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APPLICATION OF MODIFIED ATMOSPHERES IN FARM GRAIN STORAGE BINS

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Abstract—The use of a modified atmosphere for fumigation of circular, corrugated steel farm grain storage bins was investigated. The bins were 4.6 m diameter and filled to a depth of 1.5 m with wheat. Details of the concentration histories during purge with the modified atmosphere are given, and data on the effect of gas flow rate during maintenance is also provided. Comparisons were made between bins with and without drying floors, as well as between bins which were unsealed, those which were well-sealed, and those which were sealed by using a plastic film over the grain surface. It was found that satisfactory concentrations could be achieved using purge rates which produce superficial linear velocities above 30 cm/hr. At these rates, the gas volume required to purge the air from the grain is equivalent to the space occupied by the grain bulk (and its interstitial space). After purging, the concentrations may be successfully maintained by a gas rate producing a velocity of 3 cm/hr if a surface covering is used. A surface covering reduced gas maintenance requirements by a factor of 10 compared to that for a ventilated overhead space and by a factor of 2 compared to completely sealing the overhead space.

INTRODUCTION

Low oxygen atmospheres (or modified atmospheres, MA) offer a safe, residue-free alternative to chemical fumigants and protectants for controlling insects infesting stored grain and grain products. In the U.S.A., modified atmosphere treatment has been exempt from tolerance requirements on all raw and processed agricultural commodities (Anonymous, 1980, 1981). In recent years, three approaches to producing a MA lethal to insects have been studied extensively: (1) purging the grain with nitrogen from a tank of liquid until the interstitial atmosphere contains less than 2% oxygen, (2) introducing carbon dioxide from a tank of liquid until the interstitial atmosphere contains 35–90% carbon dioxide, and (3) purging the grain with a mixture of carbon dioxide and nitrogen (usually produced by burning a fossil fuel) until the interstitial atmosphere contains less than 5% oxygen. Each of these methods will effectively control insect infestations. Selection of the most appropriate procedure depends upon the availability and cost of the gas or fuel, the cost of the equipment, and the suitability of the grain storage facility. The literature on the efficacy, practicality, and costs of these approaches has been reviewed in detail (Bailey and Banks, 1974, 1980; Banks, 1978, 1984; Banks *et al.*, 1980; Storey, 1980; Soderstrom *et al.*, 1984; Love, 1984; Annis, 1986; Fleurat-Lessard and LeTorc'h, 1986).

In practice, the MA is introduced rapidly into the grain during a purge phase to displace the normal atmosphere. In deep, silo-type bins, where most prior studies have been performed, the point of introduction is usually at the bottom and little mixing of the MA and initial atmosphere occurs as the MA rises more or less evenly through the grain. Extensive mixing, due to back dispersion of air, does occur near the top surface and in the space above the grain and, as a result, low levels of oxygen may be difficult to achieve in these areas. Bailey and Banks (1974) have suggested that purge gas requirements might be minimized by reducing the open headspace above the grain. Studies have not been done to characterize the movement, distribution, and extent of surface dissipation of MA during the initial purge phase in shallow, farm-type storage bins. However, we would logically expect more uneven horizontal distribution of the MA along with increased surface loss due to dissipation in proportion to the relative increase in surface area.

The purge phase is usually followed by a maintenance phase during which the MA is maintained by continuing to introduce it at a rate that will offset leakage from the bin and will limit back dispersion of air at the surface at an acceptable level. The maintenance is continued as long as is needed to control the infestation. Although the dynamics of pest populations exposed to short-term MA treatments have not been adequately studied, times required for 100% mortality of all stages of some species have been shown to be longer than for conventional fumigants. Because of this, much recent research, particularly in Australia, has focused on materials, procedures, and standards for making bins sufficiently airtight to minimize the cost of the maintenance phase (Bailey and Banks, 1974; Banks and Ripp, 1983; Banks and Annis, 1984).

Air-tight storage bins obviously would reduce the cost of MA or even conventional fumigation, and would provide the added benefit of helping to exclude invading insects. However, in the U.S.A., over two-thirds of the grain storage capacity is in small, on-farm facilities that would require significant costs to seal. Furthermore, sealing these grain bins could interfere with the natural aeration that in much of North America helps to prevent temperature gradients and the resulting destructive moisture migration that occurs in large grain bulks. Sealing also would interfere with access for inspection of the grain and ventilation essential for removing harzardous dusts and fumes (Banks and Ripp, 1983). Thus, while modified atmosphere fumigation would be most effective in air-tight structures, it would be more useful if it could be effectively applied in bins that are not well sealed.

This study was conducted to evaluate the feasibility of using MA in the well-ventilated, corrugated steel, circular, metal bins that are the predominate type of grain storage facility on U.S. farms. We investigated different rates and methods of gas introduction and the behavior and distribution of the gas in the relatively shallow grain mass contained in these farm bins. We also investigated the effectiveness of a polyethylene film, like that used in conventional fumigation, for reducing loss from dissipation of the MA at the grain surface and as an alternative to sealing the bins.

MATERIALS AND METHODS

Four bins were treated with MA. They had the following characteristics: 4.6 m diameter, 2.1 m side wall made of corrugated steel and bolted at the joints, conical roof with two hatches, center vent at the top, continuous vents at the eaves, and a door on the side approximately 0.6 × 1.2 m. Two of these bins had a 30 cm deep drying floor, while the other two had concrete floors without aeration ducts. Obvious gaps around the doors and around the bottom edges in all the bins were sealed by caulking. One of the bins with a concrete floor was "well-sealed" through a considerable amount of effort expended in sealing the bottom, the door, the top hatch, the eave vents, and all bolted seams. In some of the experiments a polyethylene cover was used over the top surface of the grain. This was secured against the walls by using a large expandable hoop made of PVC pipe or by piling some grain on top of it around the edges. A 15 cm "X" was cut in the center to allow gas to escape. All the bins contained wheat to a depth of 1.5 m.

Probes made of 6 mm steel tubing were inserted at positions in the grain which were anticipated to be of particular interest. Usually 18 probes were used; this number being about the maximum that could be reasonably sampled during the purge phase of the experiments. Typically, 5 or more probes were arranged vertically in the center of the bin and then at two other locations about 30 cm from the wall. Other probes were placed where rapid concentration changes were anticipated. Sampling was accomplished by drawing gas through the probe, and through a polyethylene connecting tube to a Teledyne Model 320-P Portable Oxygen Analyzer with an accuracy of 0.2% oxygen. The time required to take a single concentration reading depended on the length of the connecting tubing and the response of the oxygen sensor, but generally was less than 30 sec. The modified atmosphere for the farm-type bins was produced by a mobile gas burner (Gas Atmospheres, Port Washington, Wisc., U.S.A.) with an output of up to 57 m^3/hr (2000 CFH) of gas with 86% nitrogen, 14% carbon dioxide, and less than 0.2% oxygen. The MA was dehumidified to about 20% r.h. at 25°C. Propane was used as the fuel. The density of the MA was about 7% greater than that of air.

MA at the desired flow rate was injected through a flowmeter and the concentration at the probe locations monitored until steady state was achieved, after which the flow rate was reduced to a desired maintenance flow and the concentration monitored just often enough to note the decay of the gas concentration and when steady state was again achieved. The data of interest for the purge experiments was the rate of progress toward steady state, while that for the maintenance was the final steady state. After a purge and maintenance run, the bin was purged overnight with air to remove all traces of MA. No problems of gas adsorption or desorption in the grain were encountered during any phase of the experiments. Over 100 experimental runs were made in the bins.

RESULTS AND DISCUSSION

The results for the purge experiments are shown primarily as plots of oxygen concentration in the grain vs time with height as a parameter. For the maintenance phase, time was not of interest and only the final steady state was recorded and the results are shown as steady state concentrations as a function of height and flow rate. Several of the figures are plotted in a dimensionless form as will be described below.

Purge experiments

For a bin with a drying floor, the modified atmosphere (MA) first mixed in the open volume beneath the floor, then began movement upward through the grain. Sample probes near the floor indicated a relatively rapid decrease in oxygen concentration which approached the concentration of the MA asymptotically. At sample points higher in the grain, the oxygen decrease was delayed compared to that at points lower in the grain. In addition, changes were not so rapid due to dispersion as the MA front moved upward through the grain. This dispersion effect was fairly minor in these experiments because of the short height of grain and relatively low purge velocities used. Toward the upper surface of the grain the MA concentration approached the injected concentration only at the highest purge rates. This was due to the back dispersion of air from the overhead space. Three examples of the phenomena just described are shown in Fig. 1 where the oxygen concentration at several vertical locations is given as a function of the time from the start of MA injection below the drying floor. The information for this figure is from a bin with a drying floor and with no special sealing of any kind. The data for these figures were connected using a standard fifth-order spline method. This results in some "waviness" in some of the curves, depending on the number of data points and their scatter. This fitting procedure was deemed preferable to a regression analysis on these individual curves since the objective was to show the actual shape of the curves resulting from the data.

Figure 1 also shows the effects of different purge rates on the progress of MA through the grain. The curves at the different purge rates are similar but are shifted with respect to one another on the time scale. The lower purge rates required a longer time to reach equivalent MA concentrations. If the concentration of the injected MA and/or the height of the grain had been different from one run to another, the concentration asymptotes and height parameters would also have been different

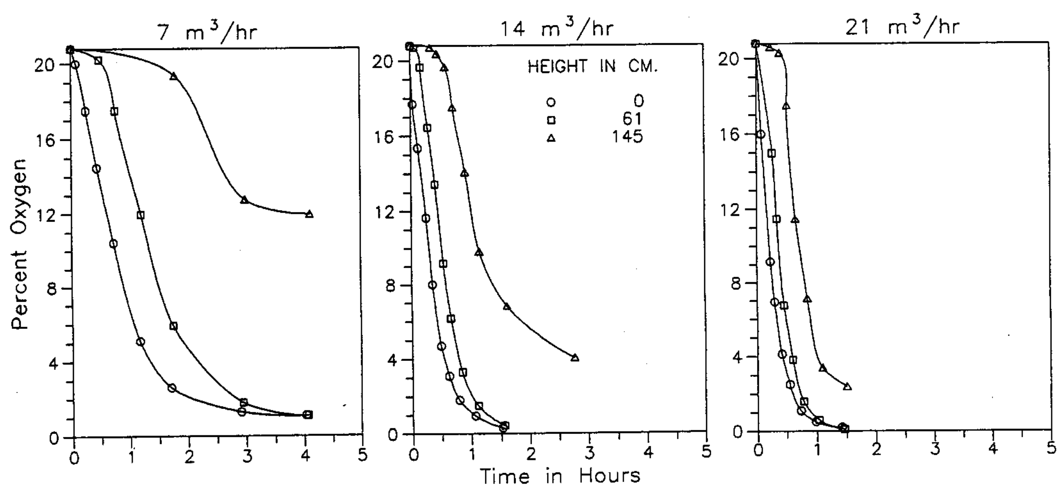

Fig. 1. Concentration histories during 7, 14 and 21 m^3/hr purge in a bin with a drying floor. Diameter—4.6 m; height of wheat = 1.5 m; 30 cm deep drying floor; data from the center of bin.

in these three figures. In order to eliminate these effects and so that concentration histories for runs at different conditions can be more easily compared, dimensionless (or normalized) coordinates are defined:

$$\text{dimensionless oxygen concentration} = \frac{O_2 \text{ conc. in grain} - O_2 \text{ conc. in MA}}{O_2 \text{ conc. in air} - O_2 \text{ conc. in MA}}$$

$$\text{number of grain volumes of gas} = \frac{(\text{purge rate})(\text{time})}{(\text{grain volume})}$$

$$\text{dimensionless height} = \frac{(\text{height from bottom})}{(\text{total grain height})}.$$

It should be especially noted that the "number of grain volumes of gas" (which is also referred to as "dimensionless time") is based on the total space occupied by the grain, that is, the volume of the grain along with its interstitial volume, but does not include the drying floor or overhead volumes. This definition was selected because it is based on the volume most often reported and one which is easily calculated. For the case of wheat the number of volumes of gas used in the purge would be about 2.5 times that reported here if calculations were based on the interstitial space alone.

Using the dimensionless quantities defined above, the data shown in Fig. 1 were converted and the results are shown in Fig. 2. It is now possible to compare the concentration histories at different flow rates. The curves for different purge rates, but at the same height, are reasonably close to one another except near the top surface. To give an indication of the reproducibility of the concentration histories the results of three identical experiments at a purge rate of 14 m^3/hr are presented (Fig. 3). The variations seen in Fig. 2 for three different purge rates are not much different from those recorded at identical rates (Fig. 3) except near the surface where back dispersion shows up to a greater degree at the low flow rates. The difference between the data from these identical runs (Fig. 3) is mainly due to variations in the MA injection rates, and wind effects. The precise quantitative relationship between wind and wind concentration was not established, but the effects were most noticeable when the head space was well-ventilated and there was no covering on the surface of the grain. Of course, these same variables affected the experimental results at all the other purge rates in a similar manner. The concentration histories at different radial positions for bins with drying floors were essentially the same indicating that the progress during purge is independent of radial position.

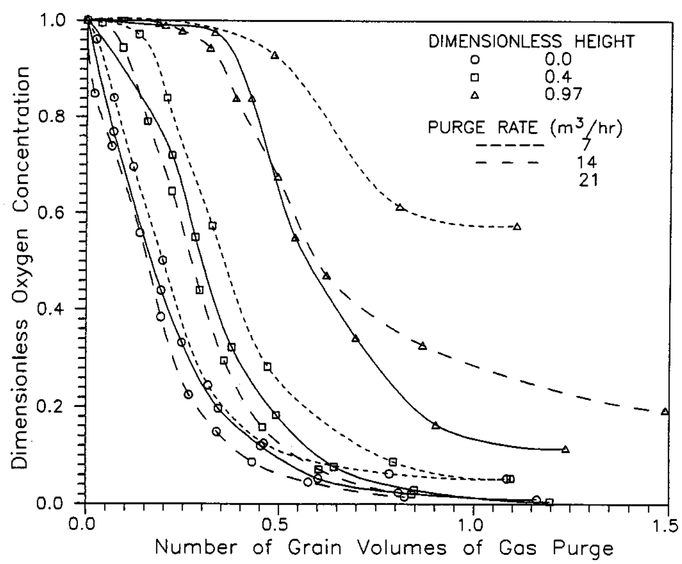

Fig. 2. Comparison of dimensionless concentration histories during purge at 7, 14 and 21 m^3/hr in a bin with a drying floor. Diameter = 4.6 m; height of wheat = 1.5 m; 30 cm deep drying floor; data from the center of bin.

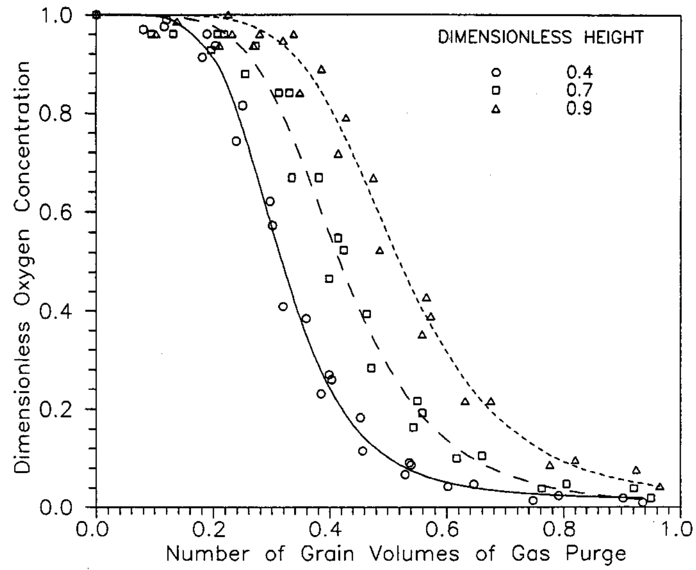

Fig. 3. Concentration histories for three identical runs. Diameter = 4.6 m; height of wheat = 1.5 m; 30 cm deep drying floor; data from the center of bin; purge rate of 14 m^3/hr.

In Fig. 3 the data were fitted to the following equation using nonlinear regression:

$$Y = \frac{(1-c)}{(1+aT^b)} + c \tag{1}$$

where

Y = the dimensionless concentration
T = number of grain volumes of gas or dimensionless time

and

a, b, c = the constants determined by regression.

It should be noted that this equation was not selected from any theoretical considerations. It simply provides a reasonably good representation of the progress of the concentration during purge in that the values and slopes of this equation at the beginning and end of the purge agree with the data. A weighting factor of $1/T$ was selected to force the curve through the initial condition (0, 1) and because it seemed reasonable that the uncertainty in the data would increase as T increased.

Data presented thus far show that a drying-floor bin may be essentially purged of air, except very near the surface, after injection of MA equivalent to about the total volume of grain. Near the surface, back dispersion of air causes an increase in the oxygen concentration especially at low purge rates. At the purge rates below 5 m^3/hr (or superficial velocities based on an empty bin of less than 30 cm/hr) considerable concentration variations near the surface were encountered when the head space was well ventilated and if there was any wind. For example, at 2.8 m^3/hr we were never able to achieve oxygen concentrations below 4% oxygen throughout the bin. No attempt was made to completely document the surface fluctuations since they depended on so many uncontrollable variables such as wind velocity and direction, head space configuration, etc. These variations were well damped out 7–15 cm under the surface and therefore data from this region down to the bottom were the most reproducible.

Because of the atmospheric effects on the surface and the difficulty of reducing the oxygen concentration at that location, many researchers have suggested some sort of sealing. For the average farm storage facility, thorough sealing procedures probably would not be practical nor implemented completely. Therefore, we evaluated the use of a polyethylene film over the grain surface as a simple and inexpensive method of reducing surface dissipation of the MA. The purge and maintenance of MA was compared in bins with no sealing, in bins using a surface cover, and in bins where the sealing was as complete as possible. It was found that the various sealing procedures had very little effect on the concentration histories during purge for MA rates of 2.5–50 m^3/hr. The only detectable result of sealing was a lowering of the oxygen concentration near the surface, and that was only noticeable when comparing runs made at the lowest purge rates. Concentration histories were determined at a number of locations throughout the grain, but measurements 15 cm beneath the surface were used as representative of the progress of the purge. At that depth, variations in concentration due to the dissipation of the MA from the surface were small even at the lowest purge rates.

The radial distribution of the MA was not the same for bins with the two different types of floor. At the flow rates tested, the drying floor facilitated equal flow up through the grain at all locations. As a result, the concentration was independent of radial position and the concentration history 15 cm beneath the center of the surface was taken to show the progress of the purge. In the solid-floor bins the MA was injected through a pipe passing through the wall with the end at the center of the bin and 30 cm above the floor. In this case, the oxygen concentration decreased more rapidly up through the center than it did near the walls and the concentration history representing the progress of the MA was taken 30 cm from the wall and 15 cm beneath the surface.

The concentration histories from the locations just described are plotted in Fig. 4 where the nonlinear regression lines using equation (1) are also shown. Considering the wide range of flow rates, surface conditions, and atmosphere conditions, the results are fairly consistent and this plot may be used to predict the purge requirements for these types of bins. The fact that the curves for the two different types of bins are very similar is due to the following: (1) the drying floors facilitated an even flow distribution up through the grain, but additional MA was required to purge the space beneath the drying floor and (2) the point injection did not produce a very even radial distribution and gas was lost through the center before the wall areas were purged. The gas lost through the center for point injection was about the same as that needed to purge the space beneath the drying floor.

As an example of the possible use of Fig. 4, consider the situation where it is desired to reduce the concentration of oxygen to under 2% from the bottom to 15 cm below the surface. For this case, the dimensionless concentration is about 0.1 and the number of grain volumes of MA needed for the purge would be 0.8 ± 0.2. For a 4.6 m bin with 1.5 m depth of wheat, the grain volume is 25 m^3. At a purge rate of 14 m^3/hr, for example, this would require about 1.1–2 hr. In bins with larger height-to-diameter ratios we would expect slightly better gas purge efficiency due to the

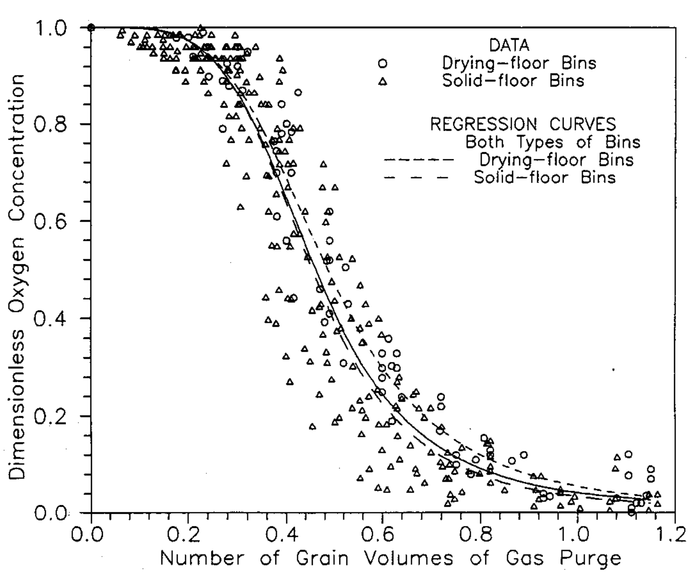

Fig. 4. Purge data from bins with drying floors and bins with solid floors. Data from 15 cm beneath the surface (dimensionless height = 0.9).

relatively smaller effect of the space beneath the drying floor or the reduced fraction of the gas lost through the center for a solid-floor bin. We would also expect that higher purge rates (i.e. higher face or superficial velocities) and the use of a surface covering would reduce the oxygen concentration in the very top portion of the grain and significantly reduce the detrimental effects of wind at the surface, resulting in slightly increased efficiency.

Maintenance experiments

After a bin is purged with the modified atmosphere, the oxygen concentration must be maintained at a low level for several days or even weeks to kill the insects. To continue the gas input rate at the purge levels would be prohibitively expensive, therefore it is generally suggested that a much lower rate be established—one which will simply maintain the gas concentration at a constant level. To see how the maintenance flow rate affects the steady state concentration profiles

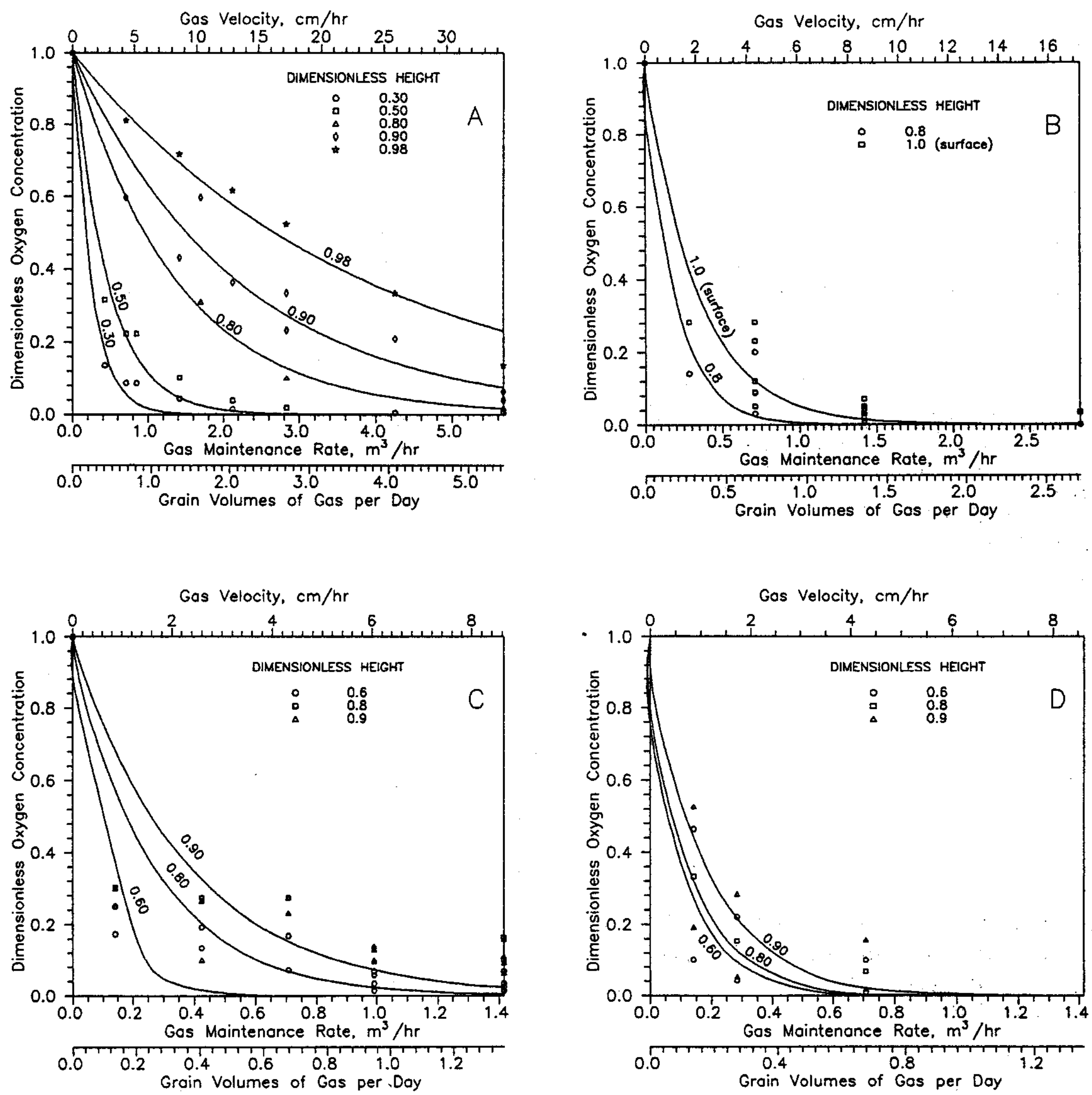

Fig. 5. Concentration during maintenance in: A—bin with a drying floor and no surface covering; B—bin with a drying floor and with surface covering; C—well-sealed bin with a solid floor, point injection, and no surface covering; D—bin with a solid floor, point injection, surface covering, and the overhead space well-ventilated.

in a bin, Figs 5A–D are shown. In each of these figures the data were fitted as a simple exponential with no weighting:

$$Y = \exp(-aG) \tag{2}$$

where

Y = dimensionless concentration
G = gas maintenance rate

and

a = the regression parameter.

This seemed to give an adequate representation for comparison of the data considering the scatter and the relatively few data points. Figure 5A shows the case for a drying-floor bin with no surface covering. Note that as the flow rate is increased, the concentration profile is lowered. This is particularly apparent near the surface. Because of the low flow rates, the changes toward steady state were quite slow, requiring many hours.

Figure 5B represents data from the same bin with a drying floor, but with the polyethylene film used as a surface cover. In this particular case some data were taken at the surface of the grain just beneath the covering. Although there is considerable scatter in the data, which is partly due to the lower concentrations measured and the very low maintenance rates, it can easily be seen, by comparison with Fig. 5A, just how beneficial the covering was. Figure 5C shows maintenance in a bin with a solid floor and point injection at the center one foot off the floor. This bin was "well-sealed" as described before. Figure 5D is data from the same bin, but with the overhead space well ventilated (by opening the top vent and the hatch) and with a surface covering. Note that the surface covering alone is slightly more effective than completely sealing the overhead space. In order to better compare the maintenance in the four cases just described, Fig. 6 is provided in which the concentration at a position 15 cm below the top grain surface is shown for each case. The curve for the drying-floor bin with covering was interpolated since data at 15 cm from the surface were not recorded. It is evident that covering the surface reduced the gas maintenance requirements by a factor of about 10 compared to no sealing at all and by a factor of about two compared to complete sealing of the overhead space. A superficial velocity of about 3 cm/hr is

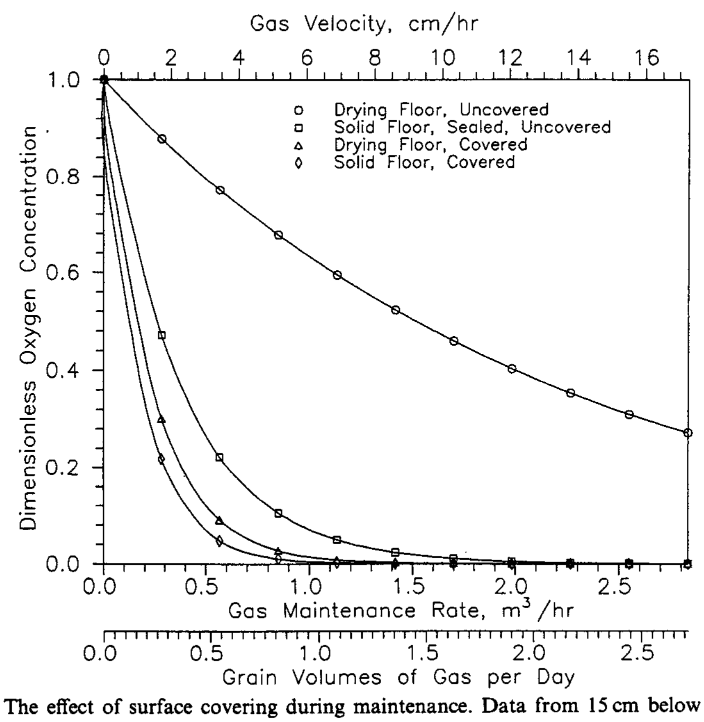

Fig. 6. The effect of surface covering during maintenance. Data from 15 cm below surface.

sufficient to maintain 90% of the grain below a concentration of 2% oxygen when the grain surface is covered.

The results presented here are for very short grain bins. As the height-to-diameter increases, we would expect the purge of oxygen from all bin configurations to be slightly more efficient, i.e. require a smaller number of grain volumes of gas to reach the same concentration levels. Also the rapid purge of the center compared to the area near the walls for the case of introduction of MA by point injection above a solid-floor bin will not be as noticeable in the taller bins. Purge rates lower than those used here (superficial velocities below about 30 cm/hr) will more than likely not produce satisfactory concentration levels in farm-type bins. Maintenance in taller bins should also be relatively easier with essentially the same linear velocity required to keep the concentration of MA at acceptable levels. Tranchino *et al.* (1980) reached similar conclusions regarding the effects of gas flow rate and bin height on the efficiency of nitrogen atmospheres.

CONCLUSIONS AND RECOMMENDATIONS

(1) There would seem to be no purpose in purging a bin at less than the maximum possible rate as dictated by the generator available and the limits of pressure drop. The higher the purge velocity, the lower will be the concentration of oxygen throughout the bin, especially near the surface.
(2) The minimum purge rate that will give reasonable surface concentrations is one which produces surface velocities above approximately 30 cm/hr. This is based on reducing at least 90% of the grain to oxygen levels of 4% or below.
(3) The rate at which a bin with a drying floor is purged is not much different from that at which a solid-floor bin with point injection is purged (Fig. 4).
(4) The use of surface covering such as a polyethylene film during purge does not have much effect except at very low purge rates.
(5) The use of surface covering during maintenance is simple, inexpensive, and can reduce the gas requirements by a factor of up to 10 compared to that for a ventilated overhead space and by a factor of 2 compared to completely sealing the overhead space (Fig. 6). The covering is particularly effective in reducing oxygen levels near the surface.

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