

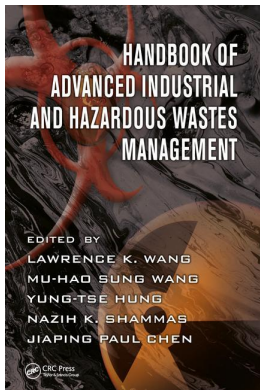
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## **Handbook of Advanced Industrial and Hazardous Wastes Management**

Lawrence K. Wang, Mu-Hao Sung Wang, Yung-Tse Hung, Nazih K. Shammass, Peter Jiaping Paul Chen

### **Recycling of Filter Backwash Water and Alum Sludge from Water Utility for Reuse**

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# 3 Recycling of Filter Backwash Water and Alum Sludge from Water Utility for Reuse

*Mu-Hao Sung Wang, Lawrence K. Wang,  
Nazih K. Shammam, and Milos Krofta*

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## ABSTRACT

The feasibility of recycling filter backwash water and alum sludge generated from water purification plants has been investigated. Actual wastewater and alum sludge used in this study were collected from a water plant employing water treatment processes including chemical addition, mixing, flocculation, clarification, filtration, and chlorination. Wastewater and sludge are generated mainly from the clarifier and the filter backwash. The waste recycle system presented here consists of (a) recycling the filter backwash water to the intake system for the reproduction of potable water, (b) dividing the combined sludge into two fractions for alum solubilization, separately, in an acid reactor and an alkaline reactor, (c) removing the inert silts from alum solutions by two separate water–solids separators for ultimate disposal, and (d) returning the solubilized alums from the two separate water–solids separators in proper proportions for reuse as flocculants.

The proposed recycle process was designed to provide a cost-effective system for achieving “zero” wastewater discharge and alum recovery from a water purification plant. Recommended process design parameters necessary to achieve the above stated goals have been established. Experimental results tend to suggest that practical designs based on the proposed water recycle and sludge thickening and alum recovery (STAR) system are technically feasible. Additional conclusions drawn from this research are (a) discharging raw alum sludge from a water treatment plant to a nearby wastewater treatment plant through a sewer system is a viable means of sludge disposal for the water utility; (b) the thickened raw alum sludge can be disposed on land as a soil amendment without adverse effect on soil if the pH of the disposed alum sludge is near neutral; (c) recycling the recovered alum for water purification within the water treatment plant is technically feasible the problem of impurity concentration (heavy metals and soluble organics) can be met by a scheduled recycling application or an automatic blowdown; (d) the U.S. Federal and the Commonwealth of Massachusetts prohibit recycling of the recovered alum for water purification within the water treatment plant because its long-term health effect is unknown; (e) employing recovered alum from a water treatment sludge as a precipitant for phosphate removal in a wastewater treatment plant is technically feasible although its economic feasibility needs to be studied; and (f) direct recycle of filter backwash water from a dissolved air flotation–filtration (DAFF) water treatment plant to the plant’s intake unit is both technically and economically feasible. The recovered alum (either aluminum sulfate or sodium aluminate) can be effectively used for removal of heavy metals and phosphorus from wastewater.

### 3.1 INTRODUCTION

#### 3.1.1 TYPICAL PHYSICOCHEMICAL TREATMENT PLANT

The flow diagram of a typical physicochemical water treatment plant with direct recycling of filter backwash water is shown in Figure 3.1 (1–3). The physicochemical treatment system is mainly used for water purification. Raw water is treated by flash mixing, flocculation, clarification, filtration, and disinfection. Clarification can be accomplished by either conventional sedimentation (1,2), or innovative dissolved air flotation (DAF). The unit operation of filtration can be sand filtration and/or granular-activated carbon (GAC) filtration. The filter effluent is disinfected and stored in a clear well where the water is ready to be pumped to the water distribution system for domestic and industrial consumption. The most common coagulants used in water purification are alum, sodium aluminate, and ferric

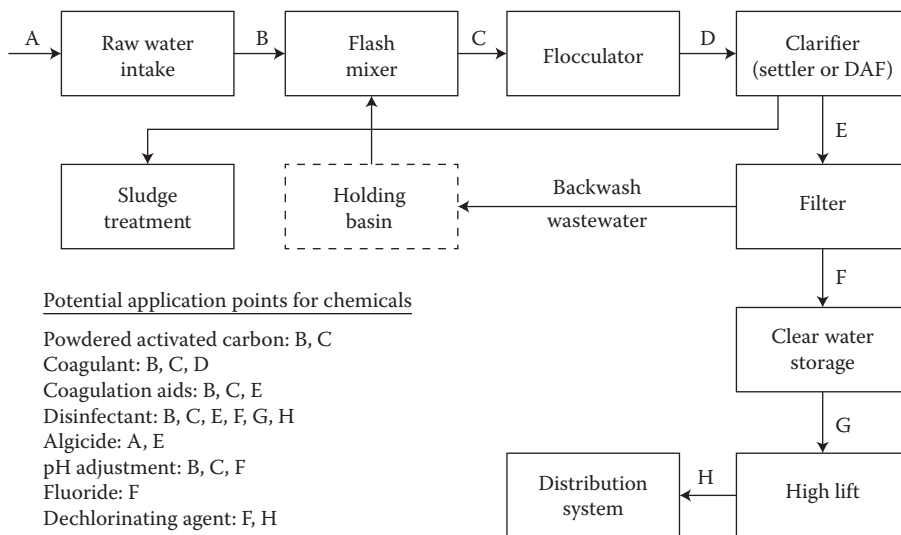


FIGURE 3.1 Flow diagram of a typical water treatment plant with direct recycling of backwash water.

sulfate. As shown in [Figure 3.1](#), the most common water treatment plant produces mainly two waste streams: (a) backwash wastewater from filters and (b) waste sludge from clarifiers. Disposal of waste sludge and wastewater becomes an important concern to environmental engineers and government officials (1–51). It is important to note that the same flow diagram shown in [Figure 3.1](#) can also be used for wastewater treatment. The Niagara Falls Wastewater Treatment Plant, Niagara Falls, New York, consisting of chemical mixing, flocculation, clarification (sedimentation), GAC filtration, and disinfection, is a complete physical–chemical plant for treating combined industrial and municipal wastewater.

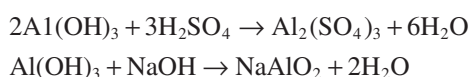
### 3.1.2 FILTER BACKWASH WATER RECYCLE AND SLUDGE THICKENING

In a water treatment plant, a holding tank shown in [Figure 3.1](#) is required for the recycling of backwash wastewater generated from a conventional water treatment plant in which sedimentation basins are used as clarifiers (1,2). If the filter backwash wastewater from a conventional plant is intended to be recycled for reuse, a huge holding tank is required to equalize the wastewater flow and to settle and separate the sludge there. Accordingly total recycle and reuse of filter backwash water in conventional plants is technically feasible but economically unattractive. Besides, the consistency of settled waste sludge from sedimentation clarifiers is in the range of 0.2%–0.5%. A separate sludge thickener is generally required if alum sludge recovery is intended.

An innovative water treatment plant using DAF cells for clarification can directly recycle its filter backwash wastewater to a mixer–flocculator for reprocessing, thus eliminating the need for a huge holding tank (4,5,8,9). Besides, the consistency of the DAF floated sludge can be as high as 2.6% if desired thus, eliminating the requirement for a separate sludge thickener if alum recovery is intended (34–37).

## 3.2 SLUDGE THICKENING AND ALUM RECOVERY SYSTEM

A STAR system stands for the sludge thickening and alum recovery system (6). Alum sludge from either conventional or innovative water treatment plants contains mainly aluminum hydroxide, which is an amphoteric species capable of reacting with both acid and alkaline reagents, as indicated in the following two reactions:



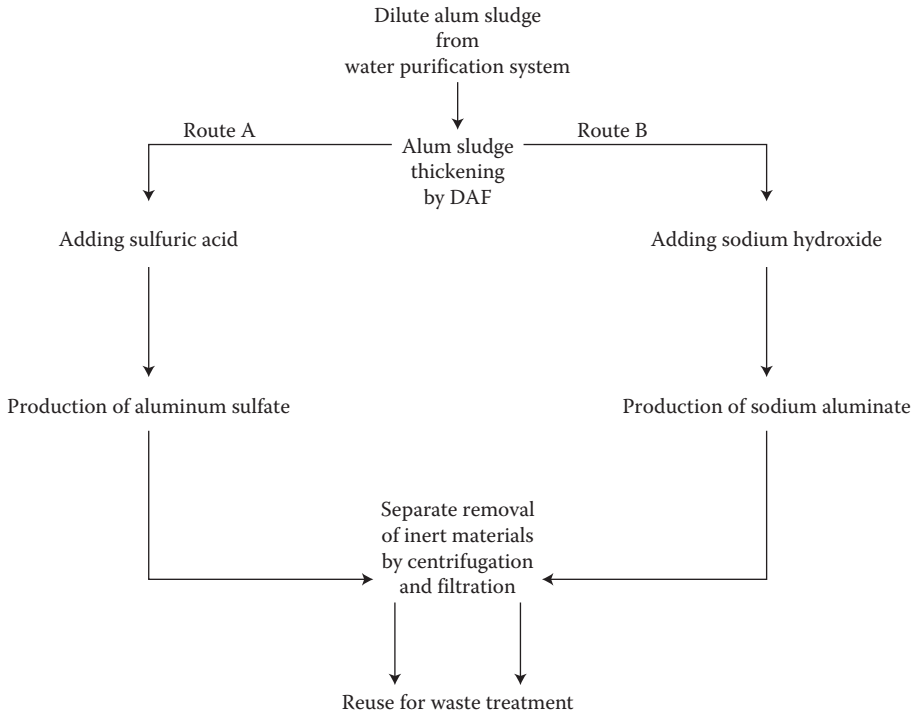
Sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and sodium hydroxide ( $\text{NaOH}$ ) are the most common acid and base, respectively, used in the STAR system.

Krofta and Wang (6) successfully used nitric acid ( $\text{HNO}_3$ ) and hydrochloric acid ( $\text{HCl}$ ) for recovery of alum sludge as aluminum nitrate and aluminum chloride, respectively.

Potassium hydroxide ( $\text{KOH}$ ) is also an effective alkaline chemical for alum recovery in the form of potassium aluminate (6).

A demonstrated alum sludge recovery scheme is presented as shown in [Figure 3.2](#). The major source of alum sludge comes from a DAF clarifier. A small portion of alum sludge could be contributed by backwashing the filters. Route A in [Figure 3.2](#) shows that alum can be recovered as aluminum sulfate (i.e., filter alum) by adding sulfuric acid. Route B shows that alum can be recovered as sodium aluminate (i.e., soda alum). Routes A and B have been demonstrated to be feasible, but a pH adjustment procedure is generally needed when either recovered alum is being recycled for reuse. This is due to the fact that the pH of the acid reactor effluent is extremely low, and the pH of the alkaline reactor effluent is extremely high. The optimum pH for alum coagulation, however, is about 6.3 (3).

An effective alum recycle alternative is that part of the alum sludge can be regenerated by adding a strong acid (Route A in [Figure 3.2](#)) and the remaining portion of the alum sludge can be



**FIGURE 3.2** Recovery and reuse of alum sludge. Alum recycling system can be route A, route B, or the combination of routes A and B.

regenerated by adding a strong base (Route B in Figure 3.2). Recycling both aluminum sulfate and sodium aluminate (or the like), at appropriate ratios, to the intake system for reuse would eliminate the additional pH adjustment requirement (3).

Figure 3.3 shows a proposed STAR operation. The alum sludge from a DAF-filtration (DAFF) clarifier is already thickened by DAF. Any commercial DAF thickener will be equally feasible for sludge thickening. Part of the thickened raw alum sludge can be converted to aluminum sulfate by the addition of sulfuric acid in an acid mixing reactor, and the remaining part of the sludge can be converted to aluminate by adding caustic soda in a base mixing reactor. After acid and alkaline treatments are over, the residual solid sludge is composed of mainly inert materials which can be separated by a separation unit, such as centrifugation or filtration. An effective water–solids separator manufactured by Krofta Engineering Corporation and the Lenox Institute of Water Technology is shown in Figure 3.4. The two liquid streams containing high concentrations of recovered alums can then be withdrawn for reuse. The parts of the Krofta water–solids separator shown in Figure 3.4 are noted below:

1. Centrifuge tank
2. Window frame
3. Inspection window
4. Pressurized air inlet
5. Tank breather
6. Sludge inlet
7. Sludge outlet
8. Gasket
9. Gasket

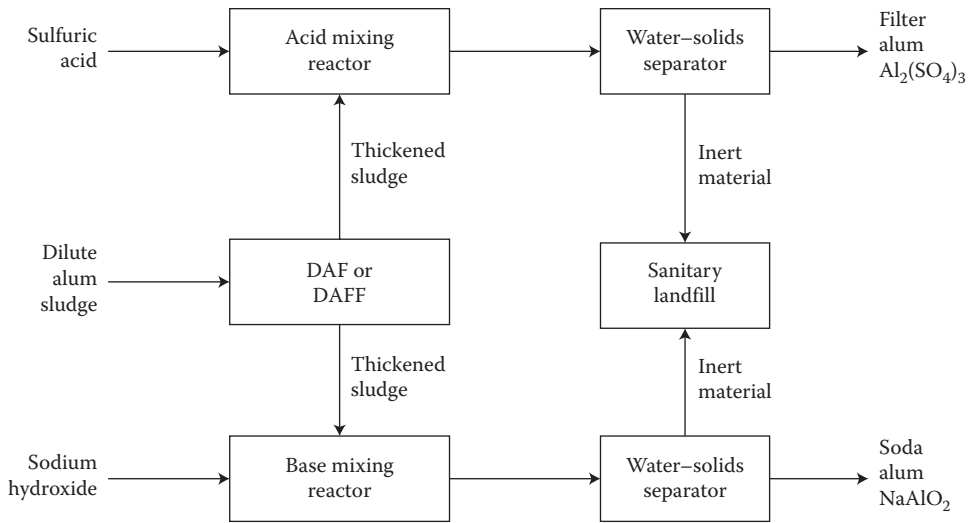


FIGURE 3.3 STAR system.

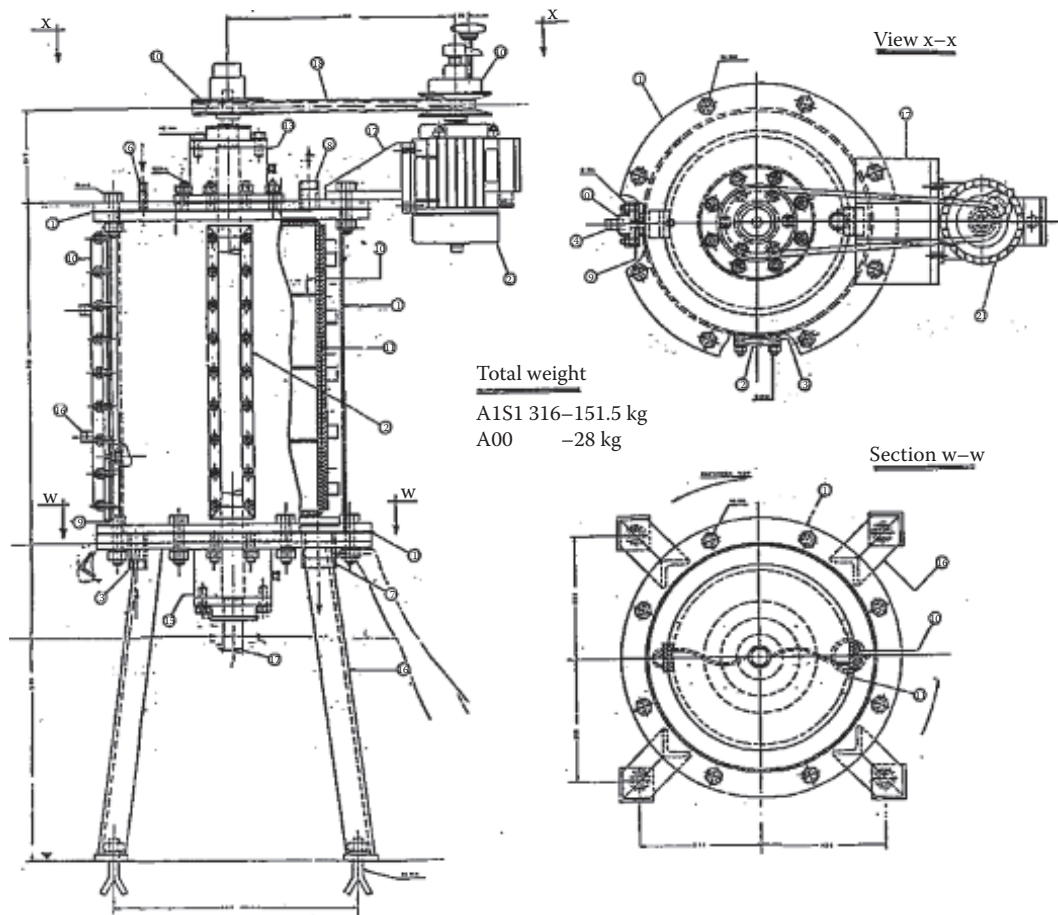
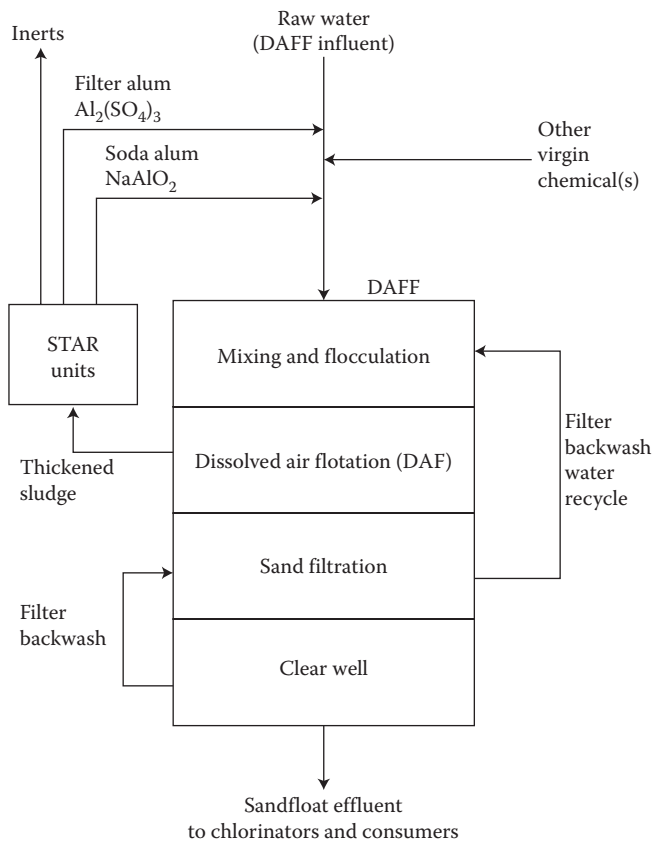


FIGURE 3.4 A Krofta water-solids separator.

10. Rotaring basket
11. Filtering cloth
12. Water outlet
13. Header spray-washers
14. Pressurized water inlet
15. Mechanical group
16. Tank support
17. Motor support
18. Variable shave
19. Driving V belt
20. Variable sheave
21. Electrical motor

Figure 3.5 shows the total waste recycle system of an improved water purification plant using alum as primary coagulant and using a DAFF clarifier for water treatment. Hundred percent of filter backwash water is recycled to DAFF clarifier’s mixing and flocculation chamber for reproduction of potable water. The alum sludge thickened by DAFF clarifier’s flotation goes to the remaining STAR units (acid mixing reactor, base mixing reactor, and water–solids separators shown in Figure 3.4) for alum recovery. The only waste produced from this plant is a small amount of inert material suitable for sanitary landfill.



**FIGURE 3.5** Innovative potable water treatment plant (DAFF plant) with filter backwash water recycle, STAR system.



### 3.3 DEMONSTRATION PROGRAM

An extensive research program was conducted in 1984–1988 and 1998–1999 at the Lenox Water Treatment Plant (LWTP) (5,6) and the Lenox Institute of Water Technology for optimization and demonstration of total filter backwash water recycle and the STAR system. The following were the specific objectives of the investigation:

1. To demonstrate the feasibility of the total filter backwash water recycle
2. To study the chemical reactions and the reaction temperature of the STAR system considering cold weather conditions
3. To study the reaction time of the STAR system
4. To optimize the sulfuric acid dosage for alum recovery, in turn to determine the sulfuric acid cost for this STAR application
5. To determine the metals and organic contents of recovered aluminum sulfate solution
6. To compare the recovered alum with commercial liquid alum

New testing data for alum recovery are presented in Tables 3.1 through 3.24. A measure of 36 N concentrated sulfuric acid was used throughout this entire study. The recovery of alum sludge in the form of sodium aluminate is reported elsewhere in 1988 (31).

### 3.4 FILTER BACKWASH WATER RECYCLE AND SLUDGE THICKENING

The total recycle and reuse of filter backwash wastewater has been successfully practiced at the Lenox Water Treatment Plant, Lenox, Massachusetts, from July 1982 to 1989. The heart of the LWTP at the time of this study was a 22-ft diameter DAFF package plant with a design capacity of 1.2 MGD (million gallons per day), or 4.542 MLD (million liters per day). The DAFF water treatment plant was mainly composed of mixing–flocculation, DAF, sand filtration, clear well, and chlorination, of which DAF was responsible for water clarification, filter backwash water treatment, and sludge thickening. The alum sludge was concentrated by DAF to about 2.6%.

**TABLE 3.1**

**Recovery of Aluminum from Lenox Alum Sludge (Test No. 1; TSS = 15,923 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temperature (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Aluminum (mg/L)	Aluminum Recovery (%)
18	0	10,000 + 0	0.05	0
23	0.25	10,000 + 100	3,240	72
22	0.50	10,000 + 100	4,180	92.8
21	1	10,000 + 100	4,060	90.2
19	2	10,000 + 100	4,060	90.2
19	4	10,000 + 100	4,060	90.2
16	20	10,000 + 100	3,940	87.6
17	23	10,000 + 100	3,600	80.0
17	26	10,000 + 100	3,660	81.3
17	92	10,000 + 100	3,890	86.4

*Note:* TSS of thickened alum sludge = 15,923 mg/L; initial A1 of thickened sludge = 4,500 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–26 h = 80 rpm; mixing rate in the period 26–92 h = 0 rpm; and settled sludge volume after 92 h = 150 mL sludge per 650 mL of total volume.



**TABLE 3.2****Recovery of Aluminum from Lenox Alum Sludge (Test No. 2; TSS = 17,283 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temperature (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Aluminum (mg/L)	Aluminum Recovery (%)
18	0	20,000 + 0	0.05	0
27	0.25	20,000 + 500	3,600	75
27	0.50	20,000 + 500	4,020	83.8
25	1	20,000 + 500	4,340	90.4
23	2	20,000 + 500	4,400	91.7
22	5	20,000 + 500	3,660	76.3
17	21	20,000 + 500	3,940	82.1
17	24	20,000 + 500	3,940	82.1
17	93	20,000 + 500	3,950	82.3
18	105	20,000 + 500	3,760	78.3

*Note:* TSS of thickened alum sludge = 17,283 mg/L; initial Al of thickened sludge = 4,800 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 80 rpm; mixing rate in the period 34–105 h = 0 rpm; and settled sludge volume after 105 h = 150 mL sludge per 830 mL of total volume.

**TABLE 3.3****Recovery of Aluminum from Lenox Alum Sludge (Test No. 3; TSS = 20,508 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temperature (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Aluminum (mg/L)	Aluminum Recovery %
Test No. 3A				
19	0	2,000 + 0	0.05	0
NA	0.25	2,000 + 50	NA	NA
27	0.50	2,000 + 50	4,840	86.4
24.5	1	2,000 + 50	4,730	84.5
22	2	2,000 + 50	4,620	82.5
17	69	2,000 + 50	5,090	90.8
Test No. 3B				
19	0	2,000 + 0	0.05	0
32	0.25	2,000 + 70	4,770	85.2
29	0.50	2,000 + 70	4,830	86.3
24.5	1	2,000 + 70	4,700	83.9
21.5	2	2,000 + 70	4,720	84.3
17	69	2,000 + 70	4,900	87.5

*Note:* TSS of thickened alum sludge = 20,508 mg/L; initial Al of thickened sludge = 5,600 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; and alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>.

**TABLE 3.4**  
**Recovery of Aluminum from Lenox Alum Sludge (Test No. 4; TSS = 23,527 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temperature (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Aluminum (mg/L)	Aluminum Recovery (%)
Test No. 4A				
19	0	2,000 + 0	0.05	0
MA	0.25	2,000 + 20	NA	NA
24.5	0.50	2,000 + 20	3,730	62.9
24	1	2,000 + 20	3,980	67.1
22	2	2,000 + 20	3,200	53.96
17	69	2,000 + 20	4,430	74.7
Test No. 4B				
19	0	2,000 + 0	0.05	0
28	0.25	2,000 + 70	4,030	68.0
27	0.50	2,000 + 70	4,130	69.6
23.5	1	2,000 + 70	4,730	79.8
23	2	2,000 + 70	4,640	78.2
17	69	2,000 + 70	4,680	78.9

*Note:* TSS of thickened alum sludge = 23,527 mg/L; initial Al of thickened sludge = 5,930 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; and alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>.

**TABLE 3.5**  
**Recovery of Aluminum from Lenox Alum Sludge (Test No. 5; TSS = 31,276 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temperature (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Aluminum (mg/L)	Aluminum Recovery (%)
Test No. 5A				
19	0	2,000 + 0	0.05	0
NA	0.25	2,000 + 20	NA	NA
25	0.50	2,000 + 20	3,460	64.0
24	1	2,000 + 20	4,230	78.33
22.5	2	2,000 + 20	4,570	84.6
17	69	2,000 + 20	NA	NA
Test No. 5B				
19	0	2,000 + 0	0.05	0
31	0.25	2,000 + 70	4,340	80.4
28	0.50	2,000 + 70	4,320	80.0
23.5	1	2,000 + 70	NA	NA
22	1.5	2,000 + 70	4,030	74.6
22	2	2,000 + 70	4,360	80.7
17	69	2,000 + 70	NA	NA

*Note:* TSS of thickened alum sludge = 31,276 mg/L; initial Al of thickened sludge = 5,400 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; and alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>.

**TABLE 3.6**  
**Effect of Initial Raw Alum Sludge TSS Concentration and Acid Dosage on Aluminum Recovery**

Test No.	Initial TSS of Raw Sludge (mg/L)	Conc. H <sub>2</sub> SO <sub>4</sub> Dosage mL/L Sludge	Aluminum Recovery (%)	Recovered Soluble Al (mg/L)
1	15,923	10	92.8–90.2	4,180–4,060
2	17,283	25	83.8–90.4	4,020–4,340
3A	20,508	25	86.4–84.5	4,840–4,730
3B	20,508	35	86.3–83.9	4,830–4,700
4A	23,527	10	62.9–67.1	3,730–3,980
4B	23,527	35	69.6–79.8	4,130–4,730
5A	31,276	10	64.0–78.33	3,460–4,230
5B	31,276	35	80.0–	4,320–

**TABLE 3.7**  
**Centrifugation of Alum Sludge Pretreated by Concentrated Sulfuric Acid**

Centrifugation Time (min)	Sludge Volume (mL)	Sludge TSS (mg/L)	Centrifugate	
			Volume (mL)	A1 (mg/L)
0	7,200	11,606	0	NA
5	1,000	71,312	6,200	3,750
10	900	72,779	6,300	3,750
15	800	87,518	6,400	3,760

*Note:* Initial raw alum sludge TSS = 17,283 mg/L before acid treatment; acid treatment = 250-mL concentrated sulfuric acid per 10 L of raw alum sludge at room temperature 17–27°C; TSS after acid treatment before centrifugation = 11,606 mg/L; and centrifuge operation = 1,725 rpm.

**TABLE 3.8**  
**Monitoring of TOC of Recovered Alum Solutions**

Test No.	Test Conditions	Raw Water TOC (mg/L)	Effluent TOC (mg/L)	Solution TOC (mg/L)
1	TSS = 15,923 mg/L 10 mL/L acid	5.8	0.78	1,080
2	TSS = 17,283 mg/L 25 mL/L acid	5.8	0.78	1,351
3A	TSS = 20,508 mg/L 25 mL/L acid	6.0	0.78	1,528
4B	TSS = 23,528 mg/L 35 mL/L acid	6.0	0.78	1,545
5B	TSS = 31,276 mg/L 35 mL/L acid	6.0	0.78	1,630

*Note:* Acid = 36 N concentrated sulfuric acid.

**TABLE 3.9**  
**Recovery of Aluminum from Lenox Alum Sludge (Test No. 9; TSS = 24,077 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temperature (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Aluminum (mg/L)	Aluminum Recovery (%)
3	0	10,000 + 0	0.05	0
4	0.25	10,000 + 250	3,680	64.7
5	0.50	10,000 + 250	3,590	63.1
3	1	10,000 + 250	3,780	66.4
2	2	10,000 + 250	4,060	71.4
1	4	10,000 + 250	4,080	71.7
1	7	10,000 + 250	4,020	70.6
5	143	10,000 + 250	3,900	68.5

*Note:* TSS of thickened alum, sludge = 24,077 mg/L; initial Al of thickened sludge = 5,690 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–7 h = 100 rpm; mixing rate in the period 7–143 h = 0 rpm; and settled sludge volume after 143 h = no noticeable sludge per 500 mL of total volume.

**TABLE 3.10**  
**Recovery of Aluminum from Lenox Alum Sludge (Test No. 10; TSS = 25,753 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temperature (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Aluminum (mg/L)	Aluminum Recovery (%)
18	0	10,000 + 0	0.05	0
20	0.75	10,000 + 170	1,387	24.86
20	1.0	10,000 + 170	1,718	30.79
19	1.5	10,000 + 170	1,945	34.86
19	2	10,000 + 170	1,647	29.52
19	126	10,000 + 170	3,180	56.98
18	150	10,000 + 170	3,814	68.4

*Note:* TSS of thickened alum sludge = 25,753 mg/L; initial Al of thickened sludge = 5,580 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–150 h = 0 rpm; and settled sludge volume after 150 h = approximately 25 mL sludge per 190 mL of total volume. Floated sludge volume after 150 h = approximately 30 mL sludge per 190 mL of total volume.

The DAFF plant used mainly poly aluminum chloride (66 mg/L average) in the winter and filter alum (73.6 mg/L) in the other three seasons. Sodium aluminate was only used occasionally for pH control. All three chemicals produced aluminum hydroxide sludge as end products.

While the entire full scale operation was successful, a complete 12-month operational data (July 1, 1986–June 30, 1987) was presented below to indicate the fact that the total recycle of filter backwash water for reuse would not adversely affect the plant effluent's water quality:

*LWTP (DAFF) influent*

Flow = 148–760 gpm (gallon per minute) = 560–2877 Lpm (liter per minute) (average 377 gpm = 1427 Lpm)

**TABLE 3.11****Recovery of Aluminum from Lenox Alum Sludge (Test No. 11; TSS = 25,830 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temp. (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Al (mg/L)	Aluminum Recovery (%)	Color Unit
14	0	10,000 + 0	0.05	0	0
14	0.25	10,000 + 10	18.5	0.35	5
14	0.5	10,000 + 10	47.4	0.90	8
15	1.0	10,000 + 10	56.1	1.10	10
18	24	10,000 + 10	84	1.6	15
17	45	10,000 + 10	101	1.9	18

*Note:* TSS of thickened alum sludge = 25,830 mg/L; initial Al of thickened sludge = 5,279 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 30 rpm; mixing rate in the period 24–45 h = 0 rpm; settled sludge volume after 45 h = 972 mL sludge per 1000 mL of total volume.

**TABLE 3.12****Recovery of Aluminum from Lenox Alum Sludge (Test No. 12; TSS = 25,830 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temp. (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Al (mg/L)	Aluminum Recovery (%)	Color Unit
14	0	10,000 + 0	0.05	0	0
14	0.25	10,000 + 20	NA	NA	20
14	0.5	10,000 + 20	250	4.7	20
15	1.0	10,000 + 20	270	5.1	20
18	24	10,000 + 20	270	5.1	20
17	45	10,000 + 20	311	5.9	23

*Note:* TSS of thickened alum sludge = 25,830 mg/L; initial Al of thickened sludge = 5,279 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 30 rpm; mixing rate in the period 24–45 h = 0 rpm; and settled sludge volume after 45 h = 943 mL sludge per 1000 mL of total volume.

Temperature = 37–75°F = 2.8–24°C (average 51.8°F = 11°C)

Turbidity = 0.65–7.35 NTU (nephelometric turbidity unit) (average 1.6 NTU)

pH = 6.7–8.6 unit (average 7.6 unit)

Alkalinity = 60–92 mg/L CaCO<sub>3</sub> (average 73.5 mg/L CaCO<sub>3</sub>)

Color = 0–15 unit (average 6 unit)

Aluminum = 0.01–0.08 mg/L Al (average 0.06 mg/L Al)

*LWTP (DAFF) effluent*

Turbidity = 0.02–0.53 NTU (average 0.08 NTU)

pH = 6.6–8.0 unit (average 7.1 unit)

**TABLE 3.13****Recovery of Aluminum from Lenox Alum Sludge (Test No. 13; TSS = 25,830 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temp. (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Al (mg/L)	Aluminum Recovery (%)	Color Unit
14	0	10,000 + 0	0.05	0	0
14	0.25	10,000 + 40	470	8.9	15
14	0.5	10,000 + 40	580	11	25
15	1.0	10,000 + 40	400	7.6	20
18	24	10,000 + 40	400	7.6	20
17	45	10,000 + 40	460	8.7	23

*Note:* TSS of thickened alum sludge = 25,830 mg/L; initial Al of thickened sludge = 5,279 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 30 rpm; mixing rate in the period 24–45 h = 0 rpm; and settled sludge volume after 45 h = 932 mL sludge per 1000 mL of total volume.

**TABLE 3.14****Recovery of Aluminum from Lenox Alum Sludge (Test No. 14; TSS = 25,830 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temp. (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Al (mg/L)	Aluminum Recovery (%)	Color Unit
14	0	10,000 + 0	0.05	0	0
14.5	0.25	10,000 + 60	840	15.9	30
14.5	0.5	10,000 + 60	910	17.3	35
16	1.0	10,000 + 60	790	15.0	35
18	24	10,000 + 60	790	15.0	50
17	45	10,000 + 60	1,128	21.4	74
17	45	10,000 + 60	1,670	31.6	85

*Note:* TSS of thickened alum sludge = 25,830 mg/L; initial Al of thickened sludge = 5,279 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 30 rpm; mixing rate in the period 24–45 h = 0 rpm; and settled sludge volume after 45 h = 932 mL sludge per 1,000 mL of total volume.

Alkalinity = 48–86 mg/L CaCO<sub>3</sub> (average 66 mg/L CaCO<sub>3</sub>)

Color = 0 unit (average 0 unit)

Aluminum = 0.01–0.10 mg/L Al (average 0.05 mg/L Al)

It can be seen that accomplishment of water purification, filter backwash recycle, and sludge thickening by the DAFF clarifier is technically feasible. The DAFF effluent quality was excellent (average effluent turbidity = 0.08 NTU; average effluent color = 0 unit). There was no accumulation of aluminum residual (average effluent Al = 0.05 mg/L) in the effluent even though the filter backwash wastewater was 100% recycled for 7 years.

**TABLE 3.15****Recovery of Aluminum from Lenox Alum Sludge (Test No. 15; TSS = 25,830 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temp. (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Al (mg/L)	Aluminum Recovery (%)	Color Unit
14	0	10,000 + 0	0.05	0	0
15	0.25	10,000 + 80	1,150	21.8	40
15	0.5	10,000 + 80	1,290	24.4	60
16	1.0	10,000 + 80	1,980	37.5	90
18	24	10,000 + 80	2,750	52.1	125
17	45	10,000 + 80	3,300	62.5	150

*Note:* TSS of thickened alum sludge = 25,830 mg/L; initial Al of thickened sludge = 5,279 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 30 rpm; mixing rate in the period 24–45 h = 0 rpm; and settled sludge volume after 45 h = 950 mL sludge per 1,000 mL of total volume.

**TABLE 3.16****Recovery of Aluminum from Lenox Alum Sludge (Test No. 16; TSS = 25,830 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temp. (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Al (mg/L)	Aluminum Recovery (%)	Color Unit
14	0	10,000 + 0	0.05	0	0
16	0.25	10,000 + 100	1,250	23.7	50
16	0.5	10,000 + 100	1,400	26.5	60
17	1.0	10,000 + 100	1,900	36.0	100
18	24	10,000 + 100	2,280	43.2	120
17	45	10,000 + 100	3,040	57.6	160

*Note:* TSS of thickened alum sludge = 25,830 mg/L; initial Al of thickened sludge = 5,279 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 30 rpm; mixing rate in the period 24–45 h = 0 rpm; and settled sludge volume after 45 h = 949 mL sludge per 1,000 mL of total volume.

### 3.5 REACTION TEMPERATURE AND REACTION TIME OF ACID REACTOR

Tests nos. 1–5 were conducted in the acid reactor under room temperatures using 36 N concentrated sulfuric acid for alum recovery. The test results are documented in [Tables 3.1](#) through [3.5](#).

From the data in [Tables 3.1](#) through [3.5](#), one can conclude that with adequate mixing (at 80 rpm) the reaction time of 30–60 min would be sufficient for alum recovery at room temperature. The percent aluminum recovery actually reduced with further increase of reaction time when raw alum sludge concentration was below 20,000 mg/L (see [Tables 3.1](#) and [3.2](#)).

[Table 3.6](#) indicates that at the reaction time of 30–60 min, the higher the initial TSS (total suspended solids) of raw alum sludge (up to 20,508 mg/L), the higher the soluble aluminum concentration in the recovered solution. A further increase in raw alum sludge concentration (23,527–31,276 mg/L) did not increase the recovered soluble aluminum concentration.

The data in [Table 3.7](#) clearly show that centrifugation is an efficient unit operation for the separation of residual inert sludge from the recovered aluminum solution. Further investigations were



**TABLE 3.17****Recovery of Aluminum from Lenox Alum Sludge (Test No. 17; TSS = 25,830 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temp. (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble AL (mg/L)	Aluminum Recovery (%)	Color Unit
15	0	10,000 + 0	0.05	0	0
20.5	0.25	10,000 + 150	2,240	42.4	230
20.5	0.5	10,000 + 150	2,530	47.9	250
20	1.0	10,000 + 150	3,350	63.5	500
18	24	10,000 + 150	4,070	76.2	600
17	45	10,000 + 150	4,288	81.2	640

*Note:* TSS of thickened alum sludge = 25,830 mg/L; initial Al of thickened sludge = 5,279 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 30 rpm; mixing rate in the period 24–45 h = 0 rpm; and settled sludge volume after 45 h = 462 mL sludge per 1,000 mL of total volume. Floated sludge volume after 45 h = 31 mL sludge per 1,000 mL of total volume.

**TABLE 3.18****Recovery of Aluminum from Lenox Alum Sludge (Test No. 18; TSS = 25,830 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temp. (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble AL (mg/L)	Aluminum Recovery (%)	Color Unit
15	0	10,000 + 0	0.05	0	0
22	0.25	10,000 + 200	2,930	55.5	1,000
21	0.5	10,000 + 200	3,960	75.0	1,500
21	1.0	10,000 + 200	4,070	77.1	2,500
18	24	10,000 + 200	4,151	78.6	2,550
17	45	10,000 + 200	4,477	84.8	2,750

*Note:* TSS of thickened alum sludge = 25,830 mg/L; initial Al of thickened sludge = 5,279 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 30 rpm; mixing rate in the period 24–45 h = 0 rpm; and settled sludge volume after 45 h = 200 mL sludge per 1,000 mL of total volume. Floated sludge volume after 45 h = 29 mL sludge per 1,000 mL of total volume.

being conducted using vacuum filtration, pressure filtration, sedimentation, slow filtration, absorption, etc. for separation of residual inert solids.

The total organic carbon (TOC) concentration in the recovered alum solutions were monitored and reported in [Table 3.8](#). At the raw sludge concentration range of 15,923–31,276 mg/L, the TOC of recovered alum solution was in the range of 1080–1630 mg/L, which was considered to be OK. After recycle and reuse of the alum, the TOC of treated water would only be slightly increased. Although TOC accumulation in the effluent was expected, it might be prevented by adequate operational procedures. For instance, after sludge recycle for a determined long period of time, DAFF plant should be fed with virgin alum and the STAR system should be fed with all fresh raw alum sludge again.

Various tests were also conducted under refrigerator-controlled temperatures to simulate operational conditions in winter.

**TABLE 3.19****Recovery of Aluminum from Lenox Alum Sludge (Test No. 19; TSS = 25,830 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temp. (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Al (mg/L)	Aluminum Recovery (%)	Color Unit
15	0	10,000 + 0	0.05	0	0
23	0.25	10,000 + 250	4,380	82.97	2,500
22	0.5	10,000 + 250	4,460	84.49	2,650
22	1.0	10,000 + 250	4,660	88.3	2,600
18	24	10,000 + 250	4,640	87.9	2,600
17	45	10,000 + 250	4,907	92.9	2,750

*Note:* TSS of thickened alum sludge = 25,830 mg/L; initial Al of thickened sludge = 5,279 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 30 rpm; mixing rate in the period 24–45 h = 0 rpm; and settled sludge volume after 45 h = 161 mL sludge per 1,000 mL of total volume. Floated sludge volume after 45 h = 32 mL sludge per 1,000 mL of total volume.

**TABLE 3.20****Recovery of Aluminum from Lenox Alum Sludge (Test No. 20; TSS = 25,830 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temp. (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Al (mg/L)	Aluminum Recovery (%)	Color Unit
15	0	10,000 + 0	0.05	0	0
24	0.25	10,000 + 300	4,130	78.2	2,250
23	0.5	10,000 + 300	4,120	78.1	2,250
23	1.0	10,000 + 300	4,577	86.7	2,500
18	24	10,000 + 300	4,761	90.2	2,600
17	45	10,000 + 300	5,035	95.4	2,750

*Note:* TSS of thickened alum sludge = 25,830 mg/L; initial Al of thickened sludge = 5,279 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; mixing rate in the period 0–24 h = 30 rpm; mixing rate in the period 24–45 h = 0 rpm; and settled sludge volume after 45 h = 229 mL sludge per 1,000 mL of total volume. Floated sludge volume after 45 h = 29 mL sludge per 1,000 mL of total volume.

Tests no. 9 (Table 3.9) and no. 19 (Table 3.19) are the simulations of winter operation and warm weather operation, respectively. In both tests, the LWTP's sludge was thickened by DAF to 24,077–25,830 mg/L of TSS before acid treatment using 36 N concentrated sulfuric acid. In both cases, 250 mL of sulfuric acid was dosed to every 10,000 mL of thickened sludge (TSS = 24,077–25,830 mg/L). It can be seen from Tables 3.9 and 3.19 that warm-temperature operation required shorter reaction time (0.5–1.0 h), produced more recovered soluble aluminum (4460–4660 mg/L Al), and had a higher percentage of aluminum recovery (84.49%–88.3%) in comparison with the cold weather operation. The following is a brief summary:

*Cold temperature at 1–5°C*

Reaction time = 2–4 h

Soluble Al = 4060–4080 mg/L

Aluminum recovery = 71.4%–71.7%

**TABLE 3.21****Recovery of Aluminum from Lenox Alum Sludge (Test No. 21; TSS = 34,690 mg/L) Using Concentrated Sulfuric Acid**

Reaction Temperature (°C)	Reaction Time (h)	mL Sludge Plus mL Conc. H <sub>2</sub> SO <sub>4</sub>	Recovered Soluble Aluminum (mg/L)	Aluminum Recovery (%)
Test 21A				
17	0	10,000 + 0	0.05	0
18	0.25	10,000 + 10	56	0.86
17.5	0.50	10,000 + 10	84	1.3
17.5	1	10,000 + 10	105	1.6
Test 21b				
17	0	10,000 + 0	0.05	0
18	0.25	10,000 + 20	104	1.6
18	0.50	10,000 + 20	237	3.7
18	1	10,000 + 20	216	3.3
Test 21C				
17	0	10,000 + 0	0.05	0
18.5	0.25	10,000 + 40	466	7.2
18.5	0.50	10,000 + 40	467	7.2
18.5	1	10,000 + 40	483	7.48
Test 21D				
17	0	10,000 + 0	0.05	0
20	0.25	10,000 + 60	750	11.6
19	0.50	10,000 + 60	798	12.4
19	1	10,000 + 60	1,130	17.0
Test 21E				
17	0	10,000 + 0	0.05	0
20	0.25	10,000 + 80	1,163	18.0
19	0.50	10,000 + 80	1,132	17.5
18.5	1	10,000 + 80	1,220	18.9
Test 21F				
17	0	10,000 + 0	0.05	0
21	0.25	10,000 + 100	1,577	24.4
21	0.50	10,000 + 100	1,625	25.2
20	1	10,000 + 100	1,936	30.0

*Note:* TSS of thickened alum sludge = 34,690 mg/L; initial Al of thickened sludge = 6454 mg/L; influent flow rate at LWTP = 560 gpm; sludge flow rate at LWTP = 3 gpm; alum dosage at LWTP = 3.9 mg/L as Al<sub>2</sub>O<sub>3</sub>; and mixing rate in the period 0–1 h = 80 rpm.

*Warm temperature at 15–23°C*

Reaction time = 0.5–1.0 h

Soluble Al = 4460–4660 mg/L

Aluminum recovery = 84.5

### 3.6 SULFURIC ACID REQUIREMENT IN ACID REACTOR

A comparison between [Table 3.9](#) (Test No. 9) and [Table 3.10](#) (Test no. 10) clearly indicates that 170 mL of 36 N sulfuric acid was insufficient for treatment of 10,000 mL of thickened Lenox alum sludge (TSS = 25,753 mg/L) even at a warm temperature (18–20°C).

**TABLE 3.22**  
**Settling Velocity of Alum Sludge Which**  
**was Pretreated by Concentrated Sulfuric**  
**Acid**

Settling Time (h)	Sludge Volume (mL)
0	400
0.25	400
0.5	400
1	395
2	395
3	395
4	390
20	390
144	215

*Note:* 500 mL graduated cylinder was used for this test; initial raw alum sludge TSS = 25,830 mg/L; acid treatment = 250 mL concentrated sulfuric acid per 10 L of raw alum sludge; temperature = 17°C; and reaction time = 45 h (Test no. 19).

**TABLE 3.23**  
**TOC of Recovered Alum Solutions**

Test No.	Test Conditions	Raw Water TOC (mg/L)	Effluent TOC (mg/L)	Soluble TOC (mg/L)
9	TSS = 24,077 mg/L 25 mL/L acid	6.0	0.78	1,508
10	TSS = 25,753 mg/L 17 mL/L acid	6.5	2.3	1,238
	TSS = 25,830 mg/L			
11	1 mL/L acid	6.7	2.4	48.4
12	2 mL/L acid	6.7	2.4	395.3
13	4 mL/L acid	6.7	2.4	474.3
14	6 mL/L acid	6.7	2.4	652.2
15	8 mL/L acid	6.7	2.4	731.2
16	10 mL/L acid	6.7	2.4	853.4
17	15 mL/L acid	6.7	2.4	1185.8
18	20 mL/L acid	6.7	2.4	1230.0
19	25 mL/L acid	6.7	2.4	1422.9
20	30 mL/L acid	6.7	2.4	1462.5
	TSS = 34,690 mg/L			
21A	1 mL/L acid	6.5	2.3	46.1
21B	2 mL/L acid	6.5	2.3	500.0
21C	4 mL/L acid	6.5	2.3	653.8
21D	6 mL/L acid	6.5	2.3	730.5
21E	8 mL/L acid	6.5	2.3	854.6
21F	10 mL/L acid	6.5	2.3	883.8

**TABLE 3.24**  
**Acid Treatment of Lenox Sludge for Alum Recovery**

Parameters	Quality of Recovered Alum
pH (unit)	<2
Total suspended solid (mg/L)	2,038
Volatile suspended solid (mg/L)	1,078
Fixed suspended solid (mg/L)	960
Aluminum (mg/L)	4,660
Arsenic (mg/L)	0
Barium (mg/L)	NA
Cadmium (mg/L)	0.01
Chromium (mg/L)	0
Copper (mg/L)	3.24
Iron (mg/L)	136.5
Lead (mg/L)	1.3
Manganese (mg/L)	8.86
Mercury (mg/L)	0
Nickel (mg/L)	1.5
Platinum (mg/L)	0
Potassium (mg/L)	18
Selenium (mg/L)	0
Sodium (mg/L)	43
Titanium (mg/L)	0
Zinc (mg/L)	0.35
Total coliform, #/100 mL	0
THMFP (mg/L)	6100.6
THM (mg/L)	0
TOC (mg/L)	1,528
COD (mg/L)	1,400
Color (unit)	2,600

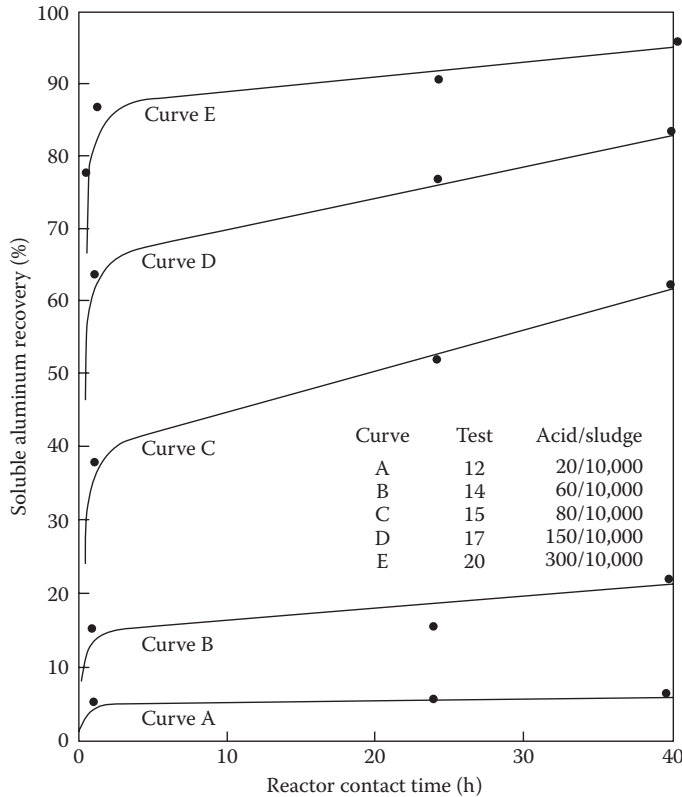
*Note:* 10,000 mL of Lenox sludge (initial TSS = 25,830 mg/L) was treated with 250 mL of concentrated sulfuric acid at room temperature (22°C) and 30 rpm of mixing for 1 h. See Test no. 19.

Accordingly an extensive study (Test nos. 11–20) was conducted to determine the optimum sulfuric acid dosage for alum recovery. Results are presented in Tables 3.11 through 3.20. For every 10,000 mL of thickened alum sludge (TSS = 25,830 mg/L), the volume of 36 N sulfuric acid dosages were dosed with an increasing trend from 10 to 20, 40, 60, 80, 100, 150, 200, 250, and 300 mL. Results are presented in Tables 3.11 through 3.20, respectively. Apparently, the optimum dosage was 150–300 mL of concentrated sulfuric acid per 10,000 mL of thickened alum sludge (TSS = 25,830 mg/L). Figure 3.6 illustrates the effect of sulfuric acid dosage on alum recovery.

It is important to note that the aluminum recovery efficiency of each acid treatment can be visually observed in accordance with the color of the recovered alum solution. The higher the color, the higher the concentration of recovered soluble aluminum (see Tables 3.11 through 3.20).

### 3.7 EFFECT OF THICKENED SLUDGE CONCENTRATION ON ALUM RECOVERY

In Test nos. 21A–21F (see Table 3.21), 10–100 mL of 36 N sulfuric acid was dosed to 10,000 mL of 3.469% thickened sludge in the acid reactor. On the other hand, in Test nos. 11–16 (Tables 3.11



**FIGURE 3.6** Effect of reactor contact time and acid-to-sludge volumetric ratio.

through 3.16), 10–100 mL of 36 N sulfuric acid was dosed to 10,000 mL of 2.583% thickened sludge. The results indicate that when sulfuric acid was underdosed, an increase in the concentration of thickened sludge (from 2.583% to 3.469%) did not increase the alum recovery efficiency. DAF alone thickened the alum sludge to 2.583%. An evaporator was earlier used for further sludge thickening to 3.469%.

It is obvious if sulfuric acid is overdosed, an increase in concentration of thickened sludge will increase linearly until the optimum ratio of sulfuric acid to thickened sludge is reached.

### 3.8 SEPARATION OF INERT SILTS FROM RECOVERED LIQUID ALUM

It was demonstrated previously that centrifugation was an efficient unit operation for separation of inert sludge from the acid/base-treated liquid solutions from two reactors (Figure 3.3). Results were reported in Table 3.7.

At a centrifugation detention time of 15 min at 172.5 rpm, the TSS of inert sludge was concentrated to 8.75% which was good. For a cost-effective operation, the centrifugation time could be set at 5 min. Figure 3.4 shows that the process unit was feasible for water–solids separation.

In a supplemental study, the use of gravity sedimentation for the same purpose was attempted, and the sedimentation results are presented in Table 3.22 for Test no. 19.

Based on the results in Table 3.22, it is concluded that plain gravity sedimentation is not feasible for the alum sludge's solid–liquid separation. After settling of 144 h, the sludge volume was only reduced from 400 to 215 mL, which was not acceptable.

### 3.9 ANALYSIS OF RECOVERED LIQUID ALUM

The TOC of recovered raw liquid alum (after centrifugation but before filtration) was extensively analyzed and reported in Table 3.23. The raw water TOC and plant effluent TOC of the LWTP are also listed in the same table for the purpose of comparison. The raw water TOC and effluent TOC were 6.0–6.7 and 0.78–2.4 mg/L, respectively.

The TOC of recovered liquid alum was indeed high, and increased with increasing acid dosage. It is also expected that the higher the recovered soluble aluminum concentration, the higher the released soluble TOC (see Tables 3.21 and 3.23).

Much more detailed chemical and microbiological examinations were performed on typical recovered liquid alum. Table 3.24 indicates the results. The recovered liquid alum had extremely low pH (<2), high soluble aluminum (4660 mg/L), no coliform bacteria, no THM (trihalomethane), no arsenic, high color (2600 units), high COD (chemical oxygen demand) (1400 mg/L), high TOC (1528 mg/L), high THMFP (trihalomethane formation potential) (6100 mg/L), and very low heavy metals, such as zinc, titanium, selenium, platinum, nickel, mercury, iron, manganese, lead, copper, chromium, cadmium, and barium.

It is encouraging to note that the volatile suspended solid (VSS) was high (1078 mg/L) which means that not all organics are solubilized by acid treatment. Such volatile suspended solids (VSSs) and fixed suspended solids (FSS) can be further reduced by a physical operation, such as the built-in filtration mechanism of the tested Krofta water–solids separator (Figure 3.4).

### 3.10 COMPARISON OF RECOVERED LIQUID ALUM AND COMMERCIAL ALUM

Commercial alum supplied by Holland Co., Adams, Massachusetts, was also analyzed for TOC. A comparison of the commercial alum and the recovered raw liquid alum is given below:

*Recovered liquid alum*

COD = 1400 mg/L

Soluble aluminum = 4660 mg/L Al

Al<sub>2</sub>O<sub>3</sub> = 8.820 mg/L

*Commercial liquid alum*

COD = 420 mg/L

Soluble aluminum = 43,941 mg/L Al

Al<sub>2</sub>O<sub>3</sub> = 83,000 mg/L

### 3.11 SUMMARY OF DEMONSTRATION PROJECT

#### 3.11.1 FILTER BACKWASH WATER RECYCLE

The 1.2-MGD (4.542 MLD) LWTP had one 22-ft diameter DAFF unit consisting of mixing-flocculation, DAF, sand filtration, clear well, and postchlorination. The DAFF unit has faithfully served the town of Lenox's 6500 residents and 3500 tourists since July 1982. With permission from the Commonwealth of Massachusetts and the U.S. Environmental Protection Agency (USEPA), in the demonstration period 100% of filter backwash wastewater was recycled to the DAFF plant's flocculation chamber for reproduction of potable water. Therefore, the total recycle of filter backwash water in a potable flotation plant is definitely feasible and cost effective, and has been practiced at the LWTP since 1982, and at the Pittsfield Water Treatment Plant (PWTP) since 1986 (34–37).



### 3.11.2 STAR SYSTEM

For liquid alum recovery in Lenox, Massachusetts, the Lenox alum sludge was thickened by a DAF clarifier (DAFF or DAF, or equivalent) from approximately 2500 to 25,830 mg/L or higher. The thickened sludge, if gently mixed (at 30 rpm) with 36 N sulfuric acid at a ratio of 250 mL acid to 10,000 mL thickened sludge at room temperature for 1 h contact time, produced a recovered liquid alum with 4660 mg/L of soluble aluminum or 8802 mg/L in terms of  $\text{Al}_2\text{O}_3$ .

Although the COD of the recovered liquid alum was about 1400 mg/L, and the other organic parameters are high (THMFP = 6100 ppb; TOC = 1528 mg/L), they were all diluted because only a very small amount of recovered liquid alum was needed to treat raw water for water purification. Considering an average alum dosage of 2.5 mg/L as  $\text{Al}_2\text{O}_3$ , the mixture of raw water and the recovered liquid alum would have the following characteristics:

$$\text{COD} = 6.34 \text{ mg/L}$$

$$\text{TOC} = 6.92 \text{ mg/L}$$

$$\text{THMFP} = 27.65 \text{ ppb}$$

which are all very reasonable. The Lenox raw water TOC was measured to be 6.0–6.7 mg/L. After alum sludge was recycled for reuse, the TOC of Lenox raw water containing chemicals only increased by 6.5%, which was negligible.

Winter operation of an alum sludge recycle system is technically feasible although the higher the temperature, the better alum recovery efficiency. For winter operation, a reactor reaction time of 2–4 h was required during the demonstration experiments. For warm weather operation, a short reaction time of 0.5–1.0 h was sufficient.

After the chemical reaction was over, the inert substances were separated from the reactor effluent for ultimate disposal by sanitary landfill. It has been demonstrated that centrifugation is a better unit operation than sedimentation for removal of inert substances. A Krofta water–solids separator which incorporates both centrifugation and filtration was ideal for this operation. Other commercial water–solids separator including centrifugation and filtration will also be acceptable.

Although the USEPA has approved all materials and chemicals used in the STAR system for the demonstration project, the STAR system has not been approved for routine long-term water treatment. The major problem associated with the recycling of alum sludge within a water utility is that organic impurities and heavy metals may be recycled as well. The impurities include inert soil materials, organic substances, and convertible mineral matters. The inert soil materials become the bulk of the sludge remaining after acidification. Organic substances especially the color-causing substances may be resolubilized by acidification, thus requiring actions for their removal. Similarly convertible mineral matter, particularly iron, manganese, and other heavy metals, are subject to dissolution. When the impurities are recycled together with the recycled alum, they may increase in concentration until the acidified supernatant from alum sludge becomes too rich in impurities to perform satisfactorily. The problem of impurity concentration can be technically met by the automatic blowdown due to only 45%–55% recovery of alum coagulant. Nevertheless both the federal and state governments must approve the recovered alum for water purification within a water plant. The recovered alum, however, can be easily approved for wastewater treatment by the governments, especially for the removal of phosphorus and heavy metals (38–43).

## 3.12 DISCUSSIONS AND CONCLUSIONS OF THIS RESEARCH

### 3.12.1 ECONOMICAL ANALYSIS OF FILTER BACKWASH WATER RECYCLE AND SLUDGE THICKENING

The water loss of a majority of conventional water treatment plants (including mainly mixing–flocculation, sedimentation, filtration, clear well, and disinfection) is about 9% of total raw water

pumpage due to the fact that the filter backwash wastewater is totally wasted (i.e., without recycle) and the settled sludge is bulky and dilute in TSS. A comparable innovative Lenox DAFF water treatment plant (including mainly mixing-flocculation, DAF, filtration, clear well, and disinfection) recycles its filter backwash wastewater and chemical flocs for reproduction of drinking water, thus its water loss is only about 0.5%, contributed by floated sludge. (*Note:* If STAR system is used for alum recovery in a DAFF plant, even the 0.5% water can be saved.) The rates of water treatment by the two types of plants can be estimated as follows:

*Conventional plant*

$$\text{Water production (effluent flow)} = \text{Plant influent flow} \times 0.91$$

$$\text{Plant influent flow} = 1.0989 \text{ water production (effluent flow)}$$

*Innovative DAFF Plant (DAFF Plant)*

$$\text{Water production (effluent flow)} = \text{Plant influent flow} \times 0.995$$

$$\text{Plant influent flow} = 1.005 \text{ water production (effluent flow)}$$

Assuming the coagulant dosages (mg coagulant per liter of influent water) for both conventional and innovative plants are identical, the conventional plant requires much more coagulants by weight (ton/day) because the conventional plant must treat about 9% more water (i.e., factor 1.0989 vs. factor 1.005) in order to supply the same volume of effluent for community consumption. The added advantage of innovative DF-filtration plant is that it conserves about 9% of water which can be very precious in drought areas.

If a conventional plant does recycle and reuse its filter backwash water, it needs a huge holding tank (see [Figure 3.1](#)) for backwash water equalization and sludge separation. The capital cost for the holding tank is high.

The settled sludge from a conventional plant's sedimentation clarifiers is low in concentration and requires a separate sludge thickener if alum recovery or other sludge treatment is intended. The requirement of a separate sludge thickener signifies another added capital cost for a conventional water treatment plant.

### 3.12.2 ECONOMICAL ANALYSIS OF STAR SYSTEM

The daily chemical treatment costs can be significantly reduced if the newly developed STAR system can be adopted.

The purpose of sludge recovery is to solve a sludge problem. Coagulant recovery offers added economic benefits.

These benefits include less coagulation chemical cost, and smaller amounts of inert solid carried to disposal by a sanitary landfill. Most of the chemical cost saving involves the acid and/or alkaline treatment. The design engineer can be assured that there will always be a cost difference between sulfuric acid and alum because the acid is required to manufacture the alum. There will be a big cost difference between sodium hydroxide and sodium aluminate, because the former is the raw chemical and the latter is the product.

White and White (7) presented an abstract of annual operating costs from their investigations. Raw water no. 3 was considered by White and White (7) to be the typical raw water source with no unusual problems, so the economics were typical of what was to be expected. Annual costs included: solubilization of alum sludge in acid reactor, dewatering costs on a stationary horizontal vacuum filtration bed for water–solids separation, and hauling and disposal of the residue. These annual costs showed a saving in favor of alum recovery of some 20% more than the cost of commercial alum itself if recovery was not practiced.

In another study in Germany (32), a computer program was developed which compared the capital and operational costs for water treatment plants with and without aluminum recovery from precipitation sludge. Annual costs of chemical consumption in a water treatment plant with aluminum recovery is at least 25% lower than in those with no coagulant recovery.

The STAR system is economically worthy of the design engineer's consideration. Such a system can be properly designed and safely operated. With the extreme variability from one raw water or wastewater to another, it is highly recommended that pilot testing be undertaken before such a design is attempted.

### 3.12.3 REUSE OF RAW ALUM SLUDGE

Pittsfield Water Treatment Plant (PWTP), Pittsfield, Massachusetts, is a DAFF water purification plant. Its DAF thickened raw alum sludge is discharged to the Pittsfield Wastewater Treatment Plant (PWWTP) for phosphorus removal (8). It is then concluded that discharge of raw alum sludge to wastewater treatment plants is a viable means of sludge disposal for the water utility.

The Lenox Water Treatment Plant (LWTP), Lenox, Massachusetts, is also a DAFF water purification plant. Its DAF thickened raw alum sludge was disposed on land for many years as a soil amendment (5,9,37,44). No adverse effect on soil was discovered when the pH of the disposed alum sludge was near neutral.

Elangovan and Subramanian (45) have concluded that raw alum sludge can be reused in clay brick manufacturing.

Recent studies (46–47) show that an alum sludge-based constructed wetland system can significantly remove organic matter and nutrients from the high-strength wastewater.

### 3.12.4 REUSE OF RECOVERED ALUM

The recovered alum from the Lenox Water Treatment Plant (LWTP; DAFF plant) in this research was directly applied to the LWTP for water purification for a very short period of time to demonstrate its technical feasibility under the condition that at least 50% virgin alum had to be used during alum recycle operation, and the recovered alum could not be continuously used for treating water over 3 days. After using 100% virgin alum for three consecutive days, then the combination of 50% recovered alum and 50% virgin alum could be applied together again for 3 days. In the entire research period, no adverse effect on water quality in terms of TOC, THM, THMFP, residual aluminum, turbidity, color, heavy metals, etc. was discovered. Nevertheless, continuous recycling of the recovered alum for water purification is not allowed by the federal and local governments because its long term health effects are unknown.

The LWTP's recovered alum was shipped to the nearby Lenox Wastewater Treatment Plant (LWWTP), Lenox, Massachusetts, for wastewater treatment as a part of this demonstration project. It was discovered that over 85% phosphorus removal could be achieved consistently in the entire research period. Under these situations, buildup caused by recycling of impurities could not occur, while advantage would accrue to both water utility and wastewater utility. It is concluded that employing recovered alum from water treatment sludge as a precipitant for phosphate removal in a wastewater treatment plant is technically feasible. The problem is economics. For instance, the LWWTP cannot possibly consume all acidified sludge supernatant (containing recovered alum) from the LWTP within its own town of Lenox boundary. The economic feasibility of this option needs to be further studied.

The AquaCritox process is a supercritical water oxidation process in which alum sludge is heated to between 374°C and 500°C at 221 bar pressure in the presence of oxygen (43). All of the organic matter is completely oxidized in an exothermic reaction producing carbon dioxide, water, aluminum hydroxide, and iron hydroxide as a water insoluble precipitate mixture. The pure precipitated coagulant hydroxide mixture is readily reacted with sulfuric acid to form fresh aluminum or iron sulfate

that is capable of meeting the USEPA specifications for coagulants. This is another option for disposal and reuse of alum generated from the water utility. Additional research data and current practices of recycling of backwash wastewater and alum sludge can be found from the literature (44–49).

## REFERENCES

1. Pallo, P. E., Schwartz, V. J., and Wang, L. K. Recycling and reuse of filter backwash water containing alum sludge, *Water and Sewage Works*, 115 (5), 123, 1972.
2. Wang, L. K., Pallo, P. E., Schwartz, V. J., and Kown, B. T. Continuous pilot plant study of recycling of filter backwash water, *Journal American Water Works Association*, 65 (5), 355–358, 1973.
3. Wang, L. K. and Yang, J. Y. Total waste recycle system for water purification plant using alum as primary coagulant, *Resource Recovery and Conservation*, 1, 67–84, 1975.
4. Krofta, M. and Wang, L. K. Application of dissolved air flotation to the Lenox Massachusetts water supply: Water purification by flotation, *Journal of New England Water Works Association*, 99, 249–264, 1985.
5. Krofta, M. and Wang, L. K. Application of dissolved air flotation to the Lenox Massachusetts water supply: Sludge thickening by flotation or lagoon, *Journal of New England Water Works Association*, 99, 265–284, 1985.
6. Krofta, M. and Wang, L. K. Municipal waste treatment by supracell flotation, chemical oxidation and star system, Technical Report No. LIR/10–86/214, Lenox Institute of Water Technology, 22pp., October 1986. NTIS-PB88 2005481/AS
7. White, A. R. and White, P. M. N. Alum recovery, an aid to the disposal of water plant solids, *Technical Paper Presented at the ASCE 1984 Spring Convention*, Atlanta, GA, May 1984.
8. Krofta, M. and Wang, L. K. Winter operation of nation's largest potable flotation plants, *Technical Papers Presented at the 1987 Joint Conference of American Water Works Association and Water Pollution Control Federation*, Cheyenne, WY, September 20–23, 1987. NTIS-PB8820056 3/AS.
9. Krofta, M. and Wang, L. K. Winter operation of the nation's first potable flotation plant, *Technical Papers Presented at the 1987 Joint Conference of American Water Works Association and Water Pollution Control Federation*, Cheyenne, WY, September 20–23, 1987. NTIS-P88 200555/AS.
10. Roberts, J. M. and Roddy, C. P. Recovery and reuse of alum sludge at Tampa, *Journal American Water Works Association*, 52 (7), 91, 1960.
11. Fulton, C. R. Alum recovery for filter plant waste treatment, *Water and Waste Engineering*, 7, 78, 1974.
12. Grurmiinger, R. M. Disposal of waste alum sludge from water treatment plants, *Journal of Water Pollution Control Federation*, 47, 543, 1975.
13. Fulton, C. P. Recover alum to reduce waste disposal costs, *Journal American Water Works Association*, 66 (5), 312, 1974.
14. Chen, B. H. H. Alum recovery from representative water treatment plant sludge, *Journal American Water Works Association*, 68 (4), 204, 1976.
15. Cornwell, D. A. and Zoltek Jr., J. Recycling of alum used for phosphorous removal in domestic wastewater treatment, *Journal of Water Pollution Control Federation*, 49 (4), 600, 1977.
16. Westerhoff, C. P. Water treatment plant sludges, Part I, *Journal American Water Works Association*, 70 (9), 498, 1978.
17. Westerhoff, C. P. Water treatment plant sludges, Part II, *Journal American Water Works Association*, 70 (10), 548, 1978.
18. Webster, 3. A. Operation and experiences at Doer water treatment works, with special reference to use of activated silica and the recovery of alum from sludge, *Journal Institute Water Engineering*, 20 (2), 167, 1966.
19. AWWA Editor. Disposal of wastes from water treatment plants, Part I, *Journal American Water Works Association*, 61 (10), 541, 1969.
20. AWWA Editor. Disposal of wastes from water treatment plants, Part II, *Journal American Water Works Association*, 61 (11), 619, 1969.
21. AWWA Editor. Disposal of wastes from water treatment plants, Part III, *Journal American Water Works Association*, 61 (12), 681, 1969.
22. AWWA Editor. Disposal of water treatment plant wastes, *Journal American Water Works Association*, 64 (12), 814, 1972.
23. O'Connor, J. L. *Management of Water Treatment Residues*, McGraw-Hill, Water Quality and Treatment, American Water Works Association, New York, 1971.

24. Cornwell, D. A. and Susan, J. A. Characteristics of acid-treated sludges, *Journal American Water Works Association*, 71 (10), 604, 1979.
25. Palm, A. T. The treatment and disposal of alum sludge, *Proceedings of Society of Water Treatment Examination*, 3, 131, 1954.
26. Issac, P. E. and Yahidi, I. The recovery of alum sludge, *Proceedings of Society of Water Treatment Examination*, 10, 19, 1969.
27. Westerhoff, C. P. and Daly, M. P. Water treatment wastes and disposal, Part I, *Journal American Water Works Association*, 66 (5), 319, 1974.
28. Westerhoff, C. P. and Daly, M. P. Water treatment wastes and disposal, Part II, *Journal American Water Works Association*, 66 (6), 378, 1974.
29. Westerhoff, C. P. and Daly, M. P. Water treatment wastes and disposal, Part III, *Journal American Water Works Association*, 66 (7), 441, 1974.
30. Lindsey, E. E. and Longsame, O. Recovery and reuse of alum from water filtration plant sludge by ultra-filtration, *American Institute of Chemical Engineers Symposium Series of Water*, 71, 185, 1975.
31. Wang, L. K. and Wu, B. C. Recovery and reuse of filter alum and soda alum in a water treatment plant, Technical Report No. LIR/06-88/309, Lenox Institute of Water Technology, Lenox, MA, June 8, 1988.
32. Kempa, J. and Juslyna, J. Methods and feasibilities of aluminum recovery from precipitation sludge, *Recovery Energy Matter, Residue Waste, Recycling Institute*, 792–799, 1982.
33. Goldman, M. L. and Watwon, F. Feasibility of alum sludge reclamation, Water Resources Research Center, Washington Technical Institute, Washington, DC, July 1975.
34. Wang, L. K., Hung, Y. T., and Shammas, N. K. (eds.). *Physicochemical Treatment Processes*, Humana Press, Totowa, NJ, 723pp., 2005.
35. Wang, L. K., Hung, Y. T., and Shammas, N. K. (eds.). *Advanced Physicochemical Treatment Processes*, Humana Press, Totowa, NJ, 690pp., 2006.
36. Wang, L. K., Hung, Y. T., and Shammas, N. K. (eds.). *Advanced Physicochemical Treatment Technologies*, Humana Press, Totowa, NJ, 710pp., 2007.
37. Wang, L. K., Shammas, N. K., Selke, W. A., and Aulenbach, D. B. (eds.). *Flotation Technology*, Humana Press, Totowa, NJ, 680pp., 2010.
38. Bugbee, G. J. and Frink, C. R., *Alum Sludge as a Soil Amendment: Effects on Soil Properties and Plant Growth*, Connecticut Agricultural Experiment Station, New Haven, CT, Bulletin 827, November 1985.
39. Faust, S. D. and Aly, O. M. *Chemistry of Water Treatment*, CRC Press, New York, 256pp, 1998.
40. Chu, W. Lead metal removal by recycled alum sludge, *Water Research*, 33 (13), 3019–3025, 1999.
41. Georgantas, D. A., Matsis, V. M., and Grigoropoulou, H. P. Soluble phosphorus removal through adsorption on spent alum sludge, *Environmental Technology*, 27 (10), 1093–1095, 2006.
42. Sanin, F. D., Clarkson, W. W., and Veslind, P. A. *Sludge Engineering: The Treatment and Disposal of Wastewater Sludges*, Technology and Engineering, New York, 393pp., 2010.
43. SCFI Group, Ltd. Alum Sludge: From Waste to Valuable Product with AquaCritox Recovery Process, SCFI Group, Ltd., Rubicon, CIT Campus, Cork, Ireland. April 2011.
44. State of Kentucky. Recycling of Water Treatment Waste Alum Sludge, Frankfort, KY, 2011.
45. Elangovan, C. and Subramanian, K. Reuse of alum sludge in clay brick manufacturing, *Water Science and Technology*, 11 (3), 333–341, 2011.
46. Hu, Y. Y., Zhao, Y., Zhao, X., and Kumar, J. L. High rate nitrogen removal in an alum sludge based intermittent aeration constructed wetland, *Environmental Science and Technology*, 46 (8), 4583–4590, 2012.
47. Ireland Environmental Protection Agency (IEPA). Development of an Alum Sludge-Based Constructed Wetland System for Improving Organic Matter and Nutrients Removal in High-Strength Wastewater, Ireland Environmental Protection Agency. Dublin, Ireland. 2012.
48. Wang, L. K. and Shammas, N. K. Waste sludge management in water utilities, in: Hung, Y. T., Wang, L. K., and Shammas, N. K. (eds.), *Handbook of Environment and Waste Management: Land and Groundwater Pollution Control*, Vol. 2, World Scientific, Singapore, pp. 1061–1091, 2014.
49. Shammas, N. K. and Wang, L. K. *Water Engineering: Hydraulic, Distribution and Treatment*, John Wiley & Sons, Inc., Hoboken, NJ, pp. 661–682, 2016.
50. Shammas, N.K. and Wang, L.K. *Water and Wastewater Engineering: Water Supply and Wastewater Removal*. Third edition. John Wiley & Sons, Inc. Hoboken, NJ, 824 pp, 2011.
51. Shammas, N.K., Wang, L.K., Queiroz Faria, L.C. and Chaves Ferro, M.A. Abastecimento de Água e Remocão de Resíduos. Grupo Editorial Nacional LTC, Rio de Janeiro. 750 pp, 2013.