ADDITIONAL INFORMATION FOR KY-TN WPC WEBINAR – AEROBIC DIGESTION

For additional information about Pathogen Reduction and Vector Attraction Reduction Criteria, see the EPA White House Manual – this is a key document in understanding what is, and is not, allowed under the 503 Rules.

https://www.epa.gov/sites/production/files/2015-04/documents/control_of_pathogens_and_vector_attraction_in_sewage_sludge_july_2003.pdf

Make sure you are using the 2003 version – older versions contain errors.

PATHOGEN REDUCTION REQUIREMENTS:

PFRP – Process to Further Reduce Pathogens: Intended to reduce pathogen densities to below detectable limits, which are:

Salmonella sp.	Less than 3 MPN per 4 grams total solids (dry weight basis)
Enteric viruses	Less than 1 PFU per 4 grams total solids (dry weight basis)
Viable helminth ova	Less than 1 viable helminth ova per 4 gram total solids (dry weight basis)

EPA Definitions for Class A Biosolids: (From EPA Manual - *Control of Pathogens and Vector Attraction in Sewage Sludge* aka White House Manual)

EPA Alternative 5: Use of PFRP [503.32(a)(7)]

The Part 503 PFRP description of thermophilic aerobic digestion is:

- Liquid sewage sludge is agitated with air or oxygen to maintain aerobic conditions and the mean cell residence time of the sewage sludge is 10 consecutive days at 55°C to 60°C (131°F to 140°F).

EPA Alternative 6: Use of a Process Equivalent to PFRP [503.32(a)(8)]

PFRP-Equivalent Process of Autothermal thermophilic aerobic digestion:

- ATAD is a two-stage, autothermal aerobic digestion process. The stages are of equal volume. Treated sludge amounting to 1/3 the volume of a stage is removed every 24 hours from the second stage as product. An equal amount then is taken from the first stage and fed to the second stage. Similarly, an equal amount of untreated sludge is then fed to the first stage. In the 24-hour period between feedings, the sludge in both stages is vigorously agitated and contacted with air. Bio-oxidation takes place and the heat produced increases the temperature. Sludge temperature in the reactors averages between 56 and 57°C for ≥ a 16-hour period, while the overall hydraulic residence time is 6 days.

EPA Alternative 1: Thermally Treated Sewage Sludge [503.32(a)(3)]

(From EPA Manual - *Control of Pathogens and Vector Attraction in Sewage Sludge* aka White House Manual)

This alternative may be used when the pathogen reduction process uses specific time-temperature regimes to reduce pathogens. Under these circumstances, time-consuming and expensive tests for the presence of specific pathogens can be avoided. It is only necessary to demonstrate that:

- Either fecal coliform densities are below 1,000 MPN per gram of total solids (dry weight basis), or Salmonella sp. bacteria are below detection limits (3 MPN per 4 grams total solids [dry weight basis]) at the time the sewage sludge is used or disposed, at the time the sewage sludge is prepared for sale or given away in a bag or other container for land application, or at the time the sewage sludge or material derived from the sewage sludge is prepared to meet the requirements in 503.10(b), 503.10(c), 503.10(e), or 503.10(f).
- And the required time-temperature regimes are met.

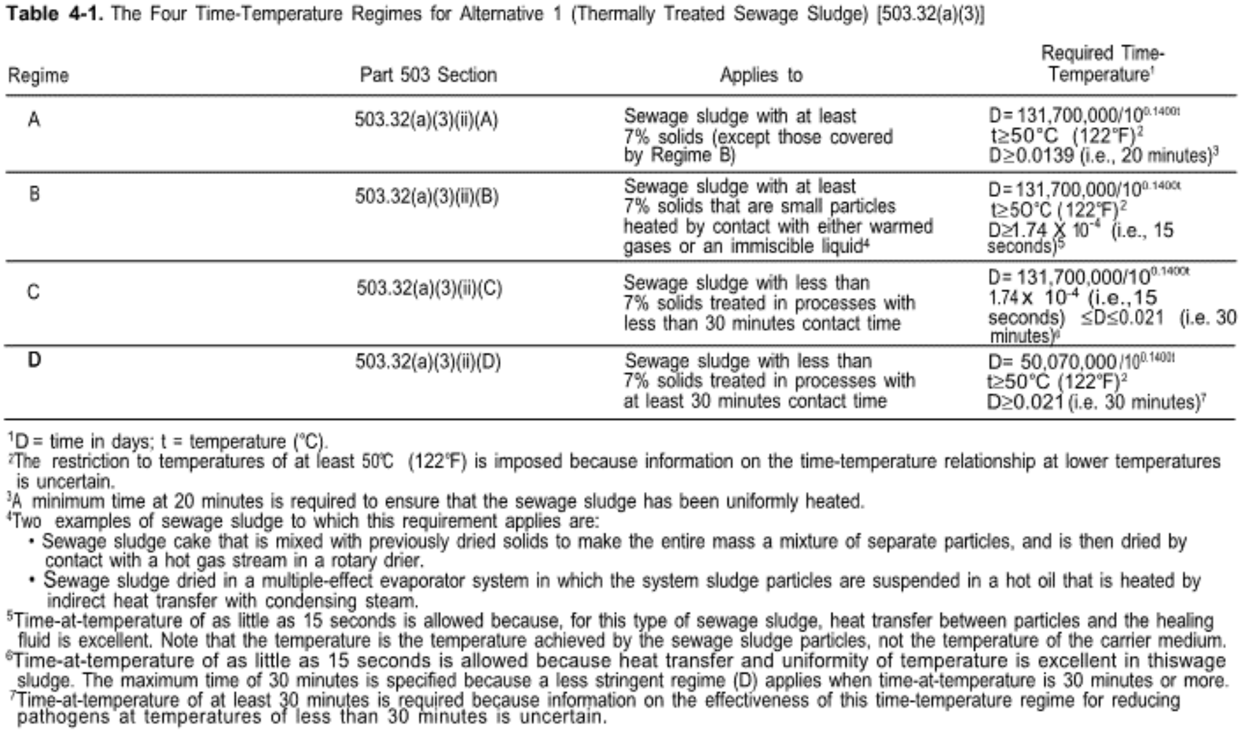


Table 4-1. The Four Time-Temperature Regimes for Alternative 1 (Thermally Treated Sewage Sludge) [503.32(a)(3)]

Regime	Part 503 Section	Applies to	Required Time-Temperature[1]
A	503.32(a)(3)(ii)(A)	Sewage sludge with at least 7% solids (except those covered by Regime B)	$D = 131{,}700{,}000/10^{0.1400t}$ $t \geq 50$°C (122°F)[2] $D \geq 0.0139$ (i.e., 20 minutes)[3]
B	503.32(a)(3)(ii)(B)	Sewage sludge with at least 7% solids that are small particles heated by contact with either warmed gases or an immiscible liquid[4]	$D = 131{,}700{,}000/10^{0.1400t}$ $t \geq 50$°C (122°F)[2] $D \geq 1.74 \times 10^{-4}$ (i.e., 15 seconds)[5]
C	503.32(a)(3)(ii)(C)	Sewage sludge with less than 7% solids treated in processes with less than 30 minutes contact time	$D = 131{,}700{,}000/10^{0.1400t}$ 1.74×10^{-4} (i.e.,15 seconds) $\leq D \leq 0.021$ (i.e. 30 minutes)[6]
D	503.32(a)(3)(ii)(D)	Sewage sludge with less than 7% solids treated in processes with at least 30 minutes contact time	$D = 50{,}070{,}000/10^{0.1400t}$ $t \geq 50$°C (122°F)[2] $D \geq 0.021$ (i.e. 30 minutes)[7]

[1] D = time in days; t = temperature (°C).

[2] The restriction to temperatures of at least 50°C (122°F) is imposed because information on the time-temperature relationship at lower temperatures is uncertain.

[3] A minimum time at 20 minutes is required to ensure that the sewage sludge has been uniformly heated.

[4] Two examples of sewage sludge to which this requirement applies are:
- Sewage sludge cake that is mixed with previously dried solids to make the entire mass a mixture of separate particles, and is then dried by contact with a hot gas stream in a rotary drier.
- Sewage sludge dried in a multiple-effect evaporator system in which the system sludge particles are suspended in a hot oil that is heated by indirect heat transfer with condensing steam.

[5] Time-at-temperature of as little as 15 seconds is allowed because, for this type of sewage sludge, heat transfer between particles and the healing fluid is excellent. Note that the temperature is the temperature achieved by the sewage sludge particles, not the temperature of the carrier medium.

[6] Time-at-temperature of as little as 15 seconds is allowed because heat transfer and uniformity of temperature is excellent in thiswage sludge. The maximum time of 30 minutes is specified because a less stringent regime (D) applies when time-at-temperature is 30 minutes or more.

[7] Time-at-temperature of at least 30 minutes is required because information on the effectiveness of this time-temperature regime for reducing pathogens at temperatures of less than 30 minutes is uncertain.

Regime D is applicable to thermophilic aerobic digesters (whether autothermal or externally-heated).

PSRP – Process to Significantly Reduce Pathogens: Process that reduces fecal coliform densities to less than 2 million CFU or MPN per gram of total solids (dry weight basis) and reduces *Salmonella* sp. and enteric virus densities in sludge by approximately a factor of 10.

Class B Sewage Sludge Alternative 1: Monitoring of Fecal Coliform [503.32(b)(2)]

Alternative 1 requires that seven samples of treated sewage sludge (biosolids) be collected and that the geometric mean fecal coliform density of these samples be less than 2 million CFU or MPN per gram of biosolids (dry weight basis). This approach uses fecal coliform density as an indicator of the average density of bacterial and viral pathogens. Over the long term, fecal coliform density is expected to correlate with bacterial and viral pathogen density in biosolids treated by biological treatment processes (EPA, 1992).

Class B Sewage Sludge Alternative 2: Use of a Process to Significantly Reduce Pathogens (PSRPs) [503.32(b)(3)]

The PSRP Class B alternative provides continuity with the 40 CFR Part 257 regulation. Under this Alternative, treated sewage sludge (biosolids) is considered to be Class B if it is treated in one of the "Processes to Significantly Reduce Pathogens" (PSRPs) listed in Appendix B of Part 503. The biological PSRP processes are sewage sludge treatment processes that have been demonstrated to result in a 2-log reduction in fecal coliform density.

Class B Sewage Sludge Alternative 4: Sewage Sludge Treated in Unknown Processes [503.32(a)(6)]

The sewage sludge must meet the following limits at the time the biosolids (or material derived from sludge) are used or disposed, at the time the sewage sludge is prepared for sale or given away in a bag or other container for land application, or at the time the sewage sludge or material derived from the sewage sludge is prepared to meet the requirements in 503.10(b), 503.10(c), 503.10(e), or 503.10(f):

- The density of enteric viruses in the sewage sludge must be less than 1 PFU per 4 grams of total solids (dry weight basis).

- The density of viable helminth ova in the sewage sludge must be less than 1 per 4 grams of total solids (dry weight basis).

In addition, as for all Class A biosolids, the sewage sludge must meet fecal coliform or Salmonella sp. limits.

VECTOR ATTRACTION REDUCTION CRITERIA

From White House Manual:

Vectors – any living organism capable of transmitting a pathogen from one organism to another either mechanically (by simply transporting the pathogen) or biologically by playing a specific role in the life cycle of the pathogen.

Typical Vectors – Birds, rodents, insects

Vector Attraction Reduction is accomplished by employing one of the following:

- Biological processes which breakdown volatile solids
- Chemical or physical conditions which stop microbial activity
- Physical barriers between vectors and volatile solids in the sewage sludge

EPA Identifies 12 specific vector attraction reduction options. Options 9 and 10 occur at time of disposal and are related to incorporating biosolids into the soil. Option 11 relates to surface disposal sites (i.e., landfills). Option 12 is strictly for septage. Of the remaining 8 options, 3 are pertinent to aerobic digestion without drying or alkaline addition.

(From EPA Manual - *Control of Pathogens and Vector Attraction in Sewage Sludge* aka White House Manual)

Option 1: Reduction in Volatile Solids Content [503.33(b)(1)]

> This option is intended for use with biological treatment systems only. Under Option 1, reduction of vector attraction is achieved if the mass of volatile solids in the sewage sludge is reduced by at least 38%. This is the percentage of volatile solids reduction that can generally be attained by the "good practice" recommended conditions for anaerobic digestion of 15 days residence time at 35°C [95°F] in a completely mixed high-rate digester. The percent volatile solids reduction can include any additional volatile solids reduction that occurs before the biosolids leave the treatment works, such as might occur when the sewage sludge is processed on drying beds or in lagoons.
>
> The starting point for measuring volatile solids in sewage sludge is at the point at which sewage sludge enters a sewage sludge treatment process.

Option 3: Additional Digestion of Aerobically Digested Sewage Sludge [503.33(b)(3)]

> Under this option, an aerobically digested sewage sludge with 2% or less solids is considered to have achieved satisfactory vector attraction reduction if it loses less than 15% additional volatile solids when it is aerobically batch-digested in the laboratory in a bench-scale unit at 20°C (68°F) for an additional 30 days. Procedures for this test and the method for calculating additional volatile solids destruction are presented in Appendix D. The test can be run on sewage sludges up to 2% solids and does not require a temperature correction for sewage sludges not initially digested at 20°C (68°F). Liquid sludges with greater than 2% solids can be diluted to 2% solids with unchlorinated effluent, and the test can then be run on the diluted sludge. This option should not be used for non-liquid sewage sludge such as dewatered cake or compost.

Option 4: Specific Oxygen Uptake Rate (SOUR) for Aerobically Digested Sewage Sludge [503.33(b)(4)]

> For an aerobically digested sewage sludge with a total solids content equal to or less than 2% which has been processed at a temperature between 10°- 30°C, reduction in vector attraction can also be demonstrated using the SOUR test. The SOUR of the sewage sludge to be used or disposed must be less than or equal to 1.5 mg of oxygen per hour per gram of total sewage sludge solids (dry weight basis) at 20°C (68°F).
>
> SOUR cannot be applied to sewage sludges digested outside the 10-30°C range (50-86°F). The actual temperature of the sewage sludge tested cannot be adjusted because temperature changes can cause short-term instability in the oxygen uptake

rate (Benedict, et al. (1973); Farrell, et al. [1996]), and this would invalidate the results of the test.

Calculating Volatile Solids Reduction – Option 1

Approximate Mass Balance Method

(From EPA Manual - *Control of Pathogens and Vector Attraction in Sewage Sludge)*

If volumetric inputs and outputs are relatively constant on a daily basis, and there is no substantial accumulation of volatile solids in the digester over the time period of the test, an approximate mass balance (AMB) may be used.

The basic relationship is stated simply:

volatile solids input rate = volatile solids output rate + rate of loss of volatile solids. (1)

The FVSR is given by Equation 2.

$$\text{FVSR} = \frac{\text{loss in volatile solids}}{\text{sum of volatile solids inputs}} \qquad (2)$$

The input and output volatile solids concentrations (Y_f and Y_b) typically will show greater coefficients of variation (standard deviation divided by arithmetic average) than the fractional volatile solids (VS is the fraction of the sewage sludge solids that is volatile-note the difference between VS and Y). If this is the case, the volatile solids reduction calculated by the approximate mass balance method from several sets of Y_f-Y_b data will show larger deviations than if it were calculated by the Van Kleeck equation using VSf -VSb data.

Grit deposition can be a serious problem in both aerobic and anaerobic digestion. The biological processes that occur in digestion dissolve or destroy the substances suspending the grit, and it tends to settle. If agitation is inadequate to keep the grit particles in suspension, they will accumulate in the digester. The approximate mass balance can be used to estimate accumulation of fixed solids.

$$F^*X_f = B^*X_b + \text{fixed solids loss} \qquad (3)$$

The material balance compares fixed solids in output with input. If some fixed solids are missing, this loss term will be a positive number. Because digestion does not consume fixed solids, it is assumed that the fixed solids are accumulating in the digester.

The following design example shows how to calculate VS destruction for 4 different cases, using both the Approximate Mass Balance method and (where appropriate) the Van Kleeck method. This example is based on the information contained in the EPA Control of Pathogens Manual. For the design parameters, see the Table below:

USCS Values			Problem Statement Number			
Parameter	Symbol	Units	1	2	3	4
Nominal Residence Time	θ	days	20	20	20	20
Time period for averages		days	60	60	60	60
Feed Sludge						
Volumetric Flow Rate	F	gpd	265,000	265,000	265,000	265,000
Volatile Solids Conc.	Yf	mg/L	5000	5000	5000	5000
Fixed Solids Concentration	Xf	mg/L	1700	1700	1700	1700
Fractional Volatile Solids	VS_f	lb/lb	0.746	0.746	0.746	0.746
Mass flow rate of solids	M_f	lb/d	14,800	14,800	14,800	14,800
Digested Biosolids (bottoms)						
Volumetric flow rate	B	gpd	265,000	265,000	Solve for	131,350
Volatile solids conc.	Yb	mg/L	3000	3000	4150	4150
Fixed solids concentration	Xb	mg/L	1700	1500	2350	2350
Fractional volatile solids	VS_b	lb/lb	0.638	0.667	0.638	0.638
Mass flow rate of solids	M_b	lb/d	10,400	9,950		
Decantate						
Volumetric flow rate	D	gpd	0	0	Solve for	133,650
Volatile solids conc.	Yd	mg/L	---	---	1300	1300
Fixed solids concentration	Xd	mg/L	---	---	725	725
Fractional volatile solids	VS_d	lb/lb	---	---	0.642	0.642
Mass flow rate of solids	M_d	lb/d	---	---		

SI Units			Problem Statement Number			
Parameter	Symbol	Units	1	2	3	4
Nominal Residence Time	θ	days	20	20	20	20

Time period for averages		days	60	60	60	60
Feed Sludge						
Volumetric Flow Rate	F	m^3/d	1000	1000	1000	1000
Volatile Solids Conc.	Y_f	kg/m^3	5.0	5.0	5.0	5.0
Fixed Solids Concentration	X_f	kg/m^3	1.7	1.7	1.7	1.7
Fractional Volatile Solids	VS_f	kg/kg	0.746	0.746	0.746	0.746
Mass flow rate of solids	M_f	kg/d	6700	6700	6700	6700
Digested Biosolids (bottoms)						
Volumetric flow rate	B	m^3/d	1000	1000	Solve for	495.7
Volatile solids conc.	Y_b	kg/m^3	3.0	3.0	4.14	4.14
Fixed solids concentration	X_b	kg/m^3	1.7	1.0	2.35	2.35
Fractional volatile solids	VS_b	kg/kg	0.638	0.667	0.638	0.638
Mass flow rate of solids	M_b	kg/d	4700	4500		
Decantate						
Volumetric flow rate	D	m^3/d	0	0	Solve for	504.3
Volatile solids conc.	Y_d	kg/m^3	---	---	1.28	1.28
Fixed solids concentration	X_d	kg/m^3	---	---	0.72	0.72
Fractional volatile solids	VS_d	kg/kg	---	---	0.64	0.64
Mass flow rate of solids	M_d		---	---		

Problem 1 – No Decantate, No Grit Accumulation (USCS)

$F*Y_f = B*Y_b + \text{loss}$
$\text{Loss} = F*Y_f - B*Y_b$
$= [(265{,}000\text{ gpd})(5000\text{ mg/L})-(265{,}000\text{ gpd})(3000\text{ mg/L})]*(10^{-6})*(8.34)$
$= 4420\text{ lb/d}$

$$\text{FVSR} = \frac{\text{Loss}}{F*Y_f}$$

$$= \frac{4420\text{ lb/d}}{(265{,}000\text{ gpd})(5000\text{ mg/L})(10^{-6})(8.34)}$$

$= 0.40$

To estimate the fixed solids loss, the mass balance can be written as follows:
$F*X_f = B*X_b + \text{fixed solids loss}$

Fixed Solids Loss = $F*X_f - B*X_b$

= $(265{,}000\text{ gpd})(1700\text{ mg/L}) - (265{,}000\text{ gpd})(1700\text{ mg/L})(10^{-6})(8.34)$

= 0

Using the Van Kleeck Equation

$$FVSR = \frac{VS_f - VS_b}{VS_f - (Vs_f * Vs_b)}$$

$$= \frac{0.746 - 0.638}{0.746 - (0.746 * 0.638)}$$

$$= 0.40$$

The Van Kleeck Equation and the Approximate Mass Balance produce the same results.

Problem 1 - No Decantate, No Grit Accumulation (SI)

$F*Y_f$ = $B*Y_b$ + loss

Loss = $F*Y_f - B*Y_b$

= $(1000\text{ m}^3\text{/d})(5.0\text{ kg/m}^3)-(1000\text{ m}^3\text{/d})(3.0\text{ kg/m}^3)$

= 2000 kg /d

$$FVSR = \frac{\text{Loss}}{F*Y_f}$$

$$= \frac{2000\text{ kg/d}}{(1000\text{ m}^3\text{/d})(5.0\text{ kg/m}^3)}$$

$$= 0.40$$

To estimate the fixed solids loss, the mass balance can be written as follows:

$F*X_f$ = $B*X_b$ + fixed solids loss

Fixed Solids Loss = $F*X_f - B*X_b$

= $(1000\text{ m}^3\text{/d})(1.7\text{ kg/m}^3) - (1000\text{ m}^3\text{/d})(1.7\text{ kg/m}^3)$

= 0

Using the Van Kleeck Equation

$$FVSR = \frac{VS_f - VS_b}{VS_f - (Vs_f * Vs_b)}$$

$$= \frac{0.746 - 0.638}{0.746 - (0.746 * 0.638)}$$

$$= 0.40$$

The Van Kleeck Equation and the Approximate Mass Balance produce the same results.

Problem 2 – No Decantate, Grit Accumulation (USCS)

$F*X_f$ = $B*X_b$ + fixed solids loss

Fixed Solids Loss = $F*X_f - B*X_b$

= $[(265{,}000\text{ gpd})(1700\text{ mg/L}) - (256{,}000\text{ gpd})(1500\text{ mg/L})]*(10^{-6})*(8.34)$

= 427 lb/d

$F*Y_f$ = $B*Y_b$ + loss

Loss = $F*Y_f - B*Y_b$

= $[(265{,}000\text{ gpd})(5000\text{ mg/L})-(265{,}000\text{ gpd})(3000\text{ mg/L})]*(10^{-6})*(8.34)$

= 4420 lb/day

$$FVSR = \frac{\text{Loss}}{F*Y_f}$$

$$= \frac{4420\text{ lb/d}}{(265{,}000\text{ gpd})(5000\text{ mg/L})(10^{-6})(8.34)}$$

= 0.40

Using the Van Kleeck Equation

$$FVSR = \frac{VS_f - VS_b}{VS_f - (Vs_f * Vs_b)}$$

$$= \frac{0.746 - 0.667}{0.746 - (0.746*0.667)}$$

= 0.318

The Van Kleeck Equation and the Approximate Mass Balance <u>do not</u> produce the same results.

Problem 2 - No Decantate, Grit Accumulation (SI)

$F*X_f$ = $B*X_b$ + fixed solids loss

Fixed Solids Loss = $F*X_f - B*X_b$

= (1000 m^3/d)(1.7 kg/m^3) – (1000 m^3/d)(1.5 kg/m^3)

= 200 kg/d

$F*Y_f$ = $B*Y_b$ + loss

Loss = $F*Y_f - B*Y_b$

= (1000 m^3/d)(5.0 kg/m^3)-(1000 m^3/d)(3.0 kg/m^3)

= 2000 kg /d

$$FVSR = \frac{Loss}{F*Y_f}$$

$$= \frac{2000 \text{ kg/d}}{(1000 \text{ m}^3\text{/d})(5.0 \text{ kg/m}^3)}$$

= 0.40

Using the Van Kleeck Equation

$$FVSR = \frac{VS_f - VS_b}{VS_f - (Vs_f * Vs_b)}$$

$$= \frac{0.746 - 0.667}{0.746 - (0.746 * 0.667)}$$

$$= 0.318$$

The Van Kleeck Equation and the Approximate Mass Balance do not produce the same results.

Problem 3 – Decant Withdrawal, No Grit Accumulation (USCS)

Volume Balance:

$F = B + D$

$265{,}000 \text{ gpd} = B + D$

$B = 265{,}000 - D$

Fixed Solids Balance:

$F * X_f = B * X_b + D * X_d$

Substituting 265,000-D for B

$F * X_f = (265{,}000 - D) * X_b + D * X_d$

$(265{,}000 \text{ gpd})(1700 \text{ mg/L})(10^{-6})(8.34) = [(265{,}000 - D \text{ gpd})(2350 \text{ mg/L}) + (D \text{ gpd})(725 \text{ mg/L})] (10^{-6})(8.34)$

$D = 106{,}000 \text{ gpd}$

$B = 159{,}000 \text{ gpd}$

$F * Y_f = B * Y_b + D * Y_d + \text{loss}$

$$FVSR = \frac{\text{loss}}{FY_f} = \frac{F * Y_f - B * Y_b - DY_d}{F * Y_f}$$

$$= \frac{(265{,}000 \text{ gpd})(5000 \text{ mg/L}) - (159{,}000 \text{ gpd})(4142 \text{ mg/L}) - (106{,}000 \text{ gpd})(1276 \text{ mg/L})}{(265{,}000 \text{ gpd})(5000 \text{ mg/L})}$$

$$= 0.40$$

Using the Van Kleeck Equation:

$$FVSR = \frac{VS_f - VS_b}{VS_f - (Vs_f * Vs_b)}$$

$$= \frac{0.746 - 0.638}{0.746 - (0.746 * 0.638)}$$

$$= 0.40$$

The Van Kleeck Equation and the Approximate Mass Balance produce the same results.

Problem 3 – Decant Withdrawal, No Grit Accumulation (SI)

Volume Balance:

$F = B + D$
$1000\ m^3/d = B + D$
$B = 1000 - D$

Fixed Solids Balance:

$F*X_f = B*X_b + D*X_d$
Substituting 1000 - D for B
$F*X_f = (1000-D)*X_b + D*X_d$
$(1000\ m^3)(1.7\ kg/m^3) = (1000-D\ m^3/d)(2.35\ kg/m^3) + (D\ m^3/d)(0.72\ kg/m^3)$
$D = 400.0\ m^3/d$
$B = 600.0\ m^3/d$
$F*Y_f = B*Yb + D*Yd + loss$

$$FVSR = \frac{loss}{FY_f} = \frac{F*Y_f-B*Y_b-DY_d}{F*Y_f}$$

$$= \frac{(1000\ m^3/d)(5.0\ kg/m^3) - (600\ m^3/d)(4.14\ kg/m^3) - (400\ m^3/d)(1.276\ kg/m^3)}{(1000\ m^3/d)(5.0\ kg/m^3)}$$

$$= 0.40$$

Using the Van Kleeck Equation:

$$FVSR = \frac{VS_f - VS_b}{VS_f - (Vs_f*Vs_b)}$$

$$= \frac{0.746 - 0.638}{0.746 - (0.746*0.638)}$$

$$= 0.40$$

The Van Kleeck Equation and the Approximate Mass Balance produce the same results.

Problem 4 – Decant Withdrawal, Grit Accumulation (USCS)

For this situation, the values of B and D must be measured. These values are provided in the table above.

For this case,

$$FVSR = \frac{loss}{FY_f} = \frac{F^*Y_f - B^*Y_b - D^*Y_d}{F^*Y_f}$$

$$= \frac{(100\ m^3/d)(50\ kg/m^3) - (49.57\ m^3/d)(41.42\ kg/m^3) - (50.43\ m^3/d)(7.24\ kg/m^3)}{(100\ m^3/d)(50\ kg/m^3)}$$

$$= 0.461$$

The Fixed Solids Loss can be calculated as follows:

$$F^*X_f = B^*X_b + D^*X_d + \text{Fixed Solids Loss}$$

$$\frac{\text{Fixed Solids Loss}}{F^*X_f} = \frac{F^*X_f - B^*X_b - D^*Xd}{F^*X_f}$$

$$= \frac{(100\ m^3/d)(17\ kg/m^3) - (49.57\ m^3/d)(2.35\ kg/m^3) - (50.43\ m^3/d)(7.24\ kg/m^3)}{(100\ m^3/d)(17\ kg/m^3)}$$

$$= 0.10$$

Using the Van Kleeck Equation

$$FVSR = \frac{VS_f - VS_b}{VS_f - (Vs_f^*Vs_b)}$$

$$= \frac{0.746 - 0.638}{0.746 - (0.746^*0.638)}$$

$$= 0.40$$

The Van Kleeck Equation and the Approximate Mass Balance <u>do not</u> produce the same results.

Problem 4 – Decant Withdrawal, Grit Accumulation (SI)

For this situation, the values of B and D must be measured. These values are provided in the table above.

For this case,

$$FVSR = \frac{loss}{FY_f} = \frac{F^*Y_f - B^*Y_b - D^*Y_d}{F^*Y_f}$$

$$= \frac{(1000\ m^3/d)(5.0\ kg/m^3) - (495.7\ m^3/d)(4.14\ kg/m^3) - (504.3\ m^3/d)(1.28\ kg/m^3)}{(1000\ m^3/d)(5.0\ kg/m^3)}$$

$$= 0.461$$

The Fixed Solids Loss can be calculated as follows:

$$F^*X_f = B^*X_b + D^*X_d + \text{Fixed Solids Loss}$$

$$\frac{\text{Fixed Solids Loss}}{F^*X_f} = \frac{F^*X_f - B^*X_b - D^*X_d}{F^*X_f}$$

$$= \frac{(1000\ m^3/d)(1.7\ kg/m^3) - (495.7\ m^3/d)(2.35\ kg/m^3) - (504.3\ m^3/d)(0.72\ kg/m^3)}{(1000\ m^3/d)(1.7\ kg/m^3)}$$

$$= 0.10$$

Using the Van Kleeck Equation

$$FVSR = \frac{VS_f - VS_b}{VS_f - (Vs_f * Vs_b)}$$

$$= \frac{0.746 - 0.638}{0.746 - (0.746*0.638)}$$

$$= 0.40$$

The Van Kleeck Equation and the Approximate Mass Balance do not produce the same results.

Therefore, the Van Kleeck equation is suitable when there is no grit accumulation. Otherwise, the approximate mass balance is more suitable.

NOTE:

If Option 3 is utilized because the biosolids do not meet Option 1 requirements, the calculation of the VSR must be made using the same method as was used for Option 1, i.e., if the VSR was calculated using the Van Kleeck equation for Option 1, the Van Kleeck equation must be used to calculate VSR after the additional 30 days.

SOLIDS RETENTION TIME

Key point to remember – detention times need to be maintained even under max conditions – typically either maximum month or maximum two weeks. If digester is sized for annual averages, it will potentially be undersized during peak events.

Regulatory Requirements

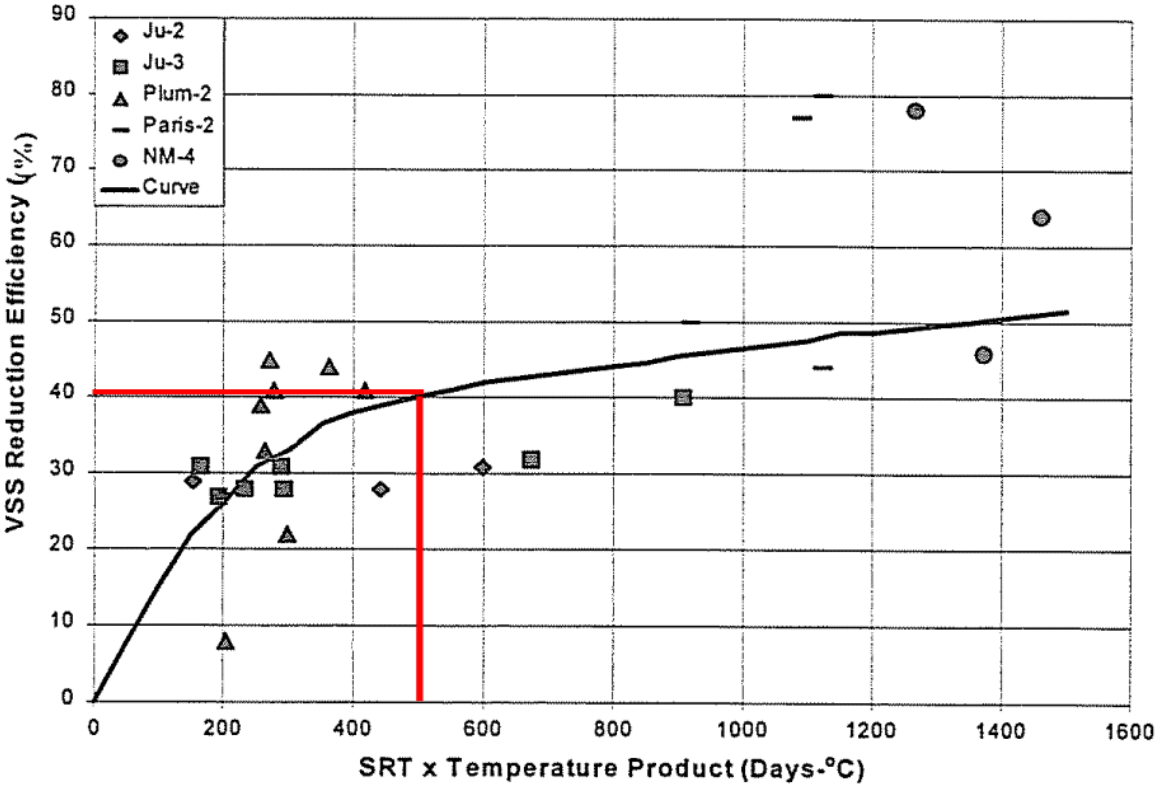
PSRP Definition – The PSRP description in Part 503 for aerobic digestion is:

- Sewage sludge is agitated with air or oxygen to maintain aerobic conditions for a specific mean cell residence time at a specific temperature. Values for the mean cell residence time and temperature shall be between 40 days at 20°C (68°F) and 60 days at 15°C (59°F). For temperatures between 15°C (59°F) and 20°C (68°F) use the relationship between time and temperature provided below to determine the required mean cell residence time.

  $$\frac{\text{Time @T°C}}{40\text{ d}} = 1.08^{(20-T)}$$

  The regulation does not differentiate between batch, intermittently fed, and continuous operation, so any method is acceptable. The mean cell residence time is considered the residence time of the sewage sludge solids.

Process Requirements:



The above graph from MOP 8 (originally by Daigger, et al) allows us to calculate the SRT required at differing temperatures for different levels of VSS reduction. For example:

To achieve a 40% VSS reduction, this graph indicates that the product of temperature (in degrees C) and the detention time (in days) should be 500.

At 20 degrees C, this would correlate to an SRT of roughly 25 days – this value is less than that required by the EPA for a PSRP aerobic digester and indicates that a properly operated aerobic digester meeting PSRP standards should also achieve sufficient VSS reduction to meet VAR criteria.

Similarly, at 10 degrees C, the SRT required to meet a 40% reduction in VSS would be 50 days. Again, this is less than the value required by EPA for a PSRP aerobic digester.

One key point is that the reaction rate slows significantly with temperature – if low wastewater temperatures are a factor, the aerobic digester will be significantly larger than a digester designed for 20 degrees C or greater temperatures.

Another key point is that the EPA does NOT define VAR criteria for aerobic digesters based on detention time. If a wastewater has significant amounts of refractory compounds, even extended digestion periods may not be sufficient to achieve the required VS reduction. In this case, alternative methods should be utilized to demonstrate vector attraction reduction criteria.

Reduction in SRT based on Multi-Stage Operation:

From Appendix E of EPA Manual:

> **Comments on Batch and Staged Operation**
>
> Sludge can be aerobically digested using a variety of process configurations (including continuously fed single-or multiple-stage completely mixed reactors), or it can be digested in a batch mode (batch operation may produce less volatile solids reduction for a primary sludge than the other options because there are lower numbers of aerobic microorganisms in it). Single-stage completely mixed reactors with continuous feed and withdrawal are the least effective of these options for bacterial and viral destruction, because organisms that have been exposed to the adverse condition of the digester for only a short time can leak through to the product sludge.
>
> Probably the most practical alternative to use of a single completely mixed reactor for aerobic digestion is staged operation, such as use of two or more completely mixed digesters in series. The amount of slightly processed sludge passing from inlet to outlet would be greatly reduced compared to single-stage operation. If the kinetics of the reduction in pathogen densities are known, it is possible to estimate how much improvement can be made by staged operation.
>
> Farrah et al. (1986) have shown that the declines in densities of enteric bacteria and viruses follow first-order kinetics. If first-order kinetics are assumed to be correct, it can be shown that a one-log reduction of organisms is achieved in half as much time in a two-stage reactor (equal volume in each stage) as in a one-stage reactor. Direct experimental verification of this prediction has not been carried out, but Lee et al. (1989) have qualitatively verified the effect.
>
> It is reasonable to give credit for an improved operating mode. Since not all factors involved in the decay of microorganisms' densities are known, some factor of safety should be introduced. It is recommended then that for staged operation using two stages of approximately equal volume, the time required be reduced to 70% of the

time required for single-stage aerobic digestion in a continuously mixed reactor. This allows a 30% reduction in time instead of the 50% estimated from theoretical considerations. The same reduction is recommended for batch operation or for more than two stages in series. Thus, the time required would be reduced from 40 days at 20°C (68°F) to 28 days at 20°C (68°F), and from 60 days at 15°C (59°F) to 42 days at 15°C (59°F). These reduced times are also more than sufficient to achieve adequate vector attraction reduction.

CALCULATING AERATION REQUIREMENTS

Oxygen Requirements:

Theoretical	1.5 kg O_2 per kg (1.5 lb O_2/lb) active cell mass (non-nitrifying system)
	2.0 kg O_2 per kg (2 lb O_2/lb) active cell mass (nitrifying system)
Practical	2.0 kg O_2 per kg (2 lb O_2/lb) active cell mass
	Plus additional oxygen for primary sludge, if present

What about multi-stage digesters?

First stage will have significantly more oxygen demand than subsequent stages. Several ways to calculate.

One way – Treat air flow requirements similar to those for plug flow aeration in MOP FD-5.

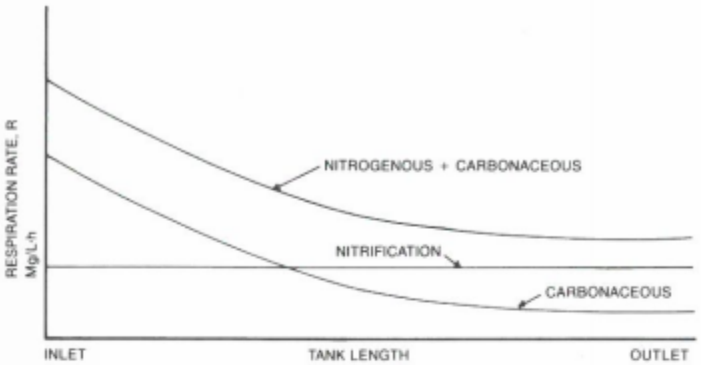
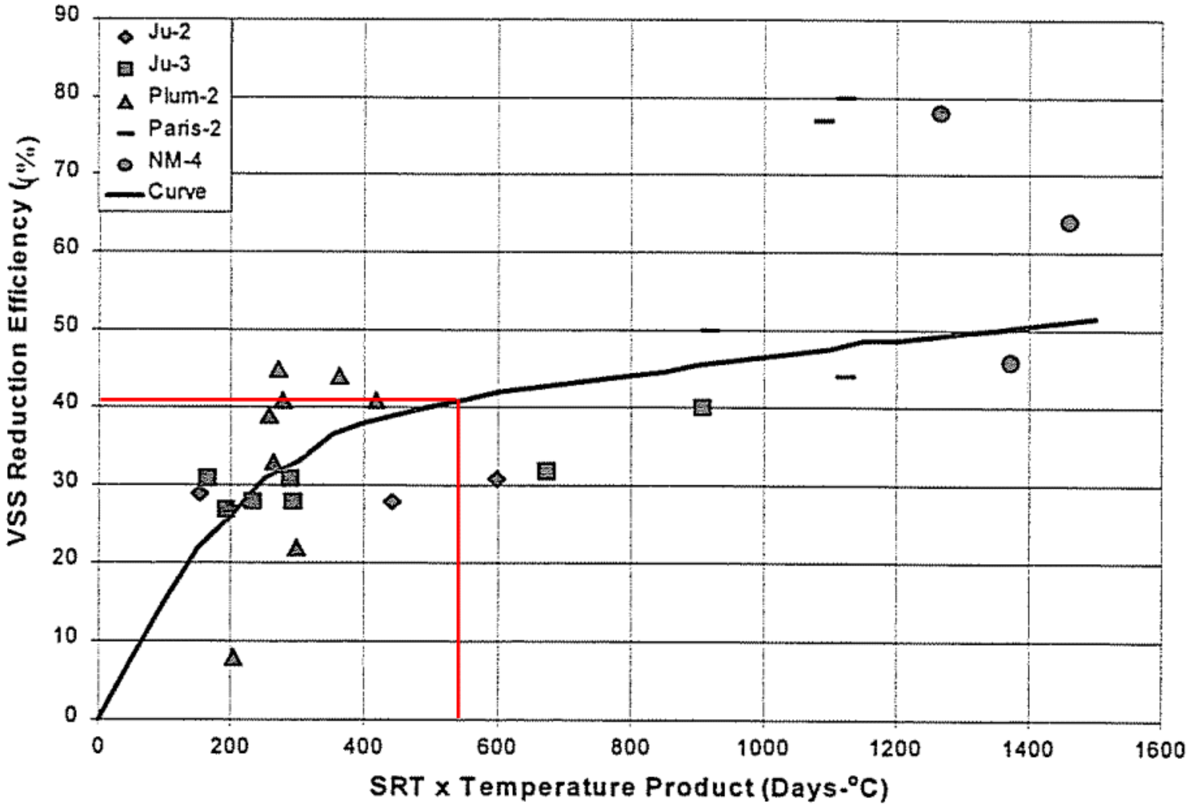


FIGURE 2.2—Typical Oxygen Uptake Curves for Plug Flow Aeration Tanks.

Table 2-1 Variation in Proportion of Oxygen Demand Along the Length of a Plug Flow Aeration Tank (L/W > 20) (12)

Proportion of Aeration Tank Volume (%)	CARBONACEOUS DEMAND		CARBONACEOUS + NITROGENOUS DEMAND	
	Proportion of Demand (%)	Diurnal Range (%)	Proportion of Demand (%)	Diurnal Range (%)
20	60	40–85	46	33–62
20	15	5–20	17	10–20
20	10	5–15	14	10–17
20	10	5–15	13	10–16
20	5	<1–10	10	7–13

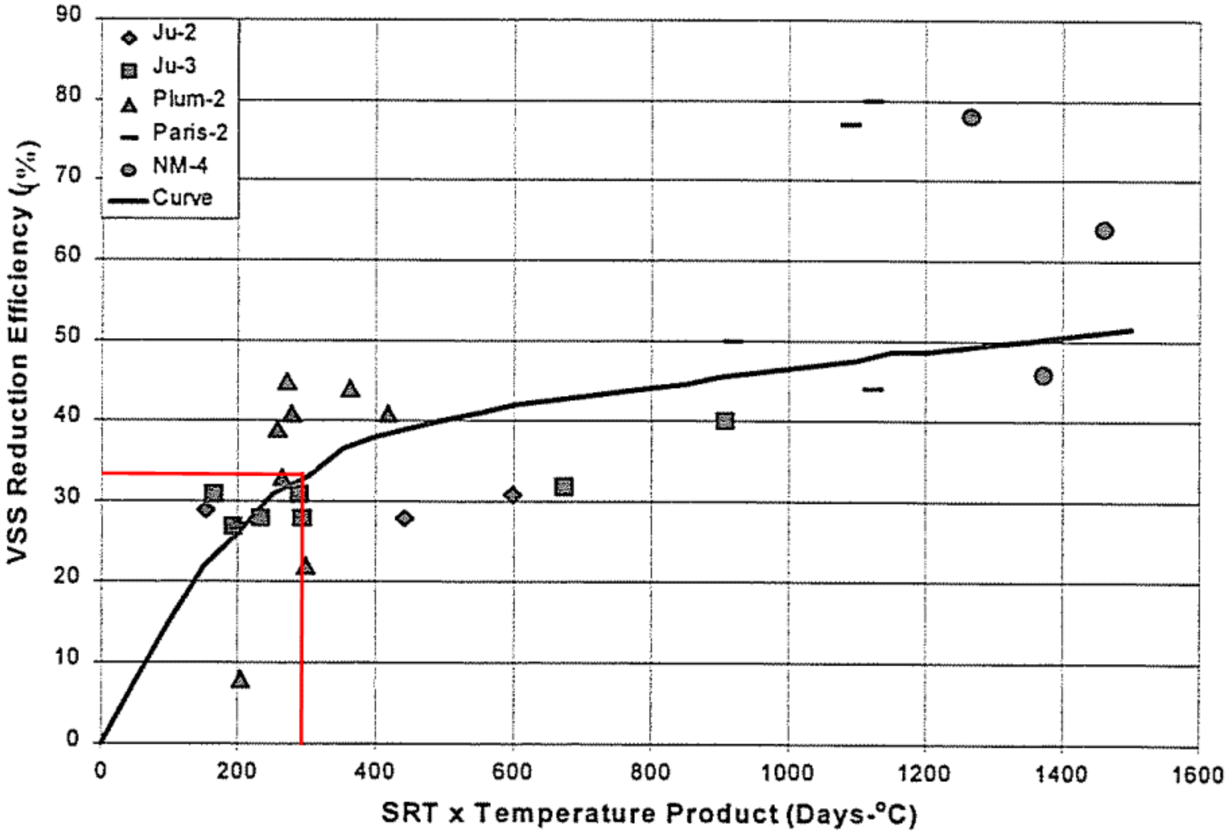
Another way – utilize Daigger graph. If digester is to be sized for a total of 560 degrees C days (28 days detention time at 40 degrees C), as shown in the first figure below, the total volatile solids reduction anticipated is roughly 42%.



If it is assumed that there is an even split in the digester volume, then the value for the first stage would be 280 degrees C days. The figure below shows this scenario. Based on this graph, the volatile solids reduction in this first stage would be 32%. Therefore, of the total oxygen requirements, the % of air required in the first stage can be calculated as:

% O2 required in first stage = <u>VSS reduction in first stage (%)</u>
Total VSS reduction across digester (%)
= 32/42 or 76%.

To ensure redundancy, it is suggested that each stage of a two-stage digester be designed to provide the potentially higher airflow requirement, but with the ability to turn down the air flow, when operated as a second-stage unit. This may require interlacing independent diffuser grids, or other means of providing sufficient turndown in the aeration system.



This concept can be expanded for three- and four-stage digester systems.

Consider including mixing in addition to aeration – allows digester to be operated more readily in anoxic/aerobic mode (discussed below). Small submersible mixers provide a great deal of flexibility, at a relatively low cost. May also allow turndown of aeration during low load periods, without reduction in mixing, reducing energy consumption.

Typical Ranges of Aeration Efficiency for Various Mechanical Aerators

(From WEF MOP FD-13 – Aeration. Italic numbers are from research by Stenstrom and Rosso)

Type	Standard Aeration Efficiency kg O_2/kW•h	Advantages	Disadvantages
Surface Centrifugal (low speed)	1.2-3.0 *1.5-2.1*	Simpler than diffused air Easier to maintain Less prone to fouling	Lack of control of oxygenation rate Potential foaming Potential for freezing
Surface Centrifugal (draft tube)	1.2-2.8 *1.5-2.1*		
Surface Axial (high speed)	1.2-2.2 *0.9-1.3*	Simpler than diffused air Lower capital cost	Less efficient Greater potential for cooling liquid
Submerged turbine, sparger	1.2-2.0 *1.2-1.8*	Oxygenation rate can be controlled Less impact from foaming	Two motors to maintain (blower and mixer)

Typical Ranges of Aeration Efficiency for Selected Diffusers

(From WEF MOP FD-13 – Aeration and MOP-8)

Type	Standard OTE at 15’ submergence (%)	Advantages	Disadvantages
Porous Plastic Tubes		• High efficiency • Good operational flexibility • Approximately 5:1 turndown	• Potential for air- or liquid-side clogging, especially if aeration is cycled. • Typically requires air filtration • May require specialized cleaning • Low alpha • Higher capital cost
Grid	28-32		
Dual spiral roll	18-28		
Single spiral roll	13-25		
Flexible Sheath Tubes			
Grid	22-29		
Quarter Points	19-24		
Single Spiral Roll	15-19		
Flexible Membrane			
Disc, 9 in. dia., grid	26-35		
Disc, 13 in dia., grid	26-35		
Single-Point diffusers		• Good mixing of deep digesters • Relatively resistant to clogging • Easy maintenance • High alpha	• Low oxygen transfer efficiency • Higher capital cost
With draft tube	11-13		
Nonporous diffusers			
Dual spiral roll	12-13		
Mid width	10-13		
Single spiral roll	9-12		
Jet Aeration	15-24	• Mechanical equipment can be located outside tank • Can handle higher solids • Higher SOTE than nonporous diffusers	• Potential for nozzle clogging • Depending on size, may need two motors – decreases efficiency

For thickened solids, both single point and draft tube aerators have been used fairly extensively. Draft tubes offer the benefit of physical “pumping” of the air and sludge through the draft tube.

Jets offer some advantages – the air can be turned off, but the motive pump left operating, providing mixing without aeration during anoxic cycles in an anoxic-aerobic digester. In addition, the shearing effect of the flow through the nozzles overcomes some of the viscosity effects found in aeration of thickened sludge. As noted above, the aeration efficiency for a jet system is relatively high, but this is somewhat offset by the need for separate pumps and blowers.

SAMPLE CALCULATION OF AERATION REQUIREMENTS

Assume an aerobic digester receives WAS only. The plant is located in a warm climate where nitrification is possible. The maximum month loading to the digester is 230 kg/day (510 lbs/day) of VS. Anticipated VS destruction is 40%.

Assuming coarse bubble diffusers, determine the airflow and # of diffusers required.

The following design parameters are utilized:

Design O_2 requirement/kg of VS is 2.0 kg O_2/kg VS (because of nitrification) or 2.0 lb O_2/lb VS

Oxygen safety factor =110% (this may vary depending on regulatory requirements and designer's preference)

Diffuser SOTE at design depth is 12% (from diffuser manufacturer's data).

Temperature = 20 degrees C (68 degrees F)

Site Elevation = sea level

Alpha (α) for the selected diffusers is 0.8

α = ratio of the transfer coefficient under process conditions to the transfer coefficient under clean water conditions

α will vary from approximately 0.2 to greater than 1.0, but is usually less than 1.0. There are many factors which impact this value, including surfactants, aeration density, tank geometry, bubble size, degree of treatment, solids concentration and other wastewater characteristics. Manufacturers' information is valuable in determining the appropriate value, but α values may be over-stated. WEF has also identified α factors in various publications, including MOP FD-13 Aeration.

Beta (ß) for the selected diffusers is 0.9

ß = ratio of the saturation concentration of oxygen under process conditions to the saturation concentration under clean water conditions

ß will vary from 0.8 to 1.0, and is usually between 0.9 and 1.0 for municipal wastewater treatment facilities.

C (the operating DO in the digester) is 2.0 mg/L.

Total Oxygen Requirement = 230 kg/day VS x 2 kg O_2/kg VS x 1.10 safety factor

506 kg/day = 21.1 kg/hr

(USCS Version 510 lbs/day VS x 2 lb O_2/lb VS x 1.10 safety factor

1122 lbs/day = 46.8 lbs/hr)

For diffused aeration systems, the relationship of field oxygen transfer rates and standard oxygen transfer rates can be determined from the following equation (from MOP FD-13)

$$SOTR = \frac{OTRf}{\frac{\alpha F\left(\tau\beta\Omega C^*_{\infty 20} - C\right) \times \theta^{(T-20)}}{C^*_{\infty 20}}}$$ Where:

α = 0.8 (from diffuser manufacturer)

F = Fouling factor – typically 1 for coarse bubble diffusers

Sometimes, these are combined, and reported as an αF value, especially in research papers on fine bubble aeration.

β = 0.9

τ = effect of temperature on the oxygen saturation concentration

= $\frac{C^*_{sT}}{C^*_{s20}}$

C^*_{sT} = DO surface saturation concentration at temperature T (see https://lakestewardsofmaine.org/wp-content/uploads/2014/01/Maximum-Dissolved-Oxygen-Concentration-Saturation-Table.pdf for a table)

C^*_{s20} = DO surface saturation concentration at T=20 degrees C

For the example problem, as the design temperature is 20 degrees C, τ = 1.0

$\theta^{(T-20)}$ = $\frac{K_L a_T}{K_L a_{20}}$

= 1.024

Ω = effect of pressure on DO saturation concentration

= $\frac{C^*_\infty \; at \; p_b}{C^*_\infty \; at \; p_S}$

P_b = atmospheric pressure at site

P_S = standard atmospheric pressure

For the example problem, as the plant is located at sea level, Ω = 1.0

$C^*_{\infty 20}$ = average DO saturation concentration at infinite time

= 9.17 mg/L for the temperature and elevation specified

Then, the required aeration rate can be calculated as:

$$SOTR = \frac{21.1\ kg/hr}{\frac{0.8\left((1.0)*(0.9)*(1.0)*9.17 - 2.0\right) \times 1.024^{(20-20)}}{9.17}}$$

$$SOTR = \frac{46.8\ lb/hr}{\frac{0.8\left((1.0)*(0.9)*(1.0)*9.17 - 2.0\right) \times 1.024^{(20-20)}}{9.17}}$$

Or 37.8 kg/hr O_2 (83.8 lb/hr O_2)

Then the air flow rate can be solved using the following equation:

$$Qa = \left(37.8\frac{\text{kg}}{\text{hr}}\text{O}_2\right)\left(\frac{1\ kg\ air}{0.23\ kg\ O_2}\right)\left(\frac{1}{1.2894\frac{kg}{m^3}}\right)\left(\frac{1}{0.12}\right)$$

= 1,062 m^3/hr (standard conditions)

USCS Values

$$Qa = \left(83.8\frac{\text{lb}}{\text{hr}}\text{O}_2\right)\left(\frac{1\ lb\ air}{0.23\ lb\ O_2}\right)\left(\frac{1}{0.075\frac{lb}{ft^3}}\right)\left(\frac{1}{0.12}\right)$$

= 40,483 ft^3/hr = 675 SCFM

Once the air flow rate is known, air mains can be sized appropriately. In the present case, assuming one air header, calculations are as follows:

(From Centrifugal Compressor Engineering, published by Hoffman Air & Filtration Systems)

Typical Air Velocities in Blower Discharge Piping

Pipe Diameter		Velocity	
(mm)	(inches)	m/s - Std Air	Ft/min - Std Air
25-75	1-3	6-9	1200-1800
100-250	4-10	9-15	1800-3000
300-600	12-24	14-20	2700-4000
750-1500	30-60	19-33	3800-6500

Based on these values, the main air header should be a minimum of 200 mm (8-inch) diameter.

Note - determining oxygen transfer efficiencies is a key factor in sizing aeration equipment. There is a tendency to overstate aeration efficiency. To maximize certainty of achieving the necessary aeration efficiency, testing should always be required in accordance with ASCE

Standard 2 – Measurement of Oxygen Transfer in Clean Water. In most cases, factory testing will provide sufficient verification of anticipated oxygen transfer efficiency. For larger installations, or where there is an emphasis on energy conservation, on-site oxygen transfer efficiency testing can be conducted to ensure that the supplied equipment meets specified standards. For existing facilities, ASCE Standard 18 – Standard Guidelines for In-Process Oxygen Transfer Testing provides guidance for testing while the treatment facility is operating.

PHOSPHORUS REMOVAL

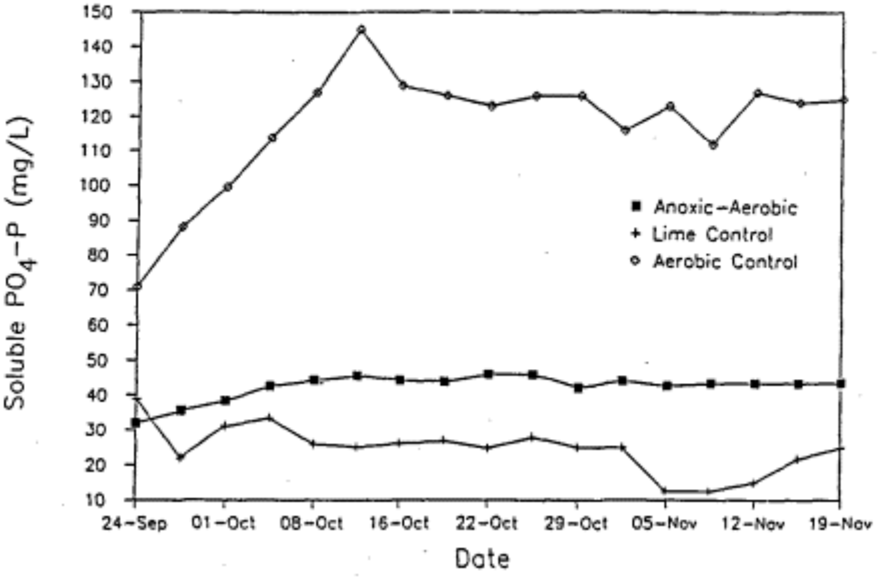


Figure 3. Supernatant Phosphorus Levels for 20 day SRT at 20°C.

From Al-Ghusain et al, 2004

This graph shows the impact on supernatant phosphorus concentrations from either anoxic/aerobic operation or from lime addition to maintain pH.

IMPACTS OF THICKENING SLUDGE ON DIGESTION

Thickening sludge prior to, or during digestion, can have a significant impact on the volume required to meet EPA requirements for a PSRP Process. For the following examples, the following feed conditions are assumed:

Q_f = 111.9 m^3/d (29,600 gpd)

TSS_f = 1,814 kg/d (4,000 lb/d)

TSS_f = 16.2 g/L (1.62%)

VSS_f = 1,435 kg/d (3,164 lb/d)

VSS_f = 12.8 g/L (1.28%)

FS_f = 379 kg/d (836 lb/d)

Assuming a 38% destruction of VSS in the digester, the solids concentrations leaving the digester will be lower than the solids concentration entering the digester.

VSS_b = (0.62)*1,435 kg/d = 890 kg/d

FS_b = 379 kg/d

TSS_b = 890 kg/d + 379 kg/d = 1,269 kg/d

For a single-stage, completely mixed digester, at 20 degrees C, a 40 day SRT is required. The following equation can be utilized to calculate the required volume:

$${}_n = \frac{VC_v}{qC_b}$$

Where:

V = reactor volume

θ_n = nominal average SRT

C_v = concentration of solids in the reactor

q = flow rate leaving the reactor

C_b = concentration of solids in exiting sewage sludge

For the example above,

q = Q_f = 111.9 m^3/day

C_b = TSS_b/q = 11.34 g/L

C_v = C_b = 11.34 g/L

V = 4,476 m^3 (1.183 million gallons)

For a two-stage digester operated in series, at 20 degrees C, a 28 day SRT is required. Assuming no thickening, the required volume would be 3,133 m^3 (828,000 gallons). This represents a 30% reduction in volume.

If the digester is decanted, then the applicable equation changes to the following:

$${}_n = \frac{VC_v}{pC_p}$$

Where:

V = reactor volume

θ_n = nominal average SRT

C_v = concentration of solids in the reactor

p = flow rate of processed sludge leaving the system

C_p = concentration of solids in processed sludge

Utilizing decanting, aerobic digesters can often be operated at 2% solids. In this case, the flow rate of processed sludge leaving the system would be

$$p = \frac{1{,}269\ \text{kg/day}}{(20.0\ \text{g/L})(10^3\ \text{L/m}^3)(1\ \text{kg/1000 g})}$$

$$= 63.5\ \text{m}^3/\text{day}$$

Cv = 20.0 g/L

Cp = 20.0 g/L

V = 2,538 m^3

This represents a 43% reduction in the volume required for the digesters.

As a final example, assume a complete mix reactor, with constant feed and withdrawal at least once a day. The volume in the digester is maintained at a relatively constant level. There is a single feed stream from the activated sludge process. Sludge is drawn off the digester, and sent to a gravity thickener, with a portion of the sludge returned to the digester, and a portion drawn off for reuse/disposal.

The design detention time is 40 days.

Cv = solids content of sludge from the digester to the thickener

= 11.34 g/L

Cp = solids content of sludge leaving the thickener

= 40 g/L

$$P = \frac{1{,}269\ \text{kg/day}}{(40.0\ \text{g/L})(10^3\ \text{L/m}^3)(1\ \text{kg/1000 g})}$$

$$= 31.75\ \text{m}^3/\text{day}$$

$$V = \frac{\theta n * p * Cp}{Cv}$$

$$V = (40*31.75*40)/11.34$$

$$= 4,\ 480\ m^3$$