Toxic gas production and silo ventilation  

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Jiang, S., Barber, E.M., Meiering, A.G. and Jofriet, J.C. 1991. Toxic gas production and silo ventilation. Can. Agric. Eng. 33:151-159. Equations were developed to predict the minimum safe duration of ventilation required in tower silos to reduce carbon dioxide and oxides of nitrogen to safe limits for human entry into the silo. Unlike previous analyses, the model developed in this paper accounts for gas production during the period of ventilation. Two key inputs to the model are the rates of gas production and the value for the ventilation mixing factor, and data for both are very limited. On the basis of data that are available, this analysis suggests that NOx will not be diluted to safe levels by ventilation with a silage blower during the period of active gas production. During this period, especially the first week after placing forage in a tower silo, workers should not enter tower silos without protection of self-contained breathing apparatus.

Previous theoretical investigations into safe ventilation times necessary for tower silos have neglected gas generation during the period of ventilation (Barber and Jan 1984; Reid et al. 1985). Also, the concentration of NOx usually has been overlooked and ventilation recommendations have been based on CO2 dilution only. In one analysis (Barber and Jan 1984), NOx was assumed to be diluted at the same rate as CO2. Ventilation that would dilute CO2 to safe levels from an initial concentration of 100% was calculated to also dilute NOx to safe levels from an initial concentration of 0.03%. That analysis did not include any allowance for gas generation, nor was it shown that the initial concentration of NOx might not commonly be higher than 0.03%. Reid et al. (1985) found in their tests that CO2 and NOx increased to above the danger level as soon as ventilation ceased, indicating that gas release into the silo headspace was continuing. They also found that in some cases, NOx was not reduced to below safe levels by ventilation rates and durations that were adequate to quickly drop CO2 to below the safe concentration. These findings suggest that omission of the continuous source of gas, and consideration of only CO2 and not NOx, in calculating safe ventilation times might lead to serious errors.

The objective of this study was to establish by numerical analysis estimates for the minimum ventilation time required for safe entry into top-unloading tower silos. It was assumed that the silo might have to be entered during the period of active gas production which has been shown to extend from just a few hours to as long as 3 weeks after placement of forage in the silo (Meiering et al. 1988). Factors to be considered included the gas generation rate, ventilation rate, ventilation efficiency, initial gas concentrations, mass of silage, and silo dimensions. Concentrations of both CO2 and NOx were considered.
THEORY

During the period of rapid gas generation, the gas pressure within the silage pore space remains very high. The ventilation air was assumed not to penetrate the silage surface. Therefore, the ventilation volume was assumed equal to the volume of the headspace. In the worst case, the silage pore space will be filled with gases generated from the fermentation and will remain filled during the ventilation period. Assume that the pore volume in silage is approximately 0.3 m$^3$/m$^3$ of silage. Total evolution of CO$_2$ from ensiled rye grass was reported by Meiering et al. (1988) to be consistently more than 5.5 g/kg of silage. Given the densities of silage and CO$_2$ as 800 and 1.8 kg/m$^3$, respectively, total CO$_2$ generation in their experiment was at least 8.1 m$^3$/m$^3$ of pore space. Therefore, except during the very first hours of fermentation, it may be assumed that the gases are released into the headspace at the same rate as they are produced.

The differential equation describing the change in gas concentration within the headspace of the silo following an increase in the ventilation rate is:

$$\frac{d(cV)}{dt} = G_s \cdot qf + qn \cdot (c_i - c_e)$$

(1)

where:
- $c =$ gas concentration within headspace (m$^3$/m$^3$),
- $c_e =$ gas concentration in exhaust air (m$^3$/m$^3$),
- $c_i =$ gas concentration in supply air (m$^3$/m$^3$),
- $C_s =$ total gas generation rate for silo (m$^3$/h),
- $qf =$ ventilation rate supplied by blower (m$^3$/h),
- $qn =$ air exchange due to natural ventilation (m$^3$/h),
- $t =$ ventilation time (h), and
- $V =$ volume of headspace (m$^3$).

Equation 1 assumes that there is no change in gas density as air enters the headspace.

For simplicity, let the total ventilation rate, $q = qf + qn$. If the headspace can be assumed to be completely mixed, then $c_e = c$. The rate of gas production, $C_s$, has been described by Meiering et al. (1988) and is a function of the total mass of ensiled material. For a given silo, the relationship can be written as:

$$C_s = G_p \cdot \rho_s \cdot \dot{V}_s / \rho_g$$

(2)

where:
- $G =$ specific gas generation rate (kg·h$^{-1}$·kg$^{-1}$ silage),
- $\rho_s =$ silage bulk density (kg dry matter/m$^3$),
- $\rho_g =$ gas density (kg/m$^3$), and
- $\dot{V}_s =$ volume of silage (m$^3$).

Assuming a constant headspace volume, and incorporating the above-noted substitutions, Eq. 1 can be rewritten as:

$$V \frac{dc}{dt} = G_p \cdot \rho_s \cdot \dot{V}_s / \rho_g + q(c_i - c)$$

(3)

The effect of incomplete mixing within the headspace can be accounted for by introducing a mixing factor, $K$, such that:

$$V \frac{dc}{dt} = G_p \cdot \rho_s \cdot \dot{V}_s / \rho_g + K q (c_i - c)$$

(4)

$K$ takes on the value of unity for complete mixing, is zero for no mixing, and is greater than unity for plug-flow ventilation.

Integrating Eq. 4 and applying the initial conditions, $c = c_0$ at $t = 0$ yields:

$$c - c_i - G_p \cdot \rho_s \cdot \dot{V}_s / \rho_g \cdot K q \cdot t = \exp(-K q t / V)$$

(5)

where
- $c_0 =$ initial gas concentration within headspace (m$^3$/m$^3$).

This solution was obtained by assuming that $V_s, V, \rho_s, \rho_g$ are constant with respect to time. Although this assumption is not valid over a time period of days, and may not even be valid in the case of $G$ for periods less than a day, it is reasonable for the shorter period of one or two hours following the initiation of ventilation.

By substituting the silo dimensions into Eq. 5 and rearranging the equation, a ventilation time to reduce the gas concentration to a maximum safe gas concentration is obtained as:

$$t_{TLV} = - \frac{(H - h_s) \pi D^2}{4 K q} \ln \left[ \frac{c_{TLV} - c_i - G_p \pi D^2 h_s / 4 K q \rho_g}{c_0 - c_i - G_p \pi D^2 h_s / 4 K q \rho_g} \right]$$

(6)

where:
- $c_{TLV} =$ maximum safe gas concentration (m$^3$/m$^3$),
- $D =$ silo diameter (m),
- $h =$ headspace depth (m),
- $h_s =$ silage depth (m),
- $H =$ $h + h_s =$ silo height (m), and
- $t_{TLV} =$ ventilation time to reduce gas concentration to $c_{TLV}$ (h).

Equation 6 can be used to study the influence of various factors on the ventilation time required before safe entry by farm workers into silos during the period of active gas production. If gas production has ceased, Eq. 6 simplifies to:

$$t_{TLV} = - \frac{(H - h_s) \pi D^2}{4 K q} \ln \left[ \frac{c_{TLV} - c_i}{c_0 - c_i} \right]$$

(7)

In some instances, it may be desirable to rearrange Eq. 5 to solve for the gas concentration at the end of some fixed ventilation period, say 30 min or 1 h. Thus,

$$c = c_0 \exp(-K q t / V) + [c_i + G_p \pi D^2 h_s / 4 K q \rho_g] \left[ 1 - \exp(-K q t / V) \right]$$

(8)
Equation 8 can be simplified considerably for the special case where both \( a \) and \( G \) are negligible or zero:

\[
c = c_0 \exp(-Kqt/V)
\]  

(9)

Under steady conditions of ventilation and gas generation, the rate of gas removal from the headspace by ventilation is equal to the rate of gas release into the headspace by gas generation:

\[
Kq(c - c_i) = G\rho_s V_s/\rho_g
\]  

(10)

This relationship can be used to calculate the following four quantities:

(a) the steady-state gas concentration attainable after a long period of ventilation;

\[
c_{\infty} = c_i + G\rho_s V_s/Kq\rho_g
\]  

(11)

where \( c_{\infty} \) = steady-state gas concentration within headspace (\( m^3/m^3 \)). Note that as \( t \to \infty \), the gas concentration is a linear function of the silage volume, or depth of silage. In the special case where \( G = 0 \), the gas concentration equals \( c_i \).

(b) the maximum gas generation rate such that the gas can be diluted to safe levels by continuous ventilation of the silo headspace;

\[
(G)_{\text{MAX}} = \frac{(c_{\text{TLV}} - c_i)(Kq\rho_g)}{(\rho_s V_s)}
\]  

(12)

(c) the minimum ventilation rate which will result in dilution of the gas to a safe level;

\[
(q)_{\text{MIN}} = \frac{(G\rho_s V_s/Kq\rho_g)}{(c_{\text{TLV}} - c_i)}
\]  

(13)

and (d) the maximum depth of silage for which ventilation at the specified rate will maintain a steady-state gas concentration at the safe level;

\[
(h_s)_{\text{MAX}} = \frac{(c_{\text{TLV}} - c_i)(4Kq\rho_g)}{(G\rho_s \pi D^2)}
\]  

(14)

The silage average density may be calculated from the silage depth and dry matter content by (Jofriet et al. 1982):

\[
\rho_{sd} = [400 h_s - 250 (1 - \exp(-0.11 h_s))/0.11]/h_s
\]  

(15)

and

\[
\rho_s = \rho_{sd}/W_s
\]  

(16)

where:

\( W_s \) = silage dry matter content (\( kg \) dm/kg silage), and \( \rho_{sd} \) = silage dry matter density (\( kg \) dm/m\(^3\)).

Equation 15 was developed for alfalfa haylage stored in a concrete silo. Equation 16 is limited to silage having a moisture content less than approximately 70%. Equations 12, 13 and 14 may be solved iteratively to determine \((h_s)_{\text{MAX}}\).

Figure 1 shows a generalized decay curve for gas concentration following a step increase in the ventilation rate. Several of the terms used in the above equations are illustrated in the graph.

**Table I. Baseline values for all parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G )</td>
<td>0.098 g/h/kg</td>
</tr>
<tr>
<td>( c_{\text{TLV}} )</td>
<td>0.9 mg/h/kg</td>
</tr>
<tr>
<td>( h_s )</td>
<td></td>
</tr>
<tr>
<td>( W_s )</td>
<td></td>
</tr>
<tr>
<td>( \rho_{sd} )</td>
<td></td>
</tr>
<tr>
<td>( \rho_s )</td>
<td></td>
</tr>
<tr>
<td>( Kq\rho_g )</td>
<td></td>
</tr>
<tr>
<td>( G\rho_s V_s )</td>
<td></td>
</tr>
<tr>
<td>( c_0 )</td>
<td></td>
</tr>
<tr>
<td>( c_i )</td>
<td></td>
</tr>
</tbody>
</table>

**PARAMETRIC ANALYSIS**

In the case where gas is not being generated, the safe ventilation period is easily obtained from Eq. 7. Inspection of this equation reveals that the minimum ventilation period is linearly related to the silo cross-sectional area and the depth of the headspace, and to the inverse of the mixing factor and the ventilation rate. A simple graph showing the dependence of the required ventilation period on these factors has been previously reported (Barber and Jan 1984).

During the period of active gas generation, the relationship between the safe ventilation period and various management and physical variables cannot be determined easily by inspection of the more complicated Eq. 6. To see these relationships more clearly, Eqs. 6 and 8 were plotted for various levels of gas generation rate, initial gas concentration, ventilation mixing factor, ventilation rate, silage and headspace depths, silo diameter, and silo height. Baseline values for all parameters are given in Table I.

The gas generation rate, \( G \), to be used as a baseline condition was determined from data reported for rye grass by Meiering et al. (1988). The maximum CO\(_2\) generation rate of 0.098 g\( \cdot \)h\(^{-1}\)\( \cdot \)kg\(^{-1}\) silage occurred in day 1 of their test 1, and the maximum NO\(_x\) generation rate of 0.9 mg\( \cdot \)h\(^{-1}\)\( \cdot \)kg\(^{-1}\) silage occurred in day 3 of their test 2. These maximum rates were used in this analysis as a worst-case scenario. The assumption was made that all of the silage mass contributed to the gas production. Although the test data were collected in small laboratory scale vessels, it has been assumed that fermentation kinetics can be scaled up proportionally for farm-scale silos. Further, it has been assumed that all of the ensiled material was placed in the silo during one day, such that each unit of the ensiled mass is contributing equally to gas production. A more detailed evaluation of other silo filling situations could be conducted by coupling a ventilation model to the fermentation model of Meiering et al. (1988) and performing simulations.

The silo and silage blower were selected to have the same
Table I: Baseline values in parametric analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>CO₂</th>
<th>NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>independent variables:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_I$</td>
<td>400 ppm</td>
<td>0 ppm</td>
</tr>
<tr>
<td>$c_o$</td>
<td>100%</td>
<td>2%</td>
</tr>
<tr>
<td>$c_{TLV}$</td>
<td>15000 ppm</td>
<td>5 ppm</td>
</tr>
<tr>
<td>D</td>
<td>6.0 m</td>
<td>6.0 m</td>
</tr>
<tr>
<td>G</td>
<td>0.098 g·h⁻¹·kg⁻¹ silage</td>
<td>0.9 mg·h⁻¹·kg⁻¹ silage</td>
</tr>
<tr>
<td>h</td>
<td>6.0 m</td>
<td>6.0 m</td>
</tr>
<tr>
<td>$h_s$</td>
<td>12.0 m</td>
<td>12.0 m</td>
</tr>
<tr>
<td>H</td>
<td>18.0 m</td>
<td>18.0 m</td>
</tr>
<tr>
<td>K</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>q</td>
<td>2880 m³/h</td>
<td>2880 m³/h</td>
</tr>
<tr>
<td>$W_s$</td>
<td>0.4 kg dm/kg silage</td>
<td>0.4 kg dm/kg silage</td>
</tr>
<tr>
<td>$\rho_g$</td>
<td>1.8 kg/m³ air</td>
<td>1.54 kg/m³ air</td>
</tr>
</tbody>
</table>

| dependent variables: |     |     |
| t TLV | 0.27 h | $\infty$ h |
| $c_o=0.5h$ | 4793 ppm | 49 ppm |
| $c_\infty$ | 4588 ppm | 45 ppm |
| (G) MAX | 0.341 g·h⁻¹·kg⁻¹ silage | 0.1 mg·h⁻¹·kg⁻¹ silage |
| (q) MIN | 826 m³/h | 25,896 m³/h |
| (h) MAX | 32.8 m | 1.3 m |

characteristics as the experimental silo monitored by Barber and Jan (1984). A normal silage blower was selected with an airflow capacity of 2880 m³/h, and natural ventilation was assumed to be zero. A mixing factor of $K = 1$ was chosen, which assumes that the ventilation air is directed down into the silo headspace. Ventilation was assumed to occur by dilution rather than by plug flow.

The threshold limit values (TLV) for safe exposure of humans to silo gases have been established by the American Conference of Governmental and Industrial Hygienists (ACGIH 1986). The maximum time weighted average (TWA) concentration for repeated or continuous exposure during an 8 h workday has been set at 5000 ppm and 3 ppm for CO₂ and NOₓ, respectively. The short term exposure limit (STEL), which allows up to 4 periods of 15 minute exposure separated by a 1 h interval, has been set at the higher values of 15,000 ppm and 5 ppm for CO₂ and NOₓ, respectively. Unless otherwise stated, the STEL values were used in this analysis.

RESULTS AND DISCUSSION

The baseline conditions described in the previous section were used with Eqs. 6, 8, 11, 12, 13 and 14 to calculate respectively $ttLV$, $c$ at $t=0.5$ h, $c_\infty$, $(G)_{MAX}$, $(q)_{MIN}$ and $(h)_MAX$. Values used for all independent variables and the calculated values for the dependent variables are summarized in Table I. Under the baseline conditions, the concentration of CO₂ was reduced from an initial level of 100% to an acceptable level of 15,000 ppm after 0.27 h of ventilation. The minimum CO₂ concentration achievable under the baseline conditions was 4588 ppm, well below the safe limit. The maximum CO₂ generation rate that could be diluted by continuous ventilation was 0.341 g·h⁻¹·kg⁻¹ silage. This rate is more than three times greater than the maximum gas generation rate reported by Meiering et al. (1988) for rye grass and indicates that CO₂ can be diluted to safe levels under practical field conditions. Similar data for CO₂ generation rates for other crops commonly ensiled are required before this conclusion can be generalised for all crops. The minimum ventilation rate needed to achieve a safe steady-state level of CO₂ under continuous ventilation was 826 m³/h. This ventilation rate is quite small and could be achieved by the silage blower even for $K$ as low as 0.29, and likely can be achieved in many silos by natural ventilation.

Unlike CO₂, NOₓ could not be reduced to the safe level of 5 ppm by the baseline ventilation rate. The minimum NOₓ concentration achievable under the baseline conditions was 45 ppm. Clearly, under these baseline conditions, the silo cannot be made safe to enter by ventilation. The maximum tolerable NOₓ generation rate that could be diluted by continuous ventilation was only 0.10 mg·h⁻¹·kg⁻¹ silage which is considerably lower than the rates of generation reported by Meiering et al. (1988). Again as in the case of CO₂, data are needed on the rates of generation of NOₓ for other common crops under various growing and fertilizing conditions. Until such data are available, silos should not be entered during the period of active gas generation, even with the silage blower being operated, unless the worker is wearing a self-contained breathing apparatus. The minimum ventilation rate required to achieve a steady-state safe level of NOₓ under continuous ventilation was 25,896 m³/h, or 153 airchanges/h. This amount of ventilation cannot be achieved by silage blowers, even when assisted by natural ventilation in exposed silos with loose fitting roofs.
The maximum silage depth from which NO\textsubscript{x} could safely be diluted under the baseline conditions was only 1.3 m.

These conclusions apply only to the baseline conditions. The results of the parametric analysis are presented as a series of graphs (Figs. 2 to 7). In the case of CO\textsubscript{2}, the ventilation time required to dilute the gas to 15,000 ppm was plotted versus each independent variable. Because even the steady state NO\textsubscript{x} concentration was greater than the safe limit of 5 ppm, similar plots for NO\textsubscript{x} would not be helpful; therefore, the concentration of NO\textsubscript{x} after fixed periods of ventilation was plotted versus each independent variable. In both cases, the plots generated for a gas generation rate of zero can be interpreted as applying to all silo gases after the period of active gas production.

**Gas generation rate**

The influence of the gas generation rate on silo ventilation is explored in more detail in Fig. 2. Figure 2a shows that the safe ventilation time for dilution of CO\textsubscript{2} between 0 and 0.098 g·h\textsuperscript{-1}·kg\textsuperscript{-1} silage. This is because even at the highest generation rate, the rate of removal of the gas by ventilation is always very much higher than the rate of release of the gas into the headspace. In the case of NO\textsubscript{x}, however, the gas generation rate has a substantial influence on the rate of decay of the gas concentration and on the final steady-state gas concentration that can be achieved (Fig. 2b). At rates of gas generation reported by Meiering et al. (1988), NO\textsubscript{x} release into the headspace is quite significant compared to the rate at which the gas can be removed by ventilation. Safety recommendations formulated by neglecting gas generation rates are valid for CO\textsubscript{2} but not likely for NO\textsubscript{x}.

**Ventilation mixing factor**

Barber and Jan (1984) reported mixing factors as low as 0.2 for the tower silo that they studied. Under conditions of no gas generation, decreasing $K$ from 1.0 to 0.2 would be expected to increase the safe ventilation period five-fold (Eq. 7). As shown in Fig. 3a, the time required to render the silo safe to enter increased from 0.3 h at $K = 1.0$ to 1.5 h at $K = 0.2$ for a gas generation rate of zero. The effect of $K$ on the ventilation time to 15,000 ppm CO\textsubscript{2} was very nearly the same for gas generation rates of 0 and 0.098 g·h\textsuperscript{-1}·kg\textsuperscript{-1} silage for $K$ down to about 0.4. In that range of $K$, the net ventilation rate still is sufficiently high that the rate of removal of gas by ventilation greatly exceeds the rate of production of the gas. Below $K =$

![Fig. 2a. Effect of gas generation rate on ventilation time to a safe CO\textsubscript{2} concentration.](image)

![Fig. 2b. Effect of gas generation rate NO\textsubscript{x} concentration after ventilation.](image)

![Fig. 3a. Effect of ventilation mixing factor on ventilation time to 15,000 ppm CO\textsubscript{2} for G=0 and 0.098 g·h\textsuperscript{-1}·kg\textsuperscript{-1}](image)

![Fig. 3b. Effect of ventilation mixing factor on NO\textsubscript{x} concentration after ventilation for G=0 and 0.9 mg·h\textsuperscript{-1}·kg\textsuperscript{-1}](image)
0.4, the time required to dilute the CO₂ gas by ventilation increases more rapidly when the gas generation rate is higher. The lowest \( K \) for which ventilation is able to ultimately dilute CO₂ to 15,000 ppm is 0.29.

Figure 3b shows that the minimum \( K \) for which NOₓ can be diluted to 5 ppm is 0.5 when the gas generation rate is zero. Though not shown by Fig. 3b, the minimum \( K \) can be calculated as 9.0 when the gas generation rate is 0.9 mg·h⁻¹·kg⁻¹ silage. Figure 3b confirms a very high \( K \) is required because even with a mixing factor of 1.0 the minimum NOₓ reached is around 42 ppm. Such a high \( K \) value could only be achieved by a ventilation flow regime approaching perfect plug flow, and is unlikely to occur in tower silos even with special ventilators.

**Initial gas concentration**

The influence of initial gas concentration on the safe ventilation time is not expected to be linear, even for a zero gas generation rate (Eqs. 6 and 7), but rather to be exponential. Figure 4a indicates an approximate doubling of the time to dilute CO₂ to 15,000 ppm when the initial gas concentration increased from 10 to 100%. Since there is little practical difference between predicted ventilation times from \( c_0 = 50\% \) or from \( c_0 = 100\% \), safety recommendations are best formulated assuming the higher level.

In the case of NOₓ where the gas generation term is very significant relative to the rate of dilution by ventilation, the effect of the initial gas concentration is of little practical consequence during the period of active gas production. The value of \( c_0 \) has no effect on the steady-state concentration achievable under continuous ventilation. Because the steady-state is very nearly reached after 1 h of ventilation, Fig. 4b shows that the NOₓ concentration after 1 h of ventilation is unchanged over a wide range of initial gas concentrations. Therefore, for NOₓ it is the gas generation rate, not the initial gas concentration, which determines whether a silo can be ventilated for safe entry. Neglecting NOₓ generation and compensating by assuming an artificially high initial concentration will introduce serious errors and is certainly not an acceptable approach to the formulation of safety guidelines.

After the period of active gas production, when \( G = 0 \), it is important to know the initial concentration of NOₓ. Figure 4b shows that the maximum initial concentration which can be reduced to below 5 ppm after 30 minutes of ventilation is approximately 2.5%. Much more research is needed to determine the maximum concentrations of NOₓ that are likely to occur in the headspace of tower silos. Unlike CO₂ where a maximum value of 100% could be accepted without imposing a large extra “cost”, a maximum initial concentration of NOₓ must be established.

**Ventilation rate**

When the gas generation rate is small or zero, the safe ventilation period is inversely proportional to the ventilation rate. This inverse relationship is also true for CO₂ even at the maximum gas generation rate (Fig. 5a) and the ventilation times are not sensitive to gas generation rate for ventilation rates above 2000 m³/h.

The steady state concentration under continuous ventilation is also inversely proportional to \( q \) for NOₓ because \( c_i \) is zero, and this fact is shown by the data in Fig. 5b. The ventilation rate is the only parameter that can be practically adjusted to bring the steady-state concentration of NOₓ below the safe
limit during the period of active gas production. However, the rates required are much higher than are immediately available to the practising farmer and become impractical.

Silo dimensions

For a given silo, the influence of silage depth and headspace depth cannot be considered independently. Equation 7 indicates that the ventilation time is expected to vary proportionally to the headspace volume when the gas generation rate is zero. Where the gas generation term is significant, the silo diameter appears inside the logarithmic term (Eq. 6), and the linear relationship with headspace volume is not expected.

As the silo is filled to greater depths, two somewhat counteracting effects occur to change the ventilation characteristics. As the depth of the headspace decreases, the ventilation time constant decreases for a fixed capacity blower, and the ventilation time to a particular gas concentration decreases. On the contrary, as the depth of the silage increases, the total mass of silage increases and the rate of gas release into the headspace increases. The increased gas production causes an increase in the ventilation time to a particular gas concentration.

The net result of these counteracting effects is shown in Fig. 6. For the case of CO₂ (Fig. 6a) and a silo with diameter of 6 m or less, the gas generation term in Eq. 6 is relatively insignificant and the ventilation time to 15,000 ppm CO₂ is linearly related to the depth of the headspace (Fig. 6a). When the silo diameter increases to 9 m, the effect of the gas generation term is more significant and the ventilation time is noticeably increased by a gas generation rate of 0.098 g·h⁻¹·kg⁻¹ silage compared to a zero gas generation rate. The maximum silage depth in a 9 m diameter silo for which the silage blower can dilute CO₂ produced at 0.098 g·h⁻¹·kg⁻¹ silage to the STEL concentration of 15,000 ppm is 16.9 m.

The influence of silage depth is more pronounced in the case of NOₓ for all silo diameters because the gas generation term in Eq. 6 is much more significant. The steady-state gas concentration, as calculated by Eq. 11 is a linear function of silage depth. For silo diameters of 4.5 and 6.0 m, the steady-state concentration is nearly achieved after 2 h of ventilation.
and the linear relationship with silage depth is apparent (Fig. 6b). For the 9.0 m diameter silo after 2 h ventilation (Fig. 6b), and for all silos after 0.5 h of ventilation, there appears to be a silage depth which yields a minimum gas concentration (Fig. 6c). This effect occurs because, at low silage depths and large headspace heights, the headspace volume is large and more time is required for dilution to a particular gas concentration. When the headspace is very small, the final gas concentration is high and the ventilation time constant is large; consequently, little time is required to reach the steady-state, albeit unsafe, gas concentration. The apparent “optimum” silage depth is of little practical importance because the steady-state NOx concentration is, for any silage depth greater than 1.6 m, higher than the safe concentration of 5 ppm. The analysis does highlight a very important aspect of silo ventilation. Whereas a small headspace may intuitively appear to be easier to ventilate, and whereas that is true when the gas generation rate is small or zero, the small headspace may be the most dangerous during the period of active gas production.

In all of the analyses to this point, the silo height was 18 m. Taller silos are common, especially at diameters greater than 6 m. The taller silos are more difficult to ventilate because the headspace may be deeper and the rate of gas release into the headspace from the greater mass of silage may be higher.

Figure 7a shows that, for 4.5 and 6 m diameter silos, a CO2 generation rate of 0.098 g·h⁻¹·kg⁻¹ silage continues to have an insignificant effect on silo ventilation compared to a zero gas generation rate for silos up to 30 m high. For the 9 m diameter silo, however, the gas generation rate becomes significant at silo heights greater than 20 m, and for a silo height of 24 m, dilution of the CO2 to safe levels may not be possible. This analysis points out the important need for more complete data on CO2 generation rates by typical silage materials, and to further investigate ventilation effectiveness in large diameter silos.

**Fig. 7a. Effect of silo height on ventilation time to 15,000 ppm CO2 for G=0 and 0.098 g·h⁻¹·kg⁻¹. Silo diameters D=4.5 m, 6.0 m and 9.0 m.**

The effect of silo height on NOx concentration after 30 min ventilation of the silo is shown in Fig. 7b. This graph is not very interesting because, at the gas generation rate used in this analysis, the steady-state NOx concentration is above the safe limit of 5 ppm at all practical silage depths and all practical silo dimensions.

Graphs such as those in Fig. 7 could be used to determine the maximum silo height for which ventilation of a particular duration, say 30 minutes, would render the silo safe to enter. For example, in the case of CO2, the maximum height of silo, filled to two-thirds its height with silage, which can be ventilated to safe levels in 30 minutes is 18 m.

**Fig. 7b. Effect of silo height on NOx concentration after ventilation for G=0 and 0.9 mg·h⁻¹·kg⁻¹. Silo diameters D=4.5 m, 6.0 m and 9.0 m.**

**CONCLUSIONS**

The theoretical analyses presented herein, albeit based on limited data from practical farm silos, suggest that ventilation with a silage blower may not, after any duration of ventilation, permit safe entry into some silos for some silages under some field conditions. The limitation on silo ventilation is greater for larger silos. Previous recommendations for ventilation of tower silos have been based on the assumption that the gas generation rate was negligible. Except for the very largest farm tower silos, this assumption may not lead to significant errors in the case of CO2, but seems likely to be greatly in error for NOx even for small silos. Silos should not be entered during the period of active gas production without protection of a self-contained pressure-demand breathing apparatus.

More data are needed for the rate of gas generation by other commonly ensiled materials under various growing and fertilizing conditions, and for the value of the ventilation mixing factor. This is especially so for large silos. With these data, the equations given in this paper provide a suitable framework on which to develop comprehensive safety guidelines for safe operator entry into tower silos.

**ACKNOWLEDGEMENTS**

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**REFERENCES**

ACGIH 1986. Threshold limit values for chemical substances in work air. American Conference of Governmental Industrial Hygienists, Cincinnati, OH.


NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>$c$</td>
<td>gas concentration within headspace ($m^3/m^3$)</td>
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<tr>
<td>$c_{ex}$</td>
<td>gas concentration in exhaust air ($m^3/m^3$)</td>
</tr>
<tr>
<td>$c_i$</td>
<td>gas concentration in supply air ($m^3/m^3$)</td>
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<td>$c_o$</td>
<td>initial gas concentration within headspace ($m^3/m^3$)</td>
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<tr>
<td>$C_s$</td>
<td>total gas generation rate for silo ($m^3/h$)</td>
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<td>$c_{TLV}$</td>
<td>maximum safe gas concentration ($m^3/m^3$)</td>
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<td>$c$</td>
<td>steady-state gas concentration within headspace ($m^3/m^3$)</td>
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<tr>
<td>$D$</td>
<td>silo diameter (m)</td>
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<td>$G$</td>
<td>specific gas generation rate ($kg^{*}h^{-1}*kg^{-1}$ silage)</td>
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<tr>
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