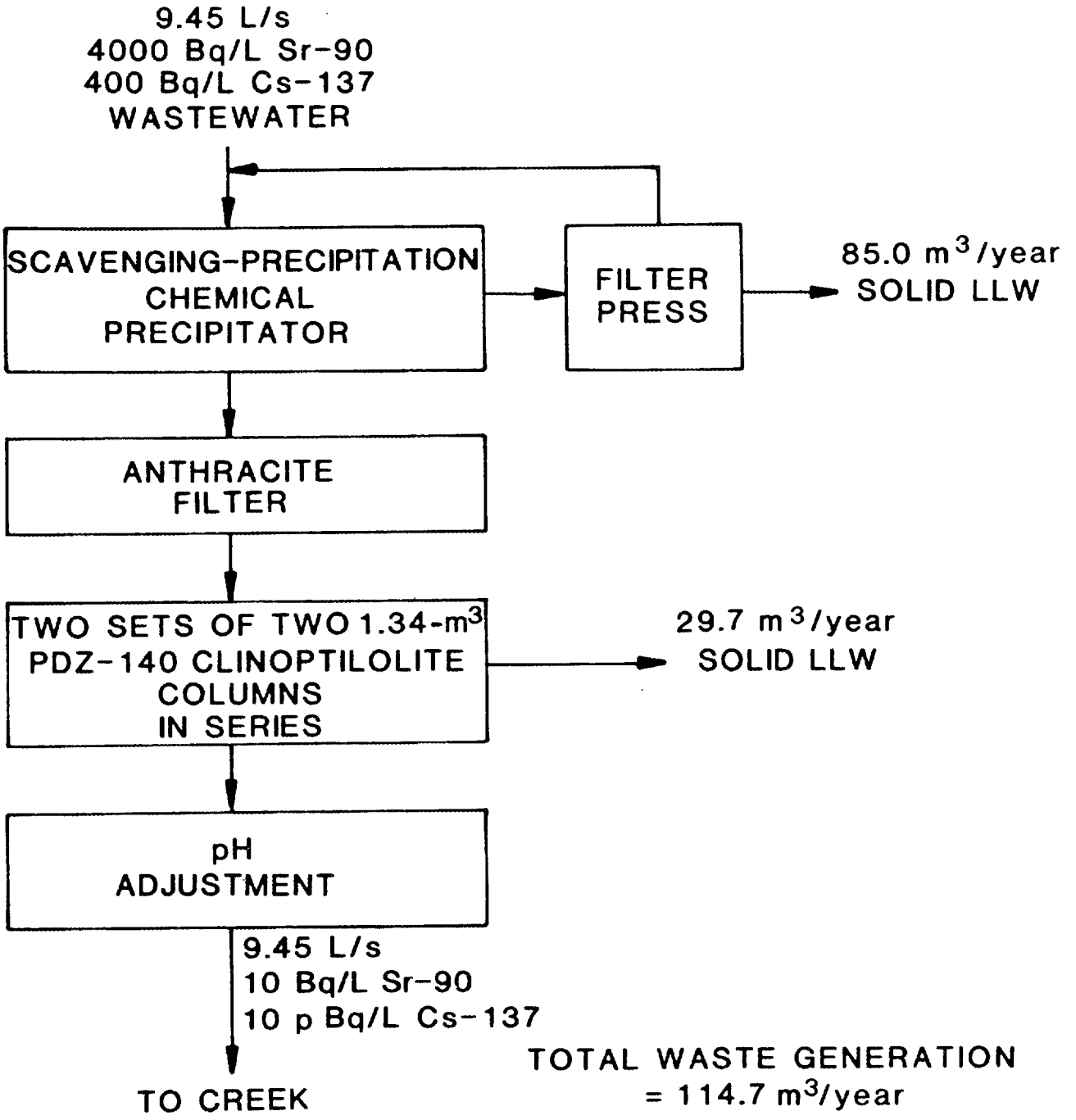


Fig. 37. Clinoptilolite flow sheet with scavenging-precipitation and CH zeolite in 1.34-m^3 columns.

ORNL DWG 87-1292

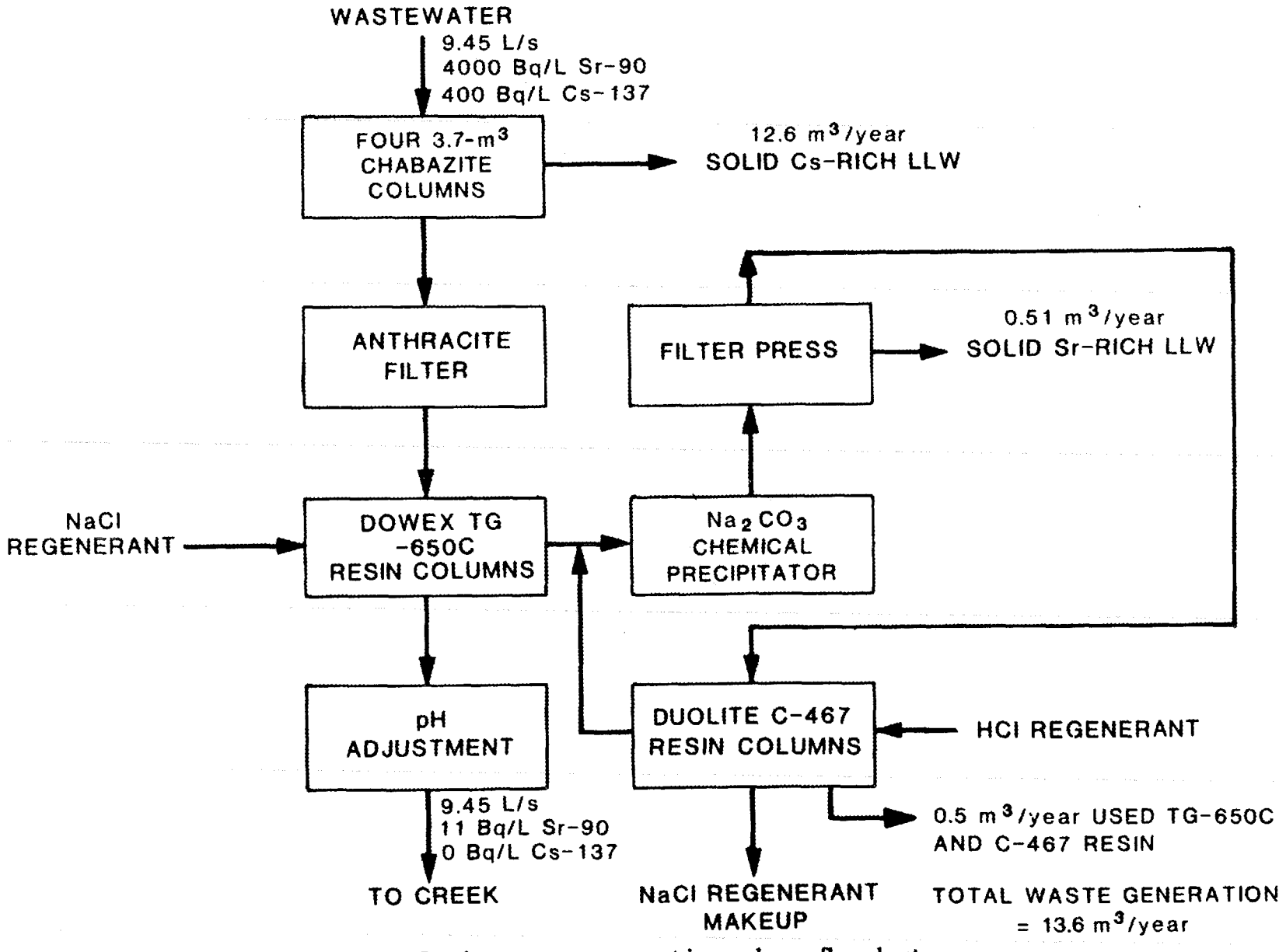
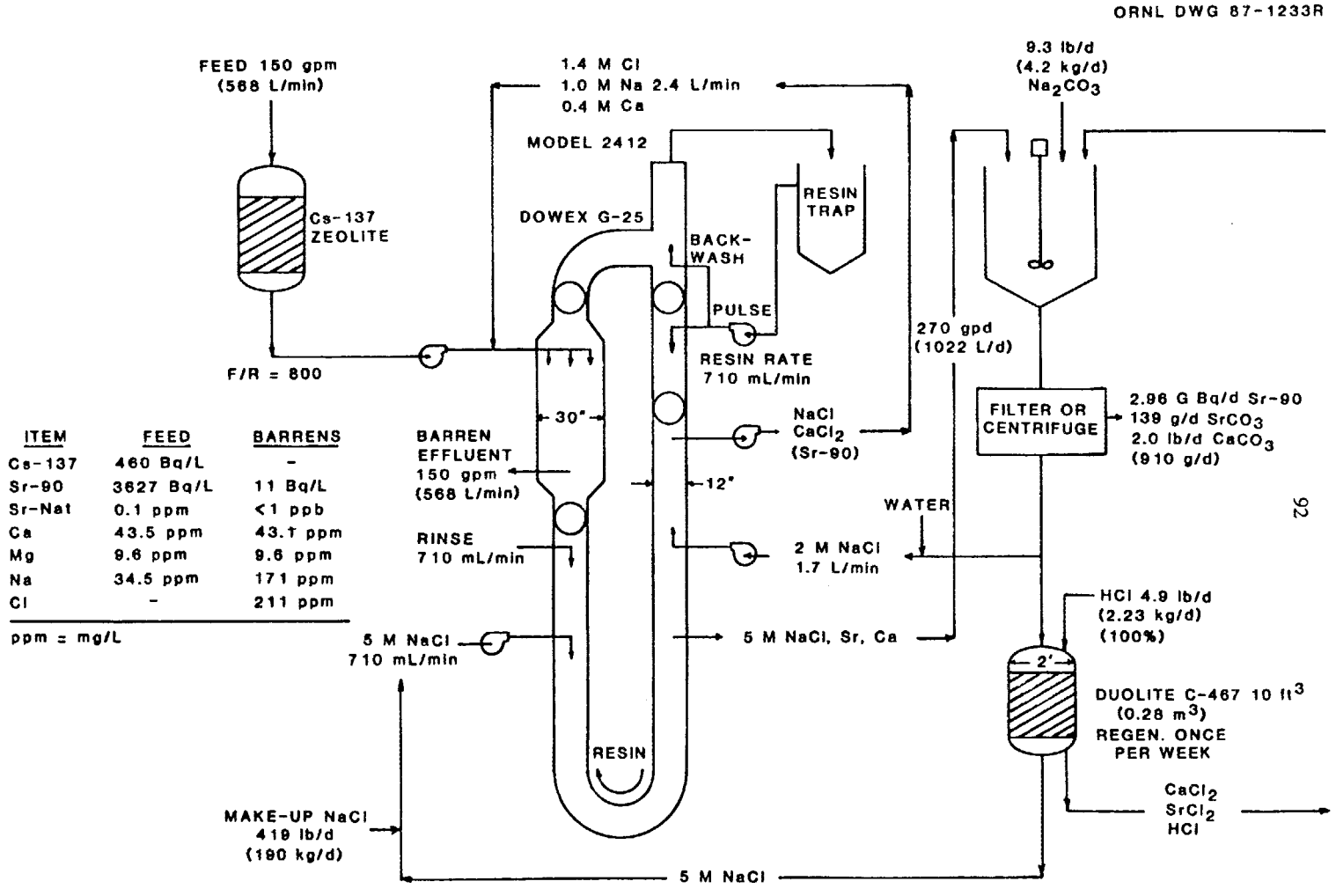


Fig. 38. Continuous countercurrent ion-exchange flow sheet.



ITEM	FEED	BARRENS
Cs-137	460 Bq/L	-
Sr-90	3627 Bq/L	11 Bq/L
Sr-Nat	0.1 ppm	<1 ppb
Ca	43.5 ppm	43.1 ppm
Mg	9.6 ppm	9.6 ppm
Na	34.5 ppm	171 ppm
Cl	-	211 ppm

ppm = mg/L

Fig. 39. Extraction of ^{90}Sr from ORNL Process Waste Treatment Plant waste by caustic-soda-ash continuous countercurrent ion exchange.

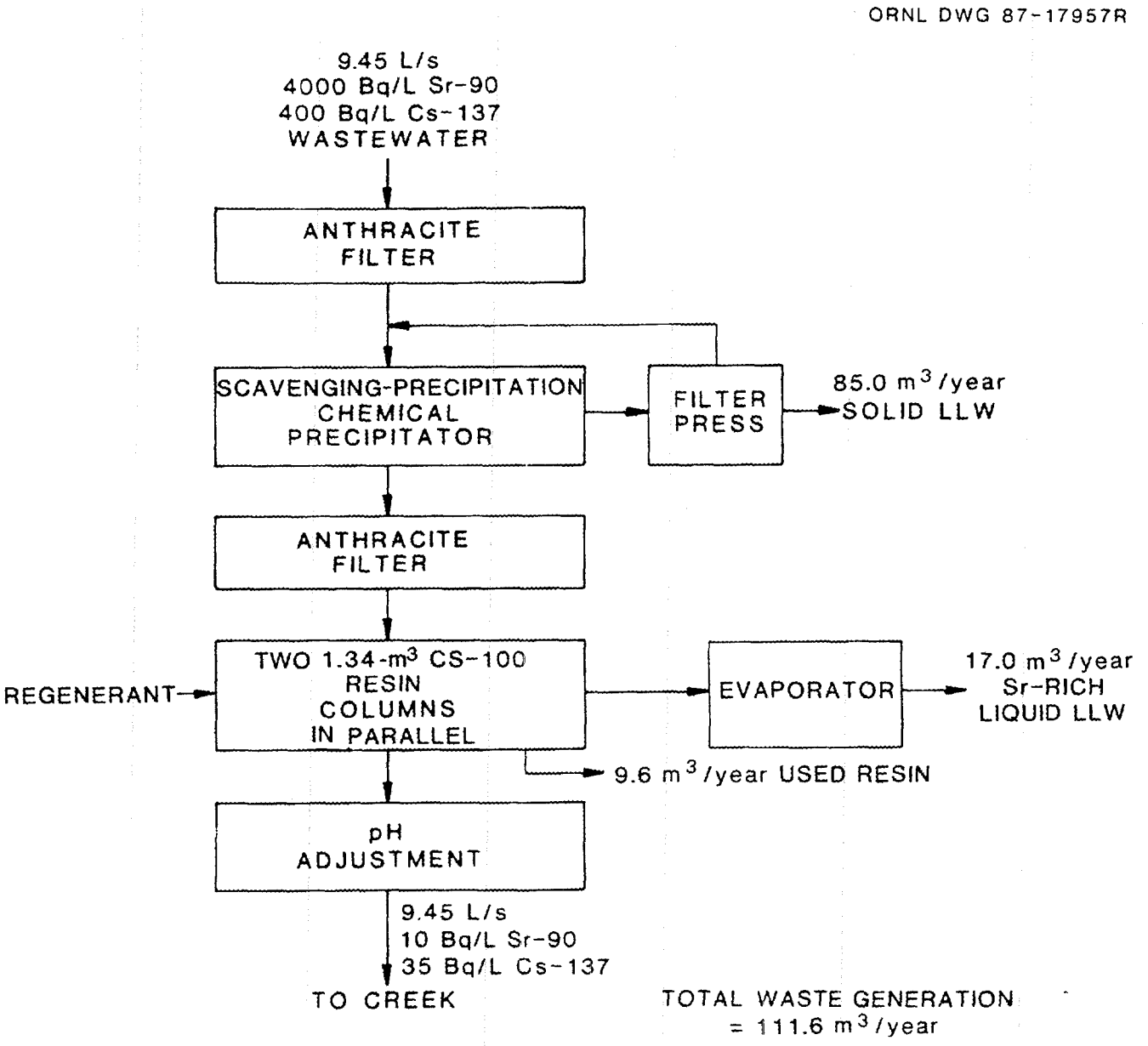


Fig. 40. Previous scavenging-precipitation/ion-exchange flow sheet.

ORNL DWG 87-1311

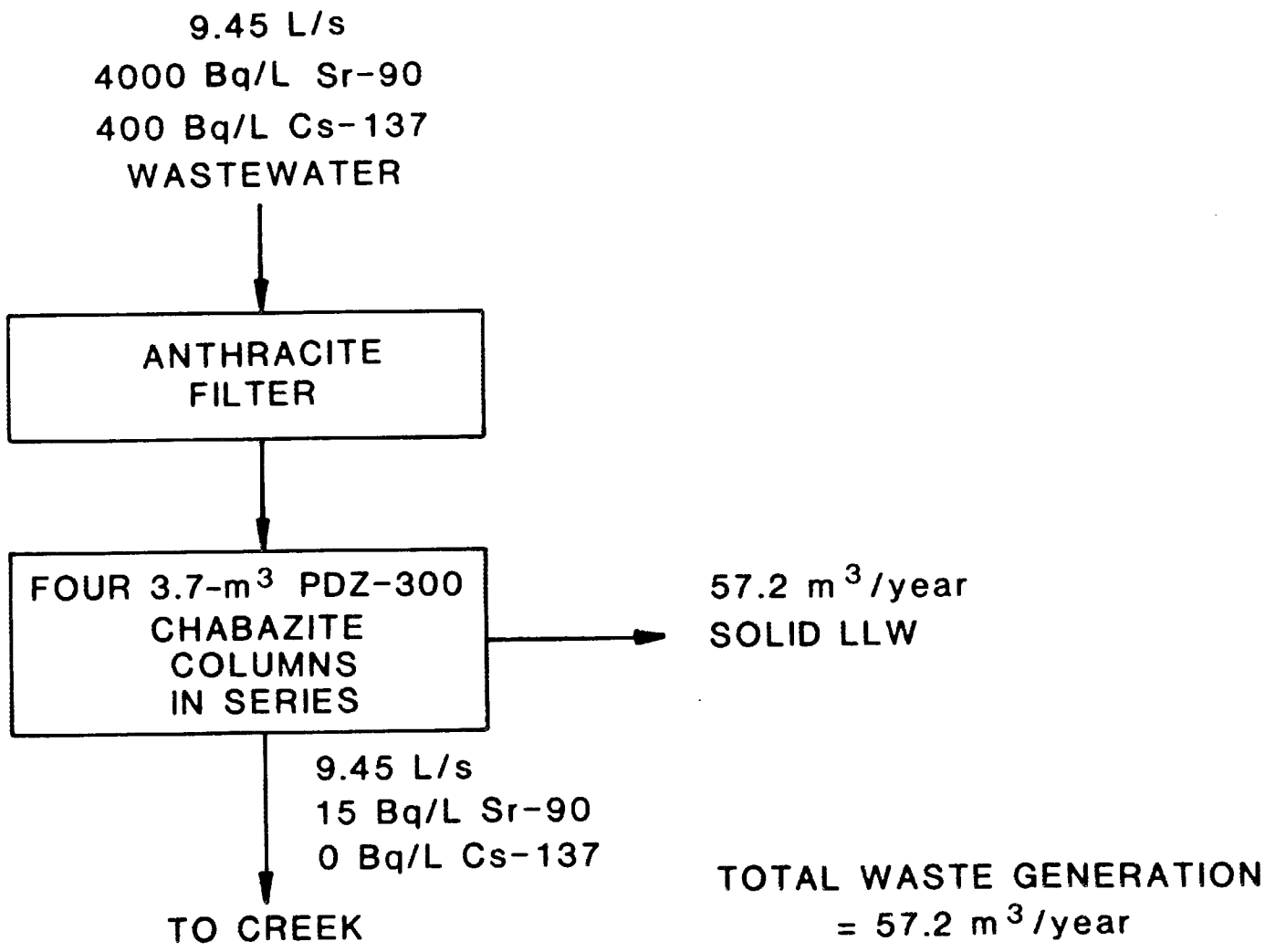


Fig. 41. Chabazite flow sheet using PDZ-300 zeolite.

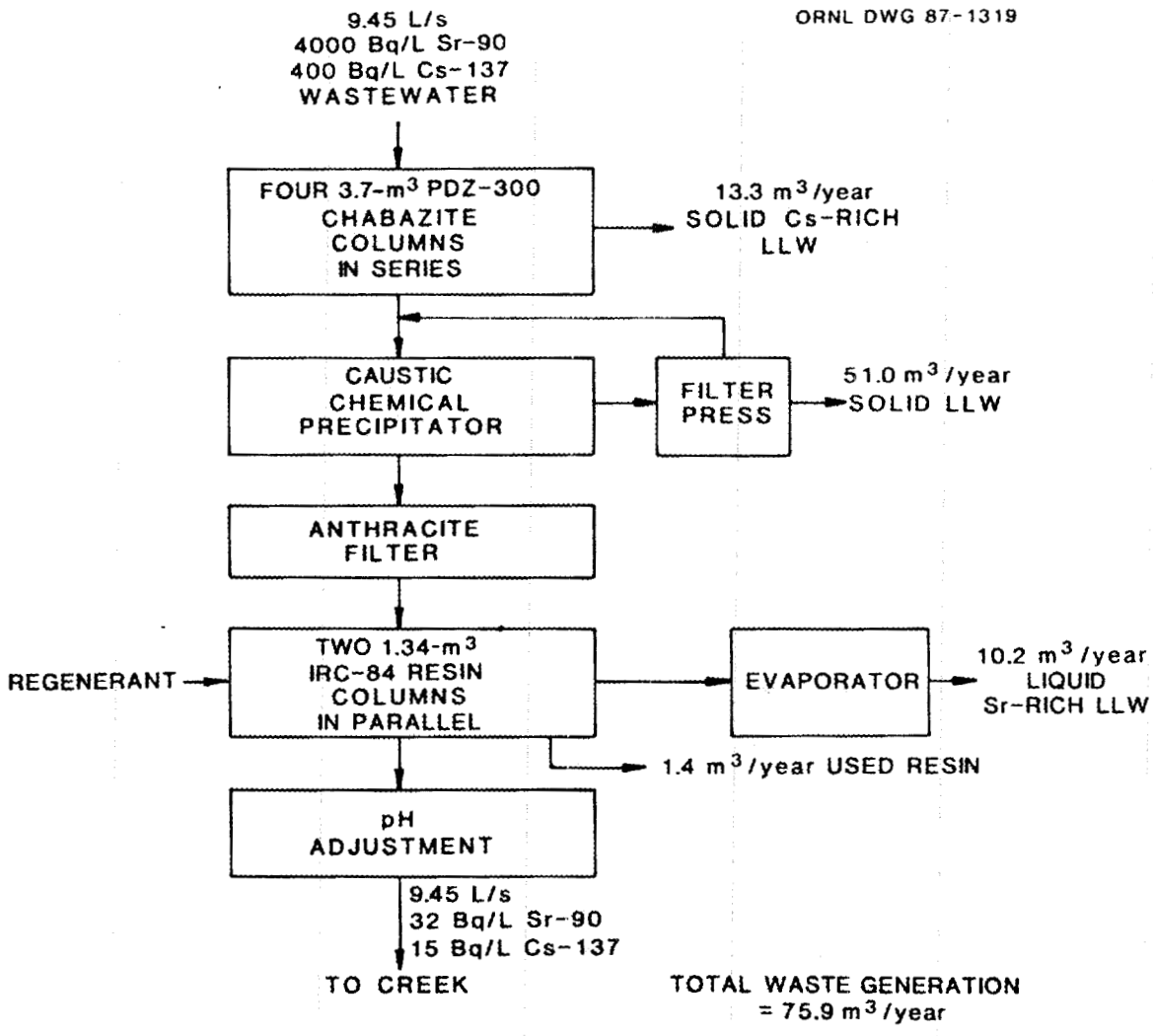


Fig. 42. IRC-84 resin flow sheet with caustic precipitation with regeneration of resin and four 3.7-m^3 chabazite columns.

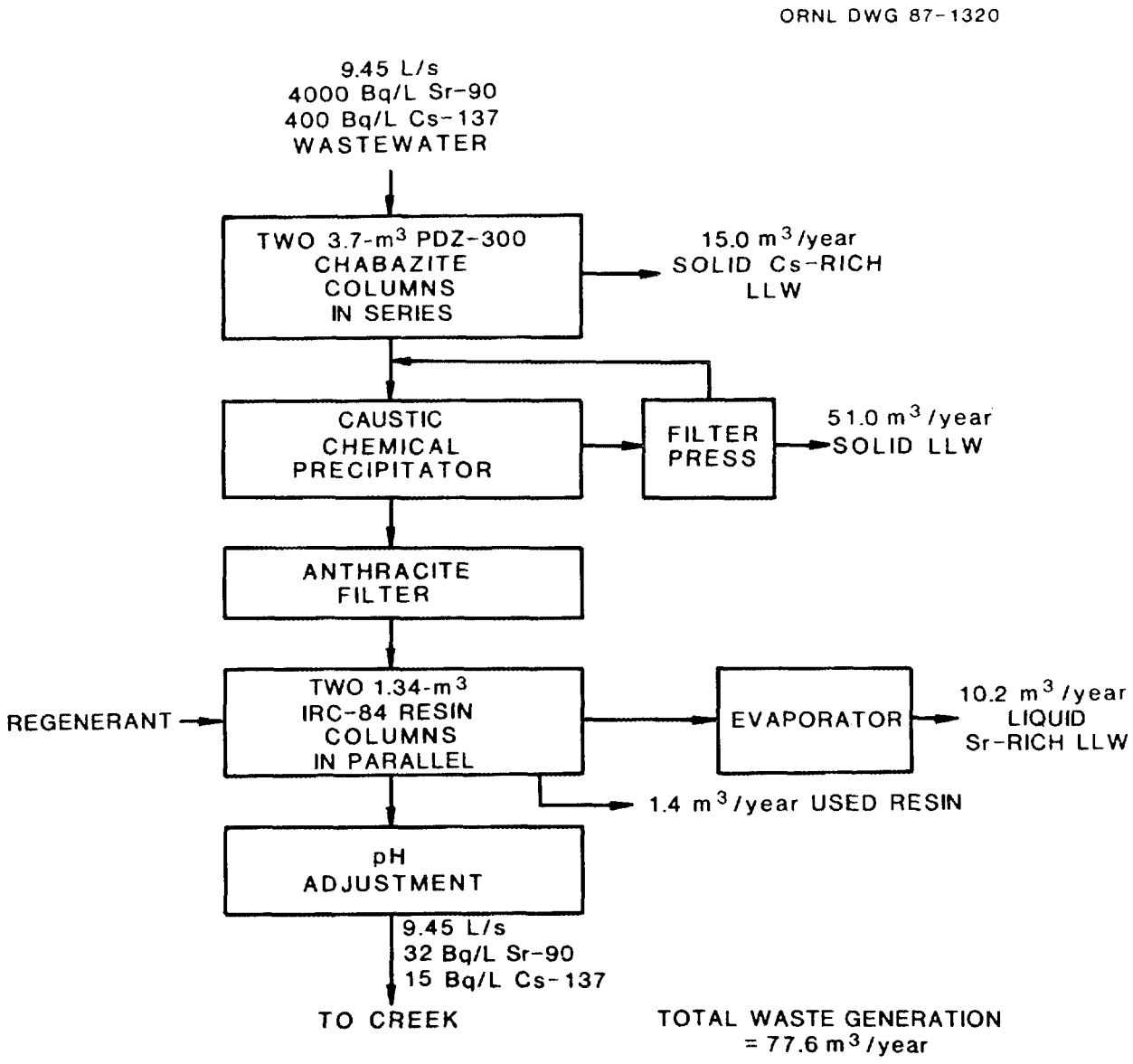


Fig. 43. IRC-84 flow sheet with caustic precipitation, regeneration of resin, and two 3.7-m^3 chabazite columns.

ORNL DWG 87-1317

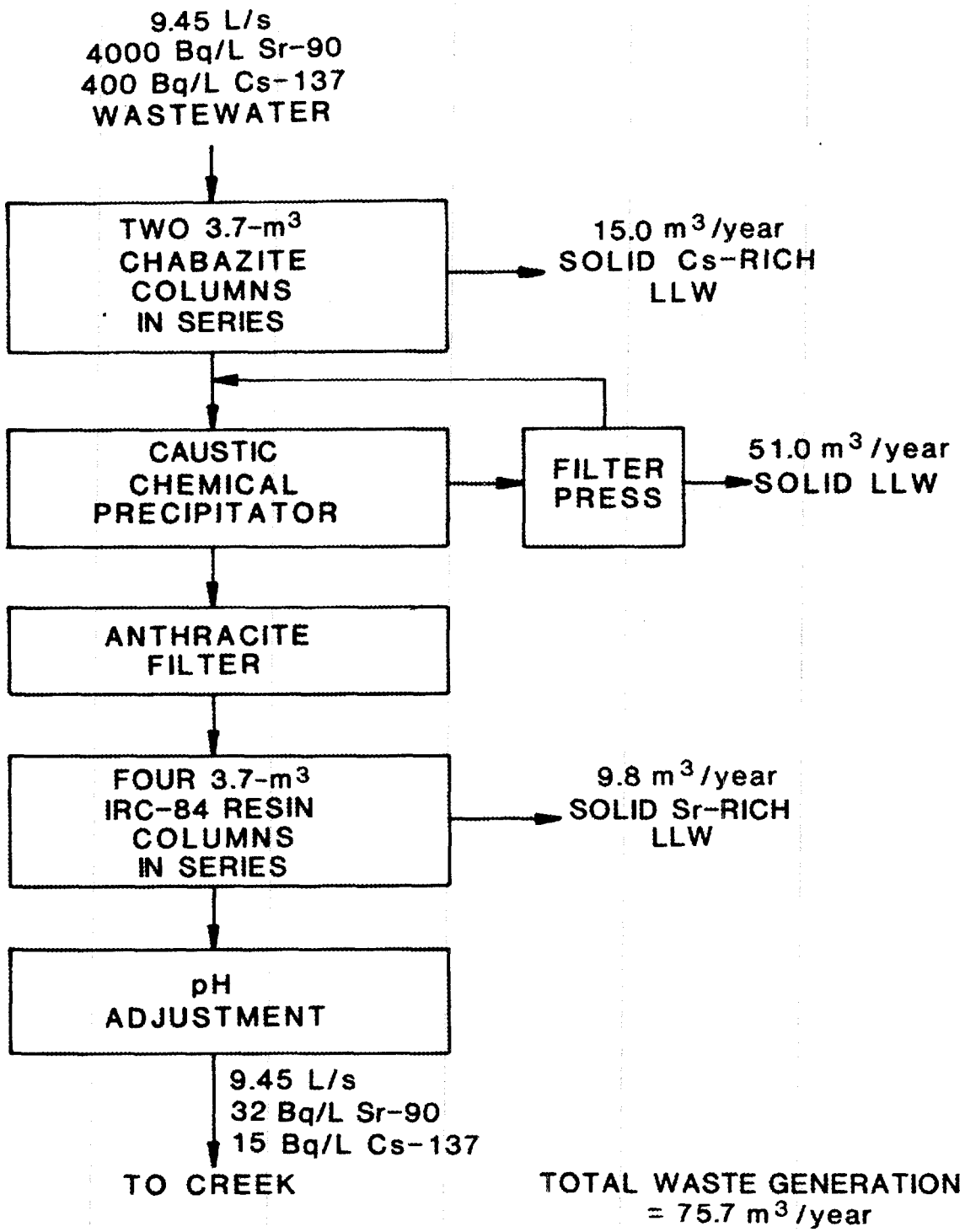


Fig. 44. IRC-84 resin flow sheet with caustic precipitation, two 3.7-m^3 chabazite columns, and direct disposal of resin from four 3.7-m^3 columns.

ORNL DWG 87-1318

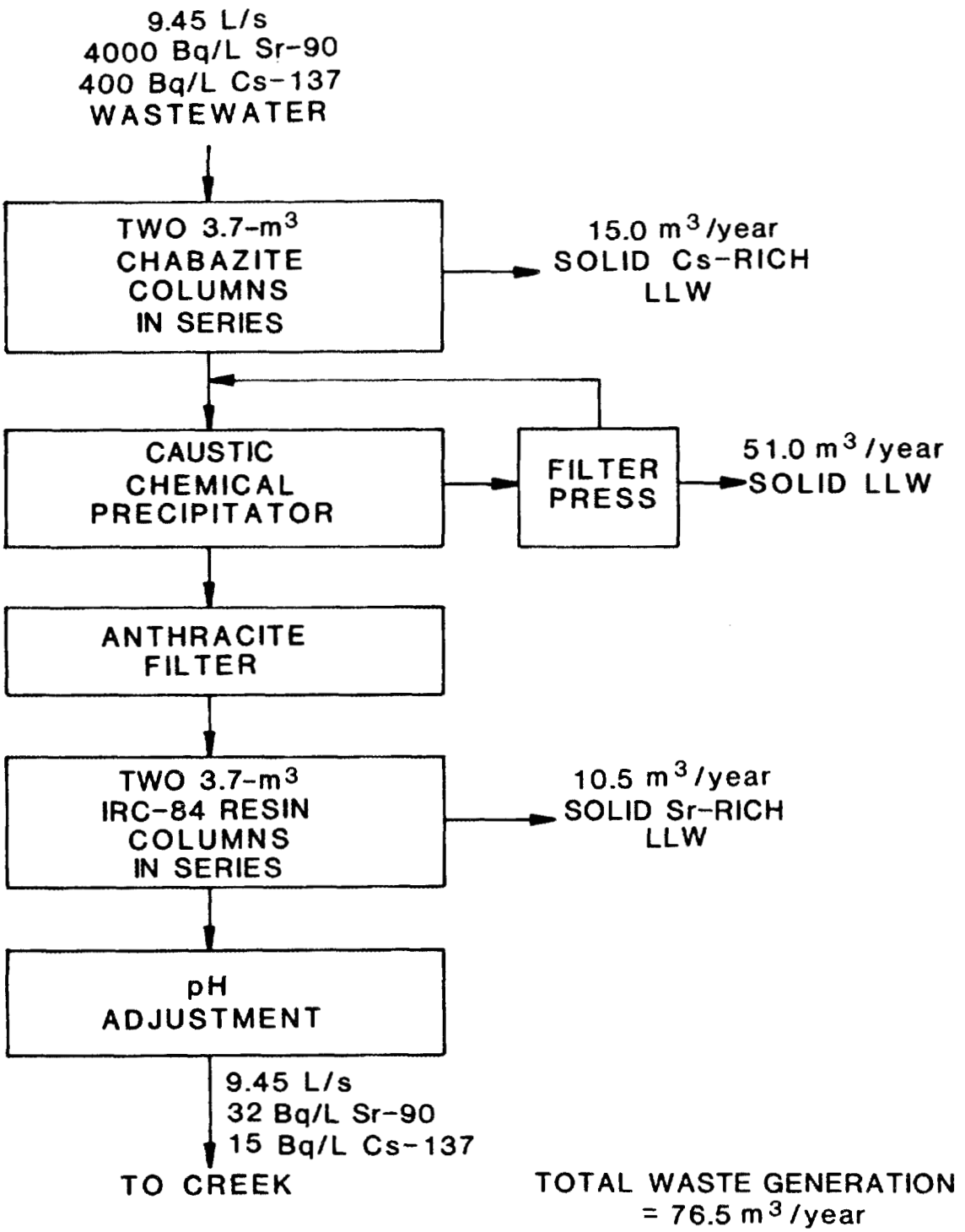


Fig. 45. IRC-84 resin flow sheet with caustic precipitation, two 3.7-m^3 chabazite columns, and direct disposal of resin from two 3.7-m^3 columns.

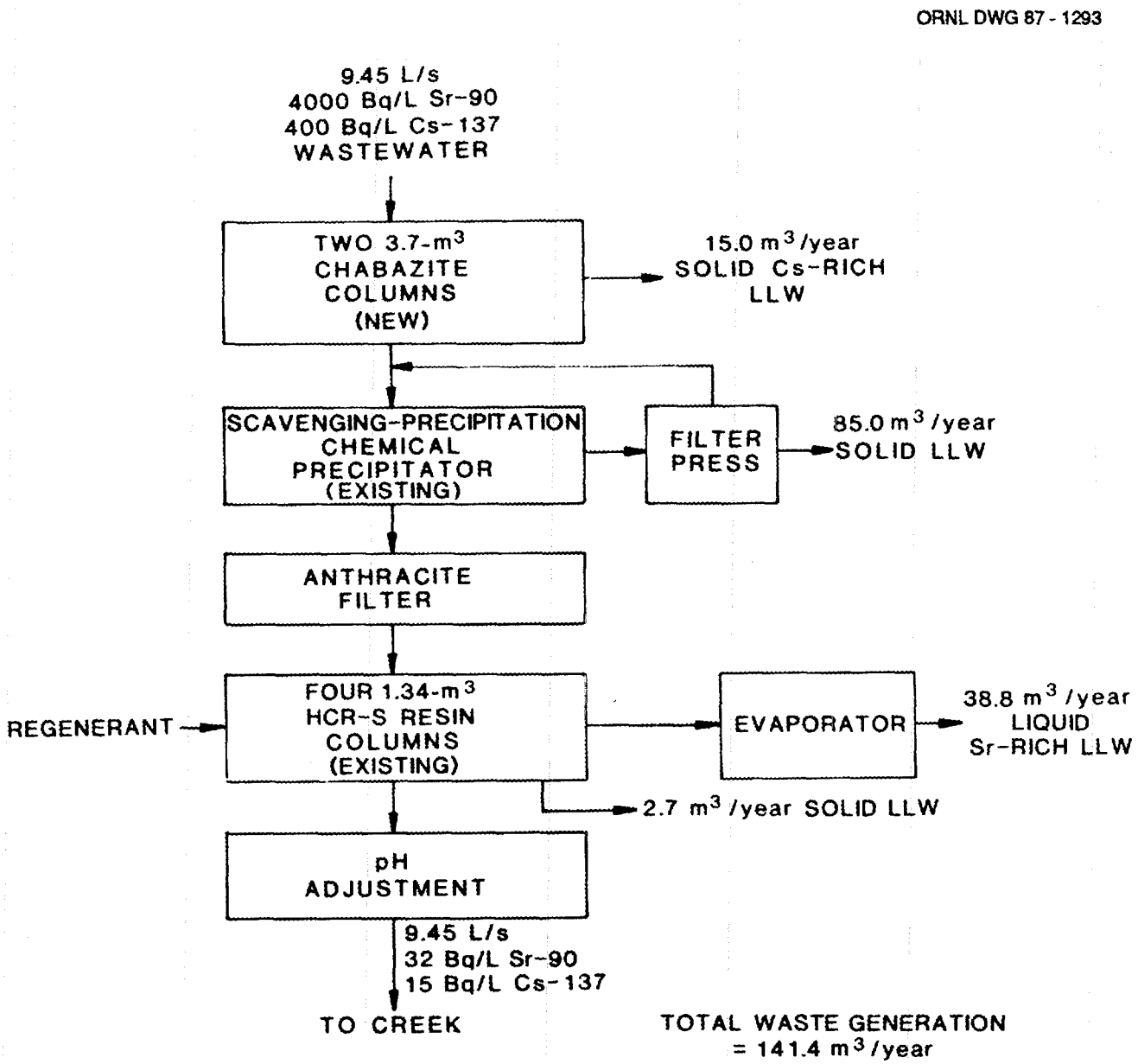


Fig. 46. Existing HCR-S flow sheet with new chabazite columns.

ORNL DWG 87-1294

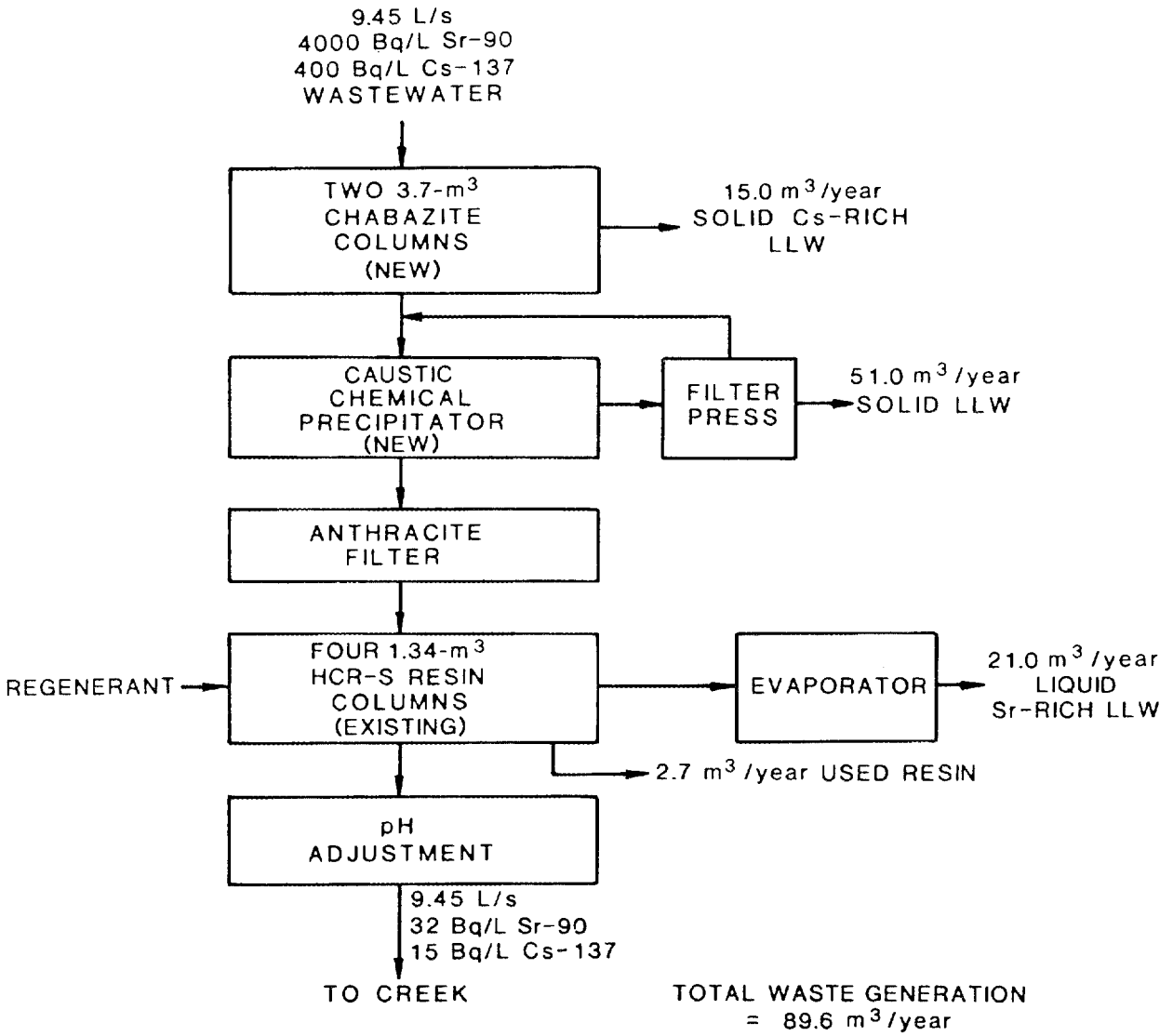


Fig. 47. Existing HCR-S flow sheet with new chabazite columns and precipitator.

ORNL DWG 87-1295

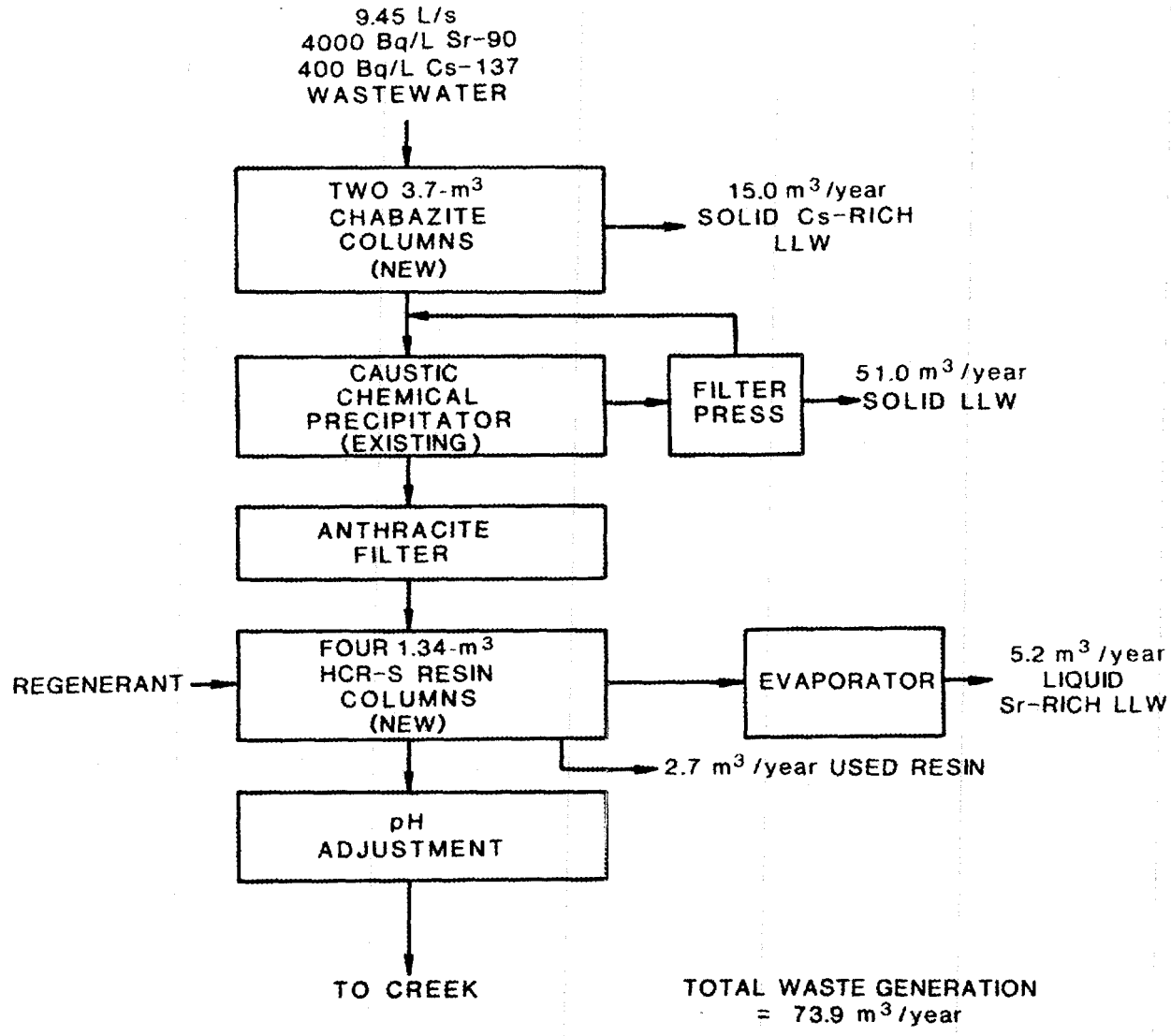


Fig. 48. Existing HCR-S flow sheet with new chabazite columns and HCR-S columns and new precipitator.

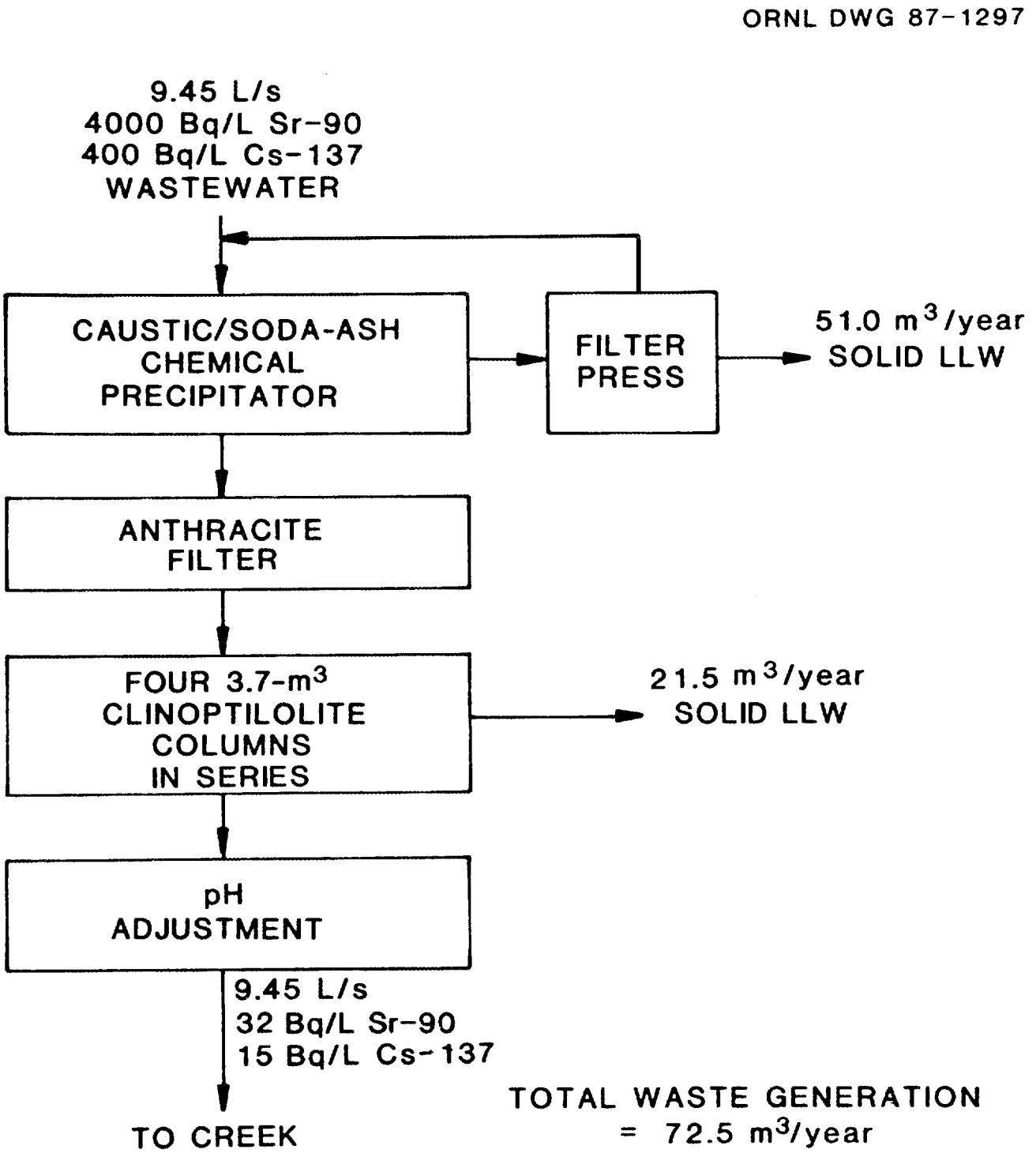


Fig. 49. Clinoptilolite flow sheet with four 3.7-m^3 columns.

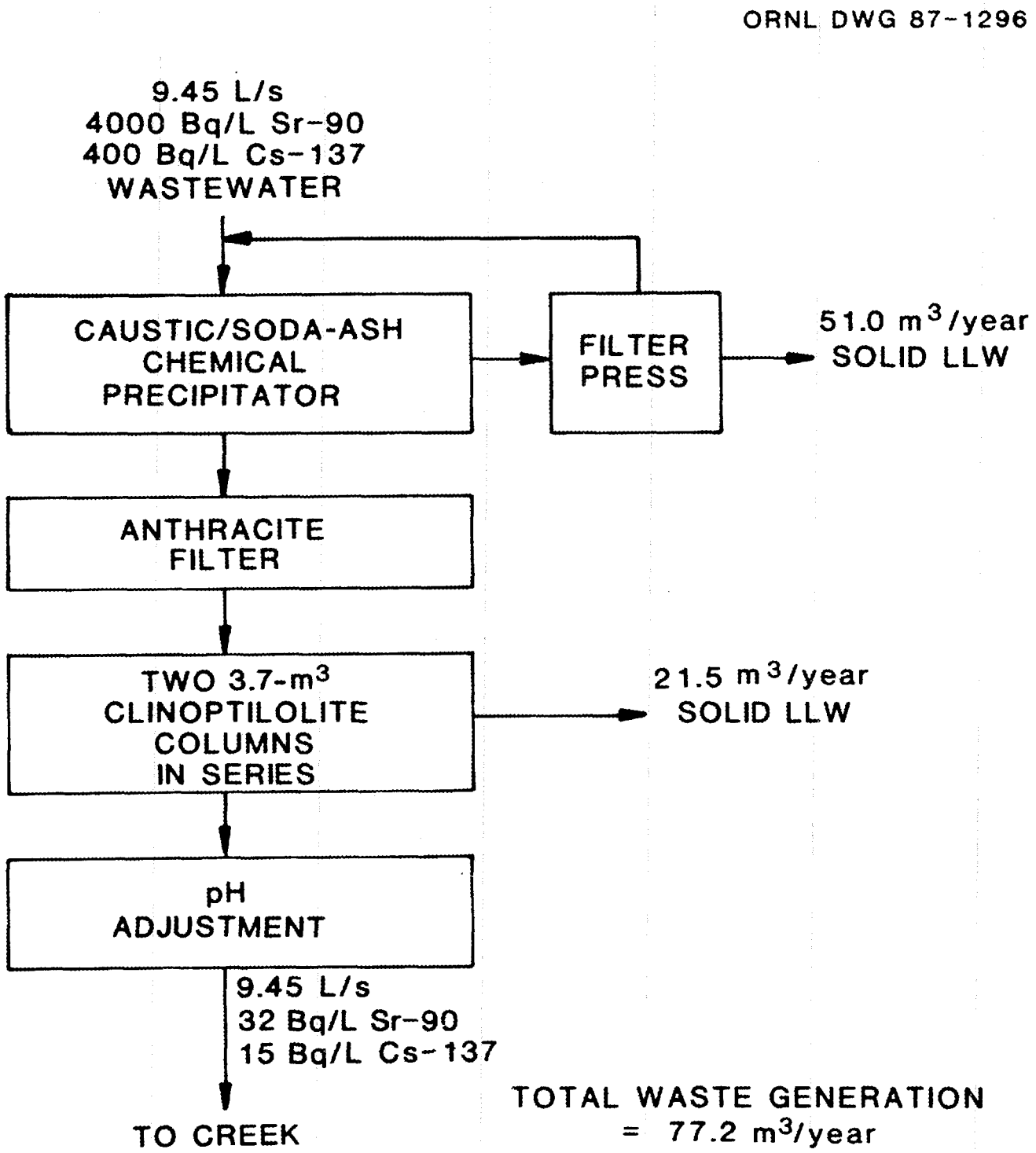


Fig. 50. Clinoptilolite flow sheet with two 3.7-m^3 columns.

ORNL DWG 87-1291

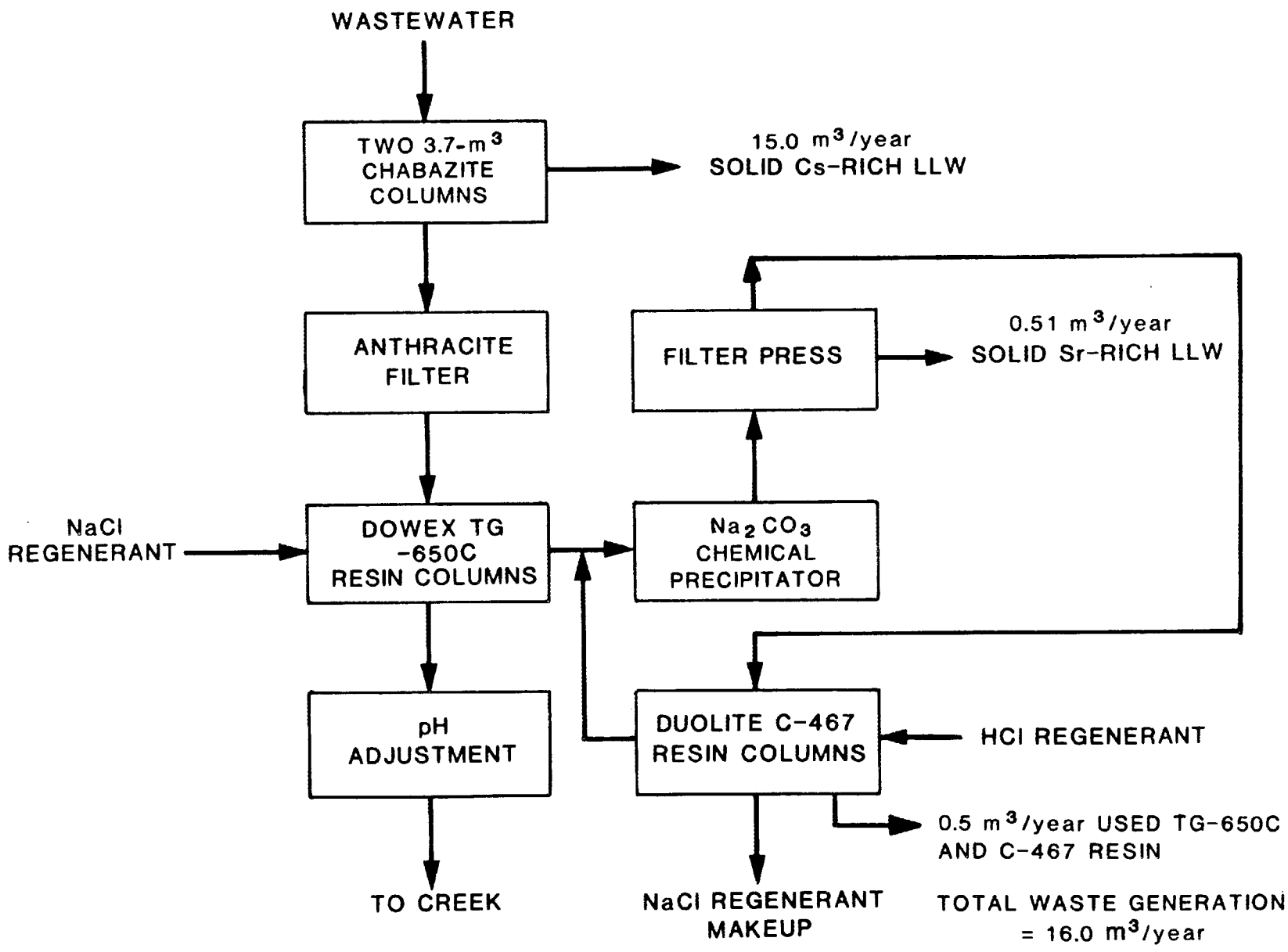
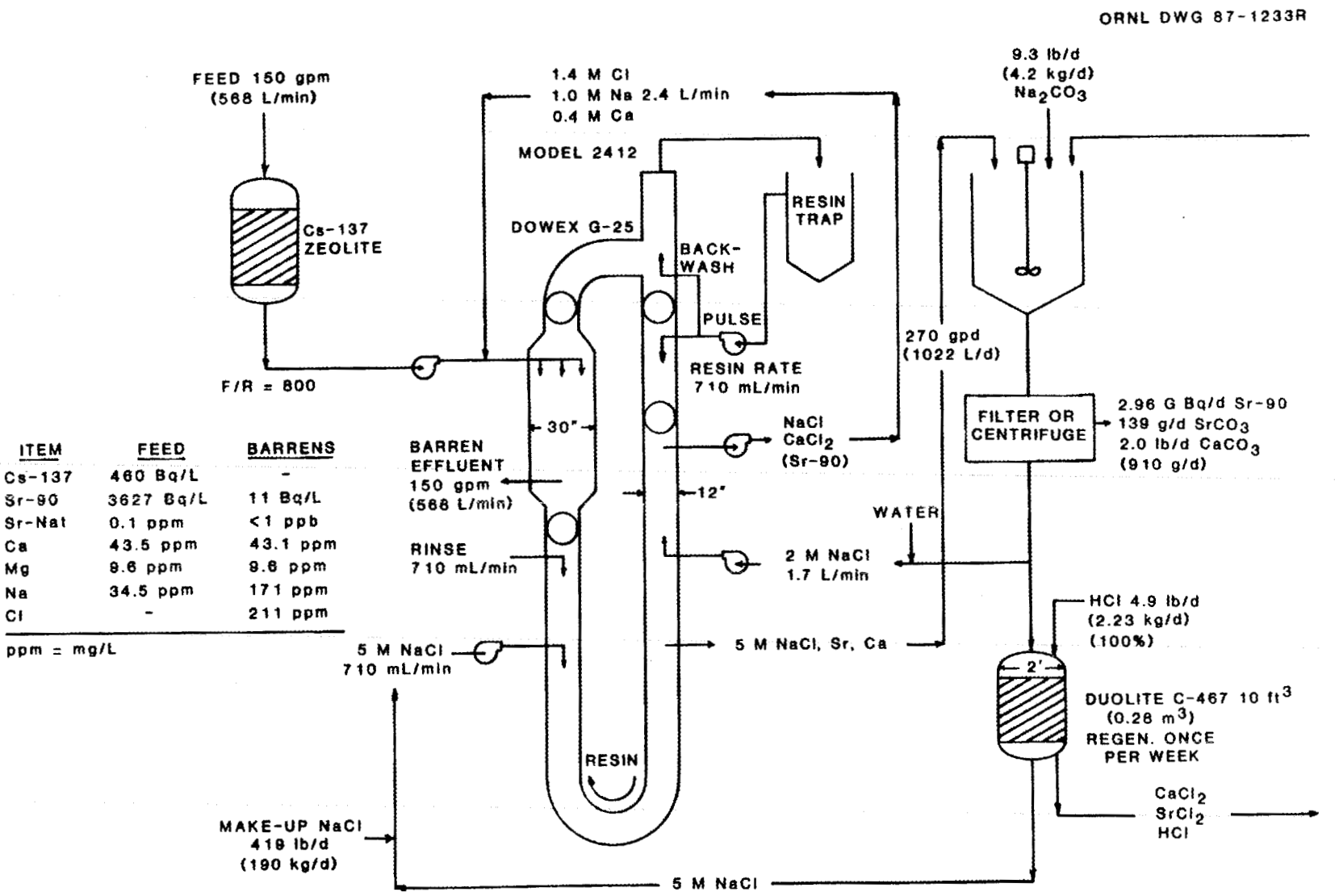


Fig. 51. Continuous countercurrent ion-exchange flow sheet.



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Mg	9.6 ppm	9.6 ppm
Na	34.5 ppm	171 ppm
Cl	-	211 ppm

ppm = mg/L

Fig. 52. Extraction of ^{90}Sr from ORNL Process Waste Treatment Plant waste by caustic-soda-ash continuous countercurrent ion exchange.

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