

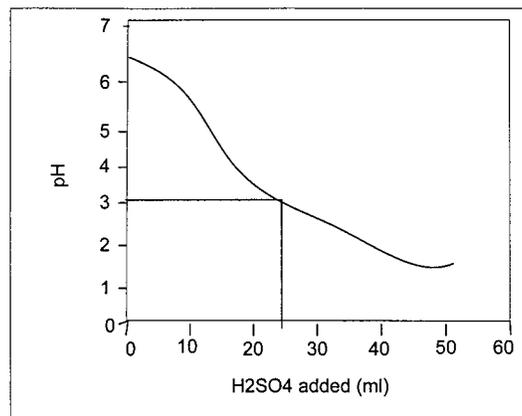
## APPENDIX C DESIGN EXAMPLES

**C-1. Problem (English Units).** 300,000 gal/day of landfill leachate and ground water have the following characteristics:

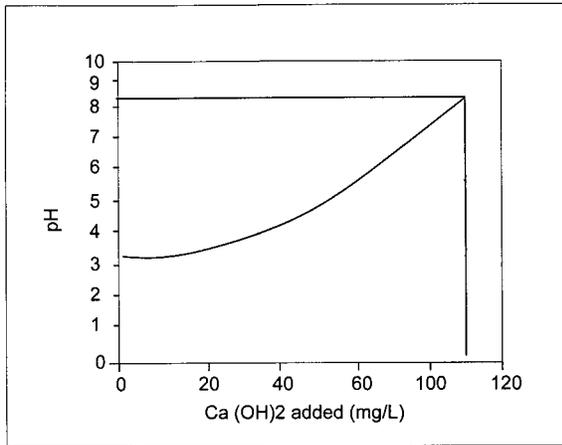
- pH: 6.5.
- $\text{Cr}^{+6}$ : 15 mg/L.
- Total Cr: 75 mg/L.
- $\text{Zn}^{2+}$ : 35 mg/L.
- Suspended solids: 25 mg/L.
- Dissolved oxygen: 2 mg/L.

*a.* The *Feasibility Study* determined that the method of treatment would be chemical reduction of chromium ( $\text{Cr}^{+6}$  to  $\text{Cr}^{+3}$ ) using sulfur dioxide, followed by hydroxide precipitation using lime, followed by coagulation, flocculation, and clarification. The full-scale treatment system will be designed to operate 24 hours/day.

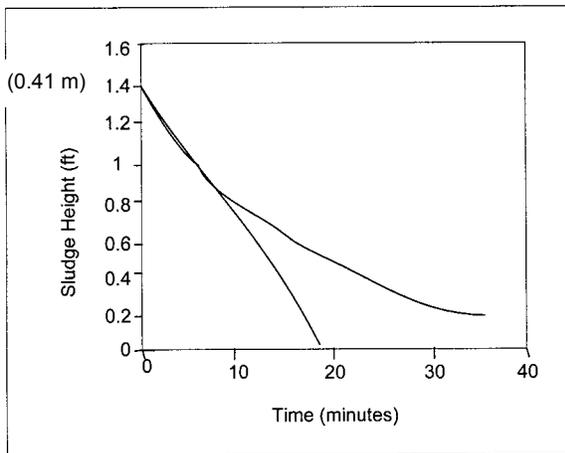
*b.* During initial bench-scale testing, a 1-L sample of raw wastewater was titrated with 0.1 N sulfuric acid and then neutralized with lime, yielding the results shown in Figures C-1 and C-2 below.



**Figure C-1. Titration curve for acidification of chromium waste.**



**Figure C-2. Titration curve for neutralization of waste following chromium reduction.**



**Figure C-3. Column testing results.**

c. Column testing was also conducted to determine the expected solids loading to the clarifier. Results of column testing are shown in Figure C-3.

d. From the data given above, determine the following:

(1) The chemical requirements to precipitate chromium and neutralize the treated wastewater, assuming that sulfur dioxide will be used as the reducing agent and that lime will be used as the precipitant. Assume that the final neutralized pH will be 8.5.

(2) The daily sludge production, assuming that 10 mg/L ferric chloride will be used as a coagulant and that 1 mg/L polymer will be used as a coagulant aid. Assume that the sludge has a specific gravity of 1.02 and is 3% solids.

(3) The required coagulation and flocculation tank volumes, using a 1-minute rapid-mix (coagulation) time and a 30-minute slow-mix (flocculation) time.

(4) The theoretical power requirement and required paddle area for the flocculation step, assuming a paddle tip speed of 1.2 ft/s.

(5) The solids settling area required for an inclined plate clarifier, assuming continuous treatment. Note the results of the column testing shown in Figure C-3.

(6) The effectiveness of the proposed method of treatment if the leachate originally contained 5 mg/L of cadmium.

(7) Additional testing to confirm the theoretical (stoichiometric calculations) results.

## C-2. Solution.

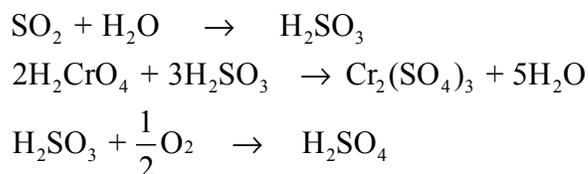
### a. Chemical Requirements.

(1) *Sulfuric Acid*. Sulfuric acid is required because chromium reduction using sulfur dioxide is typically conducted at a pH of 2.5 to 3. Examining Figure C-1 shows that approximately 25 mL of 0.1 N H<sub>2</sub>SO<sub>4</sub> is required to acidify 1 L of wastewater to pH 3.0. This is equal to an acid dose of:

$$\left(25 \frac{\text{mL}}{\text{L}}\right) \times (0.1 \text{ N}) = \frac{2.5 \text{ meq. H}_2\text{SO}_4}{\text{L}}$$

The acid feed rate required to achieve this dose will depend on the normality of acid used for treatment. (Note: Typical required retention times for chromium reduction at a pH of 3 range from 2 to 20 minutes, depending on the initial hexavalent chromium concentration.)

(2) *Sulfur Dioxide*. The equations that govern the reduction of hexavalent chromium to trivalent chromium using sulfur dioxide are as follows:



Using the above equations and molar ratios, and assuming that the reactions go to completion, gives the SO<sub>2</sub> requirements as follows for Cr<sup>+6</sup>: Because 3 moles of SO<sub>2</sub> yield 3 moles of H<sub>2</sub>SO<sub>3</sub>, then:

$$\frac{3 \times (32 + 2(16))}{2 \times 52} = 1.85 \frac{\text{mg}}{\text{L}} \text{SO}_2 \text{ per } \frac{\text{mg}}{\text{L}} \text{Cr}^{+6}$$

(Note: The quantity (32 + 2(16)), or 64, is the gram atomic weight of sulfur dioxide. The quantity 52 is the gram atomic weight of chromium.) And the requirements for O<sub>2</sub> are:

$$\frac{32 + 2(16)}{\frac{1}{2} \times 2(16)} = 4 \frac{\text{mg}}{\text{L}} \text{SO}_2 \text{ per } \frac{\text{mg}}{\text{L}} \text{O}_2$$

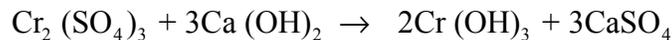
Therefore, SO<sub>2</sub> required  $\frac{\text{mg}}{\text{L}} =$

$$(1.85) 15 \frac{\text{mg}}{\text{L}} \text{Cr}^{+6} + 4 (2.0) \frac{\text{mg}}{\text{L}} \text{O}_2 = 35.8 \frac{\text{mg}}{\text{L}}$$

(3) *Lime*. Lime is required to raise the pH of the wastewater to precipitate chromium. Assume that the lime is 90% pure.

(a) The amount of lime required to neutralize the wastewater to pH 8.5, as indicated in Figure C-2, is approximately 107 mg/L.

(b) The amount of lime required to precipitate the chromium can be calculated using the equation below:

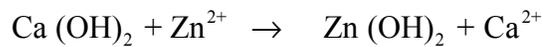


$$\frac{3 (40 + 2 (16) + 2(1))}{2 (52)} = 2.14 \frac{\text{mg}}{\text{L}} \text{ of } \text{Ca} (\text{OH})_2 \text{ per } \frac{\text{mg}}{\text{L}} \text{ of } \text{Cr}^{3+}$$

The total lime requirement to precipitate trivalent chromium is based on the combined total of trivalent and hexavalent chromium present in the raw wastewater (75 mg/L).

$$\begin{aligned} \text{Ca (OH)}_2 \text{ required (90\% pure)} &= \frac{2.14 \times 75 \text{ mg}}{0.90 \text{ L}} \\ &= 178.3 \frac{\text{mg}}{\text{L}} \end{aligned}$$

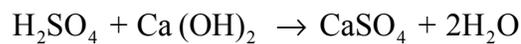
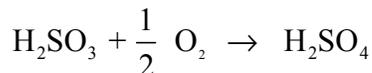
(c) Lime is also required to precipitate zinc (35 mg/L). The minimum solubility of zinc hydroxide occurs at approximately pH 9.0 (relatively close to 8.5, see Figure 2-2). Therefore, for simplicity, assume that the lime reaction with zinc goes to completion at pH 8.5. The amount of lime can be calculated using the equation below:



$$\frac{(40 + 2(16) + 2(1))}{65.4} = 1.13 \frac{\text{mg}}{\text{L}} \text{ of Ca(OH)}_2 \text{ per } \frac{\text{mg}}{\text{L}} \text{ of Zn}^{2+}$$

$$\text{Ca (OH)}_2 \text{ required (90\% pure)} = \frac{1.13 \times 35}{0.90} = 43.9 \frac{\text{mg}}{\text{L}}$$

(d) The amount of lime required to neutralize the H<sub>2</sub>SO<sub>4</sub> produced from dissolved oxygen initially present in the wastewater can be calculated from the equations below:



$$\frac{(2(1) + 32 + 16(4))}{\frac{1}{2}(2)(16)} = 6.12 \frac{\text{mg}}{\text{L}} \text{ H}_2\text{SO}_4 \text{ produced per } \frac{\text{mg}}{\text{L}} \text{ O}_2 \text{ present}$$

$$\text{H}_2\text{SO}_4 \text{ produced} = 6.12 \times 2 \frac{\text{mg}}{\text{L}} \text{ O}_2 = 12.2 \frac{\text{mg}}{\text{L}}$$

Therefore, the lime requirement, from the second equation, is:

$$\frac{(40 + 2(16) + 2(1))}{(2(1) + 32 + 4(16))} = 0.76 \frac{\text{mg}}{\text{L}} \text{ lime per } \frac{\text{mg}}{\text{L}} \text{H}_2\text{SO}_4$$

$$\begin{aligned} \text{Ca (OH)}_2 \text{ required (assuming 90\% pure)} &= \frac{0.76 \times 12.2 \frac{\text{mg}}{\text{L}}}{0.90} \\ &= 10.3 \frac{\text{mg}}{\text{L}} \end{aligned}$$

(e) Therefore, the total amount of lime = 107 + 178.3 + 43.9 + 10.3 = 339.5 mg/L

Or, in lb/day:

$$\left( 339.5 \frac{\text{mg}}{\text{L}} \right) \times \frac{8.34 \text{ lb} \times \text{L}}{\text{mg} \times \text{MG}} \times \frac{0.3 \text{ MG}}{\text{day}} = 849.4 \frac{\text{lb}}{\text{day}}$$

b. *Daily Sludge Production.*

(1) *Chromium Hydroxide Sludge.*

$$\text{Ca (OH)}_2 \text{ dosage (90\% pure): } 178.3 \frac{\text{mg}}{\text{L}}$$

$$178.3 \text{ mg} \times \frac{1 \text{ mole}}{74,000 \text{ mg}} = 0.00241 \text{ mol}$$

3 moles of Ca (OH)<sub>2</sub> forms 2 moles of Cr (OH)<sub>3</sub> sludge.

Therefore, mg of Cr(OH)<sub>3</sub> formed per liter =

$$\frac{2}{3} (0.00241 \text{ mol}) \left( 103,000 \frac{\text{mg}}{\text{mol}} \right) = 165.5 \text{ mg}$$

(2) *Zinc Hydroxide Sludge.*

$$\text{Ca (OH)}_2 \text{ dosage: } 43.9 \frac{\text{mg}}{\text{L}}$$

$$43.9 \text{ mg} \times \frac{1 \text{ mole}}{74,000 \text{ mg}} = 0.000593 \text{ mol}$$

1 mole of Ca (OH)<sub>2</sub> forms 1 mole of Zn (OH)<sub>2</sub>

Therefore, mg of Zn(OH)<sub>2</sub> formed per liter

$$(0.000593 \text{ mol}) \left( 99,400 \frac{\text{mg}}{\text{L}} \right) = 58.9 \text{ mg}$$

(3) *Suspended Solids*. Given in problem statement (25 mg/L).

(4) *Coagulant and Coagulant Aid*. Given in problem statement. Assume that all coagulant and coagulant aid settle out of solution and subsequently contribute to the sludge volume. Therefore, coagulant at 10 mg/L + coagulant aid at 1 mg/L = 11 mg/L.

(5) *Total Sludge*.

$$165.5 \text{ mg} + 58.9 \text{ mg} + 25 \text{ mg} + 11 = 260.4 \text{ mg/L}$$

or

$$\left( 260.4 \frac{\text{mg}}{\text{L}} \right) \times \frac{8.34 \text{ lb} \times \text{L}}{\text{mg} \times \text{MG}} \times \frac{0.3 \text{ MG}}{\text{day}} = 651 \frac{\text{lb}}{\text{day}}$$

As mentioned in the problem statement, with the assumption that the sludge is 3% solids and that the specific gravity of the sludge is 1.02, the volume that will require disposal each day can be calculated as follows:

$$\frac{651 \frac{\text{lb}}{\text{day}}}{\left( 62.4 \frac{\text{lb}^3}{\text{ft}} \right) (1.02) (0.03)} = 340.9 \frac{\text{ft}^3}{\text{day}} \left( 12.6 \text{ yd}^3 \right)$$

c. *Required Volumes of Coagulation and Flocculation Units*.

(1) *Coagulation Tank.*

$$\left(300,000 \frac{\text{gal}}{\text{day}}\right) \left(\frac{\text{day}}{1440 \text{ min}}\right) (1 \text{ min}) \left(\frac{\text{ft}^3}{7.48 \text{ gal}}\right) = 27.9 \text{ ft}^3$$

for a cubicle tank, approximately  $3 \times 3 \times 3$  ft.

(2) *Flocculation Tank.*

$$\left(300,000 \frac{\text{gal}}{\text{day}}\right) \left(\frac{\text{day}}{1440 \text{ min}}\right) (30 \text{ min}) \left(\frac{\text{ft}^3}{7.48 \text{ gal}}\right) = 835.6 \text{ ft}^3$$

Assume a length-to-width ratio of 2:1. A rectangular tank, 5 ft. deep, would be approximately  $18 \times 9 \times 5$  ft =  $810 \text{ ft}^3$ .

*d. Calculate the Theoretical Power Requirement and Required Paddle Area for the Flocculation Step.*

(1) *Theoretical Power Requirement.* Rearranging the equation

$$G = \left(\frac{P}{V\mu}\right)^{0.5} \text{ in Paragraph 9-1:}$$

$$P = \mu G^2 V$$

where:

$\mu$  = absolute fluid viscosity, lb-s/ft<sup>2</sup> (for water at 20°C =  $2.1 \times 10^{-4}$  lb-s/ft<sup>2</sup>)

$V$  = tank volume ft<sup>3</sup>

$P$  = power, ft-lb/s

$G$  = mean velocity gradient, ft/s-ft

(Note that typical  $G$  Value for flocculation is 30 ft/s-ft, see Chapter 9). Therefore

$$\begin{aligned} P &= (0.21 \times 10^{-4} \text{ lb-s/ft}^2) (30 \text{ ft/s-ft})^2 (810 \text{ ft}^3) \\ &= 15.3 \text{ ft-lb/s} \end{aligned}$$

$$= 15.3/500 = 0.031 \text{ HP.}$$

(2) *Paddle Area Requirement.* Rearranging the equation  $P = CA \rho V^3/2$  in Paragraph 9-1:

$$A = \frac{2P}{C_D v^3 \rho}$$

use a paddle tip speed of 1.2 fps, where:

$A$  = paddle area

$P$  = power requirement (ft-lb/s)

$C_D$  = dimensionless coefficient of drag (typically taken as 1.8)

$v$  = relative velocity of paddle in fluid, fps (Assume to be 0.75 times the paddle tip speed)

$\rho$  = mass fluid density (at 20°C, 1.94 lb-s/ft<sup>3</sup>, or slugs/ft<sup>3</sup>).

Therefore:

$$A = \frac{2(15.3)}{(1.8 \times ((0.75)(1.2))^3 (1.94))}$$

$$= 12.0 \text{ ft}^2$$

*e. Calculate the Solids Settling Area Required for Inclined Plate Clarifier.* Figure C-3 shows the results of the column testing. The column tests determined that the settling rate was 1.34 ft in 18 minutes. Convert this to commonly used units. (Note: 1.34 ft is the height of the solid/liquid interface at time zero, when the column is filled to 1000 mL.)

$$\frac{1.34 \text{ ft}}{18 \text{ min}} \times 7.48 \text{ gal/ft}^3 = 0.56 \text{ gpm/ft}^2$$

(1) For continuous rate divide by 2 (per manufacturer):

$$\frac{0.56}{2} = 0.28 \frac{\text{gpm}}{\text{ft}^2}$$
$$\left( 300,000 \frac{\text{gal}}{\text{day}} \right) \left( \frac{\text{day}}{1440 \text{ min}} \right) = 208.3 \text{ gpm}$$

$$\text{Solids settling area required} = 208.3 \text{ gpm} \times \frac{\text{ft}^2}{0.28 \text{ gpm}} = 744 \text{ ft}^2$$

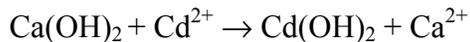
(Note: Most manufacturers of inclined plate clarifiers recommend a rate of 0.25 gpm/ft<sup>2</sup> for metal hydroxide precipitates. Rates should not exceed 1.0 gpm/ft<sup>2</sup>.)

(2) For one manufacturer, the required dimensions of an inclined plate clarifier to accommodate 744 ft<sup>2</sup> of effective settling area would be:

$$6 \text{ ft} \times 10 \text{ ft} \times 12 \text{ ft}$$

Operating weight would be approximately 34,000 lb.

*f. How Effective Would the Proposed Method of Treatment be if the Leachate Originally Contained 5 mg/L of Cadmium?* See Figure 2-2. Cadmium is removed through hydroxide precipitation as follows:



Note that the minimum solubility of cadmium hydroxide occurs at pH > 11. At a pH of 8.5, the solubility of cadmium hydroxide is high (greater than 100 mg/L). Therefore, by raising the pH to only 8.5 or 9 (to remove chromium and zinc), the cadmium concentration would not be reduced below the original concentration of 5 mg/L. To effectively remove cadmium, a second stage precipitation/clarification step would be required where the pH would be raised to 11. (Note: Results of jar testing could show that co-precipitation of cadmium hydroxide may occur, thereby effectively lowering the cadmium hydroxide concentration.)

*g. Should Additional Tests be Conducted to Confirm the Theoretical Results?* Yes, it is important that jar testing be conducted to determine if the theoretical results are accurate. Often-times, actual chemical requirements can differ significantly with stoichiometric calculations. This can be caused by a number of things (see Paragraph 2-2).

**C-3. Problem (SI Units).** 1000 m<sup>3</sup>/day of landfill leachate and ground water have the following characteristics:

- pH: 6.5
- Cr<sup>+6</sup>: 15 mg/L
- Total Cr: 75 mg/L
- Zn<sup>2+</sup>: 35 mg/L
- Suspended solids: 25 mg/L
- Dissolved oxygen: 2 mg/L

a. The *Feasibility Study* determined that the method of treatment would be chemical reduction of chromium (Cr<sup>+6</sup> to Cr<sup>+3</sup>) using sulfur dioxide, followed by hydroxide precipitation using lime, followed by coagulation, flocculation, and clarification. The full-scale treatment system will be designed to operate 24 hours/day.

b. During initial bench-scale testing, a 1-L sample of raw wastewater was titrated with 0.1 N sulfuric acid and then neutralized with lime, yielding the results shown in Figures C-1 and C-2.

c. Column testing was also conducted to determine the expected solids loading to the clarifier. Results of column testing are shown in Figure C-3.

d. From the data given above, determine the following:

(1) The chemical requirements to precipitate chromium and neutralize the treated wastewater, assuming that sulfur dioxide will be used as the reducing agent and that lime will be used as the precipitant. Assume that the final neutralized pH will be 8.5.

(2) The daily sludge production, assuming that 10 mg/L ferric chloride will be used as a coagulant and that 1 mg/L polymer will be used as a coagulant aid. Assume that the sludge has a specific gravity of 1.02 and is 3% solids.

(3) The required coagulation and flocculation tank volumes, using a 1 minute rapid-mix (coagulation) time and a 30 minute slow-mix (flocculation) time.

(4) The theoretical power requirement and required paddle area for the flocculation step, assuming a paddle tip speed of 0.4 m/s.

(5) The solids settling area required for an inclined plate clarifier, assuming continuous treatment. Note the results of the column testing shown in Figure C-3.

(6) If the leachate originally contained 5 mg/L of cadmium, how effective would the proposed method of treatment be?

(7) Should additional testing be conducted to confirm the theoretical (stoichiometric calculations) results?

#### C-4. Solution.

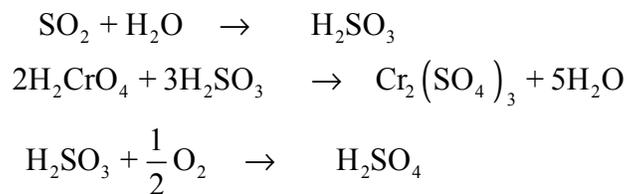
##### a. Chemical Requirements.

(1) *Sulfuric Acid.* Sulfuric acid is required because chromium reduction using sulfur dioxide is typically conducted at a pH of 2.5 to 3. Figure C-1 shows that approximately 25 mL of 0.1 N H<sub>2</sub>SO<sub>4</sub> is required to acidify 1 L of wastewater to pH 3.0. This is equal to an acid dose of:

$$\left(25 \frac{\text{mL}}{\text{L}}\right) \times (0.1 \text{ N}) = 2.5 \frac{\text{meq} \cdot \text{H}_2\text{SO}_4}{\text{L}}$$

The acid feed rate required to achieve this dose will depend on the normality of acid used for treatment. (Note: Typical required retention times for chromium reduction at a pH of 3 range from 2 to 20 minutes, depending on the initial hexavalent chromium concentration.)

(2) *Sulfur Dioxide.* The equations that govern the reduction of hexavalent chromium to trivalent chromium using sulfur dioxide are as follows:



Using the above equations and molar ratios, and assuming that the reactions go to completion, gives the SO<sub>2</sub> requirements follows for Cr<sup>+6</sup>. Because 3 moles of SO<sub>2</sub> yield 3 moles of H<sub>2</sub>SO<sub>3</sub>, then:

$$\frac{3 \times (32 + 2(16))}{2 \times 52} = 1.85 \frac{\text{mg}}{\text{L}} \text{SO}_2 \text{ per } \frac{\text{mg}}{\text{L}} \text{Cr}^{+6}$$

(Note that the quantity (32 + 2(16)), or 64, is the gram atomic -weight of sulfur dioxide. The quantity 52 is the gram atomic-weight of chromium.) And the requirements for O<sub>2</sub> are:

$$\frac{32 + 2(16)}{\frac{1}{2} \times 2(16)} = 4 \frac{\text{mg}}{\text{L}} \text{SO}_2 \text{ per } \frac{\text{mg}}{\text{L}} \text{O}_2$$

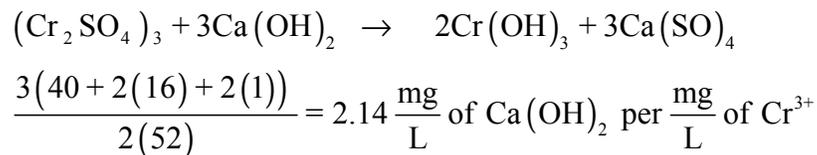
Therefore, SO<sub>2</sub> required (mg/L) =

$$(1.85)15 \frac{\text{mg}}{\text{L}} \text{Cr}^{+6} + 4(2.0) \frac{\text{mg}}{\text{L}} \text{O}_2 = 35.8 \frac{\text{mg}}{\text{L}}$$

(3) *Lime*. Lime is required to raise the pH of the wastewater to precipitate chromium. Assume that the lime is 90% pure.

(a) The amount of lime required to neutralize the wastewater to pH 8.5, as indicated in Figure 2-2, is approximately 107 mg/L.

(b) The amount of lime required to precipitate the chromium can be calculated using the equation below:



The total lime requirement to precipitate trivalent chromium is based on the combined total of trivalent and hexavalent chromium present in the raw wastewater (75 mg/L).

$$\text{Ca}(\text{OH})_2 \text{ required (90\% pure)} = \frac{2.14 \times 75 \text{ mg}}{0.90 \text{ L}}$$

$$= 178.3 \frac{\text{mg}}{\text{L}}$$

(c) Lime is also required to precipitate zinc (35 mg/L). The minimum solubility of zinc hydroxide occurs at approximately pH 9.0 (relatively close to 8.5—see Figure 2-2). Therefore, for simplicity, assume that the lime reaction with zinc goes to completion at pH 8.5. The amount of lime can be calculated using the equation below:

$$\text{Ca}(\text{OH})_2 + \text{Zn}^{2+} \rightarrow \text{Zn}(\text{OH})_2 + \text{Ca}_2^+$$

$$\frac{40 + 2(16) + 2(1)}{65.4} = 1.13 \frac{\text{mg}}{\text{L}} \text{ of Ca}(\text{OH})_2 \text{ per } \frac{\text{mg}}{\text{L}} \text{ of Zn}^{2+}$$

$$\text{Ca}(\text{OH})_2 \text{ required (90\%pure)} = \frac{1.13 \times 35}{0.90} = 43.9 \frac{\text{mg}}{\text{L}}$$

(d) The amount of lime required to neutralize the  $\text{H}_2\text{SO}_4$  produced from dissolved oxygen initially present in the wastewater can be calculated from the equations below:

$$\text{H}_2\text{SO}_3 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{SO}_4$$

$$\text{H}_2\text{SO}_4 + \text{Ca}(\text{OH})_2 \rightarrow \text{CaSO}_4 + 2\text{H}_2\text{O}$$

$$\frac{(2(1) + 32 + 16(4))}{\frac{1}{2}(2)(16)} = 6.12 \frac{\text{mg}}{\text{L}} \text{ H}_2\text{SO}_4 \text{ produced per } \frac{\text{mg}}{\text{L}} \text{ O}_2 \text{ present}$$

$$\text{H}_2\text{SO}_4 \text{ produced} = 6.12 \times 2 \frac{\text{mg}}{\text{L}} \text{ O}_2 = 12.2 \frac{\text{mg}}{\text{L}}$$

Therefore, the lime requirement, from the second equation, is:

$$\frac{(40 + 2(16) + 2(1))}{2(1) + 32 + 4(16)} = 0.76 \frac{\text{m}}{\text{L}} \text{ lime per } \frac{\text{mg}}{\text{L}} \text{ H}_2\text{SO}_4$$

$$\text{CA}(\text{OH})_2 \text{ required (assuming 90\% pure)} = \frac{0.76 \times 12.2 \frac{\text{mg}}{\text{L}}}{0.90}$$

$$= 10.3 \frac{\text{mg}}{\text{L}}$$

(e) Therefore, the total amount of lime =  $107 + 178.3 + 43.9 + 10.3 = 339.5 \text{ mg/L}$

Or, in kg/day:

$$\left(339.5 \frac{\text{mg}}{\text{L}}\right) \left(1000 \frac{\text{L}}{\text{m}^3}\right) \left(1000 \frac{\text{m}^3}{\text{day}}\right) \left(\frac{\text{kg}}{10^6 \text{mg}}\right) = 339.5 \frac{\text{kg}}{\text{day}}$$

b. *Daily Sludge Production.*

(1) *Chromium Hydroxide Sludge.*

$$\text{Ca (OH)}_2 \text{ dosage (90\% pure): } 178.3 \frac{\text{mg}}{\text{L}}$$

$$178.3 \text{ mg} \times \frac{1 \text{ mole}}{74,000 \text{ mg}} = 0.00241 \text{ mol}$$

3 moles of  $\text{Ca (OH)}_2$  forms 2 moles of  $\text{Cr (OH)}_3$  sludge.

Therefore, mg of  $\text{Cr (OH)}_3$  formed per liter =

$$\frac{2}{3} (0.00241 \text{ mol}) \left( 103,000 \frac{\text{mg}}{\text{mol}} \right) = 165.5 \text{ mg}$$

(2) *Zinc Hydroxide Sludge.*

$$\text{Ca (OH)}_2 \text{ dosage: } 43.9 \frac{\text{mg}}{\text{L}}$$

$$43.9 \text{ mg} \times \frac{1 \text{ mole}}{74,000 \text{ mg}} = 0.000593 \text{ mol}$$

1 mole of  $\text{Ca (OH)}_2$  forms 1 mole of  $\text{Zn (OH)}_2$

Therefore, mg of  $\text{Zn (OH)}_2$  formed per liter =

$$(0.000593 \text{ mol}) \left( 99,400 \frac{\text{mg}}{\text{mol}} \right) = 58.9 \text{ mg}$$

(3) *Suspended Solids.* Given in problem statement (25 mg/L).

(4) *Coagulant and Coagulant Aid.* Given in problem statement. Assume that all coagulant and coagulant aid settle out of solution and subsequently contribute to the sludge volume. Therefore 10 mg/L of coagulant + 1 mg/L of coagulant aid = 11 mg/L.

(5) *Total Sludge.*

$$165.5 \text{ mg} + 58.9 \text{ mg} + 25 \text{ mg} + 11 = 260.4 \text{ mg/L}$$

or

$$\left(260.4 \frac{\text{mg}}{\text{L}}\right) \left(1000 \frac{\text{L}}{\text{m}^3}\right) \left(1000 \frac{\text{m}^3}{\text{day}}\right) \left(\frac{\text{kg}}{10^6 \text{ mg}}\right) = 260.4 \frac{\text{kg}}{\text{day}}$$

As mentioned in the problem statement, with the assumption that the sludge is 3% solids and that the specific gravity of the sludge is 1.02, the volume that will require disposal each day can be calculated as follows:

$$\frac{260.4 \frac{\text{kg}}{\text{day}}}{1000 \frac{\text{kg}}{\text{m}^3} (1.02) (0.03)} = 8.51 \frac{\text{m}^3}{\text{day}}$$

c. *Required Volumes of Coagulation and Flocculation Units.*

(1) *Coagulation Tank.*

$$\left(1000 \frac{\text{m}^3}{\text{day}}\right) \left(\frac{\text{day}}{1440 \text{ min}}\right) (1 \text{ min}) = 0.69 \text{ m}^3$$

for a cubicle tank, approximately  $0.9 \times 0.9 \times 0.9 \text{ m}$ .

(2) *Flocculation Tank.*

$$\left(1000 \frac{\text{m}^3}{\text{day}}\right) \left(\frac{\text{day}}{1440 \text{ min}}\right) (30 \text{ min}) = 20.8 \text{ m}^3$$

Assume a length-to-width ratio of 2:1. A rectangular tank, 2 m deep, would be approximately,  $5 \times 2 \times 2 = 20 \text{ m}^3$ .

d. *Calculate the Theoretical Power Requirement and Required Paddle Area for the Flocculation Step.*

(1) *Theoretical Power Requirement.* Rearranging the equation:

$$G = \left( \frac{P}{V\mu} \right)^{0.5} \text{ in Paragraph 9-1:}$$

$$P = \mu G^2 V$$

where:  $\mu$  = absolute fluid viscosity,  $\frac{\text{N}\cdot\text{s}}{\text{m}^2}$

(for water at 20° C,  $\mu = 1 \times 10^{-3} - \frac{\text{N}\cdot\text{s}}{\text{m}^2}$ )

$V$  = tank volume,  $\text{m}^3$

$P$  = power, W

$G$  = mean velocity gradient,  $\frac{\text{m}}{\text{s}\cdot\text{m}}$

(Note that the typical  $G$  value for flocculation is 30/s, see Chapter 9.) Therefore

$$\begin{aligned} P &= \left( 1.00 \times 10^{-3} \frac{\text{N}\cdot\text{s}}{\text{m}^2} \right) \left( 30 \frac{\text{m}}{\text{s}\cdot\text{m}} \right)^2 (20 \text{ m}^3) \\ &= 18 \text{ W} \end{aligned}$$

(2) *Paddle Area Requirement.* Rearranging the equation

$$P = C_D A \frac{\rho v^3}{2} \text{ in Paragraph 9-1:}$$

$$A = \frac{2P}{C_D v^3 \rho} \text{ use a paddle tip speed of } \frac{0.4 \text{ m}}{\text{s}}$$

where:  $A$  = paddle area,  $\text{m}^2$

$P$  = Power requirement, W

$C_D$  = dimensionless coefficient of drag (typically taken as 1.8)

$v$  = relative velocity of paddle in fluid,  $\frac{\text{m}}{\text{s}}$

(Assume to be 0.75 times the paddle tip speed.)

$\rho$  = mass fluid density (at 20°C,  $\frac{\text{kg}}{\text{m}^3}$ )

Therefore

$$A = \frac{2(18)}{(1.8 \times ((0.75)(0.4))^3 (1000))}$$

$$= 0.74 \text{ m}^2$$

e. Calculate the Solids Settling Area Required for Inclined Plate Clarifier. Figure C-3 shows the results of the column testing. The column tests determined that the settling rate was 0.41 m in 18 minutes. Convert this to commonly used units (Note: 0.41 m is the height of the solid/liquid interface at time zero, when the column is filled to 1000 mL):

$$\frac{0.41 \text{ m}}{18 \text{ min}} = 0.023 \frac{\text{m}^3/\text{min}}{\text{m}^3}$$

For continuous rate divide by 2 (per manufacturer):

$$\frac{0.023}{2} = \frac{0.0115 \text{ m}^3/\text{min}}{\text{m}^3}$$

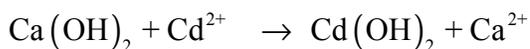
$$\left( \frac{1000 \text{ m}^3}{\text{day}} \right) \left( \frac{\text{day}}{1440 \text{ min}} \right) = 0.694 \text{ m}^3/\text{min}$$

Solids settling area required:

$$= \frac{0.694 \text{ m}^3}{\text{min}} \times \frac{\text{m}^3}{0.011 \text{ m}^3/\text{min}} = 63 \text{ m}^3$$

(Note: Most manufacturers of inclined plate clarifiers recommend a rate of 0.010 (m<sup>3</sup>/min)/m<sup>2</sup> for metal hydroxide precipitates. Rates should not exceed 0.04 (m<sup>3</sup>/min)/m<sup>2</sup>.)

f. How Effective Would the Proposed Method of Treatment be if the Leachate Originally Contained 5 mg/L of Cadmium? See Figure 2-2. Cadmium is removed through hydroxide precipitation as follows:



Note that the minimum solubility of cadmium hydroxide occurs at pH > 11. At a pH of 8.5 the solubility of cadmium hydroxide is high (greater than 100 mg/L). Therefore, by raising the pH to only 8.5 or 9 (to remove chromium and zinc), the cadmium concentration would not be reduced below the original concentration of 5 mg/L. To effectively remove cadmium, a second stage precipitation/clarification step would be required where the pH would be raised to 11.

(Note: Results of jar testing could show that co-precipitation of cadmium hydroxide may occur, thereby effectively lowering the cadmium hydroxide concentration.)

*g. Should Additional Tests be Conducted to Confirm the Theoretical Results?* Yes, it is important that jar testing be conducted to determine if the theoretical results are accurate. Oftentimes, actual chemical requirements can differ significantly with stoichiometric calculations. This can be caused by a number of things (see Paragraph 2-2).