

tions exceeding 4% have been obtained without the addition of polyelectrolytes. Air pressures up to 6 atm have been used. Experimental variation of the air pressure in the air dissolution tank should be performed to find conditions that produce the smallest bubbles with the valve in the system.

20.7 MECHANICAL SLUDGE DEWATERING

Sludge dewatering is used to remove as much water as possible from a sludge to produce a highly concentrated cake. There is a variety of dewatering devices on the market. The capital and operating expenses of these devices are usually significantly less than the costs of hauling large quantities of sludge long distances to a landfill or other disposal site.

A sludge suspension contains bulk water, which is not bound to the sludge particles, and bound water, of which there are three different types (Vesilind, 1994): interstitial water, vicinal water, and water of hydration. Interstitial water is water captured in the interstitial spaces within flocs and within cells. Vicinal water is bound to the surfaces of solids. Water of hydration is chemically bonded to the sludge. Dewatering devices primarily remove bulk water; some interstitial water can be removed but it is likely that the major fraction of bound water is vicinal water that cannot be removed mechanically (Vesilind, 1994). Freeze-thaw conditioning physically disrupts floc and cell structure and produces the greatest degree of bound water release for dewatering (Robinson and Knocke, 1992).

20.7.1 Centrifugation

Centrifuges are analogous to sedimentation tanks except that the suspended particles are accelerated by a centrifugal force that is higher than the gravity force. A schematic of a centrifuge is shown in Fig. 20.8. In this centrifuge, slurry is input into a central feed pipe. The bowl is rotated typically between 200 and 8 000 rpm, creating the centrifugal force that moves the particles to the wall of the bowl. An extraction screw rotated at a different speed from the bowl scrapes solids from the bowl wall and moves them to the solids discharge end. Liquid (centrate) is discharged at the opposite end of the centrifuge. Centrifuges may also be designed for unidirectional flow and tangential feed.

The centrate contains a significant amount of solids and it is returned to the

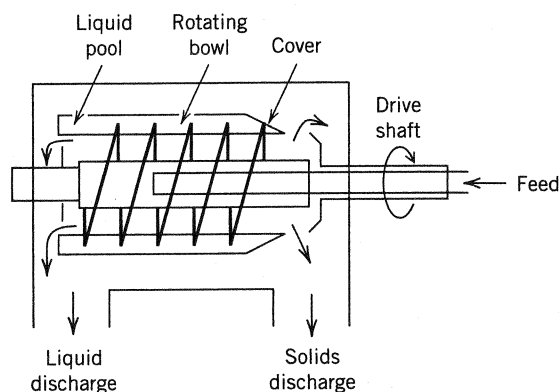


Figure 20.8 Continuous flow solid bowl centrifuge.

treatment plant. In a wastewater treatment plant it is returned ahead of the primary clarifier. Centrifuges are not as commonly used in water treatment plants because the sludge is in a liquid state. Centrate is returned to the head of the water treatment plant.

The major forces acting on a particle are the centrifugal force (Eq. 20.26) and the drag force (Eq. 20.27). The force balance is similar to the force balance on a particle settling in a fluid. The centrifugal force is

$$F_c = m_e \omega^2 r = (\rho_s - \rho) V_p \omega^2 r \quad (20.26)$$

where

- F_c is the centrifugal force
- m_e is effective mass of the particle
- ω is the angular velocity of the fluid
- r is the distance of the particle from the center
- ρ_s is the density of the particle
- ρ is the density of the fluid
- V_p is the volume of the particle

and the drag force is

$$F_D = \frac{1}{2} \rho C_D A v^2 \quad (20.27)$$

where

- F_D is the drag force
- C_D is the drag coefficient
- A is the cross-sectional area of the particle
- v is the velocity of the particle

The drag coefficient is a function of the Reynold's number as discussed in Section 11.3.

Ignoring the gravity force which is small compared to the other forces and making a force balance on a particle:

$$\rho_s V_p \frac{dv}{dt} = (\rho_s - \rho) V_p \omega^2 r - \frac{1}{2} \rho C_D A v^2$$

Making the substitution of dr/dt for v and using the nominal diameter, d , for the particle, the equation becomes

$$\rho_s \frac{\pi d^3}{6} \frac{d^2 r}{dt^2} = (\rho_s - \rho) \frac{\pi d^3}{6} \omega^2 r - \frac{1}{2} \rho C_D \frac{\pi d^2}{4} \left[\frac{dr}{dt} \right]^2$$

or

$$\frac{d^2 r}{dt^2} + C_D \frac{\rho}{\rho_s} \frac{3}{4d} \left[\frac{dr}{dt} \right]^2 - \frac{(\rho_s - \rho)}{\rho_s} \omega^2 r = 0 \quad (20.28)$$

If the particle is in a laminar flow regime, the drag coefficient is $24/Re$. Substituting this into Eq. (20.28) the differential equation becomes

$$\frac{d^2 r}{dt^2} + \frac{18\mu}{\rho_s d^2} \frac{dr}{dt} - \frac{(\rho_s - \rho)}{\rho_s} \omega^2 r = 0$$

where

- μ is the viscosity of the fluid

The solution of this differential equation is

$$r = C_1 \exp\left(\frac{-b + \sqrt{b^2 + 4c}}{2}t\right) + C_2 \exp\left(\frac{-b - \sqrt{b^2 + 4c}}{2}t\right)$$

where

$$b = \frac{18\mu}{\rho_s d^2}, c = \frac{(\rho_s - \rho)}{\rho_s} \omega^2, \text{ and for all values } b^2 + 4c > 0 \text{ (it is impossible that the roots be equal).}$$

The critical initial conditions are

$$t = 0: \quad r = 0: \quad \frac{dr}{dt} = 0$$

because the particle entering at the center of the unit has the farthest distance to travel. The velocity dr/dt must be zero at the center because of symmetry. However a particle that enters exactly at the center of the unit will not be subjected to any net centrifugal force; it will simply spin around and be moved longitudinally until it is moved from the centerline, at which time it will begin to accelerate toward the wall. The equation has no solution using these initial conditions, i.e., $r = 0$ at all times.

A slight perturbation is all that is required to move the particle from the centerline. Irregularities in the particle shape are sufficient to cause a force imbalance on the particle and initiate its movement radially. Also gravity has been ignored in the preceding development. Normal fluctuation in flow streamlines will move the particle away from the centerline or a particle may be displaced by another particle. The moment that the particle is moved from the centerline, it is subjected to the centrifugal force and travels toward the perimeter. The differential equation can be solved if an initial condition of a small displacement, δ , from the centerline is specified. Using this condition the solution of the differential equation is

$$r = \frac{\delta}{\sqrt{b^2 + 4c}} (\alpha_1 e^{\alpha_2 t} - \alpha_2 e^{\alpha_1 t}) \tag{20.29}$$

where

$$\alpha_1 = \frac{-b + \sqrt{b^2 + 4c}}{2}, \quad \alpha_2 = \frac{-b - \sqrt{b^2 + 4c}}{2}$$

Equation (20.29) can be plotted to find the time for a particle to move a given radial distance.

The acceleration of the particle is commonly ignored (or assumed to be constant). Assuming that the change in acceleration of the particle with respect to radial distance is negligible, Eq. (20.28) integrates to

$$t = \frac{18\mu}{d^2 \omega^2} \ln \frac{r_o}{r_i} \tag{20.30}$$

where

r_i and r_o are the initial and final radial distances of the particle from the centerline

The high concentration of solids in a slurry will affect the movement of the particles. This problem and the simplifying assumptions used to derive Eqs. (20.29) and (20.30) result in a more empirical approach to describe thickening in centrifuges.

Vesilind
fuge pert

20.7.2

Vacuum
determin
applied t
deposit c
zontal cy
The filte
rolled or
(the cak
scraping
centrifug
processi

The
permane
springs t
The feed
the loss
be used

Solid
falls bet
conditio
ft²/h) fo
sludges.
tioning
its perfo

Flow
theory c
equation



Figure 2

Vesilind (1979) describes the empirical modifications commonly used to model centrifuge performance.

20.7.2 Vacuum Dewatering

Vacuum filtration is the large-scale continuous flow version of a laboratory solids determination. A sludge slurry is brought into contact with a filter and a vacuum is applied to draw the water from the sludge and through the filter leaving a sludge cake deposit on the filter. The continuous flow vacuum filter (Fig. 20.9) consists of a horizontal cylinder that is 20–35% submerged in a vat of previously conditioned sludge. The filter medium is wrapped around the drum. As the drum rotates the medium is rolled on and off the drum. The cake is cleaned from the medium by roll discharge (the cake crumbles from the medium when it is passed over a small roller) or by a scraping blade. The medium is washed before it is returned to the drum. As for centrifuges, the filtrate is returned to the water or wastewater treatment plant for re-processing.

There are two types of media (USEPA, 1987). Coil spring medium consists of a permanent layer of springs on the drum, which is overlaid with a second layer of coil springs that travels off and on to the drum. The open area of the coil springs is 7–14%. The feed sludge concentration must be high with sufficient fiber content to prevent the loss of solids through the large open area. The other medium is cloth, which must be used when filtering unthickened secondary sludge.

Solids capture ranges from 85 to 99.5%. The product sludge cake moisture normally falls between 60 and 90%, depending on the feed type, solids concentration, chemical conditioning agents, and operation. Typical loading rates are 34–75 kg/m²/h (7–15 lb/ft²/h) for primary sludges and 17–24.5 kg/m²/h (3.5–5 lb/ft²/h) for mixed digested sludges. Lime, polyelectrolytes, ferric chloride, and other chemicals are used as conditioning agents. Precoating a filter with diatomaceous earth may considerably improve its performance.

Flow through the cake and the filter medium is flow through porous media. The theory of vacuum filter operation is based on an adaptation of the Carman–Kozeny equation or Darcy's law (Coackley and Jones, 1956).

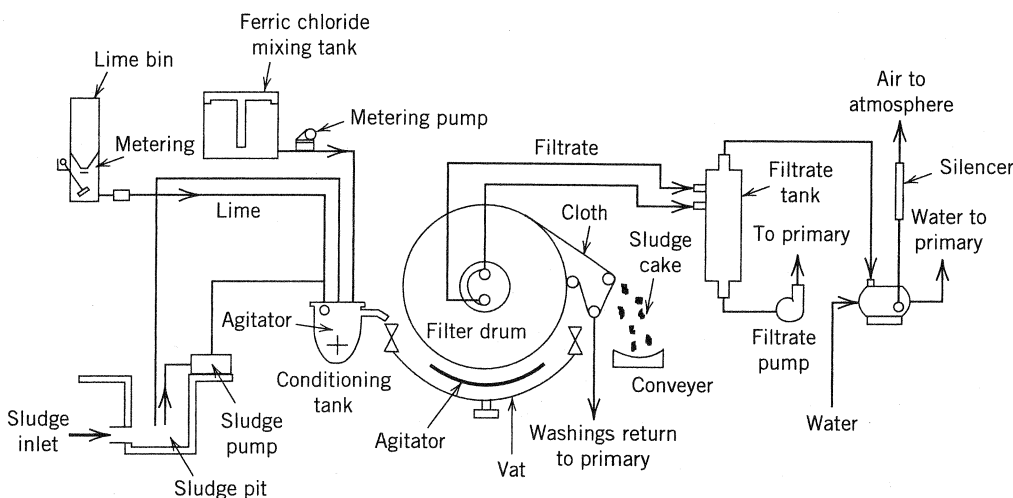


Figure 20.9 Vacuum filter system. After USEPA (1979).

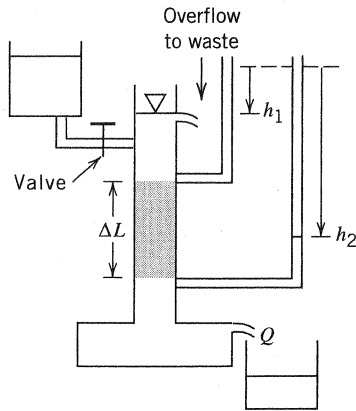


Figure 20.10 Darcy's law apparatus.

Darcy's law (see the illustration in Fig. 20.10) is

$$Q = \frac{dV}{dt} = KA \frac{\Delta h}{\Delta L} \quad (20.31)$$

where

Q is volumetric flow rate of the filtrate

V is volume of water

A is area of flow

K is conductivity

h is head

L is distance

The resistance parameter depends on the Reynold's number, porosity of the media, distribution of grains, and other characteristics of the media. From dimensional analysis or analogy to the Hagen–Poiseuille law for pipe flow:

$$K = kg/\nu \quad (20.32)$$

where

k is intrinsic permeability

ν is the kinematic viscosity

and

$$\frac{dV}{dt} = \frac{kA}{\mu} \frac{\Delta P}{\Delta L} \quad (20.33)$$

where

ΔP is the positive pressure differential

ΔL is the depth of the medium

μ is the dynamic viscosity of the filtrate

The intrinsic resistance, r can be defined as $r = 1/k$. The resistance from the cake, R_c , is

$$R_c = r_c \Delta L \quad (20.34)$$

where

r_c is the intrinsic resistance of the cake

The resistances contributed by the cake and the filter medium are considered to be independent and therefore able to be summed. The total resistance, R , is

$$R = R_c + R_f \quad (20.35)$$

where

R_f is the resistance of the filter medium

Now the volume of the cake formed, V_c , is

$$V_c = A\Delta L$$

Defining the specific deposit, σ , as the volume of cake formed per volume of filtrate obtained, the above equation becomes

$$\sigma V = A\Delta L \quad (20.36)$$

Considering the total resistance and Eqs. (20.34) and (20.36), Eq. (20.33) becomes

$$\frac{dV}{dt} = \frac{\Delta PA^2}{\mu(r_c\sigma V + R_f A)} \quad (20.37)$$

The intrinsic resistance, r_c , is on a volume basis. The resistance can also be formulated in terms of the mass of dry cake solids formed per unit volume of filtrate, w . The specific resistance, r_{wc} , is related to r_c by

$$r_{wc}w = r_c\sigma \quad (20.38)$$

Substituting this into Eq. (20.37),

$$\frac{dV}{dt} = \frac{\Delta PA^2}{\mu(r_{wc}wV + R_f A)} \quad (20.39)$$

For a constant pressure difference over time Eq. (20.39) integrates to

$$\int_0^t dt = \mu \int_0^V \left(\frac{wr_{wc}V}{\Delta PA^2} + \frac{R_f}{\Delta PA} \right) dV \quad (20.40)$$

$$t = \frac{\mu wr_{wc}V^2}{2\Delta PA^2} + \frac{\mu R_f V}{\Delta PA} \quad \text{or} \quad \frac{t}{V} = \frac{\mu wr_{wc}V}{2\Delta PA^2} + \frac{\mu R_f}{\Delta PA}$$

The terms in Eq. (20.40) can be determined from a plot of t/V versus V , which will yield a straight line. The specific resistance, r_{wc} , can be calculated from the slope, m , of the line.

$$r_{wc} = \frac{2\Delta PA^2}{\mu w} m \quad (20.41)$$

A laboratory setup to determine the specific resistance of sludge cakes is shown in Fig. 20.11. The procedure (USEPA, 1987) for the determination is to add 50–200 mL of sludge (with any conditioning agent added and mixed with the sludge) to the filter pad in the Büchner funnel. The pinch clamp is closed and the sludge is allowed to drain by gravity for 2 min. The vacuum pump, supplying a vacuum of 37 cm (14.6 in.) Hg is turned on and the clamp is opened. At 15-s intervals the volume of filtrate collected in the graduated cylinder is noted. Observations are made until the vacuum breaks or the filtrate volume does not change significantly between readings. The theory developed in this section ignores changes in resistance as the cake forms; porosity and tortuosity, among other cake characteristics, change. However, the theory

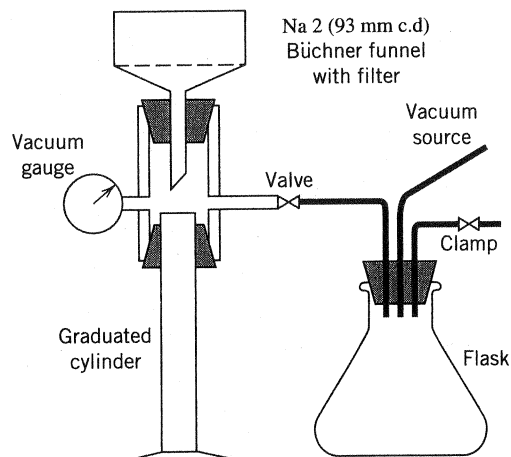


Figure 20.11 Laboratory setup to determine cake resistance.

is adequate to describe vacuum filtration and the test procedure. A plot of t/V versus V yields the specific resistance. The test is useful to evaluate different doses and combinations of sludges and conditioning agents on the specific resistance and quality of the cake. A plot of resistance versus dose and type of conditioning agent can be used to determine the optimal operating condition. Observations of performance of the full-scale unit can be related to results obtained from the laboratory setup to further improve the utility of the lab test.

The mass (weight) of solids deposited can be approximated from the solids concentration in kg/m^3 in the feed slurry.

Ranges for specific resistances of various sludges are given in Table 20.11.

20.8 LAND APPLICATION OF SLUDGE

Application of sludge to land, where feasible, is the most desirable alternative because it uses sludge in a natural cycle. Ideally, sludges produced from wastewater treatment processes contain all foreign matter introduced into water through domestic and industrial use that has not been removed or transformed into neutral substances by the wastewater treatment process. Except for chemical additions, the residues accumulated in wastewater treatment processes largely consist of organics and minerals ultimately derived from soil. Industrial processes and home use of synthetic agents may introduce metals above ambient levels and toxic compounds into sludge. Pathogens or

TABLE 20.11 Specific Resistances of Sludges^a

Sludge type	Specific resistance m/kg
Raw	$10\text{--}30 \times 10^{13}$
Raw, coagulated	$3\text{--}10 \times 10^{11}$
Digested	$3\text{--}30 \times 10^{12}$
Digested, coagulated	$2\text{--}20 \times 10^{11}$
Activated	$4\text{--}12 \times 10^{13}$

^aFrom USEPA (1987).

parasites occur in sludge as a result of sewage being a carriage vehicle for human excrement.

Per capita sludge production rates in Ontario are near 80 and 115 g/d for primary and secondary treatment, respectively, without sludge digestion (Schmidtke, 1981). Adding iron or aluminum salts for phosphorus removal will increase sludge production by about 40% for primary treatment or 25% for secondary treatment. Sludge digestion typically reduces the sludge mass by 40%. The final sludge concentration depends on the dewatering treatment applied.

Sludge may be applied in liquid, semisolid (wet cake), or dried form. Subsurface application devices may be used. Sludge transportation requirements and method of application will dictate the degree of dewatering. Liquid sludge application is preferred where feasible. Dewatering sludge removes soluble components with the liquid. About one third of the nitrogen in digested sludge is in the liquid fraction (Environment Canada, 1984); thickening and dewatering will reduce the soluble nitrogen level significantly.

Metals that are toxic and biocumulative and nutrients are constituents of interest in sludge. Composition of sludge varies widely depending on industrial activity and the treatment applied. Some typical values are given in Table 20.12. Environment Canada (1984) and USEPA (1983) contain more information on these and other constituents typically found in sludges. If the sludge contains high concentrations of toxic organics, it will be a hazardous waste subject to more restrictive disposal measures.

Sludge may be applied to agricultural lands, forests, other lands with vegetation (golf courses, turf farms, parks, and other recreational areas), or for land reclamation (surface mines or marginal lands). There are also dedicated disposal sites for sludge application. Controlling factors on the application rate are the utilization rate of nutrients by the crop or vegetation; potential of plants for uptake of toxic components, particularly metals, by the plants; accumulation of salts and metals in the soil; and aesthetics. Public health risk through direct exposure or consumption of edible crops and groundwater contamination are always considered in applying sludge to land.

Federal regulations in the United States for sludge disposal on land have been recently revised after extensive study, public consultation, and debate (Bastian et al., 1992). The regulations (Section 503 of the Clean Water Act) were promulgated in 1993 (Water Environment Federation Residuals Management Committee, 1993). Many factors influence contaminant movement through food chains. Plant uptake of toxic contaminants usually reaches a plateau with increasing sludge application rates (Chaney and Ryan, 1992). Loading rates specified in the regulations considered various food-chain pathways and the most exposed individual which could be a person, animal, or plant (Chaney and Ryan, 1992). Based on toxicity studies and bioaccumulation within individual species and through food chains the standards in Table 20.13 were determined. States or localities may adopt more severe regulations than the federal regulations.

For general land application, sludge quality and loading rates must meet the minimum quality limits given in Table 20.13. There are some restrictions on the use of minimum quality sludge in agricultural or other applications. Clean sludge can be distributed or sold to the public for virtually any use if pathogen and vector attraction limits are also attained.

Pathogen and vector attraction reduction regulations are specified in addition to metals. There are two classifications for pathogen reduction: Class A and Class B. There are a number of criteria or treatment alternatives specified in the regulations to meet either classification. Class A sludge has either fecal coliform densities under

TABLE 20.12 Typical Composition of Sludges

Constituent	Raw primary sludge ^a		All sludges ^b		Digested sludge ^c		Septage ^d	
	Range	Typical	Range	Typical	Range	Typical	Range	Typical
Total solids (%)	2.0-7.0	4.0			2.0-6.0	3.5	0.1-13	34
Volatile solids (% of TS)	60-80	65			35-65	51		63
pH	5-8	6			7.2-7.8	7.5		6.9
Alkalinity (mg/L as CaCO ₃)	500-1 500	600			200-7 600	4 800	522-4 190	970
Dry weight basis								
Total N (g/kg)	15-40	25	<1-176	33	1.6-4.0 ^e	2.7 ^e		0.69 ^e
Al (g/kg)			1-135	4	4.1-61	9.6		
As (mg/kg)			1.1-230	10				
Ca (g/kg)			1-250	39	44	26-67		
Cd (mg/kg)			3-3 410	16	5-260	10		
Cl (g/kg)					1.7-190	7.1		
Co (mg/kg)			1-18	4.0	1-42	9.0		
Cr (mg/kg)			10-99 000	500	200-1 280	375		
Cu (mg/kg)			84-10 400	850	280-2 570	970		
Fe (g/kg)	20-40	25	<1-153	11	14-110	51		
Hg (μ g/kg)			0.2-10 600	5	0.43-4.7	2.1		
K (g/kg)	0-8.3	4	0.2-26.4	3	0.04-0.16	0.09		
Mg (g/kg)			0.3-<19.7	4.5	3.1-11	6.8		
Mn (mg/kg)			18-7 100	260	170-2 090	320		
Mo (mg/kg)			5-39	30	7.0-97	12		
Na (g/kg)			0.1-30.7	2.4	0.07-0.42	0.16		
Ni (mg/kg)			2-3 520	82	23-410	120		
P (g/kg)	3.5-12.2	7	<1-143	23	14-57	24	20-760 ^f	210 ^f
Pb (mg/kg)			13-19 700	500	200-1 280	375		
Sn (mg/kg)			2.6-329	14				
Zn (mg/kg)			101-27 800	500	400-5 130	1 600		

^aFrom Metcalf and Eddy (1972).

^bFrom Chaney (1983) and Sommers (1977); includes data on aerobically and anaerobically digested sludge, lagooned, primary, tertiary, and unspecified sludges.

^cMOE (1977).

^dAdapted from USEPA (1984) for United States data.

^eNH₃ + Kjeldahl N in g/L.

^fIn mg/L.

1 000 MPN/g dry solids or *Salmonella* sp. densities under 3 MPN/g dry solids. Treatment alternatives that may be used in lieu of meeting the microorganism density criteria consist of various heat and pH treatments. The pH must be raised above 12 when the latter is used as a treatment. There are also virus reduction criteria.

For Class B sludge, the fecal coliform density requirement is relaxed to under 2×10^6 MPN/g dry solids. There are many treatment processes that can be used to meet Class B status, including aerobic and anaerobic digestion. Minimum treatment performance or other process operating constraints are specified for each treatment. Harvesting times for food crops are also specified.

Vector attraction reduction refers to reducing the potential for the application site to attract agents of disease such as flies, rodents, and birds. There are eight methods that may be used to meet vector reduction requirements for sludge that will be sold or distributed for domestic use. In addition to these methods there are two other techniques that may be used for general application of sludge to agricultural and forest lands or other sites. The treatment performance requirements or operating constraints are specified to achieve a significant reduction in septicity of the sludge. For instance,

TABLE 20.13 Land Application Standards and Guidelines

Pollutant	United States ^a					
	Minimum quality sludge		Clean sludge		Canada ^{b,c}	
	Ceiling concentration limit mg/kg	Cumulative pollutant loading ^d kg/ha	Pollutant concentration limit mg/kg	Annual pollutant loading rate kg/ha/yr	Maximum acceptable concentration mg/kg	Cumulative acceptable loading kg/ha
Arsenic	75	41	41	2.0	75	15
Cadmium	85	39	39	1.9	20	4
Chromium	3 000	3 000	1 200	150		
Cobalt					150	30
Copper	4 300	1 500	1 500	75		
Lead	840	300	300	15	500	100
Mercury	57	17	17	0.85	5	1
Molybdenum	75	18	18	0.90	20	4
Nickel	420	420	420	21	180	36
Selenium	100	100	36	5.0	14	2.8
Zinc	7 500	2 800	2 800	140	1 850	370

^aWaste Environment Federation Residuals Management Committee (1993).

^bEnvironment Canada (1984); see Bradley et al. (1992) for criteria for individual provinces.

^cThe limits are for agricultural applications.

^dThe time to achieve the cumulative loading criteria depends on the application rate and the net accumulation of the metals in the soil.

one acceptable measure is to reduce the mass of volatile solids in the sludge by a minimum of 38%. Any process can be used.

Canadian federal guidelines are also given in Table 20.13. Provinces are not required to adopt the federal guidelines. Ontario guidelines are generally near federal guidelines (MAF and MOE, 1992). At the metals concentrations in sludge specified in Table 20.13, the minimum time period to reach the cumulative pollutant loadings in soils will be 25 yr or more if the sludge is being applied to uncontaminated soils (MAF and MOE, 1992).

Land requirements are dependent on the application rate. Typical application rates for various land disposal options are given in Table 20.14. These data were generated under less severe regulations or guidelines than currently exist in North America.

Site selection and characterization are the initial steps in a design for land sludge application. Public participation is essential in the final selection. Background concentrations of metals in the soil will dictate the timespan over which sludge may be applied. Maximum possible application rates of the sludge are calculated by

$$A_T = \frac{K_c L}{C} \quad (20.42)$$

where

A_T is the application rate of sludge in tonne/ha

L is the metal limitation in kg/ha

K_c is a conversion factor (1 000 for SI; 446 for U.S.)

C is the concentration of the metal in the sludge in mg/kg (ppm)

Equation (20.42) is applied for each metal. The permissible application rate is dictated by the metal constituent that yields the lowest application rate.

TABLE 20.14 General Guidelines for Land Application of Sludge^a

Disposal option	Time period of application	Application rates (dry weight basis), ^b tonne/ha/yr (ton/acre/yr)	
		Range	Typical
Agricultural	Annual	2-70 (1-30)	11 (5)
Forest	One time or at 3- 5 yr intervals	10-220 (4-1 008)	44 (20)
Land reclamation	One time	7-450 (3-200)	112 (50)
Dedicated disposal site	Annual	220-900 (100-400)	340 (150)

^aFrom USEPA (1983).

^bRates are only for the application area and do not include area for the buffer zone, sludge storage, or other project area requirements.

The fertilizer value of sludge is one of the benefits of land application. The nutrient requirements of the crop to be grown or vegetation present on the site must be considered. Optimum application times and nutrient needs differ for various crops, growing conditions, and frequency of harvest. Table 20.15 provides information on

TABLE 20.15 Nutrients Removed in Grain and Straw^a

Crop	Yield tonne/ha (ton/acre)	Nutrients removed, kg/ha (lb/acre)			
		N	P	K	S
Alfalfa	9.0 ^b (4.0)	278 (248)	19 (17)	160 (143)	22 (20)
Barley	3.2 (1.4)	101 (90)	12 (11)	52 (46)	9 (8)
Corn	13.4 (6.0)	156 (139)	30 (27)	118 (105)	19 (17)
Flax	1.1 (0.50)	61 (54)	8 (7)	41 (37)	3.4 (3)
Grass	6.7 (3.0)	96 (86)	17 (15)	139 (124)	9 (8)
Oats	3.0 (1.3)	112 (100)	15 (13)	72 (64)	15 (13)
Potatoes	34 (15)	252 (225)	29 (26)	303 (270)	24 (21)
Rapeseed	1.7 (0.8)	133 (119)	18 (16)	67 (60)	7.8 (7)
Sugar beets	34 (15)	179 (160)	17 (15)	120 (107)	21 (19)
Wheat	2.7 (1.2)	95 (85)	13 (12)	52 (47)	9 (8)

^aFrom Alberta Farm Guide (1976).

^bLegumes obtain much of their nitrogen from the atmosphere.

TABLE 20.16 Mineralization Rates for Organic Nitrogen in Sludges^a

Time after sludge application, yr	Mineralization rate, ^b %		
	Raw sludge or septage	Digested anaerobic sludge	Composted
1	40	20	10
2	20	10	5
3	10	5	3
4	5	3	3

^aFrom USEPA (1983) and Water Environment Federation Residuals Management Committee (1993).

^bMineralization rates are 3% for years 5 through 10.

nutrient uptake of some crops (also see Table 19.8). Farmers must be advised to adjust commercial fertilizer application rates in accordance with sludge application rates.

Nitrogen is the most abundant nutrient in sludge and high application rates can pose a nitrate contamination risk to groundwaters and accelerate fertilization of surface waters. An agronomic application rate of sludge is adjusted to the nutrient demands of the crop being grown and minimizes the amount of nitrogen percolating with runoff below the root zone of the plants and the amount of nitrogen in surface runoff. (In the United States clean sludge is not required by the 503 regulations to be applied at the agronomic rate, although local permitting authorities may impose this restriction.)

Ammonia nitrogen in anaerobically digested sewage sludge is subject to losses through volatilization. If the sludge is not immediately incorporated into the soil, ammonia losses through volatilization can reach 50% (MAF and MOE, 1992). This must be incorporated into the nitrogen balance for an agronomic application rate.

For nitrogen to be available to plants it must be in a mineralized form. The USEPA in the 503 regulation (Water Environment Federation Residuals Management Committee, 1993) adopted mineralization rates¹ that were used in an earlier manual (USEPA, 1983). Through mineralization, depending on the sludge, varying amounts of organic nitrogen in the sludge is assumed to be available in the year of application and the second through the fourth years after application. Thereafter, 3% of the original organic nitrogen becomes available in each successive year until the nitrogen is exhausted. The mineralization factors during the first 4 yr are given in Table 20.16.

An equation describing the available nitrogen in the first year after application is

$$N_{a1} = k_c[(NO_3^-) + k_v(NH_3) + f_m N_o] \quad (20.43)$$

where

N_{a1} is the available nitrogen in the first year after application in kg/tonne (lb/ton) dry solids

(NO_3^-) is the mass fraction (g of NO_3^- -N/g of solids or lb of NO_3^- -N/lb of solids) of nitrate-N in the sludge

k_c is a conversion factor (1 000 kg/tonne for SI; 2 000 lb/ton for U.S.)

k_v is a volatilization factor

0.50 for surface applied sludge

1.0 for subsurface applied liquid sludge (Reed et al., 1988)

(NH_3) is the mass fraction of ammonia-N in the sludge (g of NH_3 -N/g of solids or lb of N/lb of solids)

¹There are some discrepancies for values of the mineralization factors in Water Environment Federation Residuals Management Committee (1993) (Rule 503) and USEPA (1983), but they are minor.

f_m is the mineralized fraction of the organic nitrogen based on the organic N in the freshly applied sludge (see Table 20.16)

N_o is the mass fraction of organic nitrogen in the sludge at application (g of organic N/g of solids or lb of organic N/lb of solids)

In the years following the year of application the available nitrogen is

$$N_{an} = k_c f_{mn} (N_{n-1} - f_{m,n-1} N_{n-1}) \quad (20.44)$$

where

N_{an} is the available nitrogen in year n after sludge application in kg/tonne (lb/ton) dry solids

$f_{mn}, f_{m,n-1}$ are the availability factors for years n and $n - 1$, respectively, given in Table 20.16

Equation (20.44) is applied recursively for each year.

The limiting application rate based on nitrogen requirements is calculated from

$$A_N = \frac{U_N}{N_{a1} + \sum N_{ai}} \quad (20.45)$$

where

A_N is nitrogen limiting application rate in tonne/ha/yr (ton/acre/yr)

U_N is the amount of nitrogen needed by the crop in kg/ha/yr (lb/acre/yr)

$\sum N_{ai}$ is the sum of mineralized nitrogen available from applications in previous years in kg/tonne (lb/ton), $i = 2$ to n

The loading rates are determined based on the dry solids content of the sludge. Then, using the concentration of solids in the sludge, the application rate is converted to a volumetric basis.

In the United States, septage, which is the solids accumulated in septic tanks, is not regulated as sewage sludge. Sampling and testing septage, which is usually collected by small operations (one to three or four trucks), is impractical. These septage disposal firms are widely distributed throughout rural areas. The pollutant limiting septage application is nitrogen. The maximum application rate on a volumetric basis for septage based on data from nitrogen concentrations in septage and using the above principles is

$$A_{NV} = K U_N \quad (20.46)$$

where

A_{NV} is volumetric application rate of liquid sludge, m³/ha/yr (Mgal/acre/yr)

$K = 3.2 \times 10^6$ (SI); $K = 385$ (U.S.)

U_N is in kg/ha/yr (lb/acre/yr)

There are other regulations on the land application of septage.

MAF and MOE (1992) suggest that 40% of the acid-soluble phosphorus in the sludge will be available to plants as fertilizer. Metcalf and Eddy (1991) suggest that 50% of the total phosphorus in the sludge is normally assumed to be available to plants. If phosphorus control is specified, an equation similar to Eq. (20.45) is used to find the maximum application rate.

$$A_P = \frac{U_P}{C_P P} \quad (20.47)$$

where

A_P is phosphorus limiting application rate in tonne/ha/yr (ton/acre/yr)

U_P is the amount of phosphorus needed by the crop in kg/ha/yr (lb/acre/yr)

C_P is the availability of phosphorus in the sludge in kg/kg (lb/lb)

P is the total phosphorus content of the sludge in kg/tonne (lb/ton) dry solids

The lowest application rate calculated for any constituent specified in the local regulations is the design application rate.

■ Example 20.4 Land Application of Sludge

Determine the allowable application rate based on the nitrogen constraint of raw sludge with a nitrogen content as follows: NO_3^- -N, 10 g/kg; NH_3 , 0; and N_o , 20 g/kg to agricultural land where the crops will take up 100 kg/ha of nitrogen during each year over a 3-yr period. The sludge will be applied below the ground surface. What is the volumetric application rate in the third year if the sludge concentration is 10%?

$$\text{NO}_3^- \text{-N} = 10 \text{ g}/1000 \text{ g} = 0.010 \quad N_o = 20 \text{ g}/1000 \text{ g} = 0.020$$

The nitrogen available during the first year from application of sludge is

$$N_{a1} = k_c[(\text{NO}_3^-) + k_v(\text{NH}_3) + f_m N_o] = (1000)[0.010 + 0.40(0.020)] = 18 \text{ kg/tonne}$$

$$U_N = 100 \text{ kg/ha}$$

During the first year:

$$A_{N1} = \frac{U_N}{N_{a1} + \sum N_{ai}} = \frac{100 \text{ kg/ha}}{18 \text{ kg/tonne}} = 5.56 \text{ tonne/ha}$$

The organic nitrogen remaining after the first year is

$$N_{o1} = N_o - f_1 N_o = (1000)[0.020 - 0.40(0.020)] = 12 \text{ kg/tonne}$$

The nitrogen available during the second year from the first application is

$$N_{a2} = f_2 N_{o1} = 0.20(12 \text{ kg/tonne}) = 2.4 \text{ kg/tonne}$$

The allowable application rate during the second year is

$$A_{N2} = \frac{U_N}{N_{a1} + \sum N_{ai}} = \frac{100}{18 + 2.4} = 4.90 \text{ tonne/ha}$$

The nitrogen remaining from the first sludge application is now

$$N_{o2} = N_1 - f_2 N_1 = (1000)[0.012 - 0.20(0.012)] = 9.60 \text{ kg/tonne}$$

The nitrogen released from this sludge is

$$N_{a3} = f_3 N_{o2} = 0.10(9.60 \text{ kg/tonne}) = 0.96 \text{ kg/tonne}$$

The sludge was applied at a lower rate during the second year and the nitrogen release rate from it must be reduced by the ratio of the application rates to determine an effective release rate.

$$N_{a2} = (4.90/5.56)(2.4 \text{ kg/tonne}) = 2.12 \text{ kg/tonne}$$

$$A_{N3} = \frac{100}{18 + 2.12 + 0.96} = 4.74 \text{ tonne/ha}$$

The solids concentration in the sludge is 10%. From Fig. 20.2, 1 kg of solids will occupy 9.7 L. The volume of sludge applied during the third year is

$$A_{NV} = \left(\frac{4.74 \text{ tonne}}{\text{ha-yr}} \right) \left(\frac{1000 \text{ kg}}{\text{tonne}} \right) \left(\frac{9.7 \text{ L}}{\text{kg}} \right) \left(\frac{\text{m}^3}{1000 \text{ L}} \right) = 46.0 \text{ m}^3/\text{ha}/\text{yr}$$

QUESTIONS AND PROBLEMS

- What are the s.g. and volume of 1 kg of a sludge that has a solids content of 3.5% and contains 70% VSS and 30% FSS? Assume that FSS have an s.g. of 1.75.
- If lime dosage at 150 kg/tonne (300 lb/ton) of dry solids produces a dewatered cake with a solids concentration of 20% for a sludge flow rate of 380 m³/d (0.100 Mgal/d) with a solids concentration of 2.5%, what is the volume of cake to be disposed on a daily basis? Assume that the lime produces 2.0 mg of precipitate per mg of lime added.
 - Answer the same question for a polymer dose of 1 kg/tonne (2.0 lb/ton) that produces a cake with a solids concentration of 25% and compare the result to (a). Assume that the polymer produces 1.50 mg of precipitate per mg of polymer added.
- What are the s.g. and volume of 100 kg of a 40% solids biological sludge with a VSS:FSS ratio of 80:20? Assume that the s.g. of FSS is 2.5. How many truckloads per month will be required for a plant that generates 120 kg/d of this sludge dewatered to a solids content of 40% if the capacity of the truck is 4.0 m³?
- List wastewater operations that can be used to increase the concentration of sludge.
- What are the hydraulic retention times required to reduce the biodegradable content of a sludge by 90% using aerobic sludge digestion when the k_d values are 0.15 and 0.30 d⁻¹? A continuous flow CM basin will be used.
 - What are the times required to achieve the same amount of reduction in a batch process if the batch k_d rate constants are one half of the values given in part (a)?
- Use the data in Table 20.6 and assume that the degradable VSS is 55% of influent VSS. Ignore solubilization.
 - What is the ratio of effluent VSS to influent VSS in a continuous flow reactor (assume that semicontinuous flow and continuous flow are the same) operating at a sludge age of 20 d for temperatures of 10 and 30°C?
 - Answer the same question for a batch system at the same sludge age and temperatures.
- In Fig. P1 a plot of VSS concentration remaining over time from a batch aerobic digestion laboratory study is shown. Assuming that the batch study kinetics are applicable to a continuous flow CM reactor, size a continuous flow CM reactor to remove 80% of the degradable VSS when the influent VSS is 10 000 mg/L and the flow rate is 500 m³/d (0.132 Mgal/d). Base your analysis on the overall observed "endogenous" decay.

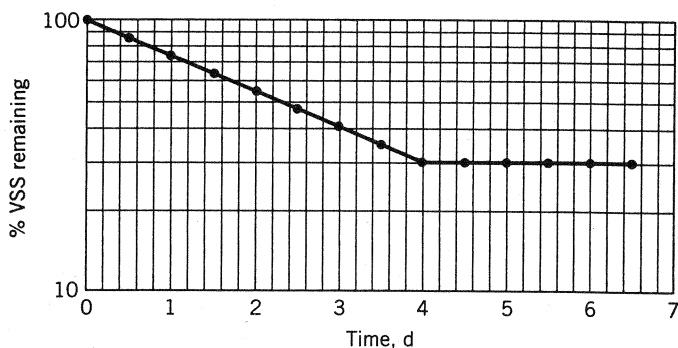


Figure P1 VSS remaining in batch aerobic digestion.