
Appendix C

Determination of Volatile Solids Reduction by Digestion

Introduction

Under 40 CFR Part 503, the ability of sewage sludge to attract vectors must be reduced when sewage sludge is applied to the land or placed on a surface disposal site. One way to reduce vector attraction is to reduce the volatile solids in the sewage sludge by 38% or more (see Section 8.2 of this document). Typically, volatile solids reduction is accomplished by anaerobic or aerobic digestion. Volatile solids reduction also occurs under other circumstances, such as when sewage sludge is stored in an anaerobic lagoon or is dried on sand beds. To give credit for this extra loss in volatile solids, the regulation allows the untreated sewage sludge to be compared with the treated sewage sludge that leaves the treatment works, which should account for all of the volatile solids reduction that could possibly occur. For most processing sequences, the processing steps downstream from the digester, such as short-term storage or dewatering, have no influence on volatile solids content. Consequently, the appropriate comparison is between the sewage sludge entering the digester and the sewage sludge leaving the digester. The remainder of the discussion is limited to this circumstance, except for the final section of this appendix, which compares incoming sewage sludge with the sewage sludge leaving the treatment works.

The Part 503 regulation does not specify a method for calculating volatile solids reduction. Fischer (1984) observed that the United Kingdom has a similar requirement for volatile solids reduction for digestion (40%), but also failed to prescribe a method for calculating volatile solids reduction. Fischer has provided a comprehensive discussion of the ways that volatile solids reduction may be calculated and their limitations. He presents the following equations for determining volatile solids reduction:

- Full mass balance equation
- Approximate mass balance equation
- “Constant ash” equation
- Van Kleeck equation

The full mass balance equation is the least restricted approach but requires more information than is currently

collected at a wastewater treatment plant. The approximate mass balance equation assumes steady state conditions. The “constant ash” equation requires the assumption of steady state conditions as well as the assumption that the ash input rate equals the ash output rate. The Van Kleeck equation, which is the equation generally suggested in publications originating in the United States (WPCF, 1968), is equivalent to the constant ash equation. Fischer calculates volatile solids reduction using a number of examples of considerable complexity and illustrates that different methods frequently yield different results.

Fischer’s paper is extremely thorough and is highly recommended for someone trying to develop a deep understanding of potential complexities in calculating volatile solids reduction. However, it was not written as a guidance document for field staff faced with the need to calculate volatile solids reduction. The nomenclature is precise but so detailed that it makes comprehension difficult. In addition, two important troublesome situations that complicate the calculation of volatile solids reduction - grit deposition in digesters and decantate removal - are not explicitly discussed. Consequently, this presentation has been prepared to present guidance that describes the major pitfalls likely to be encountered in calculating percent volatile solids reduction.

It is important to note that the calculation of volatile solids reduction is only as accurate as the measurement of volatile solids content in the sewage sludge. The principal cause of error is poor sampling. Samples should be representative, covering the entire charging and withdrawal periods. Averages should cover extended periods of time during which changes in process conditions are minimal. For some treatment, it is expected that periodic checks of volatile solids reduction will produce results so erratic that no confidence can be placed in them. In this case, adequacy of stabilization can be verified by the method described under Options 2 and 3 in Chapter 8 --periodically batch digest anaerobically digested sewage sludge for 40 additional days at 30°C (86°F) to 37°C (99°F), or aerobically digested sewage sludge for 30 additional days at 20°C (68°F). If the additional VS reduction is less than 17% for the anaerobically digested sewage sludge or less than 15% for the aerobically digested sewage sludge, the sewage sludge is sufficiently stable (see Sections 8.3 and 8.4).

Equations for FVSR

The equations for fractional volatile solids reduction (FVSR) that will be discussed below are the same as those developed by Fischer (1984), except for omission of his constant ash equation. This equation gives identical results to the Van Kleeck equation so it is not shown. Fischer's nomenclature has been avoided or replaced with simpler terms. The material balance approaches are called methods rather than equations. The material balances are drawn to fit the circumstances. There is no need to formalize the method with a rigid set of equations.

In the derivations and calculations that follow, both VS (total volatile solids content of the sewage sludge or decantate on a dry solids basis) and FVSR are expressed throughout as fractions to avoid the frequent confusion that occurs when these terms are expressed as percentages. "Decantate" is used in place of the more commonly used "supernatant" to avoid the use of "s" in subscripts. Similarly, "bottoms" is used in place of "sludge" to avoid use of "s" in subscripts.

Method Full Mass Balance

The full mass balance method must be used when steady conditions do not prevail over the time period chosen for the calculation. The chosen time period must be substantial, at least twice the nominal residence time in the digester (nominal residence time equals average volume of sludge in the digester divided by the average volumetric flow rate. Note: when there is decantate withdrawal, volume of sewage sludge withdrawn should be used to calculate the average volumetric flow rate). The reason for the long time period is to reduce the influence of short-term fluctuations in sewage sludge flow rates or compositions. If input compositions have been relatively constant for a long period of time, then the time period can be shortened.

An example where the full mass balance method would be needed is where an aerobic digester is operated as follows:

- Started with the digester 1/4 full (time zero)
- Raw sewage sludge is fed to the digester daily until the digester is full
- Supernatant is periodically decanted and raw sewage sludge is charged into the digester until settling will not occur to accommodate daily feeding (hopefully after enough days have passed for adequate digestion)
- Draw down the digester to about 1/4 full (final time), discharging the sewage sludge to sand beds

The full mass balance is written as follows:

Sum of total volatile solids inputs in feed streams during the entire digestion period = sum of volatile solids outputs in withdrawals of decantate and bottoms + loss of volatile solids + accumulation of volatile solids in the digester. (1)

Loss of volatile solids is calculated from Equation 1. FVSR is calculated by Equation 2:

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

The accumulation of volatile solids in the digester is the final volume in the digester after the drawdown times final volatile solids concentration less the initial volume at time zero times the initial volatile solids concentration.

To properly determine FVSR by the full mass balance method requires determination of all feed and withdrawal volumes, initial and final volumes in the digester, and volatile solids concentrations in all streams. In some cases, which will be presented later, simplifications are possible.

Approximate Mass Balance Method

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:

$$\text{volatile solids input rate} = \text{volatile solids output rate} + \text{rate of loss of volatile solids.} \quad (3)$$

The FVSR is given by Equation 2.

No Decantate, No Grit Accumulation (Problem 1)

Calculation of FVSR is illustrated for Problem 1 in Table C-1, which represents a simple situation with no decantate removal and no grit accumulation. An approximate mass balance is applied to the digester operated under constant flow conditions. Because no decantate is removed, the volumetric flow rate of sewage sludge leaving the digester equals the flow rate of sewage sludge entering the digester.

Applying Equations 3 and 2,

$$\text{FY}_f = \text{BY}_b + \text{loss} \quad (4)$$

$$\text{Loss} = 100(50-30) = 2000 \quad (5)$$

$$\text{FVSR} = \frac{\text{Loss}}{\text{FY}_f} \quad (6)$$

$$\text{FVSR} = \frac{2000}{(100)(50)} = 0.40 \quad (7)$$

Nomenclature is given in Table C-1. Note that the calculation did not require use of the fixed solids concentrations.

The calculation is so simple that one wonders why it is so seldom used. One possible reason is that 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

Table C-1. Quantitative Information for Example Problems ^{1,2,3}

Parameter	Symbol	Units	Problem Statement Number			
			1	2	3	4
Nominal Residence Time	θ	d	20	20	20	20
Time period for averages	—	d	60	60	60	60
Feed Sludge						
Volumetric flow rate	F	m ³ /d	100	100	100	100
Volatile solids concentration	Y_f	kg/m ³	50	50	50	50
Fixed solids concentration	X_f	kg/m ³	17	17	17	17
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 Sludge (Bottoms)						
Volumetric flow rate	B	m ³ /d	100	100		49.57
Volatile solids concentration	Y_b	kg/m ³	30	41.42	41.42	41.42
Fixed solids concentration	X_b	kg/m ³	17	15	23.50	23.50
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		50.43
Volatile solids concentration	Y_d	kg/m ³	—	—	12.76	12.76
Fixed solids concentration	X_d	kg/m ³	—	—	7.24	7.24
Fractional volatile solids	VS_d	kg/kg	—	—	0.638	0.638
Mass flow rate of solids	M_d	kg/d	—	—		

¹Conditions are steady state; all daily flows are constant. Volatile solids are not accumulating in the digester, although grit may be settling out in the digester.

²Numerical values are given at 3 or 4 significant figures. This is unrealistic considering the expected accuracy in measuring solids concentrations and sludge volumes. The purpose of extra significant figures is to allow more understandable comparisons to be made of the different calculation methods.

³All volatile solids concentrations are based on total solids, not merely on suspended 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 VS_f - VS_b 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.

For Problem 1, the balance yields the following:

$$FX_f = BX_b + \text{fixed solids loss} \quad (8)$$

$$(100)(17) = (100)(17) + \text{Fixed Solids Loss} \quad (9)$$

$$\text{Fixed Solids Loss} = 0 \quad (10)$$

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. As Equation 10 shows, the fixed solids loss equals zero. Note that for this case, where input and output sewage sludge flow rates are equal, the

fixed solids concentrations are equal when there is no grit accumulation.

Grit Deposition (Problem 2)

The calculation of fixed solids is repeated for Problem 2. Conditions in Problem 2 have been selected to show grit accumulation. Parameters are the same as in Problem 1 except for the fixed solids concentration (X_b) and parameters related to it. Fixed solids concentration in the sewage sludge is lower than in Problem 1. Consequently, VS is higher and the mass flow rate of solids leaving is lower than in Problem 1. A mass balance on fixed solids (input rate = output rate + rate of loss of fixed solids) is presented in Equations 11-13.

$$FX_f = BX_b + \text{Fixed Solids Loss} \quad (11)$$

$$\text{Fixed Solids Loss} = FX_f - BX_b \quad (12)$$

$$\text{Fixed Solids Loss} = (100)(7) - (100)(15) = 200 \text{ kg/d} \quad (13)$$

The material balance, which only looks at inputs and outputs, informs us that 200 kg/d of fixed solids have not appeared in the outputs as expected. Because fixed solids are not destroyed, it can be concluded that they are accumulating in the bottom of the digester. The calculation of FVSR for Problem 2 is exactly the same as for Problem 1 (see Equations 4 through 7) and yields the same result. The approximate mass balance method gives the

correct answer for the FVSR despite the accumulation of solids in the digester. As will be seen later, this is not the case when the Van Kleeck equation is used.

Decantate Withdrawal, No Grit Accumulation (Problem 3)

In Problem 3, decantate is withdrawn daily. Volatile and fixed solids concentrations are known for all streams but the volumetric flow rates are not known for decantate and bottoms. It is impossible to calculate FVSR without knowing the relative volumes of these streams. However, they are determined easily by taking a total volume balance and a fixed solids balance, provided it can be assumed that loss of fixed solids (i.e., accumulation in the digester) is zero.

Selecting a basis for F of 100 m³/d

$$\text{Volume balance: } 100 = B + D \quad (14)$$

$$\text{Fixed solids balance: } 100 X_f + BX_b + DX_d \quad (15)$$

Because the three Xs are known, B and D can be found. Substituting 100-D for B and the values for the Xs from Problem 3 and solving for D and B,

$$(100)(17) = (100 - D)(23.50) + (D)(7.24) \quad (16)$$

$$D = 40.0 \text{ m}^3/\text{d}, \quad B = 60.0 \text{ m}^3/\text{d} \quad (17)$$

The FVSR can now be calculated by drawing a volatile solids balance:

$$FY_f = BY_b + DY_d + \text{loss} \quad (18)$$

$$\text{FVSR} = \frac{\text{loss}}{FY_f} = \frac{FY_f - BY_b - DY_d}{FY_f} \quad (19)$$

$$\text{FVSR} = \frac{(100)(50) - (60)(41.42) - (40)(12.76)}{(100)(50)} = 0.40 \quad (20)$$

Unless information is available on actual volumes of decantate and sewage sludge (bottoms), it is not possible to determine whether grit is accumulating in the digester. If it is accumulating, the calculated FVSR will be in error.

When the calculations shown in Equations 18 through 20 are made, it is assumed that the volatile solids that are missing from the output streams are consumed by biological reactions that convert them to carbon dioxide and methane. Accumulation is assumed to be negligible. Volatile solids are less likely to accumulate than fixed solids, but it can happen. In poorly mixed digesters, the scum layer that collects at the surface is an accumulation of volatile solids. FVSR calculated by Equations 18 through 20 will be overestimated if the volatile solids accumulation rate is substantial.

Decantate Withdrawal and Grit Accumulation (Problem 4)

In Problem 4, there is suspected grit accumulation. The quantity of B and D can no longer be calculated by Equa-

tions 14 and 15 because Equation 15 is no longer correct. The values of B and D must be measured. All parameters in Problem 4 are the same as in Problem 3 except that measured values for B and D are introduced into Problem 4. Values of B and D calculated assuming no grit accumulation (Problem 3--see previous discussion), and measured quantities are compared below:

	Calculated	Measured
B	60	49.57
D	40	50.43

The differences in the values of B and D are not large but they make a substantial change in the numerical value of FVSR. The FVSR for Problem 4 is calculated below:

$$\text{FVSR} = \frac{(100)(50) - (49.57)(41.42) - (50.43)(12.76)}{(100)(50)} = 0.461 \quad (21)$$

If it had been assumed that there was no grit accumulation, FVSR would equal 0.40 (see Problem 3). It is possible to determine the amount of grit accumulation that has caused this change. A material balance on fixed solids is drawn:

$$FX_f = BX_b + DX_d + \text{Fixed Solids Loss} \quad (22)$$

The fractional fixed solids loss due to grit accumulation is found by rearranging this equation:

$$\frac{\text{Fixed Solids Loss}}{FX_f} = \frac{FX_f - BX_b - DX_d}{FX_f} \quad (23)$$

Substituting in the parameter values for Problem 4,

$$\frac{\text{Fixed Solids Loss}}{FX_f} = \frac{(100)(17) - (49.57)(23.50) - (50.43)(7.24)}{(100)(17)} = 0.100 \quad (24)$$

If this fixed solids loss of 10 percent had not been accounted for, the calculated FVSR would have been 13% lower than the correct value of 0.461. Note that if grit accumulation occurs and it is ignored, calculated FVSR will be lower than the actual value.

The Van Kleeck Equation

Van Kleeck first presented his equation without derivation in a footnote for a review paper on sewage sludge treatment processing in 1945 (Van Kleeck, 1945). The equation is easily derived from total solids and volatile solids mass balances around the digestion system. Consider a digester operated under steady state conditions with decantate and bottom sewage sludge removal. A total solids mass balance and a volatile solids mass balance are:

$$M_f = M_b + M_d + (\text{loss of total solids}) \quad (25)$$

$$M_f \cdot VS_f = M_b \cdot VS_b + M_d \cdot VS_d + (\text{loss of volatile solids}) \quad (26)$$

where

M_f , M_b , and M_d are the mass of solids in the feed, bottoms, and decantate streams.

The masses must be mass of solids rather than total mass of liquid and solid because VS is an unusual type of concentration unit—it is “mass of volatile solids per unit mass of total solids.”

It is now assumed that fixed solids are not destroyed and there is no grit deposition in the digester. The losses in Equations 25 and 26 then comprise only volatile solids so the losses are equal. It is also assumed that the VS of the decantate and of the bottoms are the same. This means that the bottoms may have a much higher solids content than the decantate but the proportion of volatile solids to fixed solids is the same for both streams. Assuming then that VS_b equals VS_d , and making this substitution in the defining equation for FVSR (Equation 2),

$$FVSR = \frac{\text{Loss of vol. solids}}{M_f \times VS_f} = 1 - \frac{(M_b + M_d) VS_b}{M_f \times VS_f} \quad (27)$$

From Equation 25, recalling that we have assumed that loss of total solids equals loss of volatile solids,

$$M_b + M_d + M_f - \text{loss of vol. solids} \quad (28)$$

Substituting for $M_b + M_d$ into Equation 27,

$$FVSR = 1 - \frac{(M_f - \text{loss of vol. solids}) \cdot VS_b}{M_f \cdot VS_f} \quad (29)$$

Simplifying further,

$$1 - (1/VS_f - FVSR) \cdot VS_b \quad (30)$$

Solving for FVSR,

$$FVSR = \frac{VS_f - VS_b}{VS_f - (VS_f \cdot VS_b)} \quad (31)$$

This is the form of the Van Kleeck equation found in WPCF Manual of Practice No. 16 (WPCF, 1968). Van Kleeck (1945) presented the equation in the following equivalent form:

$$FVSR = 1 - \frac{VS_b \times (1 - VS_f)}{VS_f \times (1 - VS_b)} \quad (32)$$

The Van Kleeck equation is applied below to Problems 1 through 4 in Table C-1 and compared to the approximate mass balance equation results:

	1	2	3	4
Approximate Mass Balance (AMB)	0.40	0.40	0.40	0.461
Van Kleeck (VK)	0.40	0.318	0.40	0.40

Problem 1: No decantate and no grit accumulation. Both methods give correct answer.

Problem 2: No decantate but grit accumulation. VK is invalid and incorrect.

Problem 3: Decantate but no grit accumulation. AMB method is valid. VK method is valid only if VS_b equals VS_d .

Problem 4: Decantate and grit accumulation. AMB method valid only if B and D are measured. VK method is invalid.

The Van Kleeck equation is seen to have serious shortcomings when applied to certain practical problems. The AMB method can be completely reliable, whereas the Van Kleeck method is useless under some circumstances.

Average Values

The concentrations and VS values used in the equations will all be averages. For the material balance methods, the averages should be weighted averages according to the mass of solids in the stream in question. The example below shows how to average the volatile solids concentration for four consecutive sewage sludge additions

Addition	Volume	Total Solids Concentration	VS
1	12 m ³	72 kg/m ³	0.75
2	8 m ³	50 kg/m ³	0.82
3	13 m ³	60 kg/m ³	0.80
4	10 m ³	55 kg/m ³	0.77

(33)

Weighted by Mass

$$VS_{av} = \frac{12 \times 72 \times 0.75 + 8 \times 50 \times 0.82 + 13 \times 60 \times 0.80 + 10 \times 55 \times 0.77}{12 \times 72 + 8 \times 50 + 13 \times 60 + 10 \times 55} = 0.795 \quad (34)$$

Weighted by Volume

$$VS_{av} = \frac{12 \times 0.75 + 8 \times 0.82 + 13 \times 0.80 + 10 \times 0.77}{12 + 8 + 13 + 10} = 0.783 \quad (35)$$

Arithmetic Average

$$VS_{av} = \frac{0.75 + 0.82 + 0.80 + 0.77}{4} = 0.785 \quad (36)$$

In this example the arithmetic average was nearly as close as the volume-weighted average to the mass-weighted average, which is the correct value.

Which Equation to Use?

Full Mass Balance Method

The full mass balance method allows calculation of volatile solids reduction for all approaches to digestion, even

processes in which the final volume in the digester does not equal the initial volume and where daily flows are not steady. A serious drawback to this method is the need for volatile solids concentration and the volumes of all streams added to or withdrawn from the digester, as well as initial and final volumes and concentrations in the digester. This can be a daunting task, particularly for the small treatment works that is most likely to run digesters in other than steady flow modes. For treatment works of this kind, an "equivalent" method that shows that the sewage sludge has undergone the proper volatile solids reduction is likely to be a better approach than trying to demonstrate 38% volatile solids reduction. An aerobic sewage sludge has received treatment equivalent to a 38% volatile solids reduction if the specific oxygen uptake rate is below a specified maximum. Anaerobically digested sewage sludge has received treatment equivalent to a 38% volatile solids reduction if volatile solids reduction after batch digestion of the sewage sludge for 40 days is less than a specified maximum (EPA, 1992).

Approximate Mass Balance Method

The approximate mass balance method assumes that daily flows are steady and reasonably uniform in composition, and that digester volume and composition do not vary substantially from day to day. Results of calculations and an appreciation of underlying assumptions show that the method is accurate for all cases, including withdrawal of decantate and deposition of grit, provided that in addition to composition of all streams the quantities of decantate and bottoms (the digested sewage sludge) are known. If the quantities of decantate and bottoms are not known, the accumulation of grit cannot be determined. If accumulation of grit is substantial and FVSR is calculated assuming it to be negligible, FVSR will be lower than the true value. The result is conservative and could be used to show that minimum volatile solids reductions are being achieved.

Van Kleeck Method

The Van Kleeck equation has underlying assumptions that should be made clear wherever the equation is presented. The equation is never valid when there is grit accumulation because it assumes the fixed solids input equals fixed solids output. Fortunately, it produces a conservative result in this case. Unlike the AMB method it does not provide a convenient way to check for accumulation of grit. It can be used when decantate is withdrawn, provided VS_b equals VS_d . Just how significant the difference between these VS values can be before an appreciable error in FVSR occurs is unknown, although it could be determined by making up a series of problems with increasing differences between the VS values, calculating FVSR using the AMB method and a Van Kleeck equation, and comparing the results.

The shortcomings of the Van Kleeck equation are substantial, but the equation has one strong point: The VS of the various sewage sludge and decantate streams are likely to show much lower coefficients of variation (standard de-

viation divided by arithmetic average) than volatile solids and fixed solids concentrations. Reviews of data are needed to determine how seriously the variation in concentrations affect the confidence interval of FVSR calculated by both methods. A hybrid approach may turn out to be advantageous. The AMB method could be used first to determine if grit accumulation is occurring. If grit is not accumulating, the Van Kleeck equation could be used. If decantate is withdrawn, the Van Kleeck equation is appropriate, particularly if the decantate is low in total solids. If not, and if VS_d differs substantially from VS_b , it could yield an incorrect answer.

Volatile Solids Loss Across All Sewage Sludge Treatment Processes

For cases when appreciable volatile solids reduction can occur downstream from the digester (for example, as would occur in air drying or lagoon storage), it is appropriate to calculate the volatile solids loss from the point at which the sewage sludge enters the digester to the point at which the sewage sludge leaves the treatment works. Under these circumstances, it is virtually never possible to use the approximate mass balance approach, because flow rates are not uniform. The full mass balance could be used in principle, but practical difficulties such as measuring the mass of the output sewage sludge (total mass, not just mass of solids) that relates to a given mass of entering sewage sludge make this also a practical impossibility. Generally then, the only option is to use the Van Kleeck equation, because only the percent volatile solids content of the entering and exiting sewage sludge is needed to make this calculation. As noted earlier, this equation will be inappropriate if there has been a selective loss of high volatility solids (e.g., bacteria) or low volatility solids (e.g., grit) in any of the sludge processing steps.

To make a good comparison, there should be good correspondence between the incoming sewage sludge and the treated sewage sludge to which it is being compared (see Section 10.4). For example, when sewage sludge is digested for 20 days, then dried on a sand bed for 3 months, and then removed, the treated sludge should be compared with the sludge fed to the digester in the preceding 3 or 4 months. If no selective loss of volatile or nonvolatile solids has occurred, the Van Kleeck equation (see Equation 31) can be used to calculate volatile solids reduction.

References

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