A COMPARISON OF PHOSPHINE FUMIGATION METHODS FOR FARM-STORED WHEAT

by

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A sincere gratitude is felt towards my wife Nanci and our two children, Landon and Lauren. Their patience and love has supported me through some of the difficult times of graduate school, and it is for them that I dedicate my work and my life.

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INTRODUCTION

The use of phosphine (hydrogen phosphide) as a fumigant, according to Halliday et al. (1983), was first developed in Germany in the 1930's. Its use as one of the major fumigants on food commodities is due to several factors. First, in 1984 Environmental Protection Agency regulations eliminated the use of most liquid fumigants. Second, phosphine is adsorbed less than other fumigants, such as methyl bromide, by the commodity being fumigated (Halliday et al. 1983). This allows for phosphine to be more active in controlling insects, since less of the active ingredient is made unavailable due to adsorption. Low adsorption also helps prevent any off flavors, odors, or health hazards from appearing in the food commodity, as well as more rapid removal of the gas from the grain mass.

Several countries have reported insect resistance to phosphine. Faulty fumigation techniques are suspected to have been the cause (Champ and Dyte 1976, Halliday 1983). Good fumigation practices can help slow resistance development in insects that infest stored grains. Once investigators establish these fumigation procedures, it will be vital to train applicators in the fumigant's proper application. Halliday et al. (1983) characterized phosphine fumigations as being a part of a general pest control package, which includes properly designed and constructed storage structures, good storage hygiene and practice, and the use of contact insecticides on the storage structure to avoid reinfestation. Training in the use of phosphine should also include these aspects of the total package.

Current legislation requires farmers in the United States to obtain Private Applicator Certification to apply restricted use pesticides. All fumigants are labeled as restricted use pesticides. Training for certification generally covers a wide range of restricted use pesticides and little time may be spent on procedures for fumigant application. The farmers are commonly advised to follow label instructions (Anonymous 1987). The label instructions have recently become quite complex and cover a wide range of situations, possibilities and requirements.

Little work has been reported to document actual phosphine fumigation procedures for farm bin storage of wheat. Likewise, no work has been done to test and compare application techniques for optimum effectiveness. Current recommendations as listed in the 1988 applicators manual for Degesch Phostoxin[1] (Anonymous 1988) are as follows:

" Leakage is the single most important cause of failures in the treatment of farm storages. Since these storages are often small, they usually have a higher leakage area in proportion to their capacity. Most wooden storage structures are so porous that they cannot be successfully fumigated unless they are completely tarped. Do not fumigate storages which will be entered by humans or animals prior to aeration. Do not fumigate areas which house sensitive equipment containing copper or other metals likely to be corroded by hydrogen phosphide gas.

Seal the bin as tightly as possible. It is recommended that the surface of the grain be covered with poly after Phostoxin has been app.ied. Tarping the grain surface will greatly reduce the leak rate of the gas as well as reduce the amount of Phostoxin required. Only the volume below the tarp must be dosed. If not tarped, the

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[1] Mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the author and does not imply its approval to the exclusion of other products that also may be available.

entire volume of the storage must be treated, whether full or empty.
Phostoxin tablets or pellets may be scattered over the surface or probed into the grain using a rigid PVC pipe about 5 to 7 feet in length and having a diameter of 1-1/4 inches. Use about 20-50 tablets or 100-250 pellets per probe. Spread the dose uniformly over the surface. Immediately cover the surface of the grain with a plastic tarpaulin. Place no more than 25 percent of the total dose at the bottom if the bin is equipped with aeration fans. Caution: Make sure that the aeration duct is dry before adding Phostoxin. Addition of Phostoxin to water in an aeration duct may result in a fire. Seal the aeration fan with 4 mil plastic sheeting.

The directions for using a probe application can be interpreted different ways. The label says that 20-50 tablets should be used per probe. Does this mean all 20-50 tablets are deposited into one location or that one tablet is deposited at 20-50 intervals as the probe is removed? The next line says to spread the dose uniformly across the surface, but leaves unexplained how much of the total dosage is spread across the top. The label says to place no more than 25 percent of the total dose at the bottom, if the bin is equipped with aeration fans. Perhaps the dosage can be put down at the bottom in bins without an aeration system.

Also listed in the applicator's manual are the requirements for protective respiratory equipment. Some of the requirements regarding respiratory protection make it very difficult for the farmers to fumigate their own bins safely using the recommended probe application. Because the probe application must be done from inside the bin, the label stipulates that "NIOSH/MSHA approved,full-face gas mask phosphine canister combination or self-contained breathing apparatus (SCBA) or its equivalent must be available at the site of application in case it is needed." It is not likely that a farmer would invest in this expensive equipment. The label further states that respiratory protection must be worn if exposure is likely to exceed the eight hour Time Weighted Average of 0.3 ppm during application. If monitoring equipment is not available and an application cannot be made from outside the structure, an approved canister respirator must be worn during application. The farmer has two choices: 1) buy expensive monitoring equipment or 2) buy expensive full face gas mask-canister combination. The only other legal alternative for self application is to use a fumigation procedure in which application is done from outside the bin. Another alternative is to have commercial applicators apply the fumigant.

Another label requirement for fumigation from within the bin is that "two persons trained in the use of phosphine" must be present during fumigation of the structure. Only one trained person is needed if the fumigation is done from outside the structure.

Our research was designed to establish the most effective means of fumigating wheat stored on the farm in steel bins. The term "effective" includes: (1) killing all stages of insects in the grain, thus preventing further grain damage and helping prevent resistance development in surviving insects; (2) ease of application; and (3) maximum safety to the applicator.

We compared the effects of fumigating a bin by probing the fumigant into the grain surface with effects of fumigating from the bottom. Floor fumigation was done with phosphine prepacs drawn through a perforated drainage pipe, that we fastened to the bin floor before we filled the bin. We also investigated effects of covering the grain surface with plastic sheeting. Weather conditions were recorded for all tests to investigate possible correlations between weather conditions and fumigation efficacy.

Placing plastic sheeting on the grain surface proved extremely important in maintaining high gas concentrations during the fumigation. Fumigating the grain bins from the bottom had some advantages over probe fumigation. This deserves more investigation. Although the fumigant is slightly heavier than air, convection currents and other air movements within the bin are believed to have caused upward movement of the fumigant.

LITERATURE REVIEW

There are many factors that affect fumigation efficacy which include; the fumigant, the structure, the grain, and the insect. Some of these factors we have complete control over, while others we have little to no control over. Nevertheless, we need to understand the role of all of these factors, in order to carry out a successful fumigation.

The Fumigant

Phosphine is one of the most toxic fumigants of stored-product insects (Banks and Annis 1984). The metal phosphide fumigants are acted upon by atmospheric moisture and temperature to produce hydrogen phosphide (phosphine, PH_3) gas. The most common metal phosphides are aluminum phosphide and magnesium phosphide (Price 1985). Ammonium carbamate is packed with the metal phosphide along with paraffin wax to form the tablet or pellet that is used for application. Temperature acts on ammonium carbamate to allow moisture in the air to react with the metal phosphide. This reaction produces ammonia and carbon dioxide, nonflammable gases that act as inert agents to reduce fire hazards. The characteristic odor commonly associated with phosphine has been attributed to an impurity, possibly diphosphine (Bond and Dumas 1967) and has been described as resembling the smell of rotting fish, carbide or garlic (Price 1985). Bond and Dumas (1967) urged caution in the use of this smell as a warning signal.

A "CT Rule", where over a certain range of concentrations and exposure times a specified concentration x time product (CTP) will give a constant level of kill, i.e. the response follows the relationship $C \times T = k$, where k is a constant for mortality, has been used to describe the toxic response of insects to some fumigants (Price and Mills 1988). This "CT Rule" does not, however, seem to apply to phosphine. Previous work on susceptible strains has shown that duration of exposure is more important than concentration in obtaining mortality at practical concentrations (Bell and Glanville 1973, Ozer and Zafar 1976, Bell 1979). The time factor allows the tolerant stages to develop into more susceptible ones during the phosphine exposure period (Winks 1986). Price and Bell (1981) reported that the tolerant stages of stored-product insects are able to continue development in the presence of phosphine. The concentration factor is less important than exposure time because high concentrations of phosphine may produce narcosis in insects which may reduce subsequent insect absorption of phosphine. But it is not known with certainty if narcosis increases an insect's chance of survival (Winks 1985).

Another characteristic of phosphine gas is its specific gravity of 1.214 with air being 1 (Monro 1969). Its low molecular weight and weak sorptive properties allows for it to diffuse rapidly and be easily moved by natural convection air currents within the grain mass (Banks and Desmarchelier 1979).

The Structure

In order to perform an effective fumigation, the structure in which grain is being fumigated, must be considered. The most important characteristic of the structure is its ability to retain the fumigant. The degree of gas loss is directly related to the degree of sealing in the structure (Banks and Desmerchelier 1979). Wind can be a major reason for gas loss. Wind forces may cause fresh air to enter the bin at one leak while displacing fumigant at another leak. The pressure differences generated by a steady wind can cause air to flow into the structure in regions of positive pressure and gas to flow out where pressures are negative (Mulhearn et al. 1976). Mulhearn et al. suggested that the flow achieved will depend on the wind strength and the location and dimension of the holes. Because his research was done on concrete silos, the effects of ribs or substantial corrugations on the walls, as found in the steel bins used in this research, have not been investigated. A constant dilution of the fumigant can be a major cause of fumigation failure. In extreme cases, a localized region of the bin may be constantly supplied with fresh air allowing for insect survival. Other researchers who have suggested wind forces as major sources of gas loss are Cotton et al. (1936), Cotton (1962), Blackith (1953), and Banks et al. (1975).

Fumigant distribution is a factor in fumigation efficacy, and is dependant on the method of application, the gas retention properties of the structure being fumigated, and convection currents within the grain mass. The two extremes of are: 1) a good distribution with a poor seal and 2) a poor distribution with a good seal. Each of these extremes are good candidates for a fumigation failure (Banks and Annis 1984). A poor seal will cause a good initial distribution to be diluted by incoming fresh air. A good seal will be of little use if the initial distribution is poor, because the gas will need to travel greater distances to reach all areas of the grain mass.

The exposure period and dosage required to obtain an effective fumigation have both been described as being dependent on the structure being fumigated. The label requirements for phosphine suggest a dosage range of 90-180 tablets per 1000 bushels with the higher dosage for leakier structures. This, however, may lead to a good distribution with a poor seal, as described by Banks and Annis (1984), and not be effective.

The Grain

The type and condition of the grain being fumigated can be a factor in fumigation effectiveness. The type of grain is not very critical with the use of phosphine, because the gas is not readily adsorbed by any of the stored products labeled for phosphine fumigation.

Temperature is an important factor in fumigation effectiveness. Temperature differentials within a mass of grain can have an effect on air movement (Foster and Tuite 1982). Substantial variation in temperatures within the grain mass or between the grain mass and the environment will result in air movement within the bin. Air currents within the grain mass may cause fumigant gases to be moved from one part of the mass to another, or to be lost from the grain mass, resulting in reduced gas concentrations. Temperature will also affect the insects' rate of respiration. Fumigants enter the insects' system primarily through respiratory openings and any factor increasing the insects' rate of respiration will also make the insect more susceptible (Monro 1969). Higher temperatures will increase the rate of respiration and susceptibility to the fumigant (Sun 1946). Higher temperatures will also increase the rate of decomposition of the tablets and pellets (Anonymous 1988). Low temperatures are also factor because low temperatures cause a slower release of the phosphine gas, and with leaks, this may prevent a lethal concentration level from being reached.

The Insect

The type of infestation in the grain can also affect fumigation efficacy. There can be wide variation of toxicity to various stages and species (Hole et al. 1976; and Bell 1976, 1977). Price and Mills

(1988) reported that concentrations of 2 g/m^3 (200 ppm) for 10-12 days exposure were required to control pupal Sitophilus granarius and S. oryzae at 15°C.

It is a common opinion of these researchers that maintaining gas concentration at a lethal level for an adequate length of time is essential to obtain an effective fumigation. This research will not address problems associated with insect species and stage of development, but problems with fumigation procedures. The objective is to investigate the best procedures to insure good distribution, adequate gas retention , and safety to the applicator.

MATERIALS AND METHODS

The Food and Feed Grains Institute Grain Storage Research and Training Facility on Kimball Avenue in Manhattan, Kansas was the site for all fumigation trials.

Grain Bins

The bins were 1500 bushel capacity corrugated galvanized steel bins (Butler Manufacturing Co.) with false floor aeration systems. The bin wall was eleven feet from the ground to the top of the bin wall. The aeration floor was secured to the bin wall one foot from the ground. The aeration fans were secured to a aeration fan housing on the side of the bin. The diameter of the bin was 15 feet. The bins had two top hatches. One at the peak of the roof, and the other in the roof panel where the personnel ladder meets the roof. Each bin had a side personnel entry door for entry to the bin when empty. The inside panel of the door had a sliding gate, to allow for the insertion of an unloading auger. The bins were also equipped with a center auger underneath the aeration floor to allow for unloading.

The Grain

We used Hard Red Winter Wheat obtained from the Manhattan Milling Company in Manhattan, Kansas. The moisture content of the wheat used was between nine and eleven percent for all tests.

Thermocouples

Thermocouple cables, made from copper constantan wire, were placed at five locations within each bin. Four were 2.5 feet from the outer wall at the north, south, east, and west; the fifth was at the center of the bin. Each thermocouple cable was designed to take temperature readings one foot from beneath the grain surface and one foot above the bin floor.

Gas Sampling Probes

Gas sampling probes were placed at approximately the same locations as the thermocouples - the north, south, east, west, and the center. At each location, gas samples were taken at one foot beneath the grain surface and one foot above the bin floor. The section of probe in the grain was steel pipe. The pipe end pieces were perforated, one foot sections that could be easily removed. This is also where insect cages were placed prior to fumigation (see Fig. 1). Perforations in the end section, allowed for gas samples to be taken at the same location as where the insects were exposed. Just above the

Figure 1.-Top - Gas sampling pipe with plastic to metal elbow connector and perforated end piece.
Bottom - Insect cage.

grain surface, the steel pipe was joined to 1/4" plastic tubing with a special plastic to metal elbow connection (see Fig. 1). The tubing then ran across the grain surface and out of the bin through the opening between the bin wall and the bin roof (see Fig. 2). The tubing then extended down the outside bin wall to where the gas samples could be taken outside of the bin during fumigation.

Sealing

We used 4 mil polyethylene sheeting on the following openings: the plenum chamber opening, the aeration fan opening, the unload door and on some of the tests we also covered and sealed the top hatches. On all tests, except the one comparing the effects of the surface cover on the probe application, the aeration fan openings were covered with a piece of sheet metal and then caulked with a rubber silicone sealant. On bins that received the "covered" treatment procedure, 4 mil plastic sheeting was used to cover the grain surface. The edges of the plastic were "tucked" in between the grain mass and the bin wall.

The Insects

Adult red flour beetles (<u>Tribolium</u> <u>castaneum</u> (Hbst.)) were used on all tests. The insects were obtained from the Kansas State University, Department of Entomology stock cultures. For insect cages, we used 5 ml serological plastic pipettes cut into six inch lengths. With one end plugged with cotton, a few grams of whole wheat flour with 5% yeast were placed into the insect cage. Twenty-five red flour beetles were placed in next, followed by another cotton plug. Insect test cages were prepared and placed in the gas sampling probes just prior to each

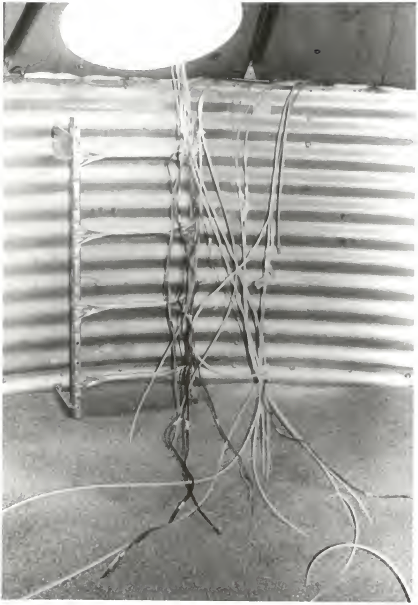

Figure 2.-Gas sampling tubes inside the bin.

fumigation trial.

The Fumigant

The "probe" fumigations were all performed using Phostoxin New Coated Tablets-R manufactured by Degesch America, Inc. The Tablets are 55% Aluminum Phosphide and 45% inert ingredients. Each tablet weighs 3 grams and releases 1 gram of hydrogen phosphide gas. They are 16 mm in diameter and bulk packaged in resealable aluminum flasks containing 500 tablets each.

The "floor" fumigations were all performed using specially packaged Phostoxin Tablet Prepacs manufactured by Degesch America, Inc. The Tablet Prepac consists of a gas permeable blister pack of Phostoxin Tablets. Each Tablet Prepac strip is 4in. x 16in. and contains 33 of the round tablets. The Prepac strips are sealed into gas-tight aluminum foil pouches (3 Prepacs per pouch) which are then packed into covered metal pails. The pails are constructed to conform to DOT specification 37A; steel drums. These Prepacs were also specially fitted with metal grommets on each strip, to allow for attachment to a rope during fumigation.

Probe Fumigation

We determined the appropriate probe placement by taking the total number of tablets required and dividing by the number of probes needed to obtain an assumed even distribution. A more detailed description will be given for each individual test.

Floor Fumigation

Preparations for this procedure must be done before the bins are filled. The use of perforated, flexible, drainage pipe in assisting phosphine distribution has been used previously for successful in-transit fumigation of export corn (Zettler et al. 1984). Similar 4" diameter perforated drainage pipe was secured to the bin floor with bailing wire approximately 3 feet from the outer wall (see Fig. 3). We threaded a rope through the pipe so that we could attach the phosphine prepacs to the rope and then pull them through to the appropriate location. The rope was marked at one foot increments so that we could determine the prepac's location. The ends of the perforated pipe loop terminate at the auger port in the unload door so that the fumigant prepacs could be attached to the rope (see Fig. 3). Once the fumigant was positioned in the bin, the auger port door could then be shut. The bin door was then sealed by taping polyethylene sheeting to the bin door opening frame and then shutting the door. The plastic was taped so that there was a continuous taping of plastic to metal.

Gas Readings

Sampling schedules were not the same for all tests and will be discussed in the results section. Gas sampling lines, at all locations, were first purged of existing gases by pulling 5, 60 cc syringe-fulls, to bring the gas concentration in the bin, to the outside where the gas concentration could then be measured. A Dräeger Multigas Detector (model 21/31) with Phosphine high level detector tubes was used to measure gas concentrations. It should be noted here

Figure 3.-Top - Drainage pipe attached to bin floor.
Bottom - Drainage pipe coming out of the unload opening in the side door.

that Leesch (1982) reported the Dräeger tubes to be accurate within 10 to 20% of the true concentration. To test for gas leaks and to test for gas levels during application, A Gastech Phosphine Detector, Model SC-7, was used.

Control Insects

Five insect cages were placed in environments similar to the conditions in the grain served as controls. Sometimes this was a full bin at the site and other times it was in a quantity of grain in a temperature controlled room with conditions similar to those in the grain bins being fumigated.

Ventilation following Fumigation

Once the exposure period was over, the top hatches were opened, and the plastic sheeting on the grain surface (when present) was removed. Once the gas levels were below .3 ppm, the insect cages were retrieved and checked for surviving insects.

Weather Conditions

Weather condition reports were obtained from the Kansas State University Weather Station Data Library for the time periods of the fumigation (see Appendix for each test). These readings were taken at the weather station located approximately one mile from the fumigation.

RESULTS

Effects of grain surface cover with probe application

Two bins were each filled with 1000 bushels of hard red winter wheat and prepared for fumigation as outlined in the materials and methods section. One bin was covered with plastic sheeting to compare with one not covered. The fumigation dosage was 100 tablets per 1000 bushels. Bin volume included headspace and plenum chamber. Each bin received 156 tablets probed into the grain on May 18, 1988, at 2 p.m. as shown in Fig. 4. The same number of tablets was used on each bin to magnify treatment effects. The Phosphine label indicates that a smaller dose may be used if a surface cover is to be used (dosage is then based on volume of space under the surface cover). Each bin had both top hatches covered with polyethylene.

Because the wheat used had been stored through winter and was warming in the spring, grain in the center of the bin was about 10 degrees cooler than at the perimeters (see Appendix A, Table II).

While probing the fumigant into the grain, we took gas readings near the applicators with a Gastech phosphine-gas detector, recorded the highest reading during five minutes as the gas exposure, and then computed a time weighted average (TWA) based on an eight-hour day as follows:

Time (min.)	X	Peak Conc. (ppm)	=	Total
5		1.20		6.0
5		2.25		11.25
5		1.30		6.50
5		1.10		5.50

29.95 + 480 (min/8 hr day) = .061 TWA

Applicators, who spent 20 minutes performing the covered-bin procedure, were exposed to a TWA of .06 ppm. The uncovered bin took 12 minutes with exposure at .07 ppm TWA. To limit exposure, the top hatches remained open while applicators were in the bin.

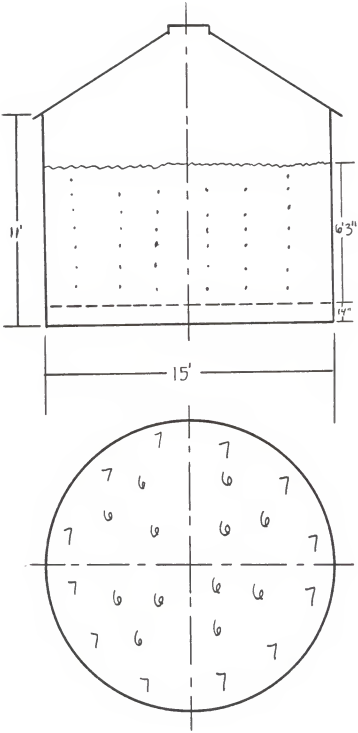

Figure 4.-Tablet placement pattern for probe application on Test 1. Numbers represent quantity of tablets probed in at that location.

Gas readings were taken every 12 hours beginning at 8:00 a.m. the morning after application. Morning readings were at the north, south, and center; evening readings were at the east, west, and center. Concentrations were consistently higher in both the top and bottom halves of the covered bin (see Figures 5 and 6). Gas concentrations are recorded in Appendix A, Table II.

Weather conditions during fumigation were typical of spring in Kansas (Appendix A, Table III). When post-fumigation gas levels had dropped below .3 ppm, the test insects were checked for survival; none survived at any location. All control insects survived.

Effects of a grain surface cover with floor application (Trials 1 and 2).

Trial 1

Two bins were prepared for fumigation as outlined in materials and methods. The bin with the surface cover contained 1056 bushels; the uncovered bin, 968 bushels. Dosage was again 100 tablets per 1000 bushels, based on total bin volume. The same procedure was used to apply the fumigant in both bins. Four and a half prepacs were used in each bin (150 tablets in the uncovered bin; 147 tablets in the covered bin). The prepacs were spaced equally and secured with wire to the rope in the pipe. The prepacs were 9 feet apart with a half prepac 4 feet from the last full prepac and 5 feet from the first prepac: prepac-9'-prepac-9'-prepac-9'-prepac-4'-half prepac-5'-beginning.

Average temperatures in the grain varied only a few degrees

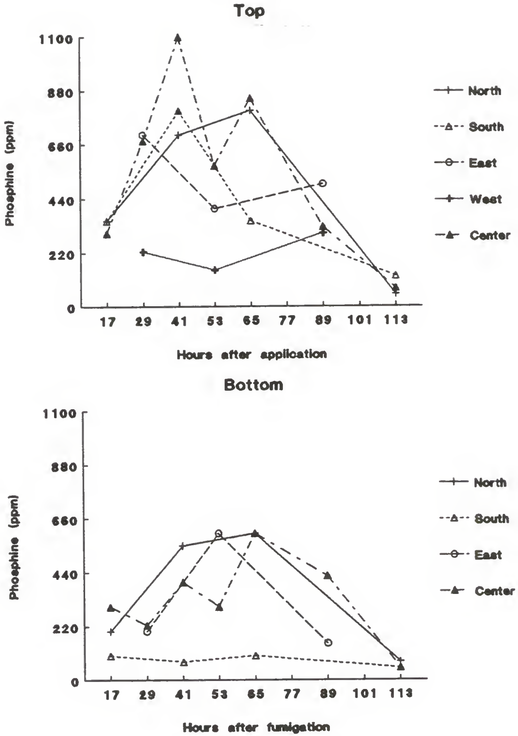

Figure 5.-Phosphine gas concentrations in the bin receiving the probe application and cover. The "top" graph represents gas concentrations at the five locations one foot below the grain surface. The "bottom" graph represents gas concentrations at the five locations one foot above the bin floor. The West sampling tube became disconnected, so information for that location is not recorded.

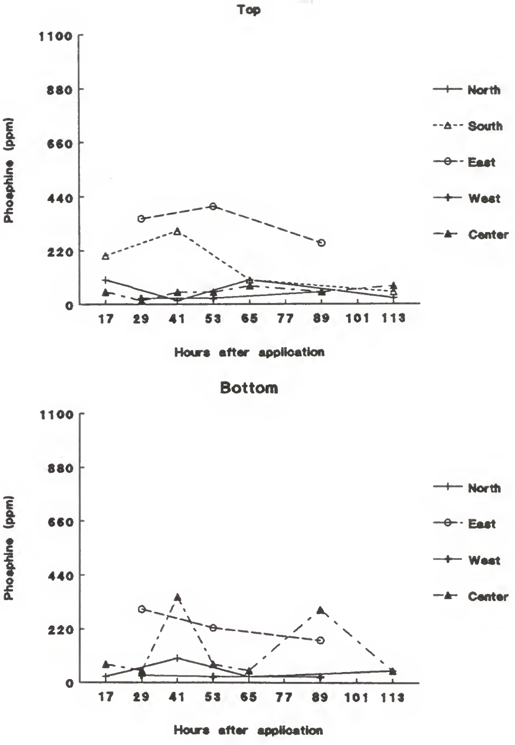

Figure 6.-Phosphine gas concentrations in the uncovered bin receiving the probe application. The "top" graph represents gas concentrations at the five location one foot below the grain surface. The "bottom" graph represents gas concentrations at the five locations one foot above the bin floor.The south sampling tube became disconnected so no information is recorded for it.

between the center and the perimeters (Appendix B, Table II). Weather conditions during fumigation are recorded in Appendix B, Table III.

During application gas readings were taken near the applicator with a Gastech phosphine gas detector, and the built-in averaging mode was used to determine exposure. The applications were completed in 15 minutes total for both bins, with .006 ppm TWA exposure to the applicators.

After the fumigant was applied, the top two roof hatches were closed on the uncovered bin. The top two roof hatches and the personnel door were covered with plastic and fastened securely with tape. The tape was applied such that it overlapped both plastic and metal to insure proper sealing.

The only noticeable difference in gas concentrations between the two bins was less variation in gas concentrations in the covered bin. The surface cover apparently helped maintain gas at a more constant level than in the uncovered bin (see Figures 7 and 8). Gas concentrations are recorded in Appendix B, Table III.

Trial 2

Each bin for Trial 2 contained approximately 1200 bushels of wheat; the same procedures were used as for Trial 1 with these modifications. To prevent fresh air from diluting the gas samples, a small piece of 1/4 inch diameter tygon tubing was used to join the gas sampling tube to the Dräeger tube (Fig. 9). The dosage was reduced to 99 tablets (3 prepacs), and swivel clips were attached to the rope to reduce application time. All locations were sampled every 12 hours,

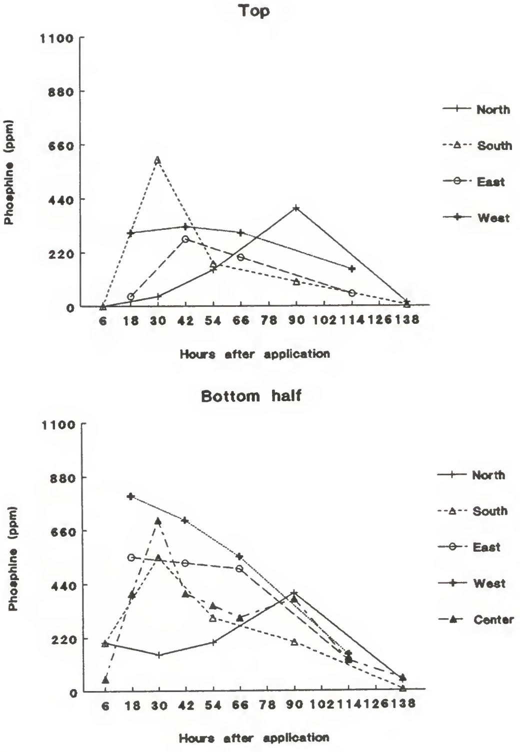

Figure 7.-Phosphine gas concentrations in the bin receiving the floor application treatment with a surface cover (Trial 1). The "top" center sampling tube became disconnected so no information for that location is recorded.

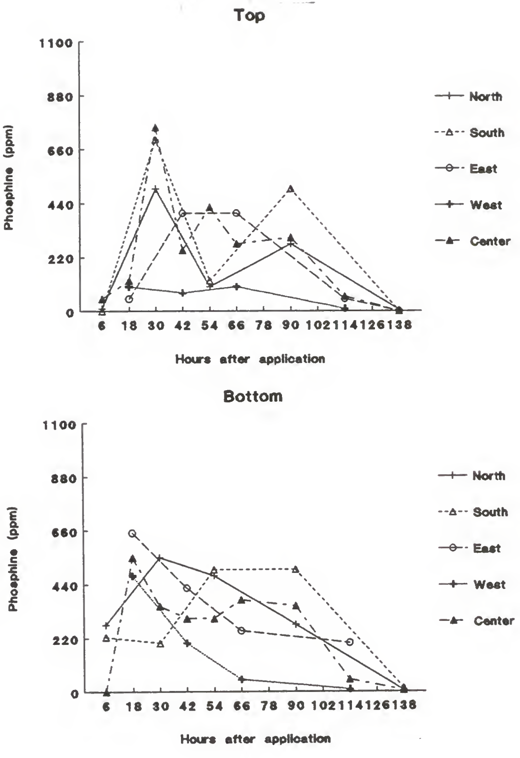

Figure 8.-Phosphine gas concentrations in the bin receiving the floor application without a surface cover (Trial 1).

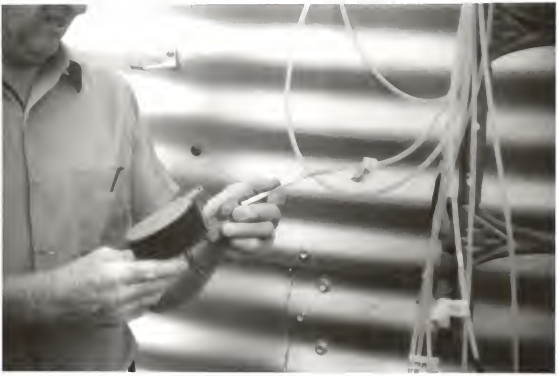

Figure 9.-Tygon tubing that was used to join the sampling tube with the detector tube.

beginning at 8:00 a.m. the morning after application. Temperatures in the bins were fairly uniform, as shown Appendix B, Table IV.

Gas concentration readings were higher in Trial 2 than Trial 1, despite the lower dosage used in Trial 2. We attributed that to using the tygon tube when taking gas samples (readings were a more accurate representation of actual gas concentrations in the bins). Concentrations in the covered bin were generally higher, and with less variation, than in the uncovered bin. Even though the fumigant was introduced at the bottom only, gas concentrations were substantial in the top half of the bin (Figures 10 and 11). Gas concentrations are recorded in Appendix B, Table V.

At the end of the exposure period, the bins were aired out until gas levels were below .3 ppm. The insects were then retrieved and checked for survival. No test insects survived at any location: all control insects survived. Weather conditions during trial 2 are recorded in Appendix B, Table VI.

Floor and probe applications compared without surface covers (Trials 1 and 2).

Trial 1

Two bins, each containing 1200 bushels of wheat were prepared for fumigation as previously outlined. The dosage for each bin was 99 tablets, lower than recommended dosage, so we could compare the two procedures with low dosages.

Average temperatures between the center and the perimeters in the

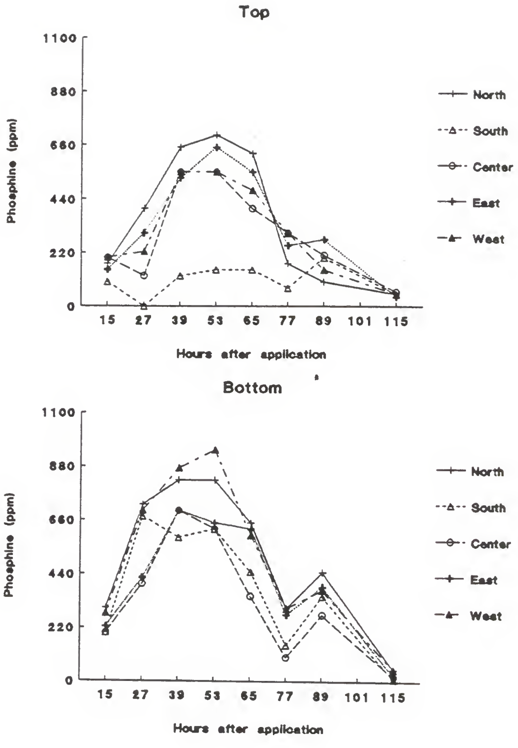

Figure 10.-Phosphine concentrations in bin receiving floor application and a surface cover (Trial 2).

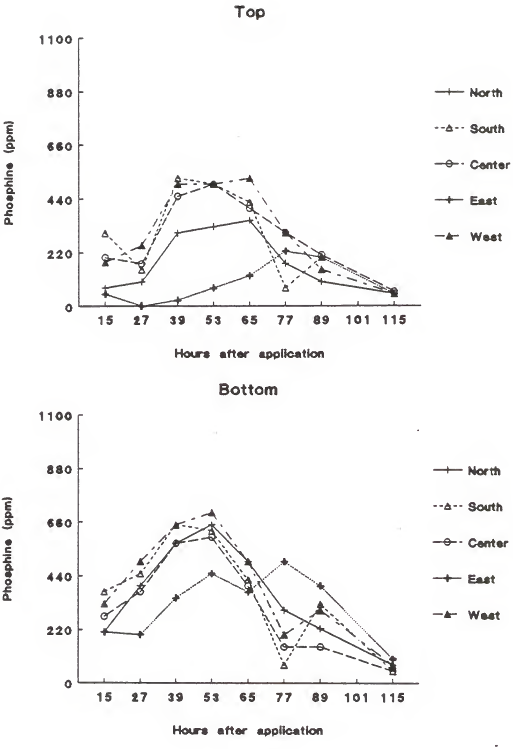

Figure 11.-Phosphine gas concentrations in the bin receiving the floor application without a surface cover (Trial 2).

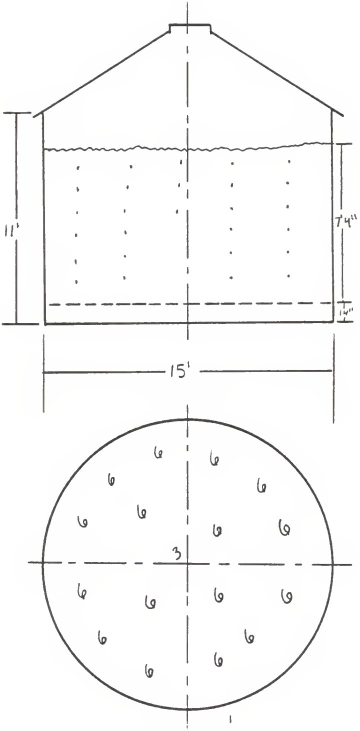

Figure 12.-Tablet placement pattern for probe application on Trials 1 and 2 of the comparison between probe and floor applications without surface covers. Numbers represent quantity of tablets probed at that location

two bins differed by only a few degrees (Appendix C, Table I).

The probe application was performed as outlined in Figure 12. The floor application was performed by attaching 3 prepacs 12 feet apart to the rope in the pipe. Applicator exposure was monitored during application with a Gastech phosphine gas detector. The exposure was .018 ppm TWA during the probe application; .015 ppm TWA during floor application. The largest exposure with the floor application came immediately upon opening of the pouch containing the fumigant prepacs. Once the initial "burst" dissipated, exposure was quite low. Gas readings were taken every 12 hours beginning at 8:00 p.m., application day. Evening readings recorded were from the north, south and center; morning readings, from the east, west, and center. Gas concentrations in the bottom half of the probed bin were consistently low. The floor application gave gas levels about the same for the top and bottom halves (Figs. 13 and 14), suggesting a general upward movement of the fumigant, instead of downward as expected, based on the phosphine's specific gravity. Gas concentrations are recorded in Appendix C, Table II.

Weather conditions during fumigation are recorded in Appendix C, Table III. None of the test insects survived at any location; again all controls survived.

Trial 2

Trial 2 repeated Trial 1 with a few modifications. First, gas sampling was every 12 hours at all locations. Second, a piece of 1/4 inch tygon tubing was used to join the sample tube to the Dräeger

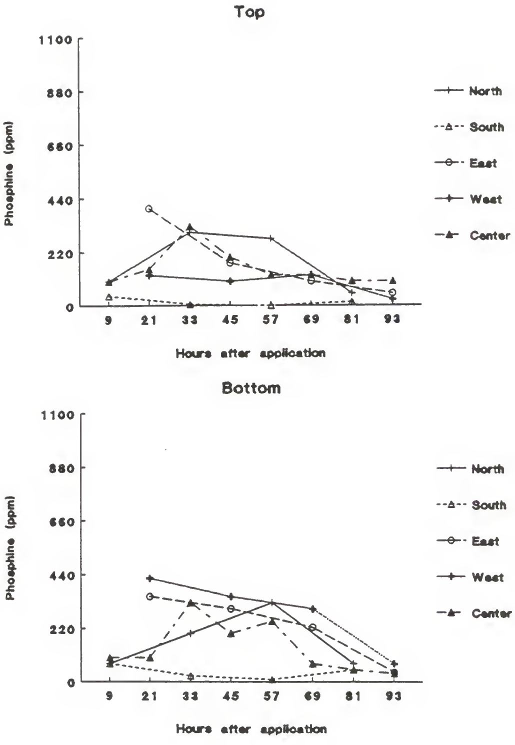

Figure 13.-Phosphine concentrations in bin receiving floor application with no cover (Trial 1).

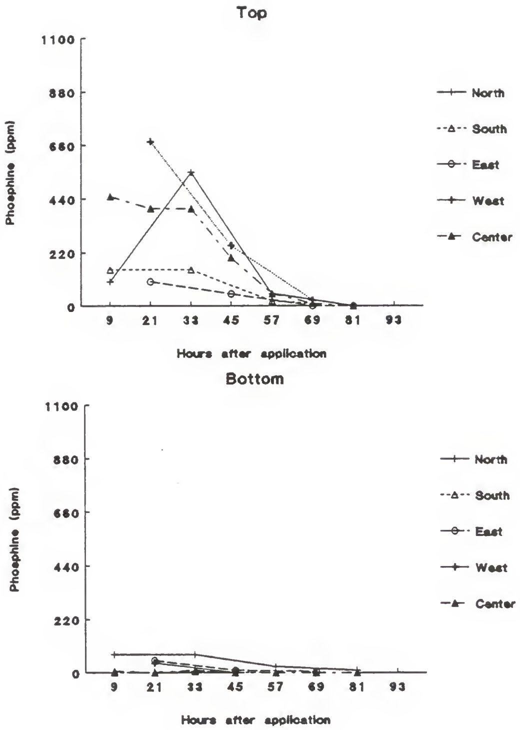

Figure 14.-Phosphine concentrations in bin receiving probe application with no cover (Trial 1).

detector tube, to prevent fresh air from diluting the sample. Fumigation was August 9, 1988 at 11:00 a.m. The first readings were at 8:00 p.m. that evening.

Average center and perimeter temperatures before fumigation differed only a few degrees (Appendix C, Table IV). Again, this small temperature gradient should not have promoted air convection currents within the bins. Gas concentrations were recorded as before. Exposure to the applicator was .064 ppm TWA for the probe procedure and .012 ppm TWA for the floor application.

Gas concentrations were extremely low in the bottom half of the probed bin and only moderate in the top half (Figs. 15 and 16). Gas concentrations are recorded in Appendix C, Table V. Concentrations were unusually high in the top, north position, probably because a southerly wind during fumigation moved the fumigant from south to north. Weather conditions recorded during Trial 2 are given in Appendix C, Table V. Concentration in the floor-application bin were higher in the north than in the south but the difference was less than in the other bin, perhaps because the fumigant had farther to travel before reaching the surface where it could be displaced by the wind. A surface cover should have minimized wind effects in both bins.

None of the test insects survived at any bin locations, and again all controls survived.

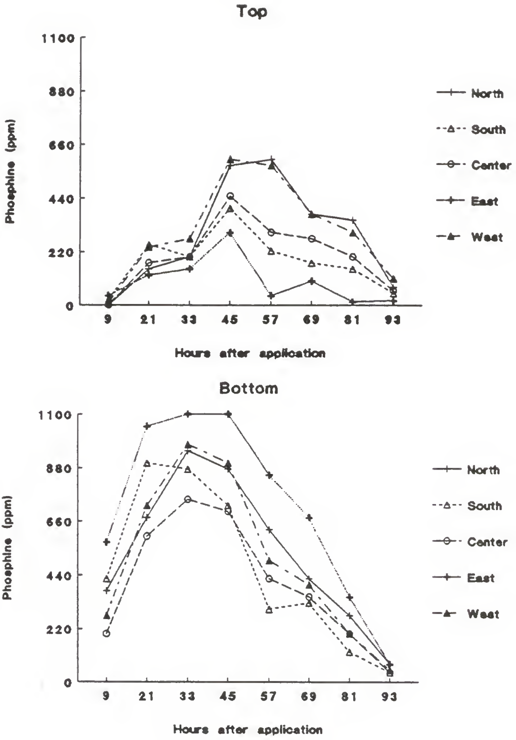

Figure 15.-Phosphine concentrations in bin receiving floor application with no cover (Trial 2).

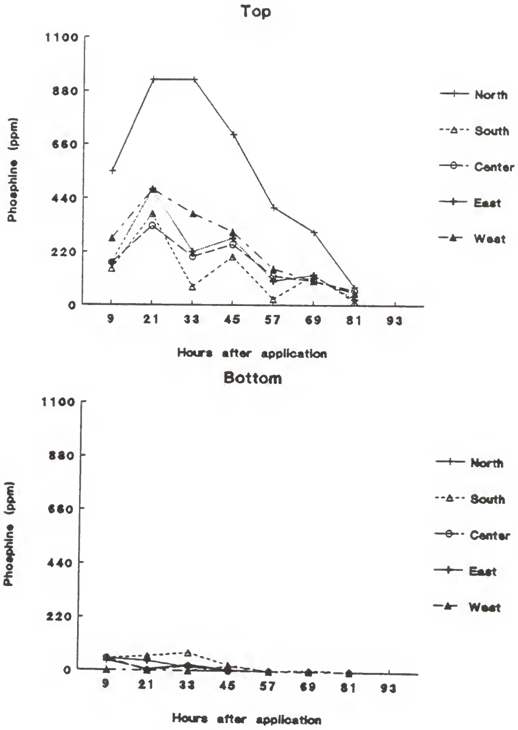

Figure 16.-Phosphine concentrations in bin receiving probe application with no cover (Trial 2).

Applicator exposure

Applicators exposure to phosphine was measured with a Gastech phosphine detector model SC-7. A time weighted average (TWA) was computed as detailed previously, with results recorded in Table I.

Table I. - phosphine exposure (ppm) to applicator

Test	Procedure	Surface cover	TWA (ppm)
Effect of surface cover on probe procedure	probe	yes	.06
	probe	no	.07
Effect of surface cover on floor procedure			
Trial 1	floor	no	.006[a]
	floor	yes	
Trial 2	floor	no	.024[a]
	floor	yes	
Comparison of Floor and probe procedure			
Trial 1	probe	no	.018
	floor	no	.015
Trial 2	probe	no	.064
	floor	no	.012

[a] TWA was computed for both bins together.

The highest exposure came with the probe procedure, the lowest with the floor procedure.

Discussion

Method of Application

Zettler et al. (1984) also used a fumigation procedure with perforated polyethylene pipe on shipholds and concluded that its use "as a means of channeling the fumigant to the bottom of the tank greatly improves the distribution of the fumigant and thus efficiency of in-transit fumigation." This type of application also has many advantages for farm bin fumigations. Applicators apply the fumigant under much less difficult conditions. Fumigation done outside the bin requires less time and involves less risk of phosphine exposure. Phosphine labels state that "monitoring is not required for outdoor operations", and "respiratory protection need not be available for applications from outside the area to be fumigated such as addition of tablets or pellets to automatic dispensing devices, outdoor applications, etc, if exposures above the permitted exposure limits will not be encountered " (Anonymous 1988).

Perceived disadvantages of the floor application include: 1) the gas may reach upper regions of high bins too slow to obtain a lethal concentration and 2) preparations for floor applications must be done before the bin is filled. Existing aeration systems may permit post-filling fumigation. With some aeration systems, it is possible to place a portion of fumigant in a retrievable container under the bin floor through the aeration duct. Care must be taken to place tablets so they are not touching each other, and not to place fumigant where it will come in contact with water. This may result in fire.

Probe applications may give a good initial distribution of fumigant, but probing the fumigant to the bottom half of the bin needs more attention. Longer probes for larger bins would be cumbersome and take more time. Most probes come in 4-foot sections, so hooking them together and unhooking them would be time consuming if done for each probe location. Trials 1 and 2, comparing the probe and floor applications, showed clearly that under conditions tested, any fumigant not probed into the bottom failed to reach the bottom by natural air movement. General movement of the fumigant was upward. Since grain temperatures were fairly uniform for all but the first experiment (test of surface cover effects with probe application) this fumigant movement upward may not be explained by convection currents.

Some other disadvantages of probing are: 1) Two trained persons are required to be present during fumigation since the application is done from inside the bin. 2) The label also states that "if monitoring equipment is not available on a farm and application of fumigant cannot be made from outside the structure, an approved canister respirator must be worn during application from within the structure being treated." 3) During the hot summer months, interiors of bins are hot and uncomfortable. A full-face, gas-mask with appropriate canister may restrict air flow and be uncomfortable. This may discourage its use and promote unsafe fumigant application. 4) When probed into the top half only, fumigant may not reach lower bin portions where insects could survive. 5) Applicators are exposed to more fumigant, longer.

Effects of a surface cover

The only disadvantage of a plastic cover on the grain surface is that when the probe procedure is used; it increases the time the applicator is in the bin and exposed to the fumigant. The cover can be installed before a floor-fumigation begins, eliminating unnecessary exposure.

Every test with a cover clearly showed the cover's advantage. It helped maintain higher concentrations in the bin and helped minimize gas losses to wind. Strong winds are characteristic of most midwest wheat-growing areas. A probable advantage of a top cover, which we did not investigate is that it should help maintain high gas levels at the grain surface where many insects live. The surface cover will help prevent the fumigant from being diluted by fresh air in the headspace.

Insect Mortality

These tests should not be used to determine exposure periods or dosage rates. While we got 100% mortality in all tests, we used only adult red flour beetles, the easiest stage of infestation to detect and control. Standard sampling techniques used on the farm can detect only insects outside the grain kernels. Even though no live adult insects are found outside the grain kernels after fumigation, other stages of internal infesting insects may remain. They may have developed resistance to the fumigant, making future control more difficult. To avoid problems, care must be taken to insure proper dosage and exposure periods. Price and Mills (1988), who found the pupal stage, the most tolerant to phosphine, stated that exposure time is more critical than dosage concentration. Their results would support the theory of increasing a structure's ability to retain gas, when fumigating a leaky structure, as opposed to increasing dosages.

Applicator Exposure

In this research, the applicator exposure was well below the .3 ppm TWA standard for both the floor and probe procedures. The lowest exposure was with the floor application. When using the floor procedure, high initial levels of phosphine were observed when the pouches containing the phosphine prepacs were first opened. These pouches, once opened, should be allowed to "aerate" a few minutes before proceeding with the application. As the concern for applicator exposure increases, more research will need to be done to provide adequate procedures for fumigations to be accomplished in a safe and economical manner.

Gas movement within grain storages

In this research, only the first test, comparing the effects of a surface cover when using a probe application, used grain that had a substantial temperature gradient between the average center and perimeter temperatures. In this first test, the temperature was cooler in the center than at the perimeters. This gradient should have resulted in cool air coming down the center, across the bottom where it is warmed, and rising to the surface (Foster and Tuite 1982). In the other tests, there were only small temperature gradients, and gas failed to reach substantial levels in the bottoms of the probed bins, while gas levels did reach substantial levels in the tops of the floor application bins. It is uncertain whether this small gradient would have promoted air convection currents within the bins sufficient to cause fumigant movement.

The lack of fumigant movement downward is supported by the work of Leesch et al. (1978) and their work with the aluminum phosphide fumigation of shipholds. They used a surface application with Detia

Gas EX-B bags containing aluminum phosphide and reported that "highest concentrations of phosphine were sustained near the surface and phosphine was slow to reach the bottom of the holds." Zettler et al. (1984) also reported, in their work with fumigating shipholds using aluminum phosphide, low levels of phosphine in hold bottoms and concluded that "fumigation of tanker ships by the surface treatment and deep probing methods is either inadequate or marginal for complete control of stored product insects." They also concluded that "air currents caused by differential temperatures in the cargo tanks do not necessarily influence gas movement within the tank."

Recommendations for fumigating farm-stored wheat

The most important factor to consider when fumigating farm-stored wheat is the structure's ability to retain gas. Fumigation will not succeed in a structure that does not maintain lethal gas levels. Fumigating a leaky structure can only develop possible phosphine-resistant insects. A surface cover of at least 4-mil plastic sheeting should be used to aid in gas retention. Other openings that should be covered with plastic and securely taped include the unloading door, aeration fan, unload auger ports, and any other openings that might allow gas to escape.

At present, probe applications are recommended if proper equipment for respiratory protection and gas monitoring are available, two trained persons are present, and the bins are small enough (or probes long enough) for fumigant to be applied at equal intervals from bottom to top. Our research supports the importance of placing the fumigant at the bottom initially, whether using a probe or a floor application. In larger bins, where probes will not reach the bottom, that are equipped with a false floor aeration system, it may be possible to place a portion of the dosage in a retrievable open container beneath the bin floor. The fumigant must be placed in this container so that the tablets or pellets do not touch each other to prevent combustion. It is also important to check the aeration plenum area for water. Fire or explosion may occur when the fumigant contacts with water.

The floor application can be used in smaller bins but more work is needed on how to apply the fumigants to top portion of the bins from outside the structure. One suggestion is to install another perforated drainage tube on the grain surface before the last load of grain is loaded into the bin. This should position the drainage pipe approximately 2-3 feet below the grain surface when the bin is full. The ends of the pipe could open out at the personnel ladder just inside nearest roof panel hatch. Presently, prepacs like the ones used in this research are not available publicly. They were special made for us for experimental purposes. Another possible aluminum phosphide prepac form would be to make prepacs that are only one tablet wide. This would allow for a better distribution when applying the fumigant, and allow for quicker penetration of lethal gas levels to all bin locations.

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APPENDICES

Appendix A The effects of a surface cover on gas retention.

Table I. - Bin temperatures (°F) for Trial 1.

Location	North	South	East	West	Perimeter average	Center
The uncovered bin:						
Top	69	73	72	73	71.6	62
Bottom	66	72	67	70	68.8	57
Average	67.5	72.5	69.5	71.5	70.2	59.5
The covered bin:						
Top	72	75	74	74	73.8	67
Bottom	69	74	70	71	71	60
Average	70.5	74.5	72	72.5	72.4	63.5

Table II. - Phosphine concentrations (ppm) for Trial 1.

Day	1[a]	1[b]	2[a]	2[b]	3[a]	4[a]	5[a]
Uncovered bin							
North-top	100		15		100		25
North-bot	25		100		25		50
South-top	200		300		100		50
South-bop[c]	0		0		0		0
Center-top	50	15	50	50	75	50	75
Center-bot	75	50	350	75	50	300	50
East-top		350		400		250	
East-bot		300		225		175	
West-top		25		25		50	
West-bot		30		25		25	
Covered bin							
North-top	350		700		800		50
North-bot	200		550		600		75
South-top	350		800		350		125
South-bot	100		75		100		50
Center-top	300	675	1100	575	850	325	75
Center-bot	300	225	400	300	600	425	50
East-top		700		400		500	
East-bot		200		600		150	
West-top		225		150		300	
West-bot[c]		50		50		75	

[a]Readings were taken beginning at 8 a.m.
[b]Readings were taken beginning at 8 p.m.
[c]Sampling tube became disconnected during fumigation giving false readings.

Appendix A The effects of a surface cover on gas retention.

Table III. - Weather conditions during Trial 1

Day	Hours after fumigation	Rel hum	Max temp (°C)	Min temp (°C)	Mean wind speed (m/s)	Max wind speed (m/s)	Wind Direction (degrees)
0	0	34.8	34.4	34.4	3.4	3.4	194.2
1	17 29	59.5	33.7	16.2	1.8	6.7	164.3
2	41 53	74.3	32.7	16.5	1.3	9.0	156.8
3	63 77	90.1	23.5	15.9	0.7	5.4	76.8
4	89 101	88.4	23.7	16.9	3.3	7.5	20.8
5	113	90.3	21.3	16.2	4.8	9.5	15.0

Appendix B The effects of a surface cover on the Floor procedure.

Table I. - Bin temperatures (°F) for Trial 1

Location	North	South	East	West	Perimeter average	Center
Uncovered bin						
Top	76	76	76	77	76.3	75
Bottom	76	75	76	75	75.5	75
Average	76	75.5	76	76	75.9	75
Covered bin						
Top	92	82	89	90	88.3	90
Bottom	81	89	89	79	84.5	78
Average	86.5	85.5	89	84.5	86.4	84

Table II. - Phosphine concentrations (ppm) for Trial 1.

Day	0_b	1_a	1_b	2_a	2_b	3_a	4_a	5_a	6_a
Covered bin									
North-top	0		40		150		400		15
NORTH-BOT	200		150		200		400		40
South-top	0		600		175		100		5
South-bot	200		550		300		200		5
Center-top[c]	0	0	0	0	0	0	0	0	0
Center-bot	50	400	700	400	350	300	375	125	50
East-top		40		275		200		50	
East-bot		550		525		500		125	
West-top		300		325		300		150	
West-bot		800		700		550		150	
Uncovered bin									
North-top	10		550		100		275		5
North-bot	275		550		475		100		15
South-top	0		700		125		50		0
South-bot	225		200		500		500		5
Center-top	50	125	750	250	425	275	300	60	0
Center-bot	0	550	350	300	300	375	350	50	5
East-top		50		400		400		50	
East-bot		650		425		250		200	
West-top		100		75		100		10	
West-bot		475		200		50		10	

[a]Readings were taken beginning at 8 a.m.
[b]Readings were taken beginning at 8 p.m.
[c]Sampling tube became disconnected during fumigation giving false readings.

Appendix B The effects of a surface cover on the floor procedure.

Table III. - Weather conditions during Trial 1.

Day	Hours after fumigation	Rel hum	Max temp (°C)	Min temp (°C)	Mean wind speed (m/s)	Max wind speed (m/s)	Wind Direction (degrees)
0	0	66.8	31.0	31.0	1.6	1.6	186.0
	6	72.1	37.7	22.0	1.6	7.8	151.0
1	18	89.4	25.5	16.7	2.6	9.1	72.7
	30						
2	42	91.1	17.7	15.4	1.9	5.0	64.3
	54						
3	66	89.5	19.7	15	0.8	3.1	63.8
	78						
4	90	77.7	32.3	17.4	1.1	3.6	158.1
	102						
5	114	67.5	36.4	19.7	1.2	3.7	158.7
	126						

Appendix B The effects of a surface cover on the Floor procedure.

Table IV. - Bin temperatures (°F) for Trial 2.

Location	North	South	East	West	Perimeter average	Center
Uncovered bin						
Top	81	84	82	82	82.3	84
Bottom	70	81	90	75	80.3	85
Average	75.5	82.5	86	78.5	81.3	84.5
Covered bin						
Top	82	84	82	84	83	84
Bottom	80	83	82	84	82.3	87
Average	81	83.5	82	84	82.7	85.5

Table V. - Phosphine concentrations (ppm) for Trial 2.

Day	1_a	1_b	2_a	2_b	3_a	3_b	4_a	4_b
Uncovered bin								
North-top	75	100	300	325	350	175	100	50
North-bot	210	400	575	650	500	300	225	75
South-top	300	150	525	500	425	75	200	50
South-bot	375	450	650	625	425	75	325	50
Center-top	200	125	450	500	400	300	210	60
Center-bot	275	375	575	600	400	150	150	50
East-top	50	0	25	75	125	225	200	50
East-bot	210	200	350	450	375	500	400	100
West-top	180	250	500	500	525	300	150	50
West-bot	325	500	650	700	500	200	300	75
Covered bin								
North-top	175	400	650	700	625	300	350	50
North-bot	300	725	825	825	650	300	350	50
South-top	100	0	175	150	150	0	175	0
South-bot	200	675	590	625	450	150	350	10
Center-top	200	125	550	550	400	150	200	15
Center-bot	200	400	700	625	350	100	275	20
East-top	150	300	525	650	550	250	275	40
East-bot	225	425	700	650	625	275	390	25
West-top	200	225	550	550	475	75	200	40
West-bot	280	700	875	950	600	300	375	50

[a]Readings were taken beginning at 8 a.m.
[b]Readings were taken beginning at 8 p.m.

Appendix B The effects of a surface cover on the Floor procedure.

Table VI. - Weather conditions during Trial 2.

Day	Hours after fumigation	Rel hum	Max temp (°C)	Min temp (°C)	Mean wind speed (m/s)	Max wind speed (m/s)	Wind Direction (degrees)
0	0	38.8	28.0	28.0	.76	.76	189
1	15 27	65.3	33.2	16.2	1.7	6.1	108
2	39 53	85.7	24.0	18.0	1.0	3.5	159.6
3	65 77	78.2	30.0	15.5	1.6	5.7	207.6
4	89 101	68.9	35.3	20.7	2.5	6.2	198.8

Appendix C A Comparison of the probe procedure with the floor procedure.

Table I. - Bin temperatures (°F) for Trial 1

Location	North	South	East	West	Perimeter average	Center
Floor application						
Top	102	102	102	103	102.3	103
Bottom	103	101	106	*	103.3	106
Average	102.5	101.5	104	103	102.8	104.5
Probe Application						
Top	94	95	94	96	94.8	94
Bottom	79	88	91	87	86.3	91
Average	86.5	91.5	92.5	91.5	90.6	92.5

* defective thermocouple

Table II. - Phosphine concentrations (ppm) for Trial 1

DAY	0_b	1_a	1_b	2_a	2_b	3_a	3_b	4_a
Probe Application								
North-top	100		550		50		0	
North-bot	75		75		25		10	
South-top	150		150		20		0	
South-bot	0		5		0		0	
Center-top	450	400	400	200	50	10	0	
Center-bot	5	0	10	0	0	0	0	
East-top		100		50		0		
East-bot		50		10		5		
West-top		675		250		25		
West-bot		40		1		0		
Floor application								
North-top	100		300		275		50	
North-bot	75		200		325		75	
South-top	40		5		0		15	
South-bot	75		25		10		50	
Center-top	100	150	325	200	125	125	100	100
Center-bot	100	100	325	200	250	75	50	35
East-top		400		175		100		50
East-bot		350		300		225		40
West-top		125		100		125		25
West-bot		425		350		300		75

[a]Readings were taken beginning at 8 a.m.
[b]Readings were taken beginning at 8 p.m.

Appendix C A Comparison of the probe procedure with the floor procedure.

Table III. - Weather conditions during Trial 1

Day	Hours after fumigation	Rel hum	Max temp (°C)	Min temp (°C)	Mean wind speed (m/s)	Max wind speed (m/s)	Wind Direction (degrees)
0	0	54.2	25.9	25.9	2.3	2.3	301
	9	63.9	29.7	13.1	1.3	4.9	349
1	21	63.2	30.7	15.1	1.7	5.8	124
	33						
2	45	65.1	33.8	18.3	2.0	4.6	144
	57						
3	69	68.7	35.5	19.2	1.2	3.9	60
	81						
4	93	65.3	32.4	18.1	2.8	6.0	32

Appendix C A Comparison of the probe procedure with the floor procedure.

Table IV. - Bin temperatures (°F) for Trial 2.

Location	North	South	East	West	Perimeter average	Center
Floor application						
Top	83	82	82	84	82.8	84
Bottom	84	87	85	88	85.3	79
Average	83.5	84.5	83.5	86	84.1	81.5
Probe application						
Top	83	82	83	82	82.5	83
Bottom	86	88	85	86	86.3	87
Average	84.5	85	84	84	84.4	85

Table V. - Phosphine concentrations (ppm) for Trial 2.

DAY	0[b]	1[a]	1[b]	2[a]	2[b]	3[a]	3[b]	4[a]
Floor application								
North-top	0	150	200	575	600	375	350	75
North-bot	375	675	950	875	625	425	275	75
South-top	25	250	200	400	225	175	150	50
South-bot	425	900	875	725	300	325	125	40
Center-top	0	175	200	450	300	275	200	60
Center-bot	200	600	750	700	425	350	200	40
East-top	40	125	150	300	40	100	15	20
East-bot	575	1000	1000	1000	850	675	350	75
West-top	10	240	275	600	575	375	300	110
West-bot	275	725	975	900	500	400	200	50
Probe application								
North-top	550	925	925	700	400	300	75	
North-bot	40	5	25	5	0	0	0	
South-top	150	375	75	200	25	125	15	
South-bot	50	60	75	25	tr	5	0	
Center-top	175	325	200	250	120	100	60	
Center-bot	50	tr	20	0	0	0	0	
East-top	175	475	220	275	100	125	25	
East-bot	50	40	15	5	0	0	0	
West-top	275	475	375	300	150	100	50	
West-bot	0	tr	tr	20	0	0	0	

[a] Readings were taken beginning at 8 a.m.
[b] Readings were taken beginning at 8 p.m.

Appendix C A Comparison of the probe procedure with the floor procedure.

Table VI. - Weather conditions during Trial 2.

Day	Hours after fumigation	Rel hum	Max temp (°C)	Min temp (°C)	Mean wind speed (m/s)	Max wind speed (m/s)	Wind Direction (degrees)
0	0	84.3	25.7	25.7	.46	.46	222
	9	80.9	31.7	21.6	.97	4.4	60.5
1	21	67.1	38.3	19.3	1.1	3.5	178.5
	33						
2	45	60.8	38.5	24	2.0	5.1	174
	57						
3	69	74.0	32.8	21.6	1.8	4.9	167
	81						
4	93	79.2	34.4	19.5	1.6	7.1	143

A COMPARISON OF PHOSPHINE FUMIGATION METHODS FOR FARM-STORED WHEAT

by

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A COMPARISON OF PHOSPHINE FUMIGATION METHODS FOR FARM-STORED WHEAT

Two application methods, along with the effectiveness of a polyethylene surface cover were tested to determine an effective way to apply phosphine fumigants in farm-stored wheat, while minimizing exposure to the applicator. One method was to uniformly probe aluminum phosphide tablets into the grain mass; the other was to introduce aluminum phosphide "rope" prepacs through a perforated 4 inch drainage pipe secured to the bin floor.

Five comparative fumigations were conducted in 1500 bushel bins to evaluate the application method and effect of a surface cover. Gas concentrations were monitored using Dräeger gas detector tubes at 12 hour intervals until gas levels dropped below 50 ppm. Other factors monitored included grain temperature, and weather conditions (temperature, wind velocity and direction, and relative humidity). Insect Mortality was monitored using test cages containing _Tribolium castaneum_ adults placed at 10 locations in each bin.

Regardless of the application method, the use of a surface cover proved essential in retaining substantial gas levels. The floor application resulted in the least exposure of gas to the applicator and was more effective in maintaining gas concentrations in the lower portions of the bins. When the probe application was used, only very low gas levels were recorded in the lower portions of the bins. General movement of the phosphine was upward in all situations tested.