SILO GAS: VENTILATION OF TOWER SILO HEADSPACES

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Previous safety recommendations and research in silo ventilation are briefly reviewed. Theoretical silo headspace ventilation requirements for safe entry are discussed in relation to headspace volume, forage blower capacity and penetration of the ventilation air into the headspace. Natural and forced ventilation were investigated using portable electric blowers and forage blowers with and without drop-tube. Portable electric blowers were too slow and cumbersome. The forage blower with a flexible drop-tube connected to the filler pipe was found to be the most effective and practical method of ventilating recently-filled silos for improved safety. Theoretical ventilation times did not agree closely with in-silo ventilation measurements, indicating that for safety the mixing effectiveness of the forage blower needs to be verified in each case, either by remote gas measurements or other means.

INTRODUCTION

Some gases produced during silage making, i.e. carbon dioxide (CO_2), nitric oxide (NO) and nitrogen oxide (NO_2) are lethal when inhaled in sufficient quantities and concentrations. Freshly-made silage produces dangerous levels of these gases in confined spaces such as the silo, feedroom and connecting barn. These gas hazards are not a new threat, as indicated by the number of safety bulletins issued previously on this subject. At present, no good method has been found to reduce the production of silo gases. Although a satisfactory remote gas concentration measurement system has been developed for silo gases (St. Denis and Sabourin 1984), the system has not yet been assembled and sold as a user-ready kit. Pressure-demand, remote breathing apparatuses are commercially available and are generally recommended for safe entry into confined spaces containing hazardous gases. However, the equipment is too expensive and technical for widespread use by untrained farmers. At this time, forced ventilation of the headspace remains the only practical method for farmers to deal with silo gas, although for absolute safety the effectiveness of the ventilation procedure needs confirmation.

The objective of this study was to investigate improved methods of ventilating silos, considering such factors as silo diameter, headspace depth, ventilation rate and effectiveness.

Forced Ventilation of Silos

Forced ventilation before entering the silo has long been a primary safety recommendation. Many authors have recommended ventilating tower silos with the forage blower, but the recommended ventilation times varied widely. Grayson (1957) and Fleetham (1978) simply stated that the blower should be turned on before entering the silo. Neidermeyer and Burris (1963) recommended 15–20 min of blower operation before entry, also stating that no one should enter the silo during the danger period without someone else standing by. Horvath et al. (1978), quoting Commins et al. (1971), recommended that the blower should be run for 30 min prior to entry. In fact Commins et al. (1971) stated that people should never enter a silo tower containing new silage without using suitable breathing apparatus. They reported that in a silo headspace 6.7 m diam. by 10 m deep, 30 min running time did not reduce silo gases to safe levels at 0.3 m height near the walls.

Other safety recommendations could be misleading. For example, Barber (1976) recommended removing all exposed silo chute doors before ventilating. Schrottmaier (1982) recommended operating the blower for as little as 2–3 min (without reference to the volume of the headspace) and for 3 min/hr when an operator is working in the silo for a long period of time. The effectiveness of the blower and the effects of removing the silo chute doors obviously needed further investigation.

Given the rate of accumulation and volume of gas accumulating in the headspace, the headspace volume, the ventilation capacity and the mixing effectiveness (as determined by equipment configuration), it might be possible to predict safe ventilation time. However, in spite of recent work in silage process modelling by Muck et al. (1983), little of this information is suitable yet to specify safe ventilation procedures.

Industrial Ventilation Methods

The ASHRAE Manual (Anonymous 1976) outlines three ventilation methods: dilution-displacement, local exhaust, and dilution combined with local exhaust. Local exhaust makes the most efficient use of air-moving capacity. This could be done in silos with a portable exhaust fan connected to a suction tube drawing unmixed silo gases from the lowest point in the headspace. Dilution-displacement on the other hand corresponds to blowing fresh air into the silo headspace with the forage blower. This requires much higher air-moving capacity and does not completely eliminate the contaminants. Local exhaust and dilution-displacement methods were both tried.

Dilution-displacement, Theoretical Approach

Barber and Ogilvie (1982) used the following general equation to describe the concentration decay rate of a tracer gas (or a contaminant, like CO_2 or NO_2) in a ventilated airspace:

$$\mathrm{Log}_n \frac{C - C_i}{C_o - C_i} = -\frac{KQt}{V} \qquad (1)$$

Where C = gas concentration (by volume), C_i = inlet gas concentration, C_o = original gas concentration, Q = ventilation rate (forage blower capacity), V = headspace volume, t = time after start of ventilation, and K = ventilation ratio or mixing factor.

Equation (1) can be rewritten for more convenient calculations, as follows:

$$\frac{C - C_i}{C_o - C_i} = e^{\frac{-KQt}{V}} \qquad (2)$$

When, for example, a silo is ventilated

to reduce CO_2 to a safe level, the incoming fresh air contains a trace of CO_2 (C_i = 0.03%). This makes C_i so low that it has negligible effect. For NO_2, C_i is practically zero. The original gas concentration, C_o, can be measured if a reliable gas detector is available, but otherwise a value for C_o must be assumed.

Headspace depth, for discussion purposes, is defined as the distance from the top of the silo wall to the top of the silage, and headspace volume is the cylindrical volume from the top of the wall to the silage surface.

The mixing factor K depends on the ability of the air-blast from the forage blower to penetrate. mix and displace the contaminated air lying in the deepest part of the silo headspace. With perfect mixing, K = 1.0 but it can be greater or less than 1.0 (Barber and Ogilvie 1982).

TEST PROCEDURES

Local Exhaust with Portable Blowers

Two portable exhausters were tested (local exhaust method). Tests were carried out on naturally produced silo gases and with CO_2 injected into the silo headspace. The injected CO_2 was supplied from pressure cylinders connected to a perforated garden hose. The initial CO_2 concentration was adjusted to about 10% by volume at 0.3 m above the silage and maintained thus for about 5 min to stabilize. Under windy conditions natural ventilation made it impossible to maintain the CO_2 concentration for 5 min and in these cases local exhaust tests were started as soon as 10% CO_2 was achieved.

The two electric blowers were each connected to 30 m of 100-mm diam. wire-wound domestic clothes-drier tubing. The first blower (chosen for its low cost and easy portability) was a small axial-flow unit rated at 92 L/sec at 100 Pa air pressure. This one was quickly judged to be too small and a large centrifugal blower was also tried (Centrimax, no. CX33A26 by Rotron Inc., Industrial Division, Sawyer Industrial Park, Saugerties, N.Y. 12477). This was rated at 215 L/sec at 240 Pa air pressure (the estimated friction loss in 30 m of drier tubing). To simplify handling of the tubing, a cord was threaded inside and secured to the remote end. Pulling the cord thus collapsed the tube to its minimum length.

Each exhaust fan was lifted to the silo roof opening. From there the suction tube was uncoiled, dropped into the silo and extended to the lowest point on the silage surface. The tube was connected to the inlet of each blower in turn. Before starting the exhauster and at 5-min intervals during ventilation an operator in the silo measured gas concentrations at 0.3-m height using chemical detector tubes.

TABLE I. FORAGE BLOWER CAPACITIES AT 540 r/min

Make	Model	Year	No. tested	Air delivery L/sec ± sd
Dion	V354	1972	1	930 —
Dion	N14	1976	4	935 ± 120
Dion	N14	1977	4	826 ± 280
New Holland	27	1976	1	960 —
Int. Harvester	—	—	1	850 —

Dilution-displacement with the Forage Blower, Distributor Attached

Using a hot-wire anemometer to measure air velocities across the blower pipe outlet, the air-moving capacities of five different forage blowers were measured. Running empty at 540 r/min (rated speed), blower outputs ranged from 800 to 1000 L/sec (Table I). This was 4–5 times the capacity of the larger portable exhauster tried previously. In spite of the ASHRAE preference for the local exhaust ventilation method it was reasoned that with these higher capacities the forage blower showed potential for rapid and easy silo ventilation. A further advantage of this method is that most farmers using silos own a forage blower.

Tests were conducted in 1980 to determine gas mixing effectiveness of the forage blower in the headspace of 10 silos. Air velocity measurements were taken 0.6 m above the silage surface in a "cross" pattern, including readings 0.3 m from the wall and closer to the silo center as well. Silo distributor types mounted in the silos included side-mounted split flow, center-fill gooseneck, rotating inclined plate and inclined plate with spinning disc.

Field Survey — Natural and Forced Ventilation

In 1980, one silo was instrumented with a CO_2 recorder (Mexa Model 221, Horiba Instruments Inc., 1021 Dungea Ave., Irvine, Calif. 92714) and four silos were similarly equipped for various periods in 1981. Sampling height was 0.3 m above the lowest point of the silage surface. Three silos were also instrumented with an NO_2 recorder (Ecolyzer Model 7230, Ecolyzer Energetics Science Co., 85 Executive Blvd., Elmsford, N.Y. 10523). The primary objective in instrumenting these silos was to study gas production (Reid et al. 1984) but important results were also obtained with respect to natural and forced ventilation.

In 1981 another series of ventilation tests was conducted using gas concentration readings as the indicator of dilution-displacement effectiveness. Eight silos selected for the tests were primarily those producing large amounts of CO_2 and/or NO_2, supplemented in some cases by CO_2 added from portable cylinders. The silo distributors (all types, including goosenecks where applicable) were positioned to give the best air movement at the silage surface, as established in previous tests. For comparison, nine other tests were completed in seven silos in which one end of a 200 mm diam. flexible drop-tube (Spring Flex tubing, Flexhaust Co., 11 Chestnut St., Ambesbury, Mass.) was squeezed into the outlet end of the blower pipe. The tube length was 5 m in all cases,

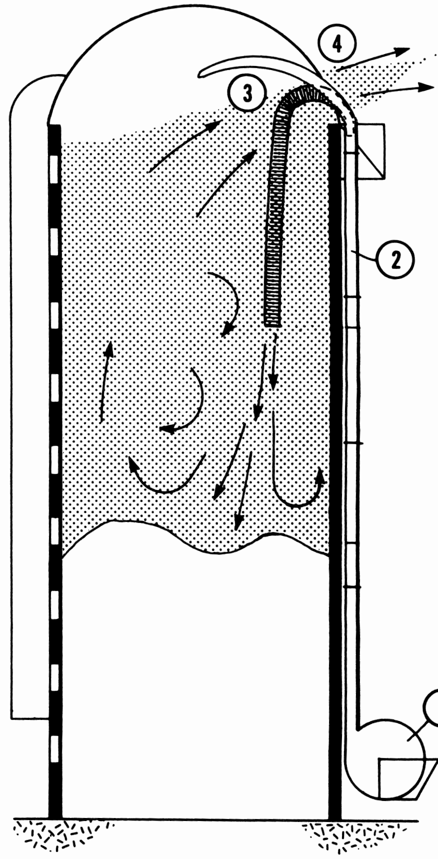
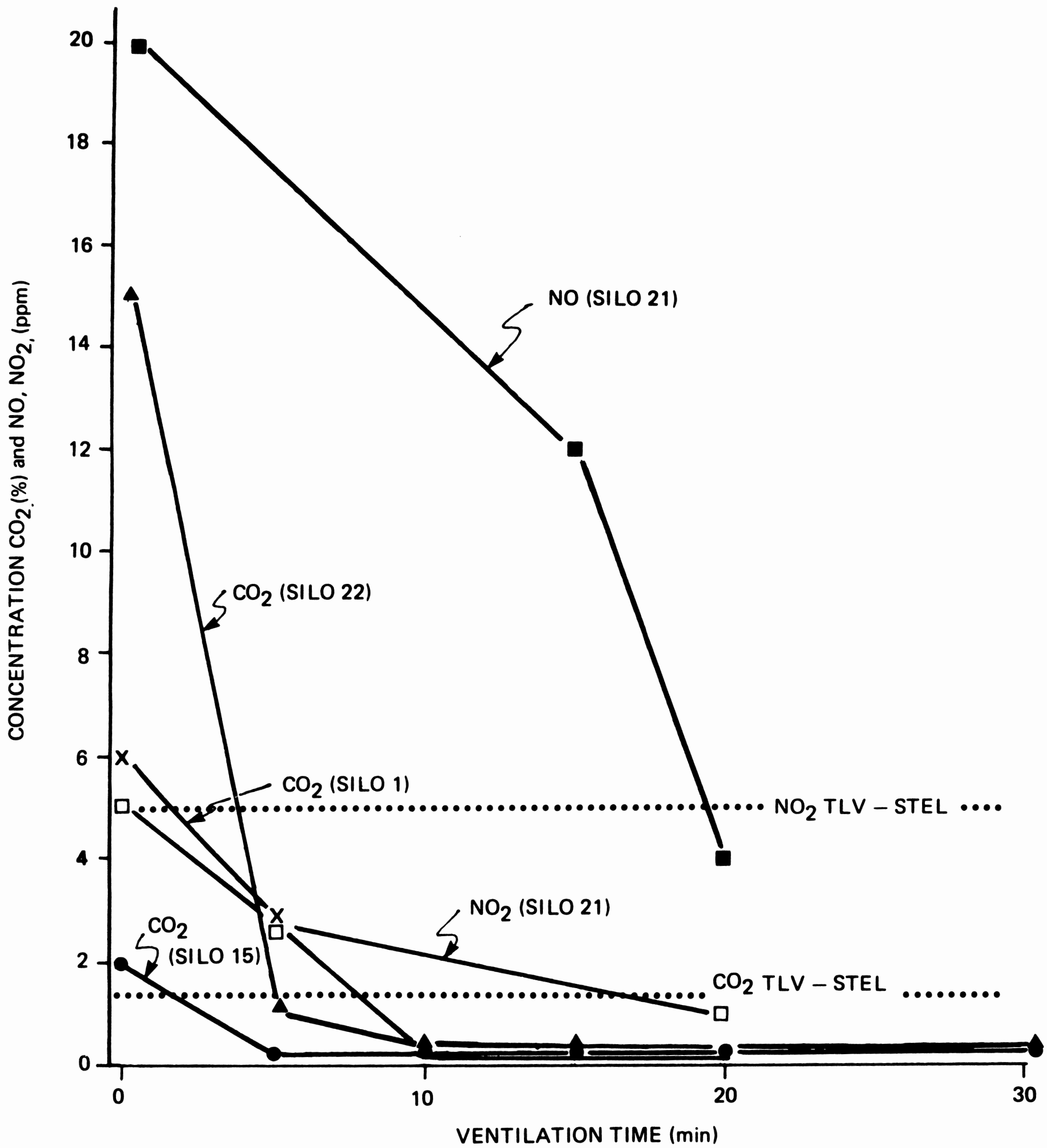


Figure 1. Silo ventilation by forage blower and flexible drop-tube. (1) forage blower, (2) fixed filler pipe, 228 mm diam., (3) 200-mm Spring Flex wire-wound tubing stuffed into (2), (4) mixed and diluted silo gas escapes through open roof hatch.

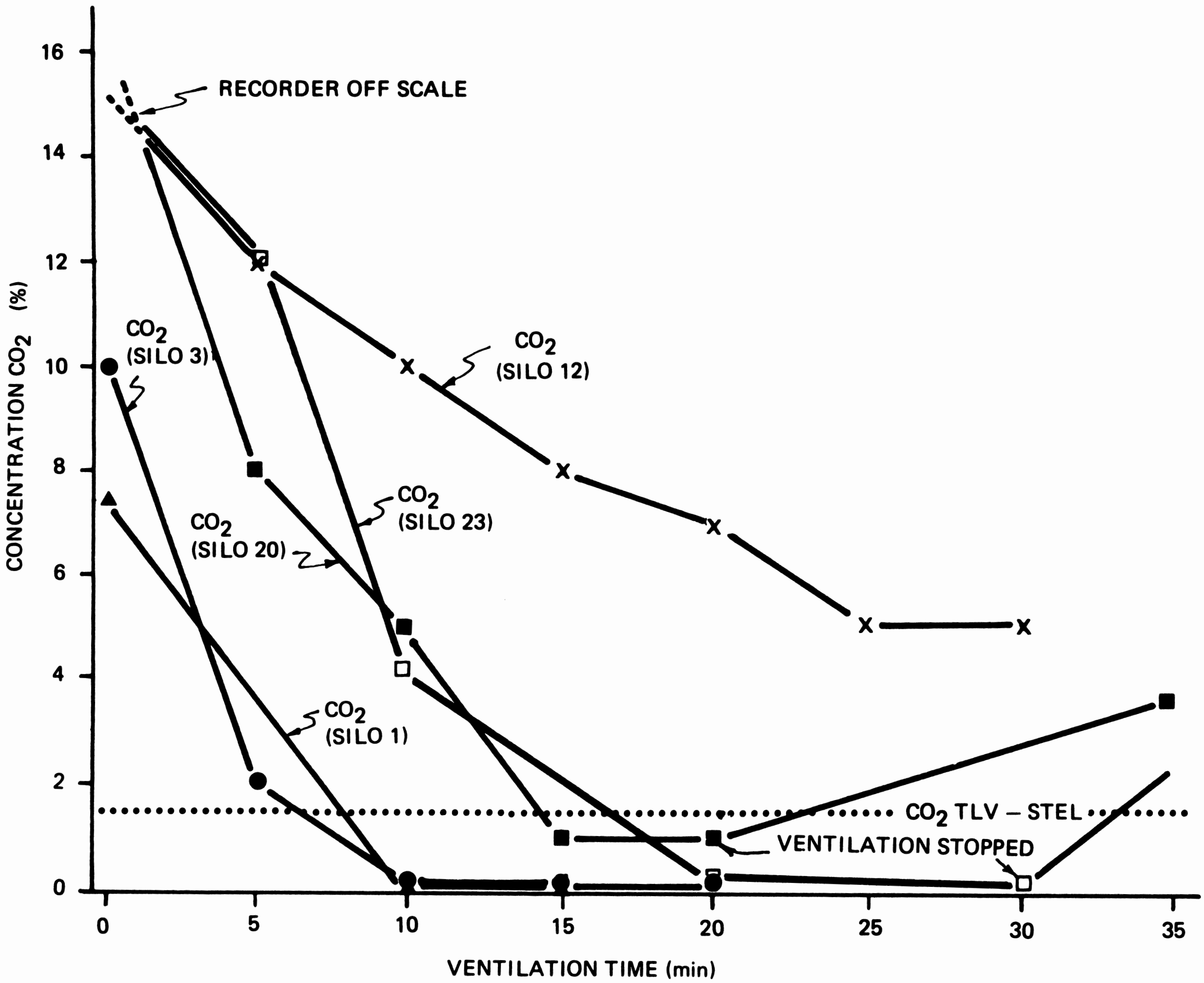


LEGEND

	Silo no.	Silo dia. (m)	Headspace depth (m)	Test gas	
X	1	4.9	3.0	CO_2	added
●	15	7.3	6.3	CO_2	natural
□	21	5.5	2.2	NO_2	"
■	21	5.5	2.2	NO	"
▲	22	6.1	8.3	CO_2	"

Figure 2. Ventilation of various farm silos with 215 L/sec portable exhaust fan and 30-m length of 100 mm wire-wound tubing.

except silo 27 where a 15-m length was used (Fig. 1). The distances from the tube outlet to the silage surfaces varied. Except when windy conditions provided some natural ventilation the injected CO_2 gas was allowed to stabilize for 5 min before starting the blower. Under windy conditions it was difficult to obtain a stable gas concentration and the ventilation was



LEGEND

	Silo no.	Silo diam. (m)	Headspace (m)	Distributor	CO_2 Gas	Time from filling (h)
▲	1	4.9	3.0	inclined rotating plate	added	
●	3	4.9	6.0	inclined rotating plate	added	
×	12	4.9	7.0	wall mtd. split flow	natural	70 (chute doors open)
■	20	5.5	13.0	inclined plate & spinning disc	natural	17
□	23	6.1	9.0	inclined plate & spinning disc	natural	18.5

Figure 3. Forced ventilation of silo headspace using the forage blower with various silage distributors adjusted for optimum ventilation. Gas concentrations were read at 0.3 m above the silage surface, using Dräger tubes and/or Mexa 221 CO_2 recorder.

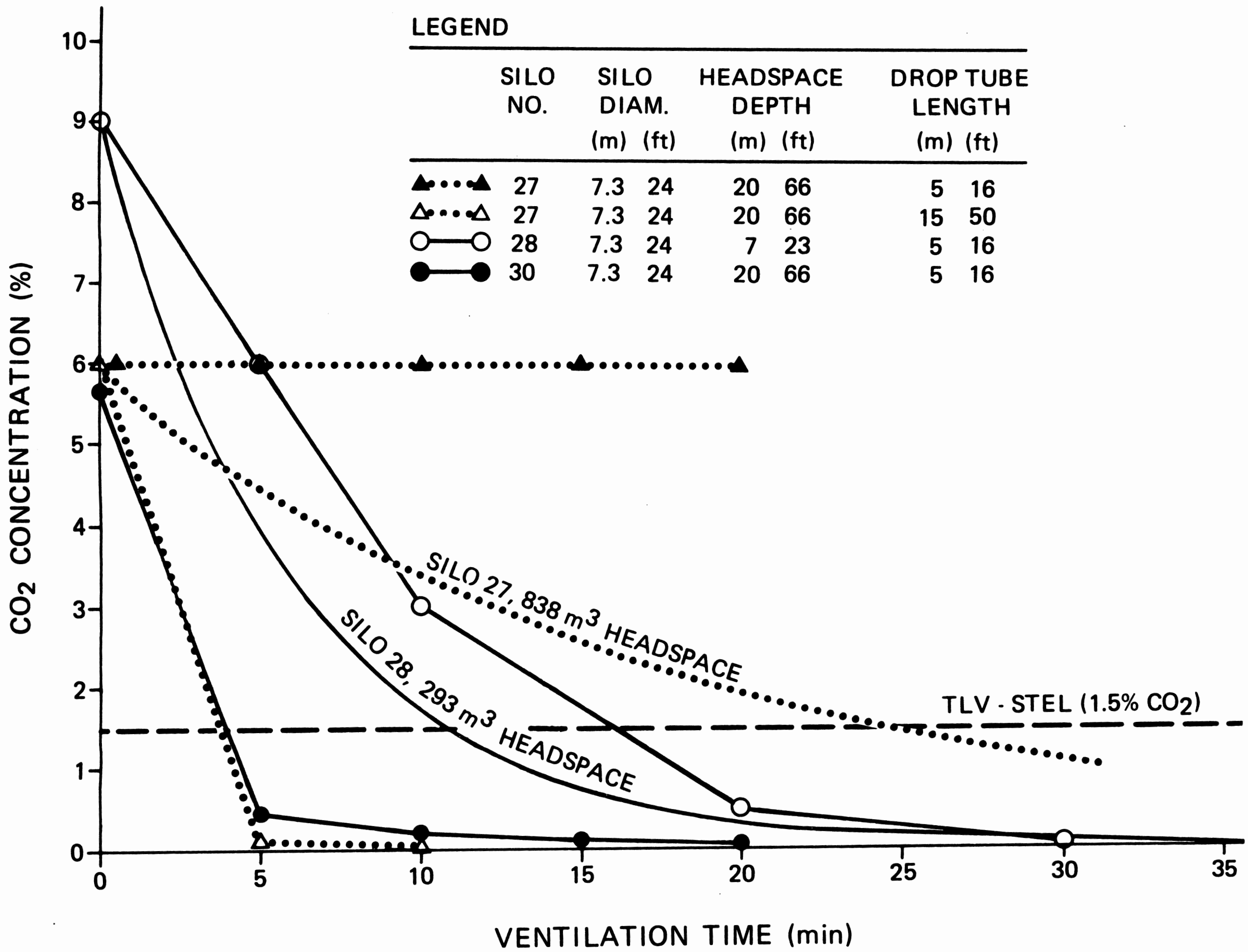


Figure 4. Forced ventilation of silo headspaces using a forage blower with flexible drop-tube attached. Point-to-point lines identified in the legend are based on CO_2 measurements taken by Dräger gas tester. Smooth curves are theoretical dilutions for silos 27 and 28, based on Barber and Ogilvie (1982).

started almost immediately.

RESULTS AND DISCUSSION

Local Exhaust By Portable Blower

Results with the larger fan (rated at 215 L/sec) are shown in Fig. 2. The drawdown curves for CO_2 and NO_2 were all satisfactory, passing down through the relevant short-term exposure limits in less than 8 min. However, the curve for NO (silo 21) required 20 min of ventilation to reach 4 ppm. The shape of this drawdown curve may imply a much deeper accumulation of NO than of NO_2.

From the outside safety cage the technician found it very difficult to cast the flexible suction tube onto the lowest point of the silage surface. Furthermore, the larger fan was judged too awkward and too expensive to be widely accepted by farmers. The local exhaust concept was therefore dropped in favor of dilution-displacement using the forage blower.

Dilution-displacement by Forage Blower, Distributor Attached

Measured air velocities at 0.6 m above the silage surface ranged from negligible to 1.02 m/sec using forage blowers with their silage distributors in various positions, including the position for best mixing as established in earlier tests. Poor mixing (negligible velocity) was observed where the headspace depth exceeded 11 m, where a side-mounted distributor was badly adjusted for air flow and where a center-mounted rotary distributor deflected the air-blast towards the silo wall. Even the center-fill gooseneck (with nothing obvious to interfere with air flow) failed to mix the headspace air adequately at 14-m depth. Probably the open underside of the gooseneck allows some entrainment of headspace air, thus reducing the velocity and penetrating power of the free jet.

Figure 3 shows some effects of silage distributors and headspace dimensions on ventilation effectiveness. In silos 1 and 3 (4.9 m diam., inclined plate distributors, 3 m and 6 m headspace depths, respectively), 10 min of ventilation reduced CO_2 to well under the 1.5% STEL.

However, in silos 12, 20 and 23 (natural CO_2), with deeper headspaces (7, 13 and 9 m, respectively), results were less encouraging. In silo 20 the blower barely maintained safety while running (minutes 15–20). After stopping the blower at minute 20, CO_2 again rose above the STEL. This also happened in silo 23 after stopping ventilation at minute 30.

Silo 12 (7 m headspace, wall-mounted split-flow distributor) still tested at 5% CO_2 after ventilating for 30 min. This poor ventilation may have been caused by air dispersion at the distributor or by airflow passing over the main volume of the headspace and escaping via the open chute doors.

From the limited results shown in Fig. 3 only tentative conclusions can be made. With headspace depths of 5 m or less the forage blower, running at rated speed (540 r/min), ventilates effectively. However, with increasing headspace depth any type of attached silage distributor seems to interfere with effective jet penetration and resulting mixing effectiveness. Therefore, some attachment is required to by-pass the distributor and

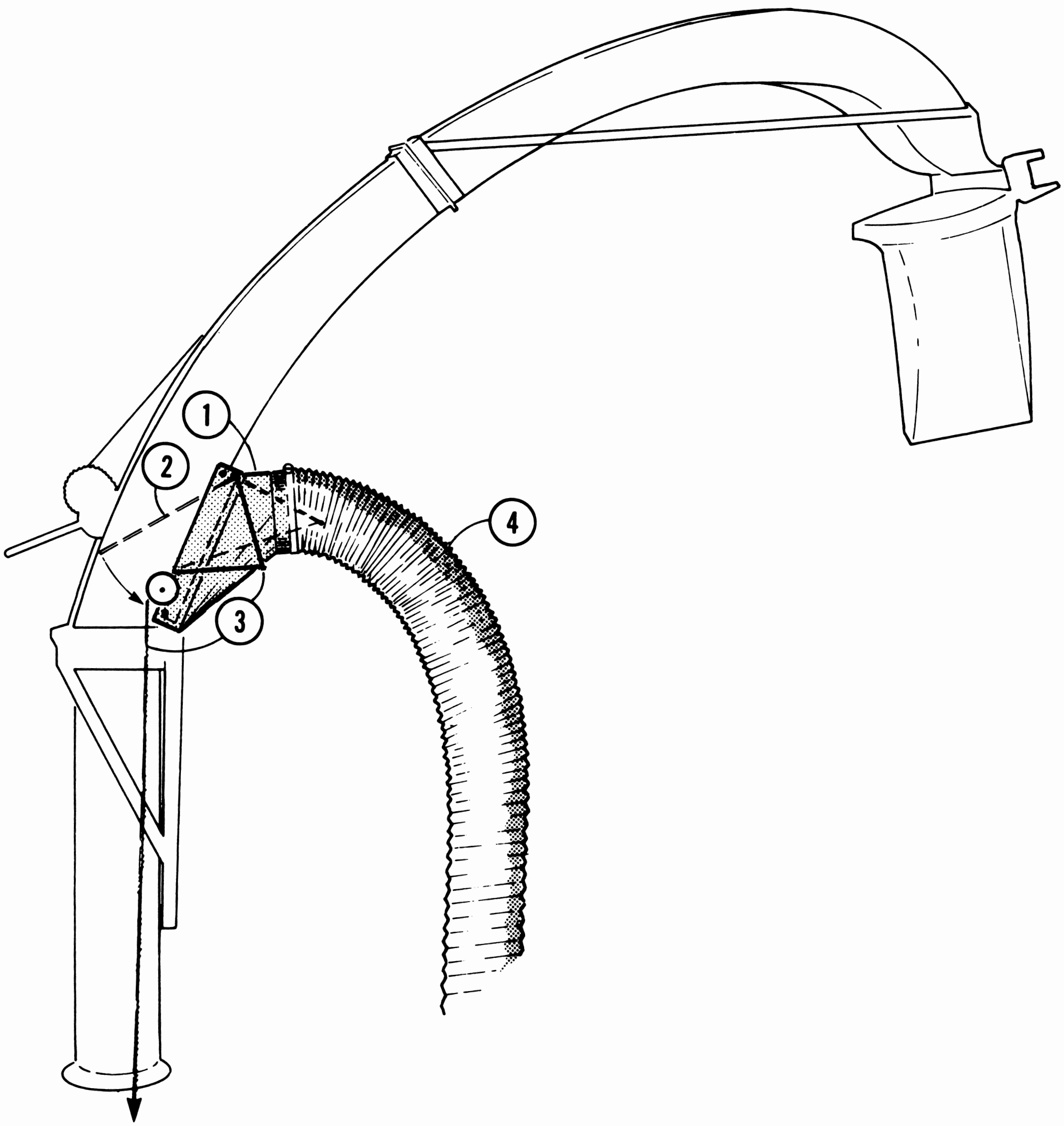


Figure 5. Proposed gooseneck attachment for diverting the ventilation down into the silo headspace (gooseneck design by Lancaster Level-Flo, Inc. Lancaster, Pennsylvania 17602). (1) Attachment fitting and rectangular-to-round transition piece; bolts to throat of gooseneck, bolt heads smooth and flush inside throat. (2) Diverter flap-valve spring-loaded to 'open' position. (3) External crank and cable pulls valve to 'bypass' position for ventilating the silo. (4) 200-mm 'Spring Flex' wire-wound ventilation tubing, gear clamp to transition piece (1).

direct the air-jet down into the deeper headspace. The chute doors should be left closed and the roof hatch open to improve mixing and to reduce the chances of displacing silo gas down the chute into the feedroom and barn. Rapid reaccumulation of dangerous CO_2 levels in silos 20 and 23, after stopping ventilation, clearly demonstrates the need to continue ventilation while working in a silo during the danger period.

Dilution-displacement by Forage Blower with Drop-tube

Figure 4 shows smooth theoretical gas drawdown curves, based on Eq. 2, for silo 27 (with 838 m^3 headspace) and for silo 28 (293 m^3). In each case the initial gas concentration C_o was taken near the bottom of the headspace (9% and 6% CO_2, silos 27 and 28, respectively). These concentrations were assumed to be uniform throughout each headspace (an oversafe assumption). Full ventilation effectiveness (K = 1.0) and ventilation rate (Q = 800 L/sec) were also assumed.

Corresponding point-to-point lines in Fig. 4 show the ventilated concentrations achieved, measured at 0.3 m above the silage. In silo 27 with a short 5-m drop-tube no ventilation was indicated (there was some doubt about the security of the drop-tube in the blower pipe outlet). However, increasing the drop-tube length to 15 m apparently achieved very effective ventilation; CO_2 dropped to 0.1% within 5 min of starting ventilation. Silo 30 was also made safe in less than 5 min, even though it had a similar 20-m deep headspace but only a 5-m drop-tube. Actual ventilation times in these two latter cases were well below the curves predicted for perfect mixing ($K > 1.0$).

Silo 28, sampled 1.0 m above the silage, showed 9% initial CO_2 and with 20-min ventilation showed 0.5% (quite safe). However, unlike silo 27 the actual curve was above the corresponding theoretical curve until almost 30 min of ventilation, indicating imperfect mixing ($K < 1.0$).

The 5-m drop-tube (with one exception, silo 27) appears to improve the reliability of silo headspace ventilation with the forage blower. For headspace

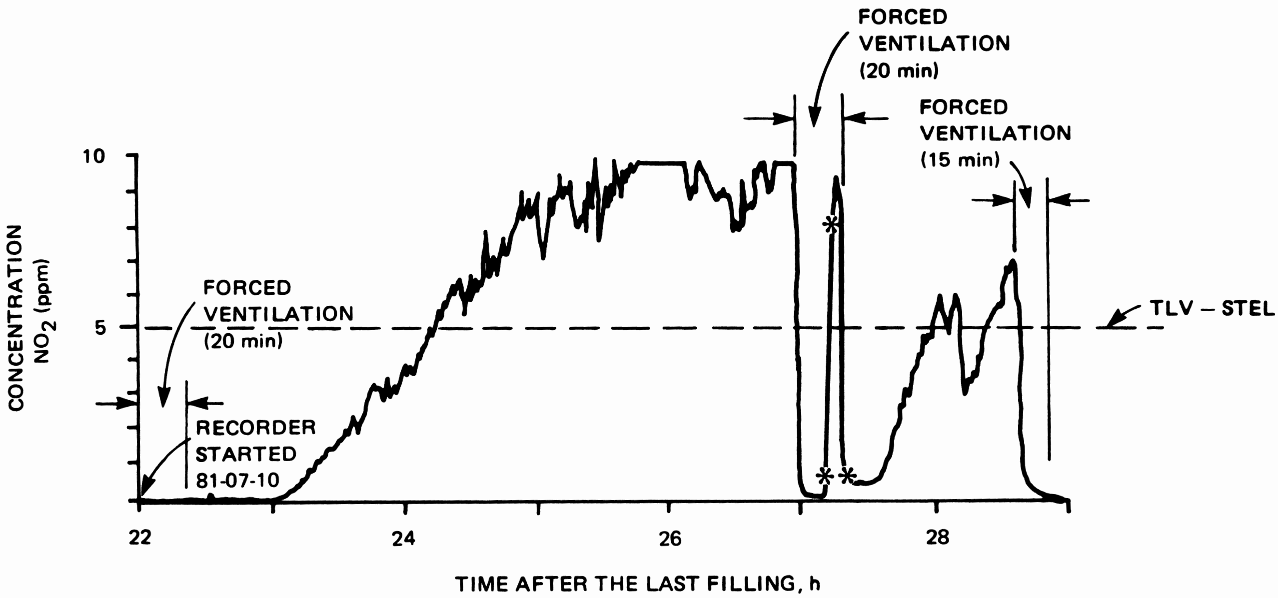


Figure 6. Recorder chart for NO_2 in silo 26 with a 5-m drop-tube (1981), 0.3-m sampling height. * spot readings taken with Dräger gas detector sampled at 1-m sampling height.

depths greater than 10 m a longer drop-tube extending to within 5 m of the silage would be safer but the longer drop-tube would be harder to handle and more bulky to store.

Also, there is some risk that the drop-tube could fall out while an operator is working in the silo. A simple and secure attachment kit for the drop-tube is badly needed. Figure 5 shows one proposed design, including a by-pass valve (2) rope-controlled from the ground.

Field Survey of Ventilation using Continuous Recorders

Silo 26 was ventilated using a 5-m drop-tube 22 h and 26.9 h after filling. Concentrations of NO_2 and CO_2 are recorded in Figs. 6 and 7. During each ventilation period, CO_2 and NO_2 dropped to low levels almost instantly. This could mean that ventilation is instantaneous (not likely), that there was almost complete local displacement of the contaminants at the gas sensor location but not necessarily elsewhere in the headspace (more likely) or that the volume of accumulated gas was small (most likely in this case). After both periods of ventilation, the concentrations of CO_2 and NO_2 again rose rapidly above their respective TLV-STEL levels. This further confirms the need for continued ventilation while working in silos. Between 24.2 and 25.1 h after filling, the sensor inlet for the CO_2 recorder was raised from 0.3 to 2.0 m above the silage surface, at which time a concentration of only 0.45% CO_2 was recorded. This implies that the total accumulation of gas was neither large nor was the concentration increasing at this sampling height. This emphasizes the need to sample gas concentration at different heights for research and also confirms the greater margin of safety if ventilation time is determined from an initial concentration observed near the silage surface at the lowest point.

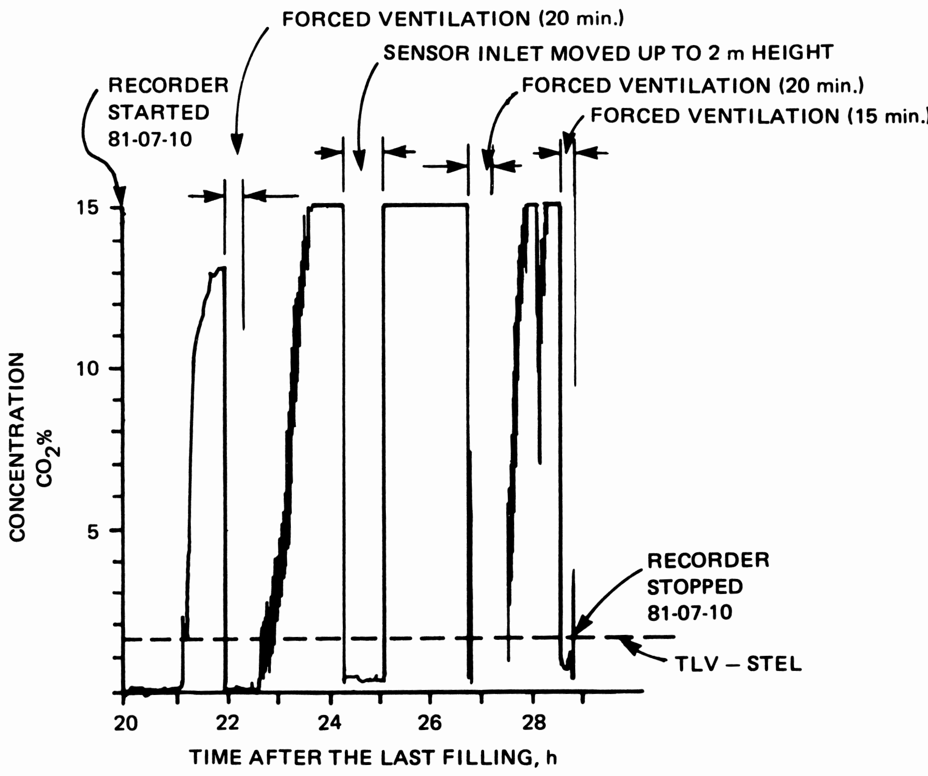


Figure 7. Recorder chart for CO_2 in silo 26 with a 5-m drop-tube (1981).

Note in Fig. 6 the abrupt 9.5 ppm NO_2 spike recorded at 0.3-m height during the second period of ventilation (hour 27) even though the concentration had previously dropped to only 0.2 ppm. This spike was confirmed by three detector tube readings (see *, Fig. 6) and lasted about 6 min. This unexplained observation implies a need to check gas concentration at least twice, say at 5-min intervals, to confirm safe conditions.

At 18 h after filling (Fig. 8), silo 23 was ventilated for 20 min without a drop-tube. The CO_2 concentration level dropped

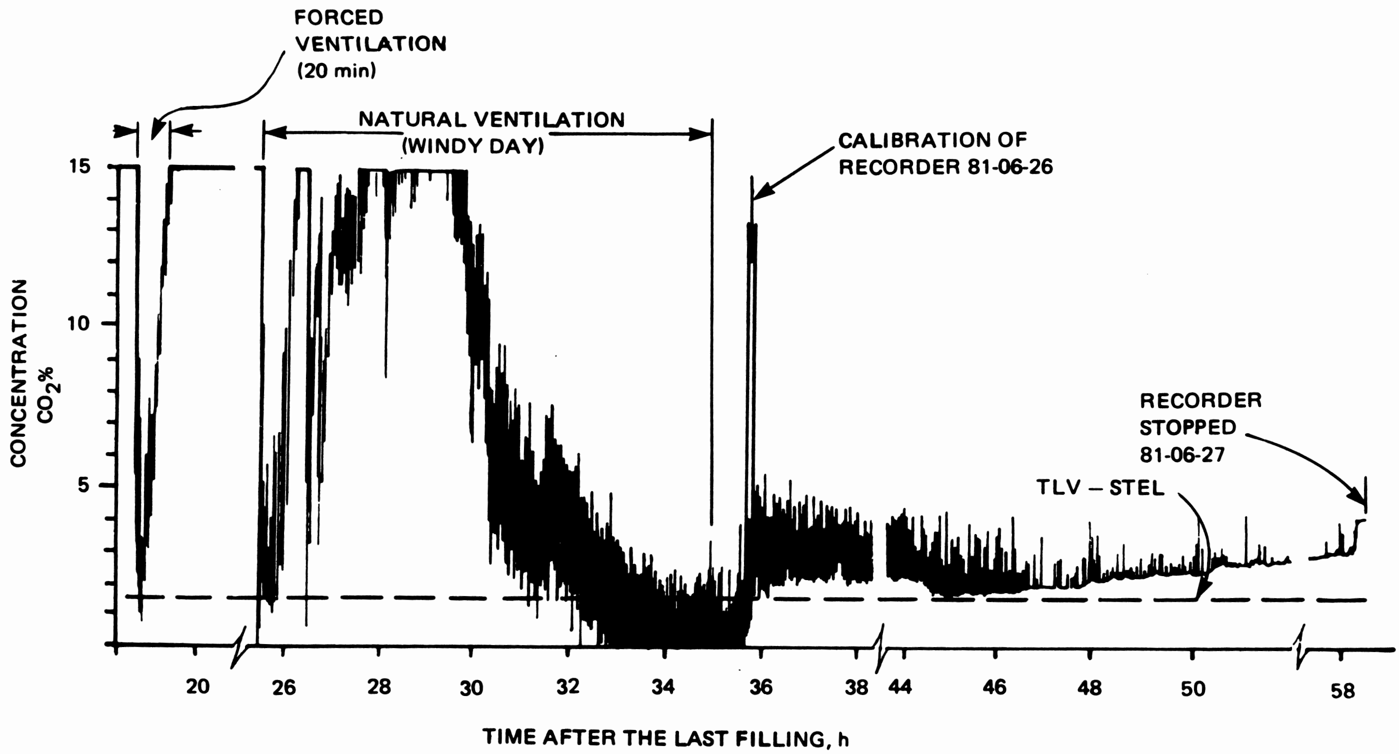


Figure 8. Recorder chart for CO_2 in silo 23 (1981).

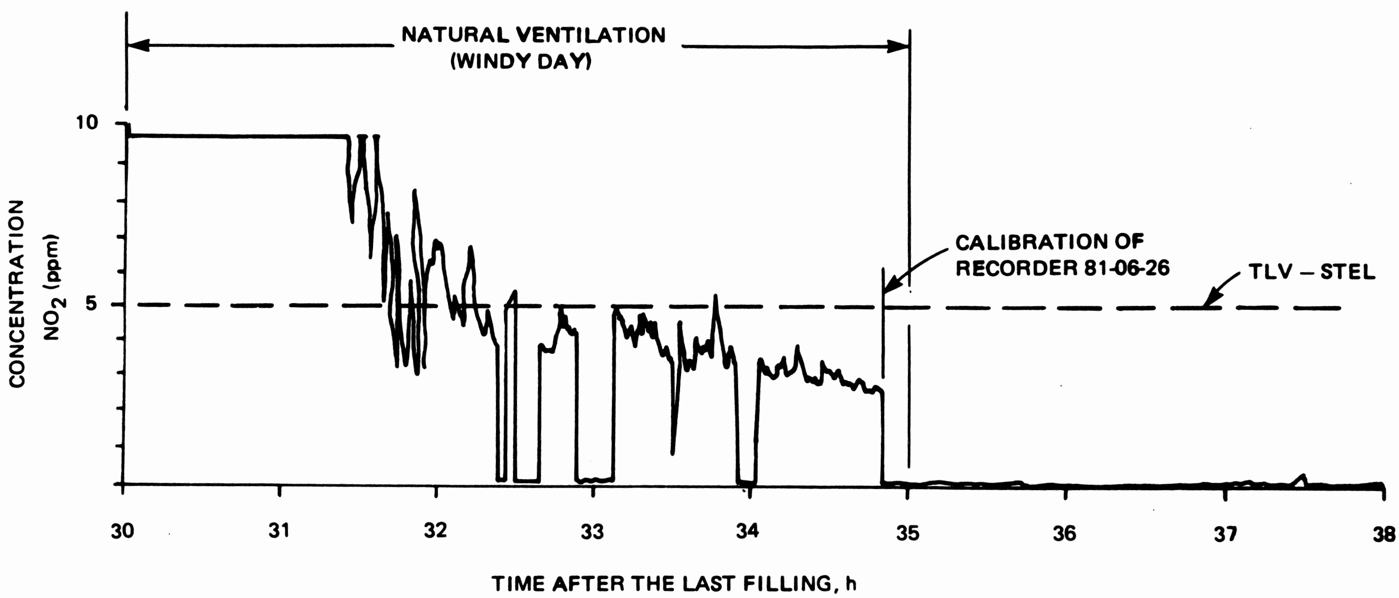


Figure 9. Recorder chart for NO_2 in silo 23 (1981).

quickly to less than 1% but returned to over 15% very soon after the ventilation was stopped. At the same time the NO_2 concentration could not be reduced below 10 ppm. This confirms the need to check for both CO_2 and NO_2, or CO_2, NO and NO_2. Figures 8 and 9 both show gradual reductions of silo gas over time, due to wind ventilation and other natural causes.

SUMMARY AND RECOMMENDATIONS

Previous safety recommendations and research in silo ventilation are reviewed. Ventilation of the silo headspace with a portable electric blower and flexible suction tube was satisfactory except when nitric oxide was being naturally produced at a high rate. However, the exhaust ventilator kit was not easy enough to handle from the silo roof opening, therefore this method is not considered a practical option.

Ventilation with the forage blower seems more practical for the typical farm situation. In partially filled silos, especially with silage distributors in place, the air blast from the forage blower was apparently diverted so that ventilation was often incomplete and unpredictable. A collapsible drop-tube greatly improved forced ventilation in deeper headspaces of silos up to 7.3 m diameter. Five to ten minutes of blower operation in most cases achieved a safe working atmosphere. During active gas production it was found necessary to keep the blower running while working in the silo.

A design is proposed for an attachment kit, with a rope-controlled by-pass valve, to improve convenience and security for attaching the flexible drop-tube.

A theoretical dilution equation (2) is presented to relate required ventilation time to original gas concentration C_o, headspace volume V, ventilation rate Q and ventilation effectiveness ratio K. The headspace volume V can be easily calculated from headspace depth and diameter, and the ventilation rate Q has been determined (Table I). Provided that full penetration of the diluting air jet into the deepest part of the headspace can somehow be confirmed, an assumed mixing effectiveness of $K = 1.0$ is probably acceptable. However, there are practical difficulties in determining the original gas concentration C_o, since two readings taken near the headspace bottom cannot indicate either the depth of gas accumulated or its rate of production. Nevertheless, Eq. 2 does provide a basis for further investigations.

Forced ventilation with all the silo chute doors closed and the roof hatch open has the advantage that silo gases would be less likely to be blown into the silo chute, feedroom and connected barn.

Until the doubtful points mentioned above have been resolved a safe ventilation time cannot be determined for absolute safety. Therefore, use of a pressure-demand, remote breathing apparatus by trained personnel is still the recommended procedure for working in silos recently filled.

Work is needed to produce and market the remote detection system developed for silo gases (St. Denis and Sabourin 1984), and to develop the drop-tube adaptor kit for attachment to the forage blower pipe. Further research is required on production and accumulation of CO_2, NO and NO_2 in typical unsealed silo headspaces. The ventilating effectiveness of the forage blower needs further confirmation, particularly in silos over 7.3 m in diameter.

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