

NUCLEAR REGULATORY COMMISSION

Docket No. 50-352/353 Official Ex. No. 172
 In the matter of PECO - Linerda 1a2

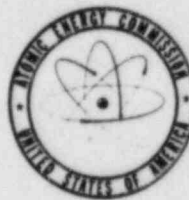
Staff _____ IDENTIFIED
 Applicant RECEIVED _____
 Intervenor _____ REJECTED _____
 Cont'g Off'r _____
 Contractor _____ DATE 6/19/84
 Other _____ ADDRESS _____
 Reporter Mary Simon

Low-Level Radioactive Wastes



Their Handling, Treatment, and Disposal

By
CONRAD P. STRAUB, M.C.E., Ph.D.
*Chief, Radiological Health Research Activities
 Division of Radiological Health
 Public Health Service
 Robert A. Taft Sanitary Engineering Center
 Cincinnati, Ohio*



Prepared under the auspices of
 DIVISION OF TECHNICAL INFORMATION
 UNITED STATES ATOMIC ENERGY COMMISSION

1964

8411280085 840619
 PDR ADOCK 05000352
 G PDR

ENCES

DR. [REDACTED], and M. W. FIRST, *Handbook of Air and Gas Cleaning for Nuclear Energy*, University School of Public Health and the U.S. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 1952.

[REDACTED] as a Tracer in the Sorting of Aerosols, *Am. Ind. Hyg. Assoc. Trans.*, 23: 13 (January 1952).

[REDACTED], Collection Efficiency of Filter Media for Aerosols of 0.5 to 0.1 Micron, *Am. Ind. Hyg. Assoc. Trans.*, 23: 13 (January 1952).

[REDACTED] *Air and Gas Cleaning for Nuclear Energy*, McGraw-Hill Book Company, New York, 1952.

[REDACTED] *Air and Gas Cleaning for Nuclear Energy*, Proceedings Conference, International Atomic Energy Agency, Vienna, 1954.

SILVERMAN, Dust Collectors Tested in the Field (May 1954).

Performance of Cyclone Dust Separators, *Am. Ind. Hyg. Assoc. Trans.*, 29: 356 (1951).

[REDACTED] *Studies: Progress Report for February 1, 1951*, Report NYO-1581, Harvard University, Cambridge, Massachusetts, 1951.

[REDACTED] *Studies: Progress Report for February 1, 1952*, Report NYO-1586, Harvard University, Cambridge, Massachusetts, 1952.

R. DENNIS, M. W. FIRST, and L. SILVERMAN, Performance of Centrifugal Scrubbers, *Chem. Eng. Progress*, 47: 40 (1951).

FIRST, and L. SILVERMAN, *Performance Report of Field Tests*, USAEC Report NYO-1581, U.S. Superintendent of Documents, Washington, D.C., Nov. 2, 1953.

[REDACTED] *Filtering of Radioactive Aerosols by High-Speed Air Pollution*, in *Radiation Hygiene*, McGraw-Hill Book Company, New York, 1955.

[REDACTED] *High-Speed Air Pollution*, in *Radiation Hygiene*, McGraw-Hill Book Company, New York, 1955.

[REDACTED] *Handling Radioactive Materials*, Panel Report 3, for conference held Nov. 27 and Dec. 1, 1954, Research Advisory Board, National Atomic Energy Commission.

FIRST, and L. SILVERMAN, How Dust Collectors Perform (February 1952): 196-198 (February 1952).

DENNIS, and L. SILVERMAN, *Laboratory Performance of Dust Collectors*, USAEC Report NYO-1581, U.S. Superintendent of Documents, Washington, D.C., Aug. 31, 1954.

Chapter 8

REMOVAL OF RADIOACTIVITY BY WATER-TREATMENT PROCESSES

The waterworks profession has had the most extensive experience of any group in treating, economically, large volumes of liquid materials to remove low concentrations of contaminating or polluting materials. Waterworks operators handle large quantities of chemicals in treatment and are familiar with sludge-disposal problems. In addition, many have knowledge and experience in removing toxic and other nuisance-like substances and therefore are in an excellent position to cope with the newer problems facing them as a result of the introduction of radioactive materials into surface waters.

It is reasonable therefore to consider the experience of this industry and to evaluate the various treatment processes for the removal of small quantities of radioactive materials contained in large volumes of liquid wastes.

An evaluation of water-treatment processes is important because much of the low-level liquid waste currently produced is released directly or through sewerage systems to water environments. Since many communities use rivers and wells as sources of water supply and utilize some form of water-treatment process before the water is consumed by the public, information is needed on how effective these processes are in the removal of radioactive materials.

This chapter describes laboratory and pilot-plant investigations on the removal of radioactive materials by conventional water-treatment processes, by nonconventional processes that could easily be incorporated into conventional facilities, and by full-scale facilities, particularly for the removal of weapons-test debris (fallout).

8-1 CONVENTIONAL PROCESSES

Conventional water-treatment processes of interest in terms of removal of radioactive materials include chemical coagulation and sedimentation, filtration, lime and soda-ash softening, and ion exchange.

Chemical coagulation involves the destabilization, aggregation, and binding together of colloids. These colloids form chemical flocs that adsorb, entrap, or otherwise bring together suspended matter, more particularly, finely divided suspended matter.¹ Commonly used

coagulants are alum and iron salts, which precipitate soluble constituents in the water as aluminum and iron hydroxides. Other coagulants used in the removal of radioactive materials from wastes will be referred to in subsequent sections. Sedimentation is the process by which suspended particles heavier than water are removed by gravitational settling.

The overall removal of impurities found in surface waters by passage of the water through granular materials is known as filtration. Filtration may be at slow rates or high rates. In the former the filters are cleaned manually by surface removal of entrapped suspended matter; in the latter, by backwashing at high rates of flow.

Water is softened by the addition of lime, which removes carbonate hardness; soda ash, which removes noncarbonate hardness; or by ion exchange, which involves an exchange of certain ions during passage of the water through a bed of resin, notably calcium and magnesium ions for sodium ions. When the resin bed is exhausted, it is regenerated with brine.

8-1.1 Coagulation and Settling

Coagulation, in association with settling, for the removal of radioactivity has been studied extensively at the laboratory and at the test-model levels. Results²⁻⁶ for the removal of a wide variety of soluble radionuclides are summarized in Table 8.1. With the exception of most cations with valences of 3, 4, or 5, including the rare-earths group, coagulation is ineffective as a method of removing soluble radioactive materials. It is considerably more effective in removing particulate-associated radioactivity, as for example, radioactivity associated with turbidity normally encountered in most surface waters. Setter and Russell⁷ have described laboratory coagulation studies for the removal of particulate matter from cistern water (essentially roof-collected rainfall) and radioactivity associated therewith. Their results showed that 97 to 100% of the radioactivity associated with particulate matter and 4 to 81% of the radioactivity associated with soluble material were removed.

Other data on the removal of radioactive materials are available from the operating records of water-treatment plants. These results are reported in Sec. 8-3.

(a) *Effect of Added Clay.* Since coagulation effects the removal of radioactive material attached to, or adsorbed on, natural turbidity, the effect of clay added prior to treatment was investigated. The addition of 100 mg of clay per liter to simulate turbidity increased removal efficiency as shown in Table 8.2. This increase was due to the sorption of soluble radioactivity onto the particulate material present and removal of the particulate-associated radioactivity. In-

s, which precipitate soluble con-
 im and iron hydroxides. Other
 radioactive materials from wastes
 sections. Sedimentation is the
 s heavier than water are removed

ies found in surface waters by
 materials is known as filtration.
 rates. In the former the filters
 removal of entrapped suspended
 at high rates of flow.

of lime, which removes carbonate
 s noncarbonate hardness; or by
 exchange of certain ions during
 d of resin, notably calcium and
 When the resin bed is exhausted,

setting, for the removal of radio-
 ily at the laboratory and at the
 removal of a wide variety of
 in Table 8.1. With the excep-
 of 3, 4, or 5, including the rare-
 ctive as a method of removing
 s considerably more effective in
 ions, as for example, radio-
 normally encountered in most
 ell' have described laboratory
 of particulate matter from cistern
 (fall) and radioactivity associated
 at 97 to 100% of the radioactivity
 and 4 to 81% of the radioactivity
 e removed.

radioactive materials are available
 -treatment plants. These results

coagulation effects the removal of
 adsorbed on, natural turbidity,
 treatment was investigated. The
 r to simulate turbidity increased
 e 8.2. This increase was due to
 onto the particulate material
 ate-associated radioactivity. In-

TABLE 8.1—REMOVAL OF SOLUBLE RADIOACTIVITY BY CHEMICAL COAGULATION

Nuclide	Chemical form	Chemical group	No. of tests	Activity range, counts/(min)(ml)	pH range		Removal, %		Ref.	Coagulants used	Coagulant dose, mg/liter
					Initial	Final	Av.	Range			
Cs ¹³⁷ -Ba ^{137m}	Cl ⁻	I A	27	19-17,390	7.5-7.8	6.5-7.8	0.5	0-37	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
		II A									
Sr ⁹⁰	Cl ⁻ or NO ₃ ⁻	II A	54	212-25,950	7.7-7.9	7.5-8.0	3	0-15	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
		II A	12				38	5-58	4	Variable amounts of clay added	
Sr ^{90m}		II A				6.8-7.0	3	2-5	8	Alum, Fe ₂ (SO ₄) ₃ , and other treat- ments	19 as Fe and as Al
Ba ¹⁴⁰ -La ¹⁴⁰	Cl ⁻	II A	81	42-17,150	7.4-7.6	7.2-8.2	59	1-84	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
		III A									
			54	42-5,520	7.4-7.6	6.6-7.9	44	19-59	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
Ba ¹⁴⁰ -La ¹⁴⁰	Cl ⁻	II A	4	17,500-46,200	7.4-7.6	7.2-7.8	52	27-72	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
		III A									
			4	17,500-46,200	7.7-7.8		64	56-71	5	CaCO ₃ and FeCl ₃ or alum	50-100
Sc ⁴⁵	Cl ⁻	III A	27	163-24,300	7.2-7.8	6.4-8.0	89	82-96	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
			27	326-20,060	7.6	7.0-7.8	92	82-99+	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
			27	202-26,100	7.5-7.9	6.9-8.2	91	69-99+	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
Y ⁹⁰	Cl ⁻	III A	54*	188-4,166	7.5-7.8	6.0-7.6	90	40-90	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
			81*	367-20,860	8.1	7.8-10.2	92	56-99+	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
			81*	202-21,450	7.8-8.0	7.6-8.4	86	48-99	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
			81†	406-21,500	7.8	7.5-9.1	75	1-98	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
			81†	222-21,500	7.1-8.4	7.4-9.5	73	33-98	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
Zr ⁹⁰ -Nb ⁹⁰	Oxylate complex	IV B	54	186-27,200	7.4-7.6	6.4-7.9	80	2-99	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
		V B									
Zr ⁹⁰ -Nb ⁹⁰	Oxylate complex	IV B	4	29,800-78,000	8.4-8.7		88	76-99	5	CaCO ₃ and FeCl ₃ or alum	40-409
		V B									
P ³²	PO ₄ ³⁻	V A	27	228-17,625	7.6	6.4-7.8	96	68-99+	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
		V A	12				97	63-99+	4		
Cr ⁵¹	Cl ⁻ , metal	VI B	54	5-758	6.7-7.3	5.3-7.8	6	0-60	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
		VI B	54	84-10,085	7.6	7.0-8.2	10	0-60	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
Mo ⁹⁹	MoO ₄	VI B	54	233-28,290	7.5-7.9	6.6-8.4	46	1-96	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
		VI B	81	198-22,490	8.0-8.1	7.5-8.4	36	4-91	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
Re ¹⁸⁶	Metal	VII B	54	95-15,230	7.6	7.2-8.0	6	0-29	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103

See footnotes at end of table.

TABLE 8.1—REMOVAL OF SOLUBLE RADIOACTIVITY BY CHEMICAL COAGULATION—Continued

Nuclide	Chemical form	Chemical group	No. of tests	Activity range, counts/(min)(ml)	pH range		Removal, %		Ref.	Coagulants used	Coagulant dose, mg/liter
					Initial	Final	Av.	Range			
I ¹³¹	Iodide	VII A	27	239-25,060	7.6	7.2-7.8	30	0-44	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
I ¹³¹	Iodide	VII A	12				3.9	0-12	4	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
I ¹³¹	Iodide	VII A	4	13,000-24,800	6.3-7.7		42	26-63	5	CaCO ₃ and FeCl ₃ or alum	50-200
Ru ¹⁰⁶	Iodide	VII A	19	2,000 [†]		5.4-7.6	0.8	0-10	6	Variety of chemicals	
Ru ¹⁰⁶	Cl ⁻	VIII	27	196-24,960	7.3-7.6	6.9-8.2	77	43-96	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
Co ⁶⁰	Cl ⁻	VIII	2	45,900-49,400	7.6-8.2		16	8-23	6	CaCO ₃ and FeCl ₃ or alum	50-100
Pr ¹⁴⁴	Pr ₂ O ₃	La series	27	102-12,050	7.2	7.4-8.0	96	83-99+	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
Ce ¹⁴⁴ -Pr ¹⁴⁴	Cl ⁻	La series	27	244-30,510	7.4-7.6	7.2-8.4	91	28-99+	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
Ce ¹⁴⁴ , Pr ¹⁴⁴ , Pm ¹⁴⁷	Cl ⁻	La series	4	41,000-55,800	7.1-7.6		98	96-99+	5	CaCO ₃ and FeCl ₃ or alum	50-200
Pm ¹⁴⁷	Cl ⁻	La series	27	136-19,040	7.4-7.6	7.0-8.2	87	4-99+	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
Sm ¹⁵²	Sm ₂ O ₃	La series	54	148-20,870	7.4-7.6	5.8-8.0	91	44-99+	3	Al ₂ (SO ₄) ₃ , FeCl ₃ , FeSO ₄ ·7H ₂ O	17.1, 34.2, and 103
Fission-product mixture	Ba 5%		1	22,200	8.1		89		5	FeCl ₃ +CaCO ₃	170-240
	Ce 27										
	Cs 1										
	Ru 3										
	Sr 17										
	TRE 44 [‡]										
Fission-product mixture	Other 3										
	Ba 5%		1	22,200	8.5		55	51-59	5	FeCl ₃ +CaCO ₃	100-400
	Ce 5										
	Cs 50										
	Ru 16										
	Sr 10										
Other 4											

* Ca(OH)₂ used as alkaline agent.

† Na₂CO₃ used as alkaline agent.

‡ Micromicrocuries per milliliter.

§ Trivalent rare earths other than cerium.

REMOVAL OF RADIOACTIVITY BY

TABLE 8.2—COAGULATION (JAR-TE)

Nuclide	Cl ₂ added (mg/l)
Ce ¹⁴⁴ -Ba ¹³⁷	10
Sr ⁹⁰	10
Cd ¹⁰⁹	10
Ba ¹³⁴ -La ¹⁴⁰	10
Sc ⁴⁴	10
Y ⁹¹	10
Zr ⁹⁵ -Nb ⁹⁵	10
Pm	10
Ce ¹⁴⁴	10
W ¹⁸⁷	10
I ¹³¹	10
Ce ¹⁴⁴	10
Fission-product mixture [‡]	10
Fission-product mixture [‡]	10
Fission-product mixture [‡]	10

[†]Local clay added.

[‡]Coagulant included alum, ferric sulfate or sodium silicate.

[§]No sodium silicate added. Where added, see footnote dissolver solution.

[¶]Synthetic mixture containing fission product as underwater detonation.

**Three-year-old fission-product mixture.

creasing the concentration of 8-2.3).

(b) *Removal of Iodine.* Because active iodine in hospitals and clinics containing it, this nuclide was (Table 8.1) showed that alum (radioiodine from the waste was Straub and coworkers⁸ and Ed that the addition of small amounts of carbon, or silver nitrate increase high as 96%. Results obtained summarized in Table 8.3.

According to Eden and coworkers⁹ 20 mg of chloride, 0.050 mg of

TABLE 8.2—COAGULATION AND SETTLING RESULTS
(JAR-TEST STUDIES)

Nuclide	Clay added,* mg/liter	Coagu- lant added,† grains/gal	Final pH	Removal, %
Cs ¹³⁷ -Ba ^{137m}	0	1		0-6
	100	1		35-65
Sr ⁹⁰	0	1.5‡	6.7-7.8	0-6
	100	0.5-6	6.7-10.7	0-51
Cd ¹¹⁵	0	1		40-60
	100	1-5		60-95
Ba ¹⁴⁰ -La ¹⁴⁰	100	1-6	7.5-8.2	28-84
Sc ⁴⁶	100	1-6	6.5-8.2	66-98
Y ⁹¹	0	1.5‡	6.8-7.1	83-93
	100	1-6	7.0-10.2	34-99
Zr ⁹⁵ -Nb ⁹⁵	0	1-5		70-98
	100	1		95-99
Pm	100	0.5-1.5‡	6.8-8.8	97-99
Cr ⁵¹	100	1-6	7.6-8.8	73-98
W ¹⁸⁵	100	1-6	7.5-8.4	5-91
I ¹³¹	100	0.5-2‡	6.9-9.0	0-10
Ce ¹⁴⁴	0	1-1.5‡	7.2-7.8	81-94
	100	0.5-2.5‡	7.0-7.8	85-96
Fission-product mixture§	100	1-3‡	7.2-8.8	61-84
Fission-product mixture¶	0	1-5	4.3-10.2	9-71
	100	1-5	4.3-10.2	12-73
Fission-product mixture**	0	10	9.9-10.0	46

*Local clay added.

†Coagulant included alum, ferrous sulfate or ferric chloride, lime, soda ash or sodium hydroxide, and sodium silicate.

‡No sodium silicate added. Where added, sodium silicate equaled 40% of the primary coagulant dose.

§Iodine dissolver solution.

¶Synthetic mixture containing fission products in the same ratios assumed to be present 30 days after an underwater detonation.

**Three-year-old fission-product mixture.

creasing the concentration of clay increases removal efficiency (Sec. 8-2.3).

(b) *Removal of Iodine.* Because of the widespread use of radioactive iodine in hospitals and the need to find ways of treating wastes containing it, this nuclide was investigated in detail. Earlier studies (Table 8.1) showed that alum or iron coagulation alone removes little radioiodine from the waste when originally present as the iodide. Straub and coworkers³ and Eden and coworkers,⁵ however, observed that the addition of small amounts of copper sulfate, activated carbon, or silver nitrate increased the removal of this anion to as high as 96%. Results obtained with these auxiliary chemicals are summarized in Table 8.3

According to Eden and coworkers,⁵ in a typical water containing 20 mg of chloride, 0.050 mg of bromide, and 0.010 mg of iodide per

TABLE 8.3—REMOVAL OF I¹³¹ BY AUXILIARY PROCESSES

Turbidity	Dosage, mg/liter			Final characteristics, mg/liter*			Removals, %		Ref.
	Alum	NaOH	Auxiliary chemical	pH	Alkalinity	Turbidity	Coagulation and settling	Coagulation, settling, and centrifuging	
103	25.7	38.9	5-15†	5.8-7.1	17-68	0-15	64-72	74-78	8
103	25.7	38.9	3.5‡	7.1	65	0	38	56	8
17.3-274	25.7	38.9	0.12-3.8§	5.8-7.5	19-74	1-40	42-74	48-76	8
	113.5		0.013-0.13	6.0-6.9			55-90		5
	247		0.13-1.1	6.3			90-92		5
	100.64¶		0.13‡	6.3			95.5		5

*Except for pH.

†Auxiliary chemical was activated carbon.

‡Auxiliary chemical was copper sulfate.

§Auxiliary chemical was silver nitrate.

¶Either 20 mg/liter as iron or 100.64 mg/liter as Fe₂(SO₄)₃·9H₂O.

liter the silver halides begin to precipitate at concentrations of 0.023, 0.060, and 0.0002 mg of dissolved silver per liter, respectively, when normal solubility relationships are maintained. If a concentration of 0.085 mg of silver per liter were added to this solution, 99% of the iodide would be precipitated at equilibrium. This precipitated silver iodide could then be removed by flocculation with alum. Thus, according to theory, if radioiodine also were present either as the iodide or in a form exchangeable with iodide, 99% of the activity could be removed in this way. As shown by the analytical data, however, the proportion removed is less than that calculated. This may be attributed to incomplete removal of precipitated silver iodide or to the formation of a suspension of colloidal material. When charged, such colloidal materials react very similarly to true ions. Also, it is probable that the various silver halides are actually precipitated as mixed crystals.

(c) *Removal of Strontium.* Since Sr^{90} is one of the more hazardous beta-emitting radionuclides, the removal of this element has been of considerable interest. Data given in Table 8.1 show that coagulation is unsatisfactory for the removal of strontium. Downing, Wheatland, and Eden⁸ carried out experiments to determine the effect of the amount of coagulant used and the effect of pH on the removal of this radionuclide. Their results showed that strontium removal from a solution at pH 7.0 increased from about 2 to 73% when the iron-coagulant dose was increased from 10 to 10,000 mg/liter. Furthermore, in the presence of 500 mg of iron per liter, strontium removals increased from 20 to 97% as the pH was raised from 7.0 to 11.0. They concluded that there may be a combination of two effects at work in alkaline solutions: ". . . enhanced adsorption on the hydroxide floc together with some co-precipitation of strontium with calcium carbonate." The adsorption of divalent ions on ferrous hydroxide was studied by Kurbatov and others.^{9,10}

Studies¹¹ of the effect of aeration on untreated and phosphate-treated samples showed that strontium phosphate was more soluble than carbonate at a comparable pH and that phosphate had a solubilizing effect during precipitation of the strontium carbonate. This effect is similar to that reported by Reitemeier and Ayers:¹² the presence of as little as 3 mg of sodium metaphosphate per liter prevented the precipitation of calcium carbonate.

(d) *Removal of Mixed Fission Products.* The removal by coagulation of activity from a mixture of radionuclides is a function of the radionuclides present. If the mixture contains an excess of such radionuclides as cesium, strontium, or iodine, the removal efficiency will be low; if it contains an excess of more easily removed radionu-

*Except for pH.

†Auxiliary chemical was activated carbon.

‡Auxiliary chemical was copper sulfate.

§Auxiliary chemical was silver nitrate.

¶Either 20 mg/liter as iron or 100.84 mg/liter as $\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$.

clides, such as the trivalent rare earths, phosphorus, and zirconium-niobium, removal efficiency will be high.

The results¹³ of coagulation and settling treatments on a variety of mixed waste solutions are summarized in Table 8.4. Removal efficiencies range from 46 to 89%.

TABLE 8.4—REMOVAL OF MIXED-FISSION-PRODUCT NUCLIDES BY COAGULATION AND SETTLING

Fission-product mixture	Removal, %
1*	61-84
3†	46
4‡	89
5§	51-59

*Iodine dissolver solution; clay added.

†Three-year-old fission-product mixture.

‡Iodine dissolver solution aged 30 days.

§Mixed-fission-product waste containing Cs¹³⁷-Ba^{137m} and Ru¹⁰⁶-Rh¹⁰⁶.

8-1.2 Sand Filtration

Except for removal by simple straining or by sorption on biological life contained in the Schmutzdecke (top layer of material on a filter), sand filters have not been effective in removing radioactive materials.^{14,15} Their major function is to remove the radioactivity previously incorporated in floc particles.

(a) *Rapid Sand Filters.* As shown in Table 8.5, removal of radioactive materials by high-rate filtration (125 million gal per acre per day) will vary with the nature of the materials studied.⁶ For example, scandium, yttrium, and zirconium-niobium, which were probably present as colloids, were readily removed; other materials,

TABLE 8.5—LABORATORY SAND-FILTRATION RESULTS

Nuclide	Initial activity, counts/(min) (n.l.)	Volume passed, mi	pH of effluent	Removal, %	
				Range	Average
Cs ¹³⁷ -Ba ^{137m}	800	500	8.3	10-70	50
Sr ⁹⁰	2700	750	8.3	1-13	4
Cd ¹¹⁵	1200	500	8.1	60-99	95
Ba ¹⁴⁰ -La ¹⁴⁰	1300	750	7.6	39-99	74
Sc ⁴⁶	1500	750	8.3	94-99	96
Y ⁹¹	5700	750	7.0	84-89	87
Zr ⁹⁵ -Nb ⁹⁵	3400	500	7.8	91-96	93
W ¹⁸⁵	2200	750	7.1	3-18	8

s, phosphorus, and zirconium-
 settling treatments on a variety
 sized in Table 8.4. Removal

ION-PRODUCT NUCLIDES BY
 SETTling

Removal, %

61-84
 46
 89
 51-59

Ru¹⁰⁶-Rh¹⁰⁶

g or by sorption on biological
 layer of material on a filter),
 removing radioactive mate-
 remove the radioactivity previ-

a in Table 8.5, removal of
 tion (125 million gal per acre
 the materials studied.⁶ For
 conium, which were
 removed; other materials,

FILTRATION RESULTS

pH of effluent	Removal, %	
	Range	Average
8.3	10-70	50
8.3	1-13	4
8.1	60-99	95
7.6	39-99	71
8.3	94-99	96
7.0	84-89	87
7.8	91-96	93
7.1	3-18	8

such as strontium, cesium, and possibly tungsten, which were present in true solution, were not affected by passage through the sand filters.

(b) *Slow Sand Filters.* The efficiency of slow sand filters (2 to 8 million gal per acre per day) for the removal of the soluble radionuclides I¹³¹, Sr⁹⁰, Ru¹⁰⁶, Ce¹⁴⁴, and Pu²³⁹ was discussed by Eden, Elkins, and Truesdale.¹⁵ Their results have been summarized in Fig. 8.1. Of the nuclides shown, ruthenium appears first in the filter effluent, followed by Sr⁹⁰, I¹³¹, Pu²³⁹, and Ce¹⁴⁴; cerium is the most effectively removed by the sand filter with only 8% of the influent activity found in the effluent after 14 days. The dashed lines in Fig. 8.1 are indica-

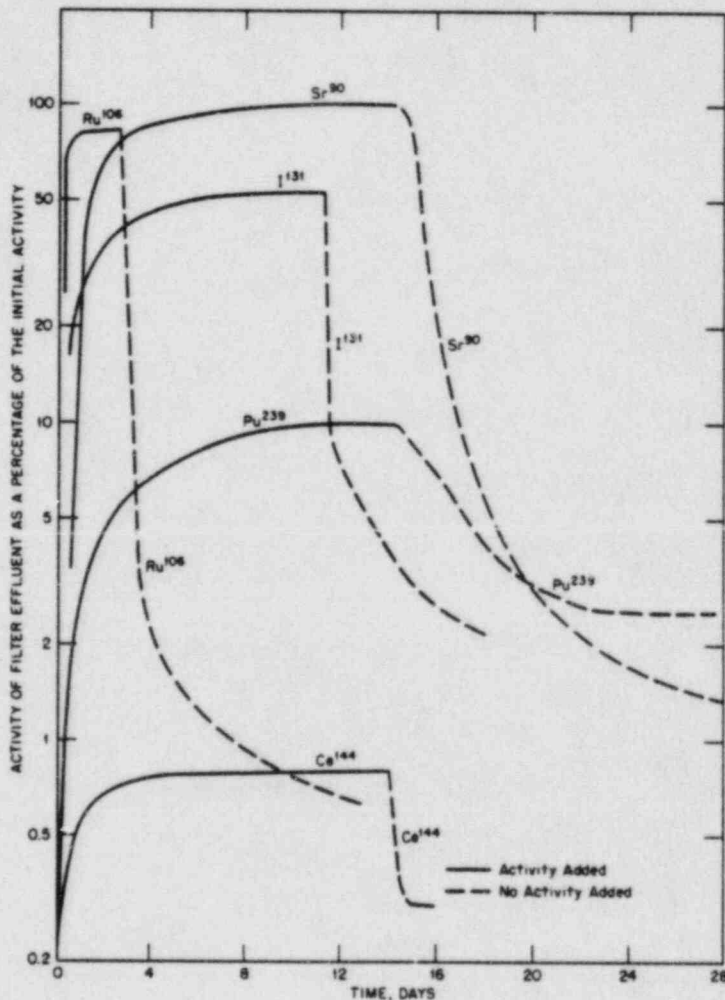


Fig. 8.1—Removal of radionuclides from water by slow sand filtration.

tive of the release rate of each nuclide previously sorbed in the filter bed when clean water was passed through the filter. It can be seen that the filter continued to release Pu^{239} , I^{131} , and Sr^{90} for some time after addition of the radionuclide. If initial concentrations were high, then this slow release from the filter would result in potentially hazardous concentrations in the filtered water.

Subsidiary experiments⁶ showed that over 99% of the strontium retained in the filter was associated with the Schmutzdecke and that this activity could be readily separated from the sand during the normal process of filter washing.

8-1.3 Combined Treatment: Coagulation, Settling, and Filtration

In the previous sections the decontamination of radioactive solutions by specific treatment processes has been discussed. These data provide a basis for evaluating the efficiency of a given process. The total efficiency resulting from a combination of processes is considered in this section.

Some of the early work on combined coagulation, settling, and filtration was carried out at the Oak Ridge National Laboratory, where pilot-plant facilities were designed and built,¹⁶ and at the Massachusetts Institute of Technology.³

At ORNL a 250 gal/day (1000 liter/day) water-treatment plant was built to establish basic criteria for the design of larger pilot plants or full-scale treatment units and to develop optimum operating procedures. This plant, which included facilities for mixing, coagulation, settling, and rapid sand filtration, is described in the literature;^{2,16} a flow sheet is shown in Fig. 8.2.

Operating results in the removal of P^{32} , I^{131} , and a fission-product mixture¹⁷ are summarized in Tables 8.6 and 8.7. In the case of P^{32} , 85% of the radioactivity was removed during coagulation and settling; 79 to 88%, during filtration. This gave an overall removal of 96 to 98%. These findings may be compared with results reported by Eliassen and coworkers,³ which are reproduced in Table 8.8. Their removals were somewhat better than those reported by ORNL.

As seen in Table 8.6, there was little removal of I^{131} by the processes indicated.

In another series of tests, batch coagulation, sedimentation, and sand filtration were employed to remove specific radionuclides from a fission-product mixture. The composition of the initial mixture, of the various effluents (settled and filtered), and of the sludge are given in Table 8.9. It should be noted that, even though the composition of this mixture is somewhat different from that previously reported (Table 8.7), the overall removal of activity by the various units comprising the treatment process are practically identical. This is believed to be due to chance, inasmuch as removals of individual

previously sorted in the filter through filter. It can be seen that ^{235}U , ^{238}U , and Sr^{90} for some time had result in potentially hazardous concentrations were high, at over 99% of the strontium with the Schmutzdecke and that removed from the sand during the

Settling, and Filtration

ation of radioactive solutions in discussed. These data provide of a given process. The total of processes is considered in

ned coagulation, settling, and large National Laboratory, where built,¹⁸ and at the Massachusetts

ay) water-treatment plant was design of larger pilot plants or develop optimum operating procedures for mixing, coagulation, described in the literature;^{2,16}

^{235}U and a fission-product ^{137}Cs . In the case of ^{235}U , during coagulation and settling; an overall removal of 96 to reported with results reported by produced in Table 8.8. Their those reported by ORNL.

removal of ^{131}I by the processes agulation, sedimentation, and re specific radionuclides from a tion of the initial mixture, of (d), and of the sludge are given, even though the composition from that previously reported vity by the various units com- ractically identical. This is rich as removals of individual

TABLE 8.6.—REMOVAL OF RADIONUCLIDES BY CONVENTIONAL WATER-TREATMENT PROCESSES*

Radio-nuclide	Initial activity, counts/(min) (ml)	Turbidity, mg/liter	Alum, grains/gal†	Alkali		Sodium silicate, grains/gal†	Carbon, mg/liter	Removal, %		
				Kind	Dose, grains/gal†			Settling	Filtration	Overall
P^{32}	130-160	95-100	0.52-0.85	NaOH	0.50-0.76			85	79-88	96-98
^{131}I	400-500	95	1.5	Lime	1.5	0.37		<0.4	<0.4	<0.4
^{131}I	400-600	100	1.5	Lime	1.5	0.42	4.0	16	11	25

*From C. P. Straub et al. *Eng. News-Record*, 147(7): 38 (Aug. 16, 1951).
 †Grains/gal=17.1 mg/liter.

TABLE 8.7.—REMOVAL OF MIXED FISSION PRODUCTS BY CONVENTIONAL WATER-TREATMENT PROCESSES*, †

Radio-nuclide‡	Percent of mixture	Turbidity, mg/liter	Dose, grains/gal			Removal, %		
			Alum	Lime	Silicate	Settling	Filtration	Overall
Total	100	100	0.9	0.8	0.4	46	44-50	70-73
Ru^{106} - Rh^{106}	15.9					75	0-30	75-82
Ce^{144} - Pr^{144}	12.1					55	46-51	76-78
Y^{91}	17.9						40-41	48-50
Sr^{90} - Y^{90}	35.4					61	17-23	68-70
Zr^{95} - Nb^{95}	14.5					68	68-78	90-93
^{131}I	4.2					39	6-53	43-72

*Activity present corresponds to activity present one month after the detonation of a nominal nuclear device.
 †From C. P. Straub et al. *Eng. News-Record*, 147(7): 38 (Aug. 16, 1951).
 ‡Ruthenium, rhodium, cesium, praseodymium, yttrium, and strontium are present in chloride form; zirconium and niobium present as oxalate complex in oxalic acid solution; and iodine present as iodide.

TABLE 8.8—REMOVAL OF P^{239} AND P^{233} BY A RAPID-SAND-FILTRATION PILOT PLANT*,†

Run No.	Water	Coagulant, mg/liter	Removal, %			Decontamination factor ($\frac{P^{239} \text{ initial}}{P^{239} \text{ final}}$)
			Coagulation + settling	Filtration (av. of six filters)	Total for plant	
1	Cambridge	Alum, 100	74.5	98.30	99.57	232
2	Cambridge	Alum, 100	81.0	99.62	99.93	1430
3	Cambridge	$Fe_2(SO_4)_3$, 30-40	80.9	99.40	99.89	910
4	Ohio River (turb. = 32 mg/liter)	$Fe_2(SO_4)_3$, 60	93.7	99.63	99.98	5000
5	Ohio River (turb. = 32 mg/liter)	Alum, 48-60	67.0	98.83	99.61	256

*Initial concentration of P^{239} was 0.01 mg/liter.†From R. Ellissen et al., *J. Am. Water Works Assoc.*, 43: 615 (1951).

5000 256

99.98 99.61

99.63 98.83

93.7 67.0

60 60
Fe₂(SO₄)₃ Alum

4 Ohio River (turb. = 32 mg/liter)
5 Ohio River (turb. = 32 mg/liter)

*Initial concentration of Pu was 0.01 mg/liter.
†From R. Ellissen et al., *J. Am. Water Works Assoc.*, 43: 615 (1951).

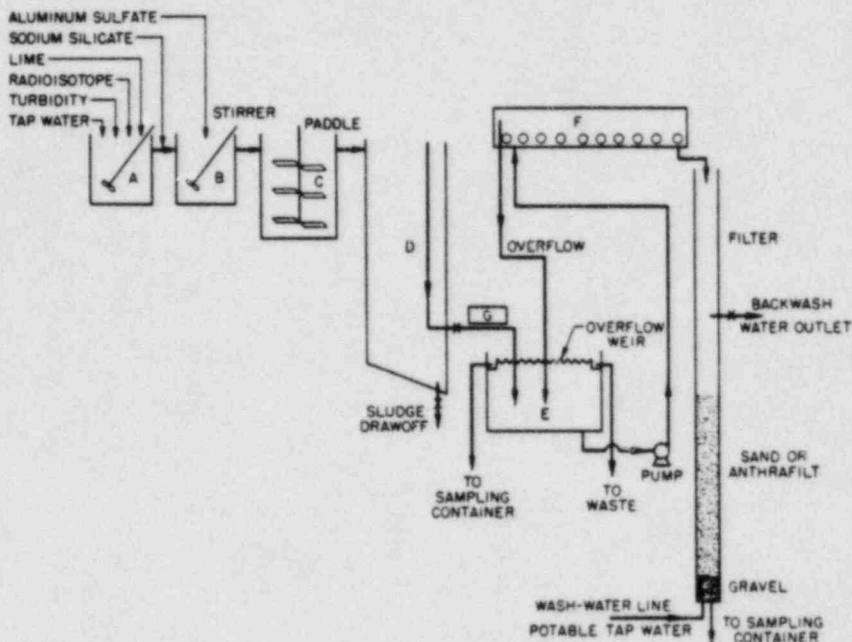


Fig. 8.2—Flow diagram of ORNL water-treatment pilot plant. A, primary mixing tank; B, secondary mixing tank; C, flocculation, or coagulation, tank; D, settling tank; E, flow proportioning and sampling tank; F, overhead orifice feed tank for feeding 10 filter columns; and G, G-M tube connected to count-rate meter and recorder. (Figure not to scale.)

nuclides in the mixtures varied considerably for the two tests. Radiochemical analyses are necessary to determine the removal of specific substances and should be performed in all instances.

8-1.4 Lime and Soda-ash Softening

Lime and soda-ash removals reported for a variety of radionuclides are summarized in Table 8.10. These data show that reasonable amounts of chemical will provide a 90% or better removal of soluble Ba¹⁴⁰-La¹⁴⁰, Sr⁹⁰, Cd¹¹⁵, Sc⁴⁶, Y⁹¹, and Zr⁹⁵-Nb⁹⁵ but that much larger quantities of chemical (up to 48 grains/gal) were ineffective for the removal of Cs¹³⁷-Ba^{137m} and W¹⁸⁵. It will also be noted that lime alone was effective for the removal of Zr⁹⁵-Nb⁹⁵. Lime and soda-ash softening has also been tested for the removal of iodine, but the results have been negative.⁵

Treatment with lime and soda ash finds its greatest use in the removal of potentially hazardous strontium. Many studies have been carried out to define the mechanism involved, namely, the coprecipitation of the strontium with the calcium. When stoichiometric amounts of chemical are used, a removal efficiency of approximately 65 to 75% of the dissolved strontium can be obtained.^{8,18,19} As

TABLE 8.9—REMOVAL OF FISSION-PRODUCT ACTIVITY BY COAGULATION, SETTLING, AND FILTRATION*

Radionuclide	Concentration, %				Removal, %		
	Raw water	Settled effluent	Filtered effluent	Sludge	Coagulation + settling	Filtration	Overall
Cs ¹³⁷ -Ba ^{137m}	27.2	40.0	17.6	17.2	21.2	75.6	80.8
Sr ⁹⁰ -Y ⁹⁰	27.6	46.5	68.9	20.1	9.5	18.3	26.0
TRE†	31.2	7.9	7.9	53.1	86.3	15.5	92.5
Ru ¹⁰⁶ -Rh ¹⁰⁶	3.9	2.4	3.5	4.0	32.1		78.7
Ce ¹⁴⁴ -Pr ¹⁴⁴	8.7	2.9	2.0	9.1	82.1	59.3	92.7
Totals	98.6	99.7‡	99.9‡	103.5	46.3	44.4	70.1

*Initial concentration of radioactive material, 22,500 counts/(min) (ml).

†Trivalent rare earths other than cerium.

‡Quantitative analytical recoveries corrected to approximately 100%.

	3.9	2.4	3.5	4.0	82.1	78.7
Ce ¹⁴⁴ -Pr ¹⁴⁴	8.7	2.9	2.0	9.1	59.3	92.7
Totals	98.6	99.9†	103.5	46.3	44.4	70.1

*Initial concentration of radioactive material, 22,500 counts/(min) (ml).
 †Trivalent rare earths other than cerium.
 ‡Quantitative analytical recoveries corrected to approximately 100%.

TABLE 8.10—APPROXIMATE MINIMUM COMBINED DOSAGE OF LIME AND SODA ASH TO GIVE STATED REMOVAL* †‡

Nuclide	Chemical dosage (grains/gal) for stated removal									
	50%		75%		90%		95%		99%	
	Lime	Soda	Lime	Soda	Lime	Soda	Lime	Soda	Lime	Soda
Ba ¹⁴⁰ -La ¹⁴⁰	2	2	4	2	6	4				
Sr ⁹⁰	4	3	5	5	7	9	20	20		
Cd ¹¹⁴	2	2	3	3	4	4	4	4	6	4
Sc ⁴⁶	3	3	3	3	5	5				
Y ⁹¹	2	2	4	4	6	6	12	6		
Zr ⁹⁴ -Nb ⁹⁴	2	0	5	0	12	0	17	0	22	0
Cs ¹³⁷ -Ba ^{137m}	48	48								
W ¹⁸⁸	48	48								

*Minimum combined dosage is defined such that, of the variable dosages studied, the number of grains per gallon of lime plus the grains per gallon of soda ash is a minimum.

shown in Table 8.11 increased removals of strontium are obtained with increased chemical dosages.^{9,18}

Coprecipitation may be accomplished by (1) formation of mixed crystals in which foreign ions are incorporated homogeneously in the crystal lattice; (2) occlusion of impurities as imperfections scattered at random throughout the crystal; and (3) surface adsorption of foreign ions by the precipitate after it has formed.^{20,21}

TABLE 8.11—REMOVAL OF STRONTIUM BY LIME AND SODA-ASH SOFTENING*

Run No.	Hardness, mg CaCO ₃ /liter		Lime added†	Na ₂ CO ₃ added‡	Strontium removed, % of initial content
	Temporary	Permanent			
1	200	0	100	0	67.6
2	200	0	100	0	73.0
3	200	0	100	0	70.5
4	150	50	100	105	70.0
5	150	50	100	105	71.6
6	50	150	100	105	60.0
7	50	150	100	105	63.5
8	200		0	328	91.2
9	200		0	310	89.5

*From A. L. Downing *et al.*, *J. Inst. Water Engrs.*, 7: 555 (1953).

†As percentage of that equivalent to all the temporary calcium hardness.

‡As percentage of that equivalent to the permanent calcium hardness.

Strontium is removed by mixed-crystal formation. Its removal is directly related to the removal of calcium. Therefore, for effective removal of strontium, it is imperative that the calcium hardness be reduced to a very low value. Such a requirement suggests a considerable excess of soda ash in the water during treatment and an initial reduction of calcium hardness to a low value. A system of repeated additions and precipitations of small quantities of calcium could then be used to reduce the radioactive strontium to a very low amount. This is the so-called "repeated-precipitation" process.²²

Although only 80 to 90% of the strontium can be removed by the initial softening reaction, a secondary process, which provides for the addition and elimination of small quantities of calcium in several steps, removes an equal percentage of activity in each stage. For instance, in a 10-stage plant, each step of which has a removal efficiency of 50%, 99.9% of the initial activity is removed. In 15 such stages, 99.996% of the initial activity is removed. These removals are ideal; in practice, however, where one treats highly variable chemical solutions, it may not be possible to obtain them.

In hot-lime and soda-ash softening at temperatures above 90°C, the addition of enough soda ash to produce a 50 mg/liter excess (as CaCO₃) over that amount required to react with noncarbonate hardness and

Studies have been made in which tap-water solutions containing added tracer amounts of soluble W^{185} , Y^{91} , Sc^{45} , Sr^{90} , Ba^{140} - La^{140} , Cs^{137} - Ba^{137m} , Cd^{115} , and Zr^{95} - Nb^{95} were passed through various synthetic ion-exchange materials. Results are given in Table 8.12. For com-

TABLE 8.12—EFFICIENCY OF ION-EXCHANGE MATERIALS IN REMOVING INDIVIDUAL NUCLIDES

Nuclide	Removal, %			
	Cation exchange	Anion exchange	Mixed bed	Greensand
W^{185}	12-16	97.2-99.2	98.9	9
Y^{91}	86-93.1	94.2-98.5	97.6-98.7	75
Sc^{45}	95.7-97.2	98.8-99.0	98.5-98.7	96.4
Sr^{90}	99.1-99.8	5-7	99.95-99.97	99.8
Ba^{140} - La^{140}	98.3-99.0	36-42	99.5-99.6	96.3
Cs^{137} - Ba^{137m}	99.8	9	99.8	
Cd^{115}	98.5	0	99.2	
Zr^{95} - Nb^{95}	58-75	96.4-99.9	90.9-99.4	

parison, results obtained using greensand (glaucinite) as the exchange material¹⁴ are also included in the table. Greensand was used in these studies because it has had extensive use in water-treatment practice.

The cation-exchange materials evaluated included IR-120 (H^+ and Na^+ cycles) and a natural greensand (Na^+ cycle); the anion exchangers included Dowex-1 (OH^- and Cl^- cycles); and the mixed beds included IR-120 (H^+) plus Dowex-1 (OH^-) and IR-120 (Na^+) plus Dowex-1 (Cl^-). In general, the particular regeneration cycle used, i.e., H^+ or Na^+ regenerated cation-exchange resin or OH^- or Cl^- regenerated anion-exchange resin, did not appreciably influence the results. In water-treatment practice the effluent pH is of significance and should be near neutrality. For the various exchange materials studied, the range in effluent pH varied as follows: IR-120 (H^+), 2.8 to 3.6; IR-120 (Na^+), 3.4 to 4.3; Dowex-1 (OH^-), 10.7 to 11.2; Dowex-1 (Cl^-), 7.2 to 8.7; and greensand, 7.1 to 8.0. From the standpoint of pH, the most satisfactory water-treatment effluents were those produced with Dowex-1 (Cl^-) and greensand. The removal efficiencies obtained with greensand do not differ significantly from the results indicated for cation-exchange resins; however, the exchange capacity of the cation-exchange resins is much greater.

From the results given in Table 8.12, it can be noted that the strontium, cesium, cadmium, and, to a lesser extent, barium-lanthanum tracers are present in solution as cations, whereas the tungsten tracer is in the anion form. Yttrium, scandium, and zirconium-niobium are apparently in colloidal form and, as such, are removed to

tap-water solutions containing ^{90}Sr , ^{137}Cs , ^{140}Ba - ^{140}La , ^{137}Cs and through various synthetic solutions given in Table 8.12. For com-

EXCHANGE MATERIALS IN
AL NUCLIDES

	Removal, %	
	Mixed bed	Greensand
2	98.9	9
5	97.6-98.7	75
0	98.5-98.7	96.4
	99.95-99.97	99.8
	99.5-99.6	96.3
	99.8	
	99.2	
9	90.9-99.4	

and (glaucanite) as the exchange material. Greensand was used in extensive use in water-treatment

tests included IR-120 (H^+ and Na^+ cycle); the anion exchangers; and the mixed beds included IR-120(Na^+) plus Dowex-1 regeneration cycle used, i.e., H^+ in one cycle or Cl^- regenerated by H^+ or Cl^- regenerated by H^+ or Cl^- . In all cases of significance and should be noted, the exchange materials studied, the IR-120(H^+), 2.8 to 3.6; IR-120(Na^+), 10.7 to 11.2; Dowex-1(Cl^-), 10.7 to 11.2. From the standpoint of pH, the effluents were those produced. The removal efficiencies obtained were significantly from the results obtained. However, the exchange capacity was greater.

2, it can be noted that the removal of strontium to a lesser extent, barium-lanthanum, whereas the tungsten, scandium, and zirconium-90, as such, are removed to

some extent on both cation- and anion-exchange resins. It has been shown^{6,14,26} that an appreciable proportion of the radiostrontium in the water would continue to be removed by a column that had long ceased to remove calcium. This was attributed to a difference in the affinity of a given exchange material for strontium, as compared with calcium; such differences are said to be greater in rigid, dense exchangers, such as the aluminosilicates,⁶ than in the organic exchangers.

Further studies by Downing and coworkers⁶ showed that there appeared to be a slight tendency for the activity in the effluent to increase in successive cycles; it was found, however, during several successive cycles that over 97% of the strontium activity initially present in the water could be removed. It was also noted that, in the first few cycles at least, the proportion of activity appearing in the effluent was less than the normal "leakage" of hardness.

Friend²⁵ carried out a more extended study of the efficiency of ion-exchange procedures for the removal of I^{131} , Sr^{90} , and mixtures of the two radionuclides. He reported a decontamination factor (influent activity/effluent activity) in excess of 10^2 (greater than 99% removal) for carrier-free I^{131} with IRA-400 resin (OH^-) or a combination of IR-120(Na^+ or H^+) and IRA-400(OH^-); a decontamination factor in excess of 10^3 (greater than 99.9% removal) for carrier-free Sr^{90} with IR-120(H^+) or a combination of IR-120(H^+ or Na^+) and IRA-400(OH^-); and a decontamination factor in excess of 10^3 (greater than 99.9% removal) for a carrier-free mixture of Sr^{90} and I^{131} with IR-120(H^+ or Na^+) and IRA-400(OH^-).

Several parameters having an influence on the removal of hardness and more particularly the removal of Sr^{90} by Amberlite IR-120(H^+) resin were studied.²⁶ It was concluded that increased flow rates decreased resin capacity and slightly decreased the efficiency of the column for removal of Sr^{90} , that resin breakthrough capacity became greater with increasing length of column, that hardness capacity and radiostrontium removal increased with decreasing resin particle size, that increased feed-water temperature slightly increased removal of Sr^{90} and resulted in a sharper breakthrough of hardness, and that, within the pH range of 2 to 10, the Sr^{90} removal efficiency and hardness capacity increased slightly with increasing pH.

(b) *Slurry Studies.* Lacy and Lindsten²⁷ studied the removal of specific radionuclides from tap water by slurring with ion-exchange resin. Typical results are shown in Figs. 8.3 and 8.4. Increased removal occurs with an increase in slurring time and concentration of resin, as shown in Fig. 8.3. Considerable difference in rates of removal for the various radionuclides is indicated in Fig. 8.4, but a concentration of 2700 mg of MB-3 resin per liter slurried for 90 min removed over 98% of all radionuclides tested. The removal of radio-

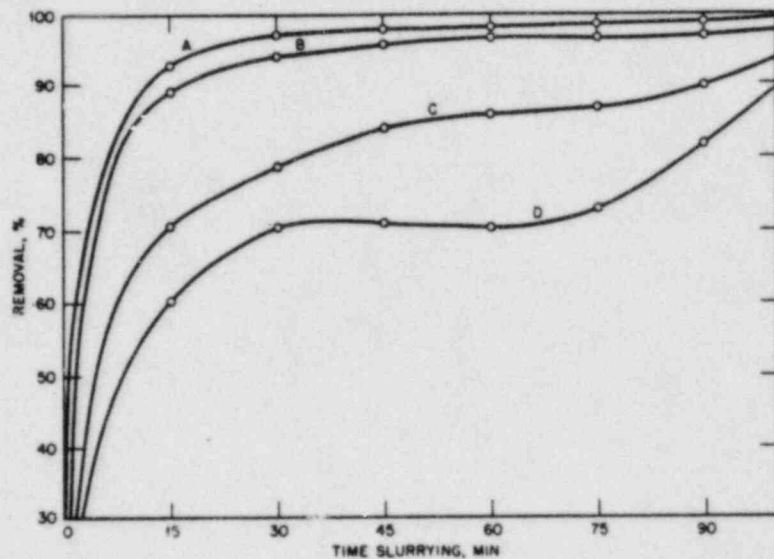


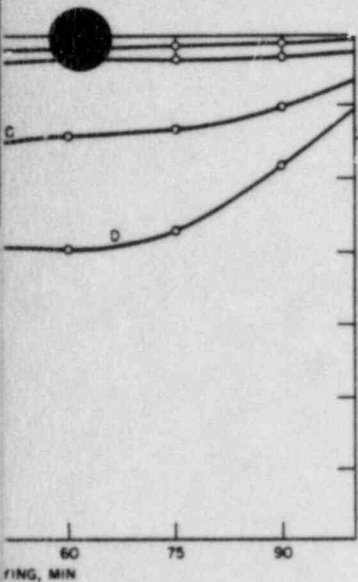
Fig. 8.3—Effect of increased contact time and concentration of ion-exchange resin on the removal of FMP-2. A, 2700 mg/liter; B, 1800 mg/liter; C, 900 mg/liter; and D, 450 mg/liter.

active contaminants did not increase proportionally with increasing resin dosage.²⁷

8-1.6 Solids-contact Softening

To confirm his laboratory findings on the removal of Sr^{90} by water-softening procedures, Hoyt¹⁸ carried out studies on a pilot-plant scale by employing a 1000 gal/day Spaulding type precipitator unit. In this unit the flow of water is downward through a cone, where the added chemicals are mixed, and then upward around the outside of the cone to an outlet weir circling the tank (see Fig. 8.5). As the water containing the chemicals passes under the cone and upward toward the effluent weir, the velocity decreases due to the increased cross-sectional area through which the liquid moves. As a result the upward velocity of the particulates is balanced by the pull of gravity, and the particles remain in equilibrium forming a layer of freely suspended particulates through which the liquid flowing upward must pass. This layer provides increased contact with particulates and some filtration and thus effects a greater degree of removal.

The results of the pilot-plant investigation are given in Table 8.13 along with the results of the laboratory jar-test studies. Higher removals were obtained in the pilot plant than in the laboratory tests with similar levels of chemical dosage. The removal of all suspended



and concentration of ion-exchange resin
 ter; B, 1800 mg/liter; C, 900 mg/liter;

proportionally with increasing

on the removal of Sr⁹⁰ by water-
 l on studies on a pilot-plant
 pauling type precipitator unit.
 ward through a cone, where the
 upward around the outside of
 the tank (see Fig. 8.5). As the
 es under the cone and upward
 decreases due to the increased
 e liquid moves. As a result the
 balanced by the pull of gravity,
 ium forming a layer of freely
 ch the liquid flowing upward
 eased contact with particulates
 greater degree of removal.

tigation are given in Table 8.13
 atory jar-test studies. Higher
 ant than in the laboratory tests
 The removal of all suspended

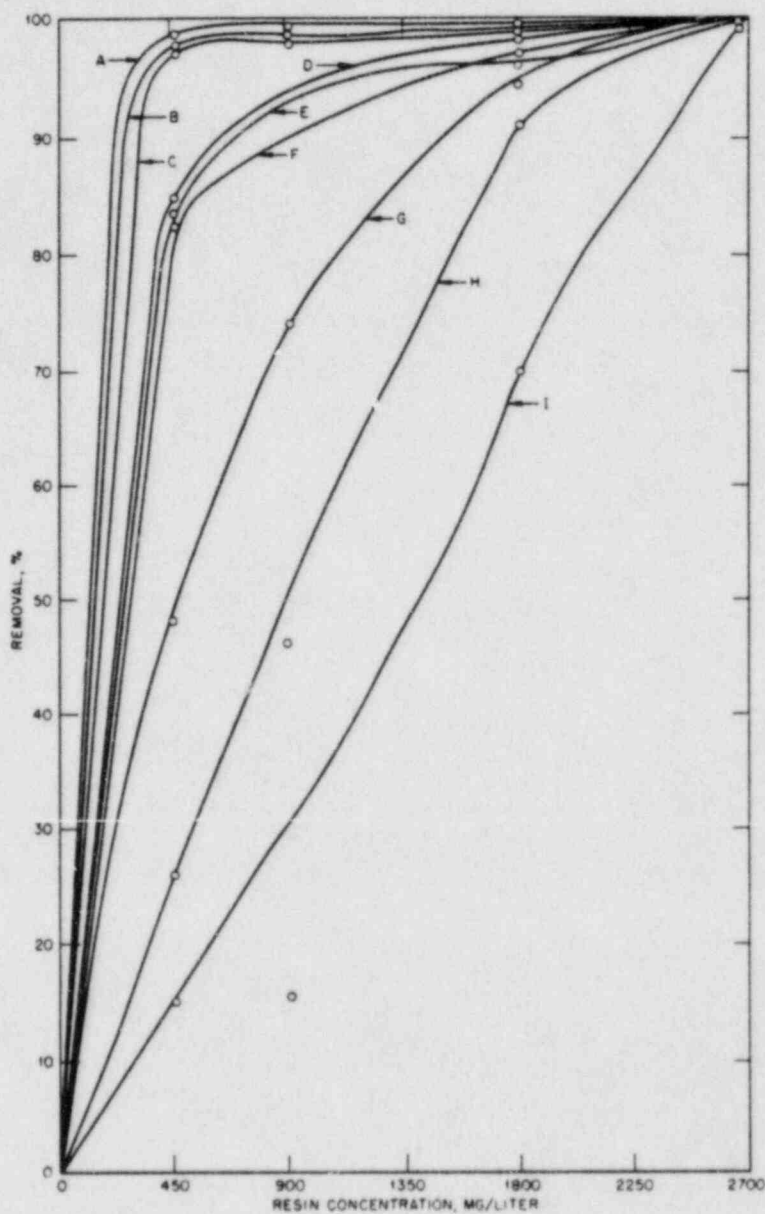


Fig. 8.4—Decontamination of radioactively contaminated water by slurring with ion-exchange resin MB-3 (90-min contact time). A, Ta¹⁸²; B, Ce¹⁴⁴-Pr¹⁴⁴; C, Zr⁹⁵-Nb⁹⁵; D, Ba¹⁴⁰-La¹⁴⁰; E, I¹³¹; F, FPM-2; G, P³²; H, Cd¹¹⁵; and I, Cs¹³⁷-Ba^{137m}.

matter from the precipitation effluent (by centrifugation or sand filtration) increased the removals of hardness and activity to 87 and 96%, respectively, when 50 mg of excess lime and soda ash per liter were added.

8-1.7 Repeated-precipitation Process

Many conventional water-treatment plants with separate mixing, coagulating, and settling basins can be modified readily to utilize the repeated-precipitation process proposed by McCauley and Eliassen.²² Suggested flow diagrams for the repeated-precipitation process (either the straight-line flow method or the upflow reaction or contact basins) are reproduced in Figs. 8.6 and 8.7.

Modifications required for the successful operation of each of these units are:

1. For the plant in part (a) of Fig. 8.6, a change in flow pattern from parallel to series operation of the upflow units should be made, and small quantities of $\text{Ca}(\text{OH})_2$ or CaCl_2 should be added to the plant flow emerging from the primary upflow unit.

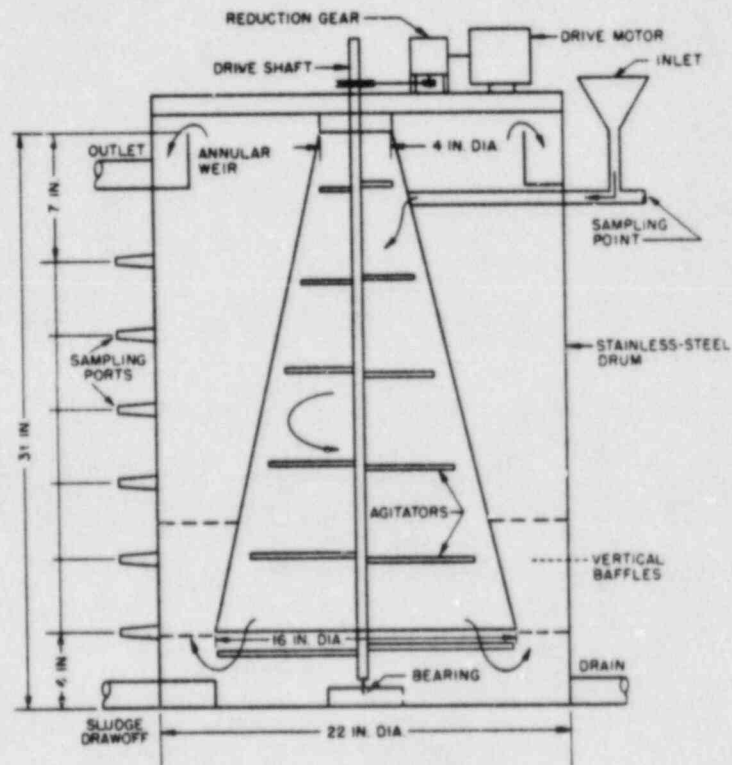


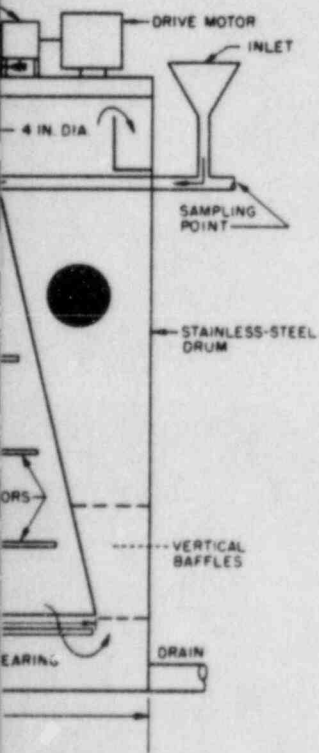
Fig. 8.5—Spaulding precipitator.

nt (by centrifugation or sand
ards and activity to 87 and
ess and soda ash per liter

t plants with separate mixing,
e modified readily to utilize the
d by McCauley and Eliassen.²²
ed-precipitation process (either
flow reaction or contact basins)

ssful operation of each of these

8.6, a change in flow pattern
e upflow units should be made,
CaCl₂ should be added to the
upflow unit.



recipitator.

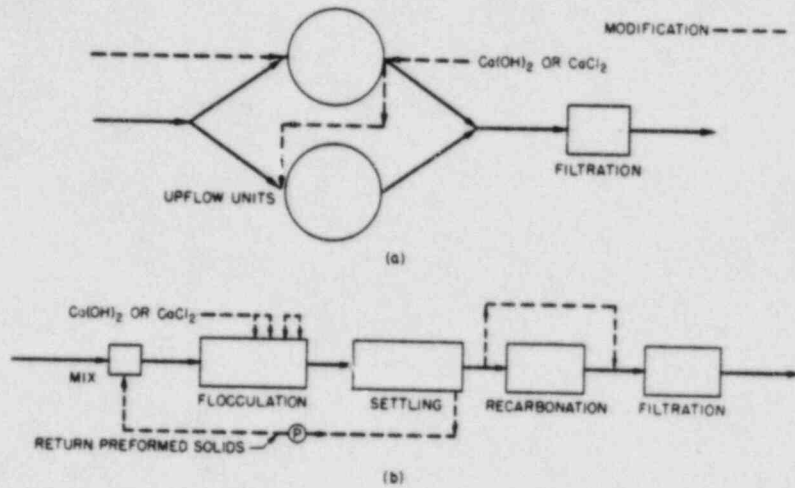


Fig. 8.6—Representative flow diagrams for lime-soda softening plants.

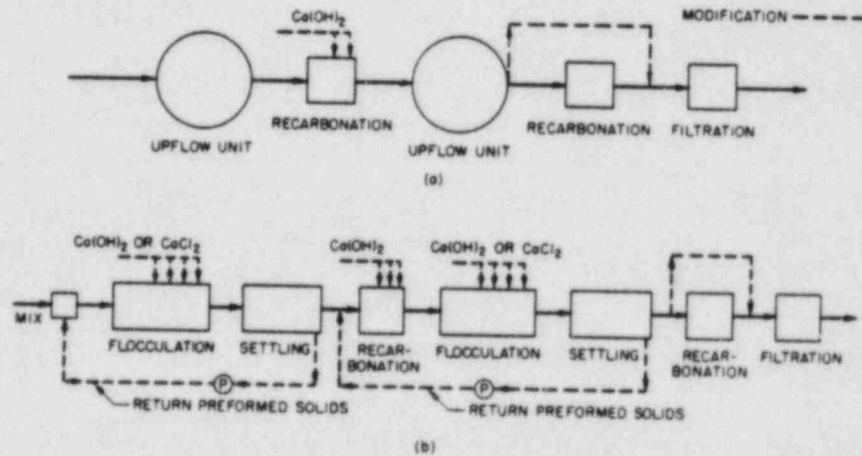


Fig. 8.7—Representative flow diagram for excess-lime softening plants.

TABLE 8.13—REMOVAL OF STRONTIUM: PILOT-PLANT AND JAR-TEST RESULTS

Treatment	Removal of activity, %		Removal of hardness, %	
	Jar test	Spaulding precipitator	Jar test	Spaulding precipitator
Required doses	75.9	79.5-86.0	52.5	59.1-68.1
Plus 50 mg/liter excess*	80.1	86.8	56.2	76.0
Plus 100 mg/liter excess*			67.3	85.5

*Lime and soda-ash excess.

2. For the plant in part (b) of Fig. 8.6, preformed solids should be recirculated from the settling tank to the mixing basin, and small quantities of $\text{Ca}(\text{OH})_2$ or CaCl_2 should be added to the flocculation basin.

3. For the plant in part (a) of Fig. 8.7, preformed solids should be added to the recarbonation basin, the CO_2 feed should be adjusted to reduce pH levels to the desired values in the tank, small quantities of lime water should be added, and provision should be made for agitation in the basin to keep preformed solids from settling. Compressed air should prove satisfactory for mixing plant flow with the added lime water and for preventing the preformed solids from settling.

4. For the plant in part (b) of Fig. 8.7, preformed solids should be recirculated from the settling tanks to the heads of the flocculation basins, and small quantities of $\text{Ca}(\text{OH})_2$ or CaCl_2 should be added to these basins. In addition, if the recarbonation basin is to be used for strontium removal, all modifications required for the plant illustrated in part (a) of Fig. 8.7 must be made.

Lacy²⁸ evaluated the efficiency of a full-scale Spaulding upflow precipitator-clarifier (Erdlator Solids-contact Clarifier, Fig. 8.8). His results, which show removals for various radionuclides and mixtures of radionuclides ranging from 46 to 93%, are summarized in Table 8.14.

8-1.8 Ion-exchange Systems

Commercial size (1.8 cu ft) ion-exchange systems were evaluated by Lacy²⁸ at ORNL; his results are summarized in Table 8.15. For the mixed wastes studied, cation-exchange resins on the Na^+ cycle were less effective than those on the H^+ cycle (67 to 70% as compared to 82 to 89% removal, respectively). However, the volume of liquid fed through the units was much greater in the case of the resins on the Na^+ cycle than for the resins on the H^+ cycle. Where a mixed-bed resin was used, a removal of 98 to 99% was indicated, but the throughput was reduced to 1500 gal.

8-1.9 Small-scale Commercial Units

Two types of commercial water-purification units were evaluated with respect to their effectiveness in removing radioactive components from a solution of fission products. In all, 12 units were tested, each of which contained 36 g of a mixture of diatomaceous earth and activated carbon, 22 g of Nalcite SAR resin, and 22 g of Nalcite HCR resin; 9 of the 12 units contained, in addition, 42 g of powdered iron. The solution used in these studies had an activity of approximately 10,000 counts/(min)(ml) (10% geometry) and had the following percentage composition: strontium-yttrium, 27.6; cerium-prase-

Fig. 8.6, preformed solids should be added to the flocculation

Fig. 8.7, preformed solids should be added to the heads of the flocculation (OH)₂ or CaCl₂ should be added to the recarbonation basin is to be used for the plant illustration required for the plant illustration.

Fig. 8.7, preformed solids should be added to the heads of the flocculation (OH)₂ or CaCl₂ should be added to the recarbonation basin is to be used for the plant illustration required for the plant illustration.

exchange systems were evaluated summarized in Table 8.15. For exchange resins on the Na⁺ cycle (67 to 70% as compared to H⁺). However, the volume of liquid water in the case of the resins on the H⁺ cycle. Where a mixed-bed system was indicated, but the

purification units were evaluated removing radioactive components. In all, 12 units were tested, each containing diatomaceous earth and R resin, and 22 g of Nalcite HCR resin, and 42 g of powdered iron. In addition, 42 g of powdered iron. had an activity of approximately 1000 (mCi/ml) and had the following activity: cesium-137, 27.6; cerium-prase-

TABLE 8.14—DECONTAMINATION OF RADIOACTIVE WATER WITH ERDLATOR SOLIDS-CONTACT CLARIFIER (30 GAL/MIN)**

Run	Contaminant†	Raw water and activity			Treatment			Effluent				Length of run, hr	Amount removed, %		
		pH	Alkali, mg/liter	Turbidity, mg/liter	Activity, counts/(min)(ml)‡	FeCl ₃ , mg/liter	CaCO ₃ , mg/liter	Ca(OCl) ₂ , mg/liter	pH	Alkali, mg/liter	Turbidity, mg/liter			Residual chlorine, mg/liter	Activity, counts/(min)(ml)‡
1	None	7.9	123	43		37.4	58.2	8.9	7.9	130	1.6	1.9		10	
2	None	7.2	134	47		24.9	24.1	8.5	7.5	133	2.0	1.8		7	
3	FPM-1	7.7	113	96	4900	29.1	24.1	7.75	7.6	113	1.3	1.7	800	10	83.7
4	P ³²	7.8	102	46	2465	45.7	58.2	5.25	7.6	69	2.4	1.5	180	10	93.3
5	I ¹³¹	8.0	123	72	1850	54.0	24.1	5.25	7.6	79	1.2	1.7	990	9	66.5
6	FPM-1	7.8	121	70	2010	58.1	24.1	5.3	7.5	96	3.0	1.4	787	9	63.8
7	FPM-1	7.8	115	69	3120	47.7	24.1	6.2	7.6	77	2.0	2.0	1130	8	60.8
8	FPM-4	7.8	98	15	3550	29.5	43.7	4.0	7.6	94	2.3	1.0	1760	21	50.4
9	FPM-4	8.0	97	25	220	33.2	24.1	2.0	7.3	98	1.9	0.6	95	7	56.8
10	FPM-3	7.9	100	35	1740	23.3	36.4	3.1	7.5	98	1.0	1.1	530	56	69.5
11	FPM-3	7.9	99	46	3470	24.9	24.1	4.0	7.6	105	0.8	1.2	1190	21	65.7

*Source of water, White Oak Creek; output, 30 gal/min; Graham transmission setting, 90 rpm; Neusol water pressure, 30 psi; coagulant, FeCl₃, CaCO₃, and HTH; coagulant charge at start, 100 g of FeCl₃ and 950 g of CaCO₃.
 †See footnote to Table 8.4 for a description of the contaminants.
 ‡No correction has been made for counter efficiency (approximately 10%).

TABLE 8.15—ION-EXCHANGE REMOVAL OF RADIOACTIVITY FROM WATER CONTAINING MIXED FISSION PRODUCTS^{a,b}

Run No.	Resin	Cycle	Contam- inant†	Influent			Cumulative break- through, gal‡	Rate, gal/ (min)(sq ft)	Removal, %
				Activity, counts/ (min)(ml)	pH	Hardness, mg CaCO ₃ / liter			
1	Permutit Q	Na ⁺	FPM-4	5690	8.0	108	6990	10	70
2	Permutit Q	H ⁺	FPM-5	6470	7.6	106	3500	10	89
3	Amberlite IR-120	Na ⁺	FPM-5	6630	7.8	108	6600	10	67
4	Amberlite IR-120	H ⁺	FPM-5	7590	7.6	116	3700	10	82
5	Amberlite MB-3	(H ⁺ -OH ⁻)	FPM-5	5580	7.8	112	1500	10	98-99

^aUnits 1.8 cu ft.

^bFPM-4 by composition of its radioactivity was 72.5% cations and 27.5% anions; FPM-5 by composition of its radioactivity was 90.5% cations and 9.5% anions.

^cCumulative breakthrough in the sense used is cumulative volume to degree of hardness breakthrough. In runs 1 through 3 and in run 5, breakthrough was determined when effluent hardness exceeded 2% of the influent, and in run 4, when it exceeded 5%.

	Na ⁺	FPM-5	6630	7.8	108	6600	10	67
3 Amberlite IR-120	H ⁺	FPM-5	7590	7.6	116	3700	10	82
4 Amberlite IR-120	(H ⁺ -OH ⁻)	FPM-5	5580	7.8	112	1500	10	9
5 Amberlite MB-3								

*Units 1.8 cu ft.

FPM-4 by composition of its radioactivity was 72.3% cations and 27.7% anions; FPM-4 by composition of its radioactivity was 90.9% anions and 9.1% cations.

†Cumulative breakthrough in the sense used is cumulative volume to degree of hardness breakthrough. In runs 1 through 3 acid in run 4, breakthrough was determined when effluent hardness exceeded 2% of the influent, and in run 4, when it exceeded 9%.

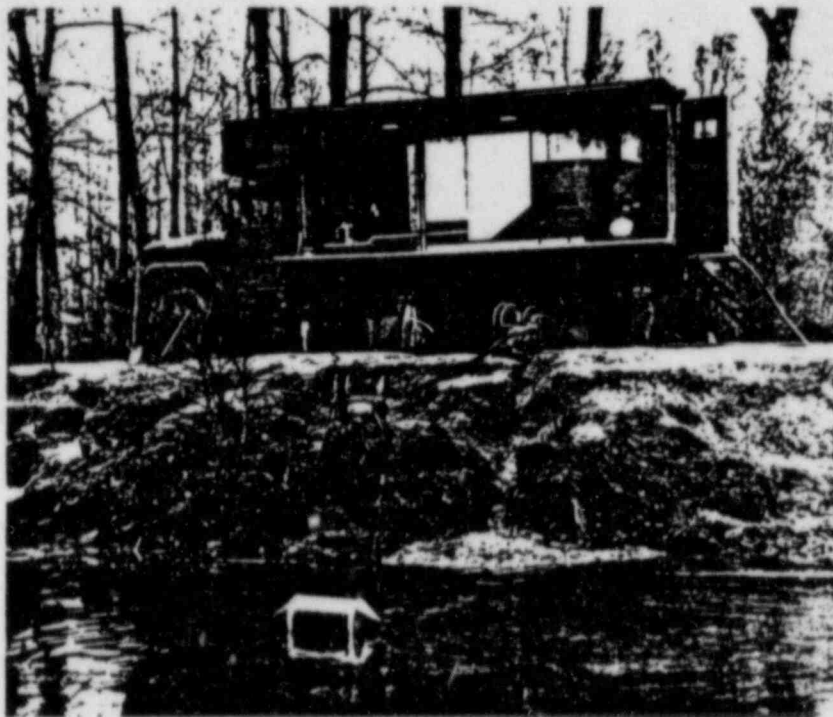


Fig. 8.8—Side view of Erdlator Solids-contact Clarifier, 30 gal/min.

odymium, 17.4; ruthenium-rhodium, 3.9; promethium, 22.1; samarium, 1.4; cesium, 27.2; and other radionuclides, 0.4. The results of the 12 runs are summarized in Table 8.16. It can be noted that the percentages of removal were quite variable even under similar test conditions. When tap water was used as a diluent, the highest removals observed were 98%. With distilled water initial removals of 99% were obtained.

8-2 NONCONVENTIONAL PROCESSES

Several methods for the removal of radioactive constituents from water which differ somewhat from the conventional processes just discussed have been studied. These nonconventional processes include phosphate coagulation, electro dialysis with permselective membranes, the addition of metallic dusts, and the addition of clay materials. Only those methods that can be utilized in conjunction with conventional water-treatment plants are described here; others are discussed in subsequent chapters (see Chaps. 10 through 12).

TABLE 8.16—REMOVAL OF RADIOACTIVITY BY SMALL-SCALE COMMERCIAL UNITS

Series	Influent activity, counts/(min)(ml)	Removal for various volumes of throughput, %				Average removal in first 40 liters of throughput, %	Flow rate*	pH of influent	pH range of effluent	Presence of visible iron floc	Remarks
		20 liters	40 liters	60 liters	80 liters						
A	10,970	38	39	39	54	40	0.28 liter/min	7.8	8.9-10.0	None	Distilled water flushed through unit for first 20 liters at 3.78 liters/min
B	12,260	95	92	77	60	94.8	20 liters at 3.78 liters/min, 2 liters at 0.014 liter/min, 54 liters at 0.47 liter/min	7.7	7.3-7.7	Much	Spiked solution flushed through units for initial 5-min period at 3.78 liters/min
C-1	11,540	98	95	90	84	98.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	7.4	6.8-7.6	Much	Spiked solution flushed through units for initial 5-min period at 3.78 liters/min
C-2	9,100	94	88	82		93.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	7.4	7.0-7.6	Much	Spiked solution flushed through units for initial 5-min period at 3.78 liters/min
C-3	9,100	87	76			85.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	7.4	6.5-7.1	Much	Spiked solution flushed through units for initial

C-1	11,540	98	95	90	84	98.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	7.4	6.8-7.6	Much	3.78 liters/min Spiked solution flushed through units for initial 5-min period at 3.78 liters/min
C-2	9,100	94	88	82		93.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	7.4	7.0-7.6	Much	Spiked solution flushed through units for initial 5-min period at 3.78 liters/min
C-3	9,100	87	76			85.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	7.4	6.5-7.1	Much	Spiked solution flushed through units for initial

D-1	9,100	75	51			36.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	7.4	6.0-7.2	None	5-min period at 3.78 liters/min Unit contained no powdered iron
D-2	9,100	84	49			76.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	7.4	6.0-7.2	None	Unit contained no powdered iron
D-3	5,380	84	48	43		75.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	7.4	6.2-7.1	None	Unit contained no powdered iron
E-1	10,380	54	42			58.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	10.0	8.2-9.4	Little	Influent pretreated by alum coagulation and sand filtration
E-2	10,380	62	47			64.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	10.0	7.6-8.6	Little	Influent pretreated by alum coagulation and sand filtration
E-3	10,380	54	38			56.0	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	7.4	6.2-7.4	Little	Influent pretreated by alum coagulation and sand filtration
F	1,790	99	99	99	43	98.8	20 liters at 3.78 liters/min, remainder at 0.47 liter/min	4.4	4.9-6.0	Dissolved iron present	Radioactive material diluted with distilled water

*Manufacturer's operating instructions are in terms of gallons and of pints per minute: 3.785 liters/min = 1 gal/min; 0.473 liter/min = 1 pint/min.

8-2.1 Phosphate Coagulation

Since laboratory findings have indicated that the usual coagulation procedures employing alum or iron salts with lime have not been too satisfactory in the removal of radioactive contaminants, other systems have been studied. Lauderdale²⁹ investigated phosphate coagulation for the removal of radioactivity since many polyvalent cations form relatively insoluble phosphate compounds and since phosphate floc can be formed in solution at high pH. He studied the removal of individual radionuclides in distilled water by adding either potassium dihydrogen phosphate or trisodium phosphate and calcium hydroxide. Maximum removals are shown in Table 8.17.

TABLE 8.17—REMOVAL OF RADIONUCLIDES BY PHOSPHATE COAGULATION*

Nuclide	Coagulant	Coagulant dose, mg/liter	Removal, %
Ce ¹⁴⁴	KH ₂ PO ₄	200	99.8
		120	99.9
Sr ⁹⁰	KH ₂ PO ₄	100	81.3
		240	97.8
Y ⁹¹	KH ₂ PO ₄	100	99.9
Sb ¹²⁴	KH ₂ PO ₄	100	66.1
		120	67.4
Zn ⁶⁵	KH ₂ PO ₄	50	99.6
W ¹⁸⁷	KH ₂ PO ₄	200	10.7
Zr ⁹⁵	KH ₂ PO ₄	100	99.5
Nb ⁹⁵	KH ₂ PO ₄	100	99.2

*From R. A. Lauderdale, Jr., USAEC Report ORNL-482, Oak Ridge National Laboratory, Jan. 23, 1951.

Removals of over 99% of the Ce¹⁴⁴, Zn⁶⁵, Y⁹¹, Nb⁹⁵, and Zr⁹⁵ were obtained. Although the conditions of precipitation had little effect on the removal of these nuclides, marked differences occurred in the removal of Sb¹²⁴ and Sr⁹⁰ when the pH and coagulant dosages were varied. As a result, Sr⁹⁰ was selected for special study. It was found that at a pH of 11.3, with a phosphate to calcium ratio greater than 2.2 to 1 (corresponding to a 46% excess of phosphate), a high removal of Sr⁹⁰ was effected; above a pH of 11.3 the increase in removal was negligible (Fig. 8.9). These data indicate that, if an excess of phosphate were used at a pH of 11.3 or above, maximum hazard reduction could be obtained in the treatment of fission-product mixtures in which radiostrontium is one of the more hazardous constituents. Consequently tests incorporating these conditions were carried out with a fission-product mixture containing the following percentage composition of radionuclides: trivalent rare earths, 43.5;

icate that the usual coagulation salts with lime have not been too effective for radioactive contaminants, other systems have been investigated. Phosphate coagulation with many polyvalent cations forms insoluble compounds and since phosphate flocculation is more effective than lime. He studied the removal of strontium from water by adding either potassium phosphate and calcium hydroxide. See Table 8.17.

REMOVAL OF STRONTIUM BY PHOSPHATE COAGULATION*

Coagulant dose, mg/liter	Removal, %
200	99.8
120	99.9
100	81.3
240	97.8
100	99.9
100	66.1
120	67.4
50	99.6
200	10.7
100	99.5
100	99.2

* National Laboratory, Jan. 23, 1961.

^{90}Sr , ^{90}Zr , ^{90}Y , ^{90}Nb , and ^{90}Zr were precipitated. The effect of precipitation had little effect on the removal of strontium. Marked differences occurred in the removal of strontium at different pH and coagulant dosages were studied for special study. It was found that a phosphate to calcium ratio greater than 1.0 (10% excess of phosphate), a high pH of 11.3 the increase in removal. The data indicate that, if an excess of 1.3 or above, maximum hazard reduction of fission-product mixture of the more hazardous constituents. Under these conditions were studied. The mixture containing the following constituents: trivalent rare earths, 43.5;

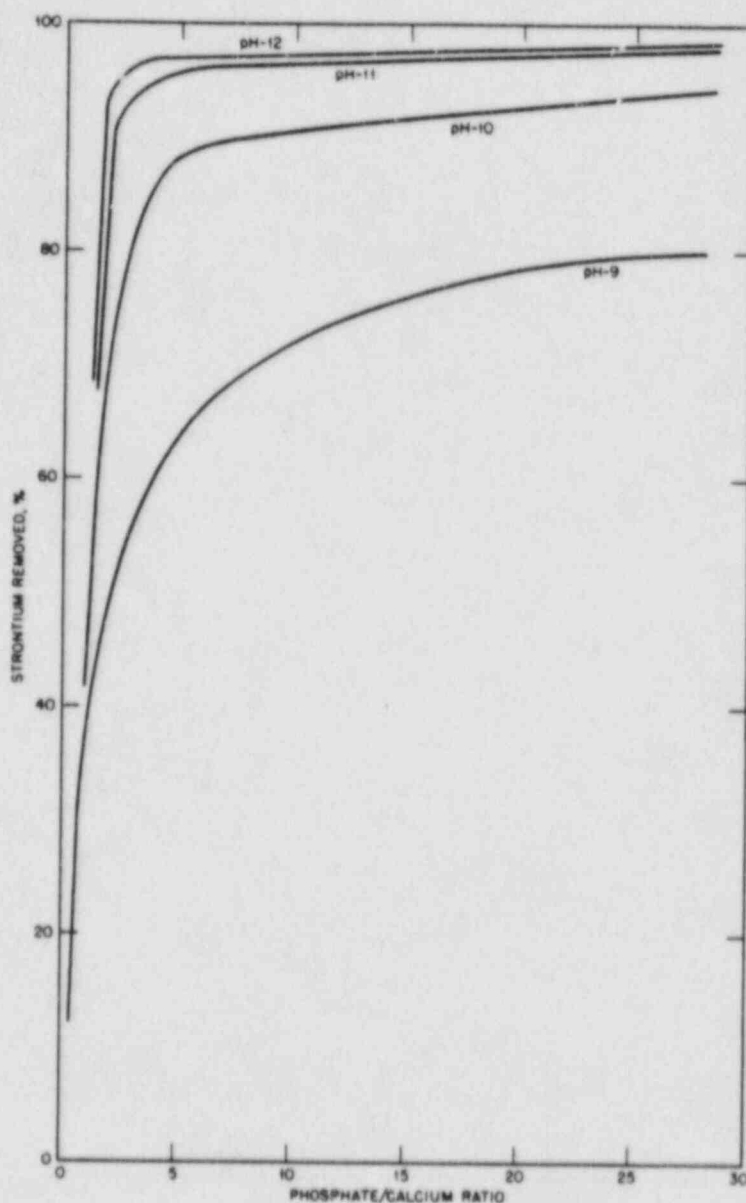


Fig. 8.9—Relation between phosphate-calcium ratio and pH in the removal of strontium.

cerium, 27.0; strontium, 17.4; barium, 5.1; ruthenium, 2.9; cesium, 1.1; and others, 3.0. This mixture was diluted with tap water, and the pH was raised to 11.5 to 12.0 with NaOH. Removals in excess

of 99% (99.2 to 99.6%) were obtained through the addition of 100 mg of Na_3PO_4 per liter and 100 mg of clay per liter or through the addition of 100 mg of Na_3PO_4 per liter and 100 mg of $\text{Ca}(\text{OH})_2$ per liter. It should be emphasized that efficiencies of removal depend on the composition of the waste.

Other phosphate-coagulation studies have been carried out³⁰ using scandium, strontium, tungsten, and yttrium radionuclides. These were diluted with tap water, 100 mg of local clay per liter was added, and the initial pH was adjusted to 11.5 by the addition of NaOH. Some studies were carried out in which the lime dosage was kept at 51 mg/liter and the Na_3PO_4 dosages to 250 mg/liter. The maximum removals in percent were Sr⁹⁰, 95.5; W¹⁸⁵, 11.0; Y⁹¹, 99.5; and Sc⁴⁶, 99.6; these essentially confirm Lauderdale's findings.²⁹ With Sc⁴⁶, increasing the pH to 11.5 alone effected removal of 99.2% after settling.

In commenting on the use of phosphate coagulation in municipal water-treatment practice, Nesbitt, Kaufman, McCauley, and Eliassen³¹ indicated that to treat Ohio River water with the required 84 mg of PO_4^{3-} per liter would cost \$147 per million gal (at the average 1960 market price of tribasic sodium phosphate, \$5.25 per 100-lb bag).

8-2.2 Metallic Dusts

Lacy³² studied the removal of specific soluble radioactive contaminants by slurring various metal dusts in the solution. In these laboratory experiments the radionuclides listed in Table 8.18 were

TABLE 8.18—REMOVAL OF RADIOACTIVE CONTAMINANTS BY METALLIC DUSTS*†

Contaminant	Stock solution pH	Initial activity, counts/(min) (ml)	Removal, %			
			Iron‡	Zinc	Copper	Aluminum
Ru ¹⁰⁶ -Rh ¹⁰⁶	8.0-8.2	1,975-3,950	99.6	98.4	93.7	92.8
Y ⁹¹	7.9-8.0	1,610-3,230	98.0	98.0		
Zr ⁹⁵ -Nb ⁹⁵	7.2-8.3	1,210-4,470	99.1	97.9	99.1	99.8
P ³²	7.8-8.4	128-12,000	99.8	98.1		84.2
I ¹³¹	6.5-8.2	4,288-6,689	37.2	45.7	42.2	23.2
Ce ^{141,144} -Pr ¹⁴⁴	7.9-8.1	3,915-4,491	99.9	99.9	99.5	99.8
Ba ¹⁴⁰	7.9-8.2	4,644-10,205	94.8	74.5	65.7	73.8
Co ⁶⁰	8.0-8.2	1,571-4,792	92.2§¶		47.8	30.2§
Cs ¹³⁷ -Ba ^{137m}	8.0	13,085	8.6			
FPM-5***	2.0-7.2	2,890-4,220	55.5	39.6	49.3	8.2
FPM-6††	7.2-8.0	2,730-10,375	85.8	76.6	92.1	89.4

*From W. J. Lacy, *J. Am. Water Works Assoc.*, 44: 824 (1952).

†Metal dust, 1000 mg/liter, 90-min contact time, filtered sample counted.

‡Iron samples were centrifuged before they were counted.

§Metal dust, 500 mg/liter.

¶Sixty-minute contact.

***FPM-5, mixed fission-product waste containing mainly Cs¹³⁷-Ba^{137m} and Ru¹⁰⁶-Rh¹⁰⁶.

††FPM-6, iodine dissolver solution aged 20 days.

ned through the addition of 100 mg
ay per liter or through the addition
100 mg of Ca(OH)₂ per liter. It
ncies of removal depend on the

udies have been carried out³⁰ using
nd yttrium radionuclides. These
g of local clay per liter was added,
o 11.5 by the addition of NaOH.
hich the lime dosage was kept at
s to 250 mg/liter. The maximum
5; W¹⁸⁵, 11.0; Y⁹¹, 99.5; and Sc⁴⁶,
uderdale's findings.²⁹ With Sc⁴⁶,
ed removal of 99.2% after settling.
osphate coagulation in municipal
Kaufman, McCauley, and Elias-
ver water with the required 84 mg
r million gal (at the average 1960
osphate, \$5.25 per 100-lb bag).

pecific soluble radioactive contami-
dusts in the solution. In these
nuclides listed in Table 8.18 were

ACTIVE CONTAMINANTS BY
DUSTS*†

	Removal, %			
	Iron	Zinc	Copper	Aluminum
99.6	98.4	93.7	92.8	
98.0	98.0			
99.1	97.9	99.1	99.8	
99.8	98.1		84.2	
37.2	45.7	42.2	23.2	
99.9	99.9	99.5	99.8	
94.8	74.5	65.7	73.8	
92.2		47.8	30.2	
8.6				
55.5	39.6	49.3	8.2	
85.8	76.6	92.1	89.4	

* (1952).
† Sample counted.
ed.

only Cs¹³⁷-Ba^{137m} and Ru¹⁰⁶-Rh¹⁰⁶.

added to Oak Ridge tap water. Various amounts of powdered alu-
minum, copper, iron, and zinc, corresponding to 100, 500, 1000, and
2000 mg of powdered metal per liter, were placed in beakers to which
500 ml of the radioactive solutions were added. After stirring periods
of 15, 30, 45, 60, 75, and 90 min, samples of the supernatant were
filtered and counted. In general, it was found that removal increas-
ed with increased contact time and dust concentrations.

Removals obtained with 1000 mg of the metal dusts per liter after a
90-min contact time are given in Table 8.18. Under the conditions
reported, removals with iron, with the exceptions of the fission-product
mixtures, iodine, and cesium, were in excess of 90% for the radio-
nuclides studied.

Studies by Lauderdale,³³ Eliassen,³⁴ and Mead,³⁵ utilizing metallic
dusts for the removal of specific radionuclides, are described in Chap.
10.

8-2.3 Clay Treatment

The effect of small additions of clay (100 mg/liter) on the removal of
radionuclides by coagulation and sedimentation is shown in Table 8.2.
Additional data have been reported on the use of this method for
increasing the removal of radioactivity by conventional water-treat-
ment methods.^{5, 36-38} Some results are given in Table 8.19. Although
the addition of clay materially improves the removal of radioactivity,
its use creates the problem of handling large volumes of clay both
initially and as a mass of contaminated material. Furthermore, if it
was used in combination with chemical coagulation, still larger
volumes of contaminated sludge would have to be disposed of.

TABLE 8.19—REMOVAL OF RADIONUCLIDES BY SLURRYING WITH
LOCAL CLAY

Radionuclide	Removal, %		
	100 mg/ liter*	750 mg/ liter	5000 mg/ liter
Ba ¹⁴⁰ -La ¹⁴⁰	41	58	85
Cd ¹¹⁵	3	30	64
Ce ¹⁴⁴ -Pr ¹⁴⁴	70-80	86	99+
Cs ¹³⁷ -Ba ^{137m}	38	87	98.0
Sc ⁴⁶	53	91.7	96.9
Sr ⁹⁰	2-12	14-22	49-52
W ¹⁸⁵	0	4	49
Y ⁹¹	22-45	56-70	93.6
Zr ⁹⁵ -Nb ⁹⁵	93.5	99.0	98.0
P ³²			78-82
I ¹³¹			9-20
Co ⁶⁰			85-99+

*Local ORNL clay added to produce turbidity.

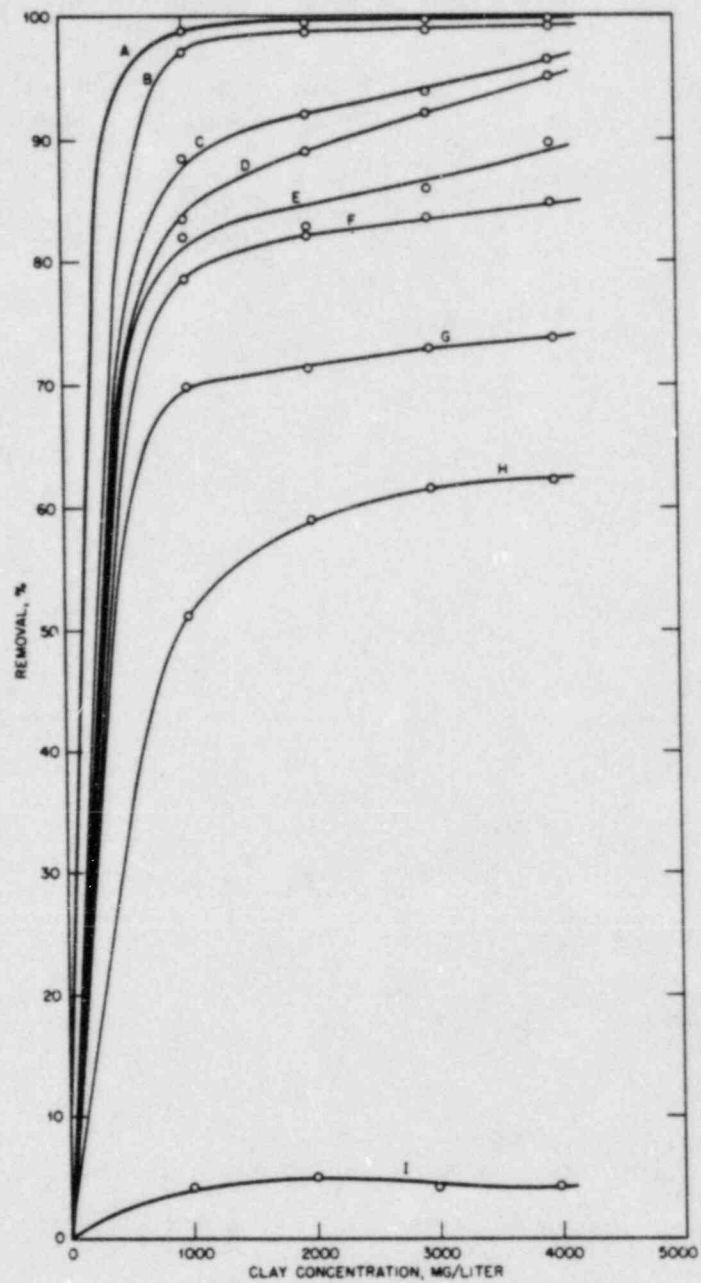
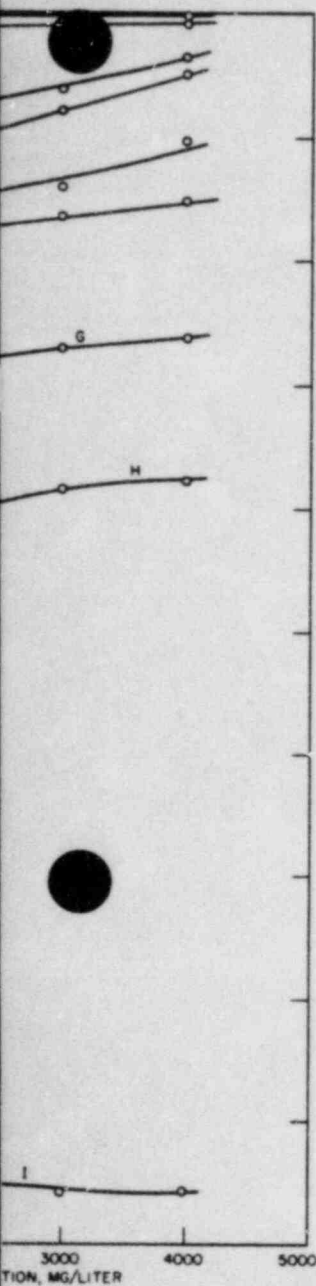


Fig. 8.10—Decontamination of radioactively contaminated water by slurring with clay (90-min contact time). A, Ce^{137} - Pr^{144} ; B, Zr^{95} - Nb^{95} ; C, Ba^{140} - La^{140} ; D, Sr^{90} - Y^{90} ; E, FPM-1; F, FPM-3; G, FPM-2; H, Ru^{106} - Rh^{106} ; and I, I^{131} .



ely contaminated water by slurring
 $^{141,144}\text{Pr}$; B, $\text{Zr}^{95}\text{-Nb}^{95}$; C, $\text{Ba}^{140}\text{-}$
 3; G, FPM-2; H, $\text{Ru}^{106}\text{-Rh}^{106}$; and I,

Results of Lacy's studies³⁸ are summarized in Fig. 8.10, and Tables 8.20 and 8.21. Variable removal efficiencies are indicated in Fig. 8.10, with the fission-product mixtures, $\text{Ru}^{106}\text{-Rh}^{106}$, and I^{131} showing the lowest removals. Although removals increased with increases in clay concentration, the maximum rates of uptake occurred in the added clay increment 0 to 1000 mg/liter. Above this concentration additional removals took place; these higher concentrations, however, were wasteful of clay, and the benefit derived from the added clay was nullified by the problems associated with handling increased amounts of contaminated clay sludges. As shown by the data in Table 8.20, an increase in pH (from 3 to 11) is associated with an increase in removal efficiency. An increase in calcium concentration from 20 to 200 mg/liter had little, if any, effect on the removal of mixed-fission-product activity by clay, as shown in Table 8.21.

TABLE 8.20—EFFECT OF pH ON REMOVAL OF MIXED FISSION PRODUCTS BY CLAY SLURRY*

pH	Removal, %, following indicated slurry times						
	15 min	30 min	45 min	60 min	75 min	90 min	90 min†
Initial activity, 2730 counts/(min)(ml) ‡							
3	49.2	50.9	50.1	51.6	51.4	52.9	55.3
5	64.6	66.6	72.6	74.0	75.2	76.2	75.9
7	64.0	66.7	72.9	74.9	78.2	78.7	78.6
9	64.2	67.5	73.5	76.3	79.5	80.4	80.5
11	80.3	80.1	81.1	81.7	82.2	82.6	83.4
Initial activity, 3400 counts/(min)(ml) ‡							
4	49.6	51.3	52.3	52.9	54.9	55.2	54.0
6	66.4	68.5	74.3	76.1	75.9	76.0	76.2
7	65.5	60.0	75.7	76.7	78.7	78.8	78.5
8	70.6	74.1	73.1	79.2	79.5	80.8	81.0
10	76.6	77.1	79.4	79.1	78.8	70.2	78.9

*Radioactive contaminant FPM-3; concentration of clay, 1000 mg/liter. (See Table 8.4 for description of FPM-3.)

†All removal figures, %, are based on filtered samples except this column, which is for centrifuged samples.

‡No correction has been made for counter efficiency (approximately 10%).

8-2.4 Diatomaceous Earth

Diatomaceous-earth filters have been used for the removal of radioactivity. Studies with P^{32} described by Baumann, Zobel, and Babbitt³⁹ indicated that diatomaceous earth alone is ineffective for the removal of radiophosphorus, particularly in the presence of increased concentrations of stable phosphorus. Removals varied greatly, the highest, as indicated in Table 8.22, being obtained with activated carbon and a proprietary diatomite.

TABLE 8.21—EFFECT OF CALCIUM-ION CONCENTRATION ON REMOVAL OF MIXED FISSION PRODUCTS BY CLAY SLURRY*

Ca, mg/liter	pH	Removal, %, following indicated slurry times							
		15 min	30 min	45 min	60 min	75 min	90 min	90 min†	
Initial activity, 3590 counts/(min) (ml),‡ Ca added as Ca(OH) ₂									
20	7.20	71.9	72.8	74.9	75.5	76.0	77.2	76.6	
40	7.35	72.8	73.9	78.0	78.2	78.8	79.9	79.2	
60	7.45	72.6	75.2	77.7	78.0	78.6	78.9	78.5	
100	7.70	72.2	74.3	78.2	78.3	78.9	79.2	79.3	
200	7.90	72.9	75.0	78.1	78.5	78.4	78.8	79.1	
Initial activity, 2680 counts/(min) (ml),‡ Ca added as CaCl ₂									
40	7.05	71.3	71.9	75.0	74.1	74.7	75.2	75.3	
80	7.15	71.0	73.1	75.3	73.7	75.3	75.8	75.6	
120	7.00	70.0	71.2	72.9	73.2	74.7	75.2	75.4	
150	7.20	69.7	72.4	73.5	73.7	74.4	75.0	75.0	

*Radioactive contaminant FPM-3; concentration of clay, 1000 mg/liter. (See Table 8.4 for description of FPM-3.)

†All removal figures, %, are based on filtered samples except this column, which is for centrifuged samples. ‡No correction has been made for counter efficiency (approximately 10%).

Studies with a standard military diatomite filter were reported by the Engineer Research and Development Laboratories.⁴⁰ This unit has a capacity of 15 gal/min. The equipment treats 500 gal of water per batch. In these studies the contaminant was a three-year-old fission-product mixture that contained approximately 40% Ce¹⁴⁴-Pr¹⁴⁴, 20% Pm¹⁴⁷, 18% Sr⁹⁰-Y⁹⁰, 14% Cs¹³⁷-Ba^{137m}, 6% Ru¹⁰⁶-Rh¹⁰⁶, and 2% other radionuclides.

The contaminated water was pretreated with powdered iron, local-clay slurry, or by ferric chloride-limestone coagulation, and was then allowed to settle. The supernatant was coagulated with ferric chloride and calcium carbonate. After settling, the supernatant liquid was passed through a diatomite filter; the effluent contained the activity levels indicated in Table 8.23. These data show that diatomite filters do not materially aid removal of radioactive materials from solutions containing mixed fission products.

8-3 REMOVAL OF NUCLEAR-TEST DEBRIS (FALLOUT) FROM WATER

The removal of fission products from a natural environment poses problems that are quite different from those encountered in the removal of reactor-produced or reactor-separated radionuclides from laboratory solutions. The debris from a nuclear detonation contains radioactivity in soluble form as well as in association with particu-

ACTIVE WASTES

ION CONCENTRATION ON RE-
ODU BY CLAY SLURRY*

Following indicated slurry times

in 60 min 75 min 90 min 90 min†

(ml), † Ca added as Ca(OH)₂

9	75.5	76.0	77.2	76.6
0	78.2	78.8	79.9	79.2
7	78.0	78.6	78.9	78.5
2	78.3	78.9	79.2	79.3
1	78.5	78.4	78.8	79.1

n) (ml), † Ca added as CaCl₂

0	74.1	74.7	75.2	75.3
3	73.7	75.3	75.8	75.6
9	73.2	74.7	75.2	75.4
5	73.7	74.4	75.0	75.0

slurry, 1000 mg/liter. (See Table 8.4 for description)

† Except this column, which is for centrifuged samples, approximately 10%.

diatomite filter were reported by
ment Laboratories.⁴⁰ This unit
quipment treats 500 gal of water
ntaminant was a three-year-old
ined approximately 40% Ce¹⁴⁴-
% Cs¹³⁷-Ba^{137m}, 6% Ru¹⁰⁶-Rh¹⁰⁶,
retreated with powdered iron,
-limestone coagulation, and was
stant was coagulated with ferric
After settling, the supernatant
e filter; the effluent contained the
3. These data show that diato-
removal of radioactive materials
on products.

BEST DEBRIS (FALLOUT) FROM
ER

om a natural environment poses
om those encountered in the re-
or-separated radionuclides from
m a nuclear detonation contains
as in association with particu-

TABLE 8.22—EFFECT OF DIATOMACEOUS-EARTH FILTERS ON THE
REMOVAL OF RADIOACTIVE PHOSPHORUS FROM WATER³⁹

Test No.	Precoat medium	Filter apparatus and notes	Weight of coat, lb/sq ft	Rate, gal/(min) (sq ft)	Removal of radioactivity, %
1	JM535	Complete precoat; filter water recirculated 15 min before sampling	1		12.3
2	D4200		1		17.9
3	JM535	Buchner filter apparatus	1	0.16	93.0
4	Crystal Flo	Buchner filter apparatus	1	0.58	88.4
5	JM535	Buchner filter apparatus	1	0.58	52.4
6	D4200	Buchner filter apparatus	1	0.39	72.4
7	Everpure*	Buchner filter apparatus	1	0.29	100
8a	JM535	Buchner filter apparatus	1	1.20	52.2
8b	JM535	Buchner filter apparatus	1	0.39	51.7
8c	JM535	Buchner filter apparatus	1	0.08	85.6
8d	JM535	Buchner filter apparatus	1	0.29	45.8
9	Sparkler pad; gravity flow through filter	Pad contained silver		0.80	69.3
10	Sparkler pad; gravity flow through filter	Pad contained finely divided silver		0.80	74.5
11	Sparkler pad; gravity flow through filter	Pad contained activated carbon		0.80	100
12	Everpure*	Commercial filter	0.15	0.70	97.3
12a	Everpure*	Uncontaminated water through cake of 12			No radioactivity carried to filter from pad
13	Everpure*	1 mole of stable phosphate added to stock solution	0.15	0.70	64.6
14	Everpure*	1 mole of stable phosphate added to stock solution	0.34	0.70	81.7

*Contains activated carbon.

TABLE 8.23—EVALUATION OF DIATOMITE FILTER SET NO. 2

Run No.	Initial conditions			Treatment		Final conditions			
	pH	Alkalinity, mg/liter	Activity, counts/(min)(ml)	Pretreatment*	Coagulation and filtration	pH	Alkalinity, mg/liter	Activity, † counts/(min)(ml)	Activity removed, %
1	7.6	80	2780	335g of powdered iron	335g of FeCl ₃ , 450g of CaCO ₃	5.6	15	1079	60
2	7.4	82	2781	1890g of powdered clay	335g of FeCl ₃ , 900g of CaCO ₃	6.2	32	810	71
3	7.8	81	2722	First coagulation: 335g of FeCl ₃ and 900g of CaCO ₃	Second coagulation: 335g of FeCl ₃ and 1350g of CaCO ₃	5.7	21	1060	61

*Pretreatment with powdered iron removed 55% of the activity; pretreatment with powdered clay removed 60% of the activity; pretreatment by coagulation removed 53% of the activity.

†Uncorrected for geometry and coincidence.

TABLE 8.24—ACTIVITY IN SAMPLES FROM THE LAWRENCE WATER TREATMENT PLANT, NOV. 6, 1951⁴³

Sample	Activity, counts/ (min) (liter)	Removal, %	Decontam- ination factor*
Raw water at intake	400		
Coagulated and settled water	320	20	1.2
Rapid-sand-filter effluent	120	70	3.3
Distribution system†	65	84	6.2

*Decontamination factor is equal to raw-water activity/effluent activity.
†Average of two samples at different locations.

Comparable removal of radioactivity from reservoirs in the Troy-Albany area was reported by Kilcawley and coworkers.⁴⁵ Reservoir radioactivity levels of 4 to 246 $\mu\mu\text{c/liter}$ were reduced to 6 to 24 $\mu\mu\text{c/liter}$ in Troy tap water; the overall level was reduced an average of 61% by coagulation and filtration. Over the period May 18 to July 13, 1953, the Albany reservoir activity levels ranged from 5 to 84 $\mu\mu\text{c/liter}$, with an average of 36 $\mu\mu\text{c/liter}$. In the aeration, chemical coagulation, and filtration of this water, the overall reduction amounted to 28.7% (see Table 8.25).

These data compare with laboratory results reported by Setter and Russell⁷ for removal of activity from rain, cistern, and surface waters by coagulation (Table 8.26). Calculations show that all the activity associated with suspended matter and from 0 to 58% (average 28) of the dissolved activity was removed. Removal by natural agents (surface adsorption and subsidence) left those radioactive constituents that are most difficult to remove by chemical coagulation and filtration.

Alexander, Nusbaum, and MacDonald¹⁰ have reported on the removal of stable strontium by municipal water-treatment plants. Their data are summarized in Table 8.27 and may be compared with removals of radiostrontium reported in Tables 8.1, 8.2, 8.5, 8.9, 8.10, and 8.13.

Small-scale laboratory studies using radioactively contaminated rainfall diluted with demineralized water were described by Eliassen and Lauderdale.⁴⁶ Their reported removals for gross activity and strontium are summarized in Table 8.28.

All data reported in this section show that conventional water-treatment processes are not very effective for the hard-to-remove radioactive materials in surface waters. Natural processes remove the bulk of the easy-to-remove radioactivity, but the longer-lived more-hazardous radionuclides remain.

FROM THE LAWRENCE WATER
TREATMENT PLANT, N. Y., 1951⁴⁵

Activity counts/ (min) (liter)	Removal, %	Decontam- ination factor ^a
400	20	1.2
320	70	3.3
120	84	6.2
65		

/radiant activity.

ity from reservoirs in the Troy-
ley and coworkers.⁴⁵ Reservoir
ter were reduced to 6 to 24 $\mu\text{mc}/$
level was reduced an average of
Over the period May 18 to July
y levels ranged from 5 to 84 $\mu\text{mc}/$
er. In the aeration, chemical
water, the overall reduction
y results reported by Setter and
rain, cistern, and surface waters
ations show that all the activity
from 0 to 58% (average 28) of
Removal by natural agents
fit those radioactive constituents
by chemical coagulation and

onals have reported on the
icipal water-treatment plants.
.27 and may be compared with
n Tables 8.1, 8.2, 8.5, 8.9, 8.10,
g radioactively contaminated
ter were described by Eliassen
movals for gross activity and
28.
how that conventional water-
ective for the hard-to-remove
rs. Natural processes remove
activity, but the longer-lived

TABLE 8.25—REMOVAL OF GROSS ACTIVITY BY WATER-TREATMENT PLANTS^{44,45}

Plant	No. of tests during period indicated	Date of sampling	Removals, %			
			Coagulation and settling	Filtration	Overall treatment	Overall tap water ^a
Cambridge, Mass.	3	Apr. 8 to July 3, 1953	20.5-37.2	13.5-23.3	33.9-51.8	23.7-84.0
Lawrence, Mass.	4	Nov. 6, 1951 to June 30, 1953	16.4-56.2	0-67.4	12.7-75.0	40.4-80.8
Rochester, N. Y.	11	Mar. 16, 1951 to June 12, 1953		0-62.3†	0-64.8	0-66.1
Albany, N. Y.	‡	May 18 to July 13, 1953	23.5‡	6.8	28.7	

^aSamples taken from distribution system instead of from treatment plant.
[†]Slow-sand filter results.

‡Number of tests not indicated in original report.
 †Includes aeration.

TABLE 8.26—REMOVAL OF GROSS ACTIVITY FROM RAIN, CISTERN, AND SURFACE WATERS BY COAGULATION*

Type of sample	Total solids, mg/liter	Dissolved beta activity, $\mu\mu\text{c/liter}$	Coagulating chemicals added, mg/liter	pH range	Removals, %	
					Total beta (range)	Dissolved beta (range)
Rain	41-151	185-1630	13-90	5.3-8.2	71-84	0-35
Rain	24-94	1300-9600	13-56	5.2-9.8	62-86	0-63
Cistern	65	1180	13-67	4.3-10.6	54-72	4-42
Cistern	43	1910	20-73	4.9-10.7	45-81	8-68
Cistern	77-188	120-1430	20-100	4.9-10.2	34-95	0-81
Surface water	200-474	50-2460	43-125	6.6-10.1	30-76	0-48

*From L. R. Setter and H. H. Russell, *J. Am. Water Works Assoc.*, 50: 590 (1958).

TABLE 8.27—STRONTIUM REMOVAL BY CHEMICAL TREATMENT*

Type of treatment	Strontium removal, %		No. of cities
	Average	Range	
Alum or ferrous sulfate	12	10-31	7
Alum or ferrous sulfate plus lime	37	10-75	11
Alum or ferrous sulfate plus lime and soda ash	54	10-85	3
Alum or ferrous sulfate plus lime and phosphate	42	10-70	5
Softening only (phosphate, ion exchanger)	73	69-76	2
None (except chlorine, fluoride, carbon, or ammonia)	10		8

*From G. V. Alexander *et al.*, *J. Am. Water Works Assoc.*, 46: 643 (1954).

TABLE 8.28—REMOVAL OF GROSS ACTIVITY AND STRONTIUM FROM FALLOUT BY WATER-TREATMENT PROCESSES**

Treatment process	Removal, %	
	Gross beta	Strontium
Coagulation; iron and alum salts	30-70	35-80
Coagulation; calcium phosphate, pH 11.0 to 11.5	85-95	65-95
Two-stage lime and soda softening	75	75
Demineralization; cation and anion exchangers	99	95

8-3.1 Filter Backwash-water Activity

The activity levels in slow-sand-filter backwash water (Rochester, N.Y., water-treatment plant) reported by Bell and coworkers are summarized in Table 8.29. Backwash-water activity levels varied, but in all cases the activity levels were approximately five or more times greater than those in raw water. If high raw-water activities are encountered, it may be necessary to consider the safe disposal of contaminated wash waters and the release of activity from the backwash-water solids.

ACTIVITY FROM RAIN, CISTERN,
BY COAGULATION*

Coagulating chemicals added, mg/liter	pH range	Removals, %	
		Total beta (range)	Dissoived beta (range)
3-90	5.3-8.2	71-84	0-35
3-56	5.2-9.8	62-86	0-63
3-67	4.3-10.6	54-72	4-42
20-73	4.9-10.7	45-81	8-68
20-100	4.9-10.2	34-95	0-81
13-125	6.6-10.1	30-76	0-48

Water Resour. Assoc., 50: 590 (1958).

BY CHEMICAL TREATMENT*

Strontium removal, %		No. of cities
Average	Range	
12	10-31	7
37	10-75	11
54	10-85	3
42	10-70	5
73	69-76	2
10		8

Water Resour. Assoc., 46: 643 (1954).

ACTIVITY AND STRONTIUM FROM
TREATMENT PROCESSES**

	Removal, %	
	Gross beta	Strontium
11.5	30-70	35-80
	85-95	65-95
	75	75
gers	99	95

ter backwash water (Rochester,
ted by Bell and coworkers are
ash-water activity levels varied,
ere approximately five or more
er. If high raw-water activities
y to consider the safe disposal
he release of activity from the

TABLE 8.29—SLOW-SAND-FILTER BACKWASH ACTIVITY LEVELS IN
ROCHESTER, N.Y.**

Period	No. of samples*	Activity, counts/ (min)(liter)		Concen- tration factor†
		Raw water	Backwash water	
Mar. 16 to Oct. 31, 1951	39;37	0.70	3.75	5.35
Nov. 1 to Nov. 15, 1951	12;12	12.3	205	16.6
Nov. 16, 1951 to Jan. 1, 1952	31;30	0.89	22.1	24.7
Jan. 2 to June 3, 1952	81;81	0.44	3.20	7.28
June 4 to June 20, 1952	15;14	3.72	48.8	13.1
June 21 to July 20, 1952	7;7	1.29	13.6	10.6
July 21 to Nov. 1, 1952	29;29	0.352	2.40	6.82
Nov. 2, 1952 to Feb. 1, 1953	26;26	0.26	2.25	8.70
Feb. 3 to Mar. 20, 1953	14;14	0.54	2.60	4.82
Jan. 2 to May 12, 1953	37;37	0.398	2.53	6.35
May 15 to June 12, 1953	8;9	0.53	7.62	14.4

*Number of tests on raw water and backwash water, respectively.

†Concentration factor is equal to backwash-water activity/raw-water activity.

8-3.2 Sludge Activity

Where chemical treatment is employed in the removal of radioactivity, activity associated with the settled or precipitated sludge is accumulated, and thus considerable care must be exercised in the disposal of this contaminated sludge. Sludge activity levels encountered in the Rochester, N.Y., water-treatment plant** are summarized in Table 8.30. Sludge concentration factors ranging from 25 to 114 times the raw-water activity levels are indicated.

8-4 SUMMARY

Highly variable decontamination factors are possible with the many water-treatment processes used for the removal of low-level radioactivity from liquids. Generally, higher decontamination levels may be possible for some particular radionuclides than are indicated for mixtures of radioactive materials. Most of the data reported previously have been summarized in Table 8.31. The conventional process offering most promise is ion exchange, particularly where mixed-bed cation- and anion-exchange resins are used. Of the non-conventional processes phosphate coagulation and metallic dusts show decontamination factors as high as 1000.

In general, it can be stated that water-treatment processes can provide decontamination factors as high as 10 with slightly higher results obtainable with modified methods. This means that for mixtures of radioactive materials where the total activity exceeds the MPC by a factor of 10 water-treatment processes are ineffective for reducing radioactivity. In some instances, however, if the radioac-

tivity is associated with a specific radionuclide, it may be possible to obtain decontamination factors higher than 10.

TABLE 8.30—SLUDGE ACTIVITY LEVELS AT THE ROCHESTER, N.Y., WATER TREATMENT PLANT*

Period	No. of samples*	Activity, counts/(min) (liter)		Concentration factor†
		Raw water	Sludge	
Mar. 16 to Oct. 31, 1951	39;37	0.70	31.5	45.0
Nov. 1 to Nov. 15, 1951	12;11	12.3	1390	114
Nov. 16, 1951 to Jan. 1, 1952	31;24	0.89	65.0	73.0
Jan. 2 to June 3, 1952	81;58	0.44	24.2	55.0
June 4 to June 20, 1952	15;11	3.72	387	104
June 21 to July 20, 1952	7;6	1.29	63.8	49.5
July 21 to Nov. 1, 1952	29;25	0.352	20.4	57.9
Nov. 2, 1952 to Feb. 1, 1953	26;23	0.26	22.0	85.0
Feb. 3 to Mar. 20, 1953	14;14	0.54	21.2	39.2
Jan. 2 to May 12, 1953	37;36	0.398	10.2	25.6
May 15 to June 12, 1953	8;8	0.53	40.1	75.6

*Number of tests on raw water and sludge, respectively.
 †Concentration factor is equal to sludge activity/raw-water activity.

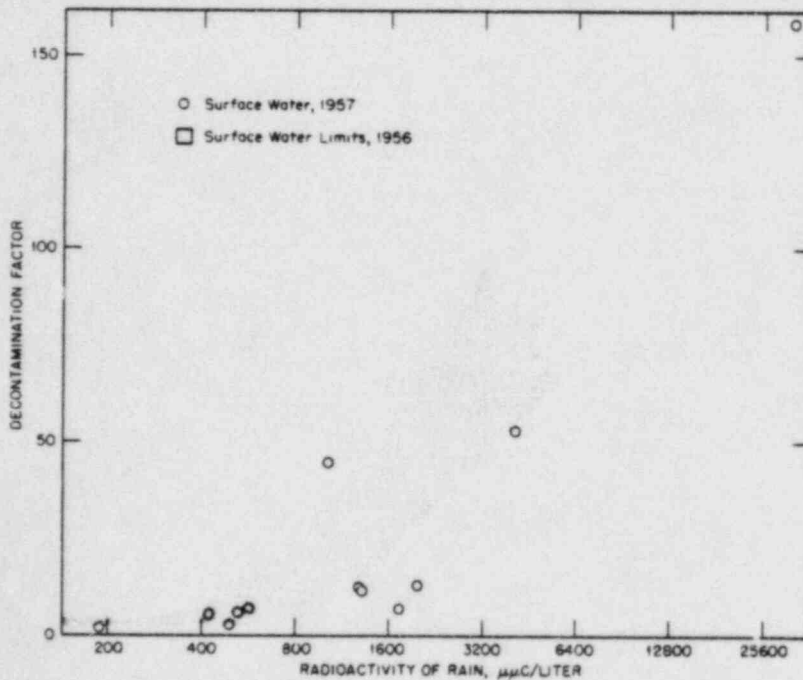


Fig. 8.11—The decontamination of rain by natural agencies.

REMOVAL OF RADIOACTIVITY BY

TABLE 8.31—SUMMARY OF REMOVAL METHODS AND TREATMENT PROCESSES

Process	Removal Factor
Conventional	
Coagulation and settling	
Clay addition, coagulation, and settling	
Coagulation and settling	
Sand filtration	
Coagulation, settling, and filtration	
Coagulation, settling, and filtration	
Coagulation, settling, and filtration	
Lime-soda ash softening	
Ion exchange, cation	
Ion exchange, anion	
Ion exchange, mixed bed	
Solids-contact clarifier	
Ion exchange, cation	
Ion exchange, mixed bed	
Nonconventional	
Ion exchange	
Phosphate	
Metallic dusts	
Clay treatment	
Diatomaceous earth	

1. G. M. FAIR and J. C. GEYER, *Water Decontamination*, John Wiley & Sons, Inc., New York, 1957.
 2. C. P. STRAUB, *Water Decontamination*, meeting of the American Society of Water Engineers, Report of the Joint Program on Radioisotope Removal from Waters, USAEC Report ORNL-1000, 1957.
 3. R. ELIASSEN, W. J. KAUFMAN, *Water Decontamination*, Water Works Assoc., 43: 615 (1951).
 4. W. J. LACY, *Water Decontamination*, *Water Sewage Works*, 100: 4 (1951).

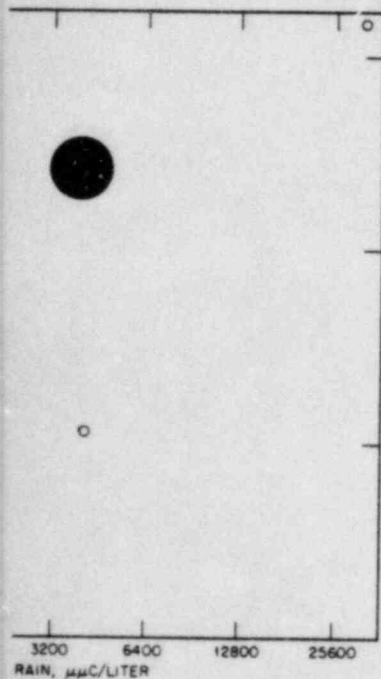
ACTIVE WASTES

radionuclide, it may be possible higher than 10.

LEVELS AT THE ROCHESTER, N. Y., TREATMENT PLANT "

of les*	Activity, counts/(min) (liter)		Concentration factor†
	Raw water	Sludge	
37	0.70	31.5	45.0
11	12.3	1390	114
24	0.89	65.0	73.0
58	0.44	24.2	55.0
11	3.72	387	104
5	1.29	63.8	49.5
25	0.352	20.4	57.9
13	0.26	22.0	85.0
4	0.54	21.2	39.2
16	0.398	10.2	25.6
1	0.53	40.1	75.6

ly.
water activity.



of rain by natural agencies.

REMOVAL OF RADIOACTIVITY BY WATER-TREATMENT PROCESSES 199

TABLE 8.31—SUMMARY OF REMOVAL OF ACTIVITY BY WATER-TREATMENT PROCESSES

Process	Decontamination factors		Source of data
	Individual radionuclides	Mixed fission products	
Conventional			
Coagulation and settling	0-100+	2-9.1	Table 8.1
Clay addition, coagulation, and settling	0-100	1.1-6.2	Table 8.2
Coagulation and settling		2.6-9.1	Table 8.4
Sand filtration	1-100		Table 8.5
Coagulation, settling, and filtration	1-50		Table 8.6
Coagulation, settling, and filtration	1.8-14	3.3-3.7	Table 8.7
Coagulation, settling, and filtration		1.4-13.3	Table 8.9
Lime-soda ash softening	2-100		Tables 8.10 and 8.11
Ion exchange, cation	1.1-500		Table 8.12
Ion exchange, anion	0-125		Table 8.12
Ion exchange, mixed bed	11-3300		Table 8.12
Solids-contact clarifier	1.9-15	2.0-6.1	Table 8.14
Ion exchange, cation		3.0-9.1	Table 8.15
Ion exchange, mixed bed		50-100	Table 8.15
Nonconventional			
Ion exchange		2.3-19	Table 8.16
Phosphate	1.2-1000	125-250	Table 8.17 and Sec. 8-2.1
Metallic dusts	1.1-1000	1.1-8.6	Table 8.18
Clay treatment	0-100+		Table 8.19
		2.0-6.0	Tables 8.20 and 8.21
Diatomaceous earth	1.1-∞		Table 8.22

REFERENCES

1. G. M. FAIR and J. C. GEYER, *Water Supply and Waste-Water Disposal*, John Wiley & Sons, Inc., New York, 1954.
2. C. P. STRAUB, Water Decontamination, paper presented at the San Diego meeting of the American Society of Civil Engineers, Feb. 9, 1955; also in *Report of the Joint Program of Studies on the Decontamination of Radioactive Waters*, USAEC Report ORNL-2557, p. 15, Oak Ridge National Laboratory and Robert A. Taft Sanitary Engineering Center, Feb. 11, 1959.
3. R. ELIASSEN, W. J. KAUFMAN, J. B. NESBITT, and M. I. GOLDMAN, Studies on Radioisotope Removal by Water Treatment Processes, *J. Am. Water Works Assoc.*, 43: 615 (1951).
4. W. J. LACY, Removing Radioactive Materials from Water by Coagulation, *Water Sewage Works*, 100: 410 (1953).

5. G. E. EDEN, A. L. DOWNING, and A. B. WHEATLAND, Observations on the Removal of Radioisotopes during Purification of Domestic Water Supplies: I. Radioiodine, *J. Inst. Water Engrs.*, **6**: 511 (1952).
6. A. L. DOWNING, A. B. WHEATLAND, and G. E. EDEN, Observations on the Removal of Radioisotopes during the Treatment of Domestic Water Supplies: II. Radiostrontium, *J. Inst. Water Engrs.*, **7**: 555 (1953).
7. L. R. SETTER and H. H. RUSSELL, Chemical Coagulation Studies on Removal of Radioactivity in Waters, *J. Am. Water Works Assoc.*, **50**: 590 (1958).
8. C. P. STRAUB, R. J. MORTON, and O. R. PLACAK, Studies on the Removal of Radioactive Contaminants from Water, *J. Am. Water Works Assoc.*, **43**: 713 (1951).
9. J. D. KURBATOV, J. L. KULP, and E. MACK, JR., Adsorption of Strontium and Barium Ions and Their Exchange on Hydrous Ferric Oxide, *J. Am. Chem. Soc.*, **67**: 1923 (1945).
10. M. H. KURBATOV, G. B. WOOD, and J. D. KURBATOV, Application of the Mass Law to Adsorption of Divalent Ions on Hydrous Ferric Oxide, *J. Chem. Phys.*, **19**: 258 (1951).
11. S. GOODGAL, E. F. GLOYNA, and D. E. CARRITT, Reduction of Radioactivity in Water, *J. Am. Water Works Assoc.*, **46**: 66 (1954).
12. R. F. REITEMEIER and A. D. AYERS, Calcium Ion Activities in Supersaturated Solutions Stabilized by Sodium Metaphosphate as Determined by Clay Membrane Electrodes, *J. Am. Chem. Soc.*, **69**: 2759 (1947).
13. C. P. STRAUB, W. J. LACY, and R. J. MORTON, Methods for the Decontamination of Low-Level Radioactive Liquid Wastes, in *Proceedings of the First International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955*, Vol. 9, p. 24, United Nations, New York, 1956.
14. C. P. STRAUB, Limitations of Water Treatment Methods for Removing Radioactive Contaminants, *Public Health Rept. (U.S.)*, **70**: 897 (1955).
15. G. E. EDEN, G. H. J. ELKINS, and G. A. TRUESDALE, Removal of Radioactive Substances from Water by Biological Treatment Processes, *Atomics and Atomic Technol.*, **5**: 133 (1954).
16. C. P. STRAUB, Removal of Radioactive Waste from Water, *Nucleonics*, **10** (1): 40 (January 1952).
17. C. P. STRAUB, R. J. MORTON and O. R. PLACAK, Oak Ridge Reports Results on Water Decontamination Study, *Eng. News-Record*, **147** (7): 38 (Aug. 16, 1951).
18. W. A. HOYT, *The Effects of the Lime-Soda Water Softening Process on the Removal of Radioactive Strontium-90-Yttrium-90*, M.S. Thesis, North Carolina State College, Raleigh, N.C., 1952.
19. G. V. ALEXANDER, R. E. NUSBAUM, and N. S. MACDONALD, Strontium and Calcium in Municipal Water Supplies, *J. Am. Water Works Assoc.*, **46**: 643 (1954).
20. I. M. KOLTHOFF, Theory of Coprecipitation: The Formation and Properties of Crystalline Precipitates, *J. Phys. Chem.*, **36**: 860 (1932).
21. R. E. KIRK and D. F. OTHMER (Eds.), *Encyclopedia of Chemical Technology*, Vol. 4, p. 645, Interscience Encyclopedia, Inc., New York, 1950.
22. R. F. McCAULEY and R. ELIASSEN, Radioactive Strontium Removal by Lime-Soda Softening, *J. Am. Water Works Assoc.*, **47**: 494 (1955).
23. J. A. AYRES, Treatment of Radioactive Waste by Ion Exchange, *Ind. Eng. Chem.*, **43**: 1526 (1951).
24. H. G. SWOPE, Mixed-Bed Ion Exchange for the Removal of Radioactivity, *J. Am. Water Works Assoc.*, **49**: 1085 (1957).

25. A. G. FRIEND, *Report on the Involvement of Strontium (^{90}Sr) from Water by Polytechnic Institute, 1952.*
26. K. Z. MORGAN, *Health Physics Digest Ending January 31, 1956*, USAEC Laboratory, May 3, 1956.
27. W. J. LACY and D. C. LINDSTEN, *Removal of Radioactive Strontium from Water by Ion Exchange Slurries*, Oak Ridge National Laboratory Report ORNL-332, Oak Ridge National Laboratory, 1952.
28. W. J. LACY, Engineer Research Station, Belvoir, Va., personal communication.
29. R. A. LAUDERDALE, JR., Treatment of Radioactive Wastes by Precipitation, *Ind. Eng. Chem. Anal. Ed.*, **26**: 100 (1954), ORNL-932, Oak Ridge National Laboratory, 1952.
30. C. P. STRAUB, D. A. PECSOK, H. G. SWOPE, and W. J. LACY, *Removal of Radioactive Strontium from Water by Ion Exchange Slurries*, Oak Ridge National Laboratory Report ORNL-332, Oak Ridge National Laboratory, 1952.
31. J. B. NESBITT, W. J. KAUFMAN, and C. P. STRAUB, *Removal of Radioactive Strontium from Water by Ion Exchange Slurries*, USAEC Report NYO-4435, M-1000, 1952.
32. W. J. LACY, Removal of Radioactive Strontium from Water by Ion Exchange Slurries, *J. Am. Water Works Assoc.*, **46**: 66 (1954).
33. R. A. LAUDERDALE, JR., Decontamination of Radioactive Wastes by Precipitation, *Engineering Conference Held Chicago, USAEC Report WASH-275*, USAEC Report WASH-275, Sept. 11, 1952.
34. R. ELIASSEN and N. C. BURBANK, *Removal of Radioactive Strontium from Water by Ion Exchange Slurries*, in *Sanitary Engineering Conference, 1954*, USAEC Report WASHINGTON, August 1955.
35. F. C. MEAD, JR., The Decontamination of Radioactive Wastes by Precipitation, *Engineering Conference, Baltimore, 1955*, Report WASH-275, pp. 23-24, August 1955.
36. T. W. BROCKETT, JR., and O. R. PLACAK, *Removal of Radioactive Strontium from Water by Ion Exchange Slurries*, in *Waste Solutions by Soils—Soil Decontamination*, 8th Industrial Wastes Conference, Purdue University Extension, Lafayette, Ind., July 1955.
37. C. P. STRAUB and H. L. KRUMHOLTZ, *Removal of Radioactive Strontium from Water by Ion Exchange Slurries*, in *Sanitary Engineering Conference, 1954*, Purdue University Extension, Lafayette, Ind., January 1955.
38. W. J. LACY, Decontamination of Radioactive Wastes by Slurrying with Clay, *Ind. Eng. Chem. Anal. Ed.*, **26**: 100 (1954).
39. E. R. BAUMAN, H. F. ZOBEL, and J. W. HARRIS, *Effectiveness of a Diphosphorus from Water*, Sanitary Engineering Conference, Illinois, Urbana, Ill., Nov. 1, 1955.
40. K. Z. MORGAN, *Health Physics Digest, 1952, to July 20, 1952*, USAEC Laboratory, Oct. 6, 1952.

25. A. G. FRIEND, *Report on the Investigation of the Removal of Iodine (I^{131}) and Strontium (Sr^{90}) from Water by Ion Exchange Resins*, M.S. Thesis, Virginia Polytechnic Institute, 1952.
26. K. Z. MORGAN, *Health Physics Division Semiannual Progress Report for Period Ending January 31, 1956*, USAEC Report ORNL-2049, Oak Ridge National Laboratory, May 3, 1956.
27. W. J. LACY and D. C. LINDSTEN, *Removal of Radioactive Contaminants from Water by Ion Exchange Slurry*, USAEC Report ORNL-CF-55-1-200, Oak Ridge National Laboratory, Jan. 25, 1955.
28. W. J. LACY, Engineer Research and Development Laboratories, Fort Belvoir, Va., personal communication, 1953.
29. R. A. LAUDERDALE, JR., *Treatment of Radioactive Water by Phosphate Precipitation*, *Ind. Eng. Chem.*, **43**: 1538 (1951); also USAEC Report ORNL-932, Oak Ridge National Laboratory, Jan. 23, 1951.
30. C. P. STRAUB, D. A. PECOK, H. L. KRIEGER, M. S. SEAL, and M. W. CARTER, Oak Ridge National Laboratory, unpublished data, 1954.
31. J. B. NESBITT, W. J. KAUFMAN, R. F. MCCAULEY, and R. ELIASSEN, *The Removal of Radioactive Strontium from Water by Phosphate Coagulation*, USAEC Report NYO-4435, Massachusetts Institute of Technology, Feb. 15, 1952.
32. W. J. LACY, *Removal of Radioactive Material from Water by Slurrying with Powdered Metal*, *J. Am. Water Works Assoc.*, **44**: 824 (1952).
33. R. A. LAUDERDALE, JR., *Decontamination of Radioactive Water*, in *Sanitary Engineering Conference Held at South District Filtration Plant, City of Chicago*, USAEC Report WASH-129, pp. 1-4, Division of Reactor Development, Sept. 11, 1952.
34. R. ELIASSEN and N. C. BURBANK, *Summary Report on AEC Research Project*, in *Sanitary Engineering Conference, Baltimore, Maryland, April 15-16, 1954*, USAEC Report WASH-275, pp. 81-88, Division of Reactor Development, August 1955.
35. F. C. MEAD, JR., *The Decontamination of Fission Product Wastes*, in *Sanitary Engineering Conference, Baltimore, Maryland, April 15-16, 1954*, USAEC Report WASH-275, pp. 231-245, Division of Reactor Development, August 1955.
36. T. W. BROCKETT, JR., and O. R. PLACAK, *Removal of Radioisotopes from Waste Solutions by Soils—Soil Studies with Conasauga Shale*, in *Proceedings of the 8th Industrial Wastes Conference, Purdue University, May 4, 5, and 6, 1953*, Purdue University Extension Series No. 83, pp. 393-409, Purdue University, Lafayette, Ind., January 1954.
37. C. P. STRAUB and H. L. KRIEGER, *Removal of Radioisotopes from Waste Solutions—Soil Suspension Studies*, in *Proceedings of the 8th Industrial Wastes Conference, Purdue University, May 4, 5, and 6, 1953*, Purdue University Extension Series No. 83, pp. 415-438, Purdue University, Lafayette, Ind., January 1954.
38. W. J. LACY, *Decontamination of Radioactively Contaminated Water by Slurrying with Clay*, *Ind. Eng. Chem.*, **46**: 1061 (1954).
39. E. R. BAUMAN, H. F. ZOBEL, and H. E. BABBITT, *A Preliminary Investigation of the Effectiveness of a Diatomite Filter in the Removal of Radioactive Phosphorus from Water*, Sanitary Engineering Series No. 1, University of Illinois, Urbana, Ill., Nov. 1, 1951.
40. K. Z. MORGAN, *Health Physics Division Progress Report for Period Jan. 20, 1952, to July 20, 1952*, USAEC Report ORNL-1353, Oak Ridge National Laboratory, Oct. 6, 1952.

41. L. R. SETTER and C. P. STRAUB, The Distribution of Radioactivity from Rain, *Trans. Am. Geophys. Union*, **39**: 451 (1958).
42. L. R. SETTER and H. H. RUSSELL, Radioactive Contamination of the Environment in the Cincinnati Area, *J. Am. Water Works Assoc.*, **51**: 449 (1959).
43. H. A. THOMAS, JR., R. S. KLEINSCHMIDT, F. L. PARKER, and C. G. BELL, JR., Fallout in Surface Waters of Massachusetts, in *Sanitary Engineering Conference Held at South District Filtration Plant, City of Chicago*, USAEC Report WASH-129, pp. 48-59, Division of Reactor Development, Sept. 11, 1952.
44. C. G. BELL, JR., H. A. THOMAS, JR., and B. L. ROSENTHAL, Passage of Nuclear Detonation Debris Through Municipal Water Treatment Plants, in *Sanitary Engineering Conference, Baltimore, Maryland, April 15-16, 1954*, USAEC Report WASH-275, pp. 89-111, Division of Reactor Development, August 1955.
45. E. J. KILCAWLEY, H. M. CLARK, H. L. EHRLICH, W. J. KELLEHER, H. E. SCHULTZE, and N. L. KRASCCELLA, *The Fate of Fission Products Deposited in the Reservoirs of the Troy, New York, Area Following Nuclear Detonations During the Spring Tests of 1963*, USAEC Report NYO-4569, Rensselaer Polytechnic Institute, Dec. 16, 1953.
46. R. ELIASSEN and R. A. LAUDERDALE, *Decontamination of Radioactive Water Supplies*, paper presented at the Nuclear Engineering and Science Congress, December 12-16, 1955, Cleveland, Ohio.

TREATMENT OF RADIOACTIVE WASTES BY BIOLOGICAL MEANS

In Chap. 4 it was stated that the most convenient means for the disposal of radioactive wastes is to convey them to water courses. At sewage treatment plants where processing beyond primary treatment and some form of biological treatment is required, the organic matter present in the receiving stream, and the biological processes in the receiving stream, and the

The practice of sewer disposal of radioactive wastes at sewage-treatment plants has been discussed in terms of the various processes for radioactive waste.

In treatment of radioactive wastes, both organic and inorganic solids, and the additional processing of the sludge. If long-lived high-energy radionuclides are present, they pose additional public-health problems.

The sewage-treatment processes, such as precipitation, adsorption, chemical precipitation, and filtration through coarse and fine screens and ponds.

9-1 PRIMARY TREATMENT

9-1.1 Sedimentation

Primary treatment consists of the removal of solids from the liquid carrier. This is accomplished by although mechanical screens and settling tanks in the separated solids and sludge compartments designed to remove suspended solids. In Imhoff tanks, the separated wastes are released to the bottom of the tank where the sludge undergoes decomposition. The gases produced are utilized in prime movers, but these gases should contain little or no radioactive material. These substances are volatilized.