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INSECT DISTRIBUTION AND CONTROL IN WHEAT-FILLED SILOS

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INSECT DISTRIBUTION AND CONTROL IN WHEAT-FILLED SILOS

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EXECUTIVE SUMMARY

The silo is a useful facility for storage of bulk wheat in Pakistan, but the lack of an efficient method of grain protection restricts its use. The only method of grain protection in a filled silo is phosphine fumigation by placing the Aluminum phosphide (AlP) tablets on the top of the grain mass. This method proved ineffective and it was found that lethal concentrations of gas cannot penetrate the middle and bottom parts of the silo. To improve the phosphine fumigation in the filled silo, a method (flow-through method) was developed and tested in a silo. In this method, the AlP tablets were placed on the grain surface and the grain was recirculated in the same silo for two hours. In this way, the AlP tablets were distributed in the whole grain mass along with the grain. The results showed that the phosphine gas was distributed in the silo uniformly and in sufficient concentration to get complete mortality.

Methyl bromide was also tested in a silo as an alternatative to phosphine and proved successful to control phosphine resistant insects. But the residual problem in the grain and the difficulty in application restrict its use.

The knowledge about insect dispersion in a grain mass is useful for their control. Contrary to the general impression, it was found that insects can live and breed in the whole depth of the grain mass throughout the storage period. Although their numbers were high at the grain surface and the bottom layers near the aeration duct, they were also present in appreciable numbers in the middle parts of the grain mass.

SECTION I

INTRODUCTION

Bulk Wheat Storage System in Pakistan

Food handling agencies store wheat in two forms: bagged and bulk. For bulk storage, the Pakistan Agricultural Storage and Services Corporation (PASSCO) and the Provincial Food Departments (PFD's) use different types of storage facilities. These include house-type godowns, hexagonal bins, open bulkheads, and vertical silos. In house-type godowns, PASSCO uses a bag-cum-bulk storage system while in other facilities complete bulk storage is practiced. The bulk storage capacities of the above structures were mentioned by Ahmad et al., 1991.

A vertical silo is a very useful and modern facility for bulk grain storage. Such storage is common in developed countries. As attempts are being made to amplify the bulk handling and storage of wheat in Pakistan, the silo can play an important role for the storage of wheat. The vertical silos situated at Khaipur and Chichawatni are owned by PASSCO, while those at Multan and Faisalabad belong to the Punjab Food Department. The National Logistic Cell (NLC), a component of the Ministry of Defense, built a silo in Quetta but it is not presently in use because of technical problems. Another silo complex is under construction in Karachi. The present total silo storage capacity in the country is about 302,000 mt.

Introduction of the Present Study

Insect management in bulk grain storage facilities has attracted little attention in the country. The Storage Technology Development and Transfer (STDT) project, in collaboration with the Pakistan Agricultural Research Council (PARC) devised practicable insect management methods for bulk grain. In this program, researchers examined the prevailing pest control methods in different storage facilities and found them to be ineffective. They developed new and effective pest management procedures for hexagonal bins (Mahmood et al., 1991a and Ahmad and Mahmood, 1992) and open bulkheads (Ahmad et al., 1992).

Insect Distribution

The knowledge about insect dispersion and population in a grain mass is very useful for their control and to avoid losses of stored grain. It is generally believed that insect infestation in bulk grain is restricted to the top layers only. However, recent studies of Mahmood et al., (1991a) and Hagstrum (1989) have shown the presence of insects in live form at a depth of up to 5.50 m of a bin, though their number in the top grain layer was the highest. Other authors also studied the abundance and spread of stored-grain insects in different farm silos (Barak and Harein, 1981; Smith, 1978, 1983; Cuperus et al., 1986; and Hagstrum, 1987).

Grain sampling throughout the whole depth of a filled silo is not possible with ordinary bulk probes. Recently, a new bulk probe was designed which can draw samples from deeper areas of a silo (details of this probe have been given else-

where in this report). The acquisition of this probe provided the necessary means for the present study to monitor the insect population in a 22 m high concrete silo.

Grain Fumigation

The common method in use for grain protection in silos is phosphine fumigation. However, the improper procedure of aluminum phosphide (AlP) tablet application and inadequate gas-tight situations in the silos normally lead to failure or partial success of this important pest management tool. In developed countries, automatic pellet dispensers are used to dispense the AlP pellets during the loading of silos. In Pakistan, some silos have a pellet dispenser for phosphine fumigation. However, managers seldom use these because the silo is not filled at one time due to unpredictable and slow receipt of wheat. It often takes three to seven weeks to fill a single silo. Under these circumstances, phosphine fumigation is not possible during the loading operation. To fumigate a filled silo, the placing of AlP tablets on the grain surface is being practiced by PASSCO and PFD. This type of application has already been determined to be useless in hexagonal bins (Mahmood et al., loc cit) although they are smaller than the silo.

Phosphine fumigation is an easy and effective way of insect management in bulk grain. Safety in application, easy transportation, and almost no equipment required for application are the major factors which support the use of phosphine throughout the world. But adoption of improper methods of application, inadequate sealing, and fumigation by untrained personnel created situations in which the effectiveness of this fumigant has badly suffered. This undesirable situation not only increases grain protection cost but also makes the insects less susceptible to the toxic action of this gas. The phosphine dosage determination studies by Mahmood et al., (1991b) highlighted that comparatively longer exposure periods are required to control the major stored grain insect pests at most of the sites. Longer exposure periods cannot be attained by following present practices. To attain the better distribution and retention of phosphine gas, a simple method (flow-through method) was developed. This method was tested at a steel silo in Multan and the results are being reported.

Fumigation with other fumigants, like methyl bromide, provides an alternatative to phosphine in controlling the insect infestation, especially for phosphine-resistant insects (Winks, 1986). Methyl bromide is a low boiling point liquid and is supplied in pressurized cylinders. It is a widely used fumigant and its insecticidal properties have been known for almost half a century (Le Goupil, 1932). Besides controlling the phosphine-resistant insects, methyl bromide fumigation is used in situations where short exposure periods are required. In the present study, this fumigant was tried in the same silo where the insect distribution study was conducted to control the phosphine-resistant insects.

Objectives

The main objectives of the present study were:

1. To determine insect distribution in different grain depths during the storage period.

2. To evaluate the effectiveness of current phosphine fumigation practice and to develop a methodology for its improvement.

3. To test methyl bromide as an alternative to phosphine.

SECTION II

MATERIALS AND METHODS

Insect distribution

Grain sampling

The PARC/STDT team conducted the study at the PASSCO silo complex in Chichawatni. The height of the silo at Chichawatni was about 22 m (72 ft) and its diameter was 15.84 m (52 ft). The total storage capacity of the silo is 3,000 mt, however it contained only 2,600 mt of wheat.

Grain samples were drawn each month with the help of a Gilbert's probe (Figure 1). The probe consists of four units: (1) a vacuum pump, (2) a corrugated flexible pipe, (3) a grain collector, and (4) steel pipes. The vacuum pump is the basic unit of the probe, mounted on a trolley and driven by a five horsepower petrol engine. It has a cyclone equipped with a Y-valve serving as discharge outlets. The cyclone is further connected through the corrugated flexible pipe with another small cyclone used as the grain collector. The grain collector has a discharge spout for the grain samples. The fourth unit of the grain probe is composed of steel pipes. Each pipe is 4 ft (1.13 m) long with an inside diameter of 3 cm. The pipes have an interlocking system for quick connection. The first pipe has perforations up to 35 cm from one end. A small length of flexible pipe linked the steel pipes with the grain collector. Researchers push the perforated pipe followed by the other pipes up to the required depth (Figure 2). The pump creates a negative pressure and sucks the grain through the open end of the pipe. The perforations on the first pipe assist in the suction process. The grain samples collect at the grain collector, and discharge into sample bags by opening the flap (Figure 3).

Insect Monitoring

Grain samples were drawn from each pipe length (4 ft) of wheat depth up to the bottom of the silo from three different points. These points were 0.5 m, 2 m, and 4 m from the wall of the silo and are referred to as peripheral, semi-peripheral, and central, respectively. The grain samples (each weighing about 1 kg) were kept in polyethylene bags, labeled (Figure 4) and analyzed in the laboratory for presence of live and dead insects. The insects were separated from the grain with a dockage tester (Carter-Day Company, Minneapolis, USA) having sieves of 0.089 T and 5/64 R meshes and a No. 2 riddle.

The insects were collected, identified, and counted. After separating the live and dead insects, each sample was incubated for four to five weeks at a temperature of 30 ± 2^0 C and a humidity level of 65 ± 5% to observe the survival of eggs or pupae. After the stipulated incubation period, each sample was sieved and newly emerged insects were collected, identified, and counted in a similar way. The moisture content of each sample was also determined before insect separation by using a Burrow's moisture computer (Burrows Equipment Co., Illinois, USA).

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Phosphine Fumigation

By the Current Procedure (Placing the AlP Tablets on the Grain Surface). In September 1991 the PASSCO staff carried out phosphine fumigation in the silo at Chichawatni by using the current procedure. They used a total number of 3,994 AlP tablets for the fumigation at a dose rate of one tablet per cubic meter. They placed about 3200 tablets on the grain surface and threw the rest in the aeration duct at the bottom of the silo. The ventilators, manhole, and aeration duct were sealed by wrapping with polyethylene sheets. The PARC/STDT team collected grain samples 25 days after the date of application of fumigant to determine the effectiveness of fumigation. Grain samples were drawn from predetermined depths.

In July 1992 the phosphine fumigation was done by PFD's personnel by putting the whole number of AlP tablets (4,662) on the grain surface. The same silo was used for the present study. Before fumigation, grain sampling was done with a Gilbert's probe from three points (as described earlier) to determine the effectiveness of previous fumigation.

By Flow-Through Method. This newly developed method was tested in PFD 's steel silo located at Multan (Figure 5). Its height was 16.15 m (53 ft) while diameter was 18.29 m (60 ft). The storage capacity of the silo under study was 2,500 mt but 2,437 mt wheat was stored. For fumigation, the same number (4,662) of AlP tablets were utilized. The dose rate was 1.15 tablet/cu m. The total number of tablets was divided into two portions. The first portion (75% of the total number) was spread on the grain surface at central and semi-peripheral points. The grain was then moved by running the bottom unloading auger and directing the grain into the same silo for two hours. When the unloading valve is opened and the unloading auger is started, grain flows from the top surface down a center core to the unloading auger (Ross et al., 1973). This is called the funneling effect. The grain across the bottom and around the sides of the bin does not move. The AlP tablets spread on the grain surface will flow down along with the moving grain and make a vertical column throughout the grain depth. The second portion (25% of the total number) was applied through the hatch immediately after turning off the unloading auger. These tablets occupied the top surface of the grain pile. All gas leakage points were sealed by using polyethylene and PVC self adhesive tape.

For monitoring the phosphine gas, nylon capillary tubes were installed prior to application of the AlP tablets. AlP tablets were applied in the top, middle, and bottom grain layers at the central and peripheral zones by pushing down with the help of steel rods (Figure 6). One tube was fixed in the free space above the grain surface. The tubes were fixed in place against the roof and extended out through the manhole.

Gas monitoring was done 24 hours after the application of the fumigant and daily for seven days by using a phosphine gas monitor (Bedfont Technical Instruments Ltd. UK).

Methyl Bromide Fumigation

The methyl bromide fumigation was done in December 1991 at Chichawatni using the same silo where the insect distribution study was performed. The dose was calculated by volume and quantity of wheat stored in the silo using the following formula (Anonymous, 1989):

Methyl bromide required (gm) = S x Total volume of enclosure +
M x Tonnage of grain

Where S = Space dosage (10 for wheat)
M = Commodity dosage (20 for wheat)

Because it has higher specific gravity than air, the fumigant was applied from the top of the silo through a distribution system shown in Figure 7. This system was fixed two meters above the grain surface in the silo. The nozzles were adjusted in such a way that the fumigant could not come into contact directly with the grain. A total of 95.35 kg (210 pounds) liquid methyl bromide was used in this fumigation. The aeration fan at the bottom of the silo was run for a few minutes after six hours of application for forced circulation of the methyl bromide gas. The gas was retained in the silo for about 48 hours.

A methyl bromide detection meter (Bedfont Technical Instruments Ltd, UK) was used to record the gas concentration from different gas sampling points through nylon tubes installed in the grain mass as indicated in Figure 7. After a 48 hour retention period, the gas was vented out by opening the ventilators and the manhole on the roof top, and running the aeration fan. The aeration was done for three days at intervals of three to four hours.

Grain sampling was done before and after methyl bromide fumigation similarly as described earlier to confirm the success of fumigation. The grain samples were analyzed for live and dead insects immediately on receipt in the laboratory and after a five week incubation period.

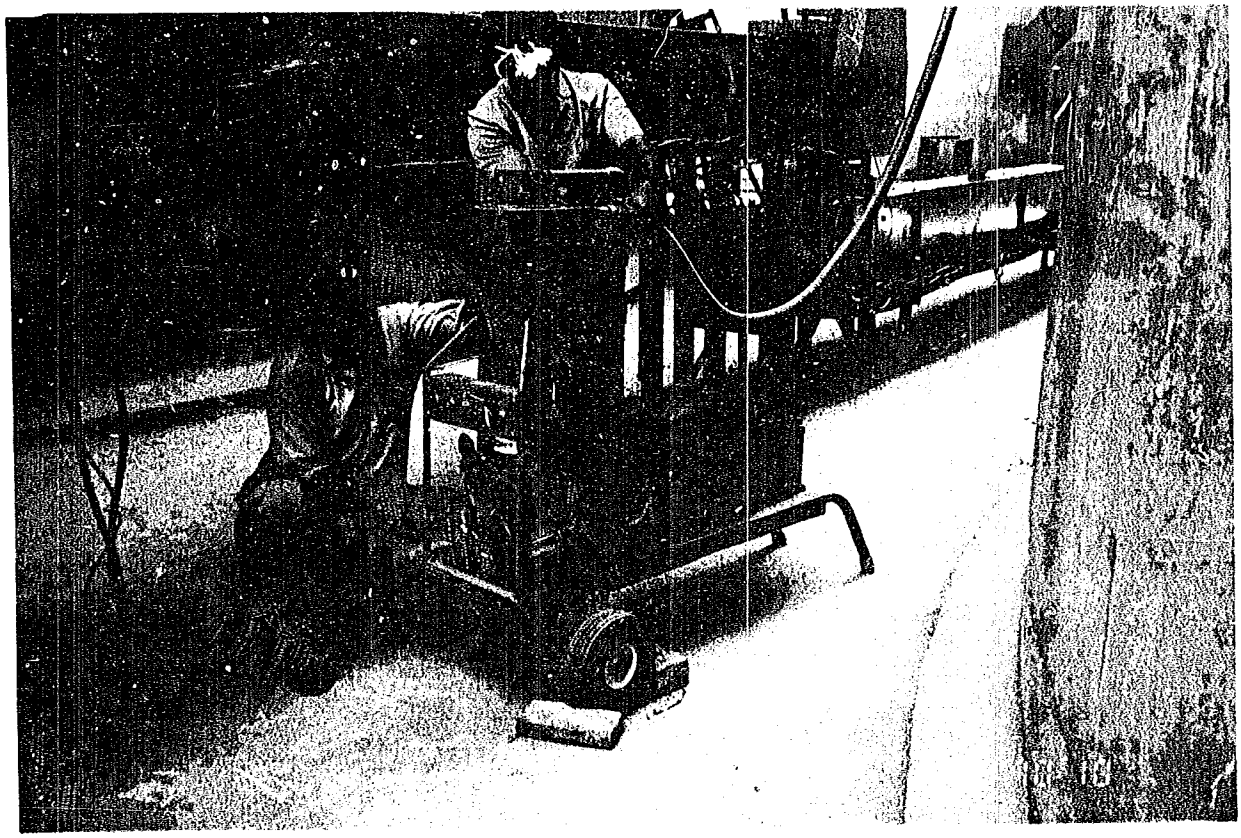

Figure 1. Gilbert's Probe.

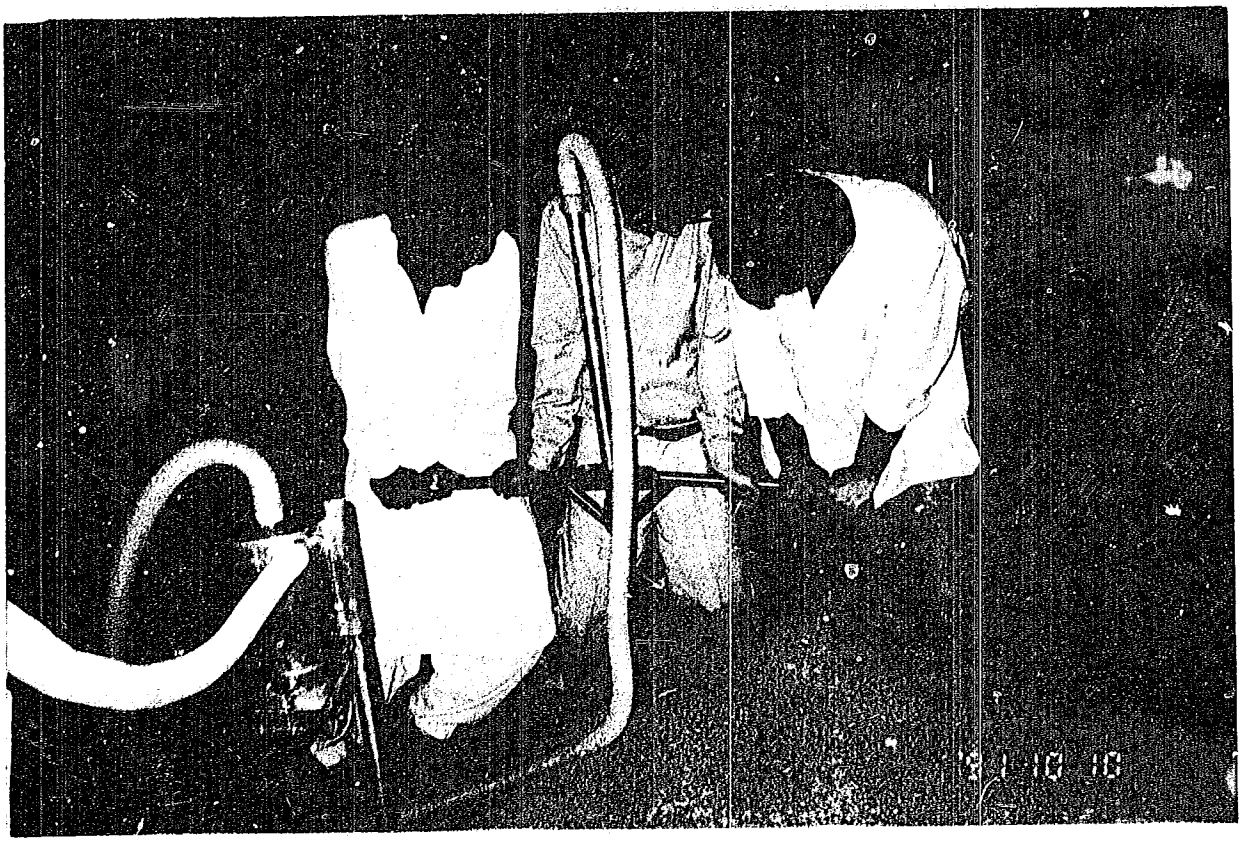

Figure 2. Pushing the Steel Pipes in to the Grain Mass.

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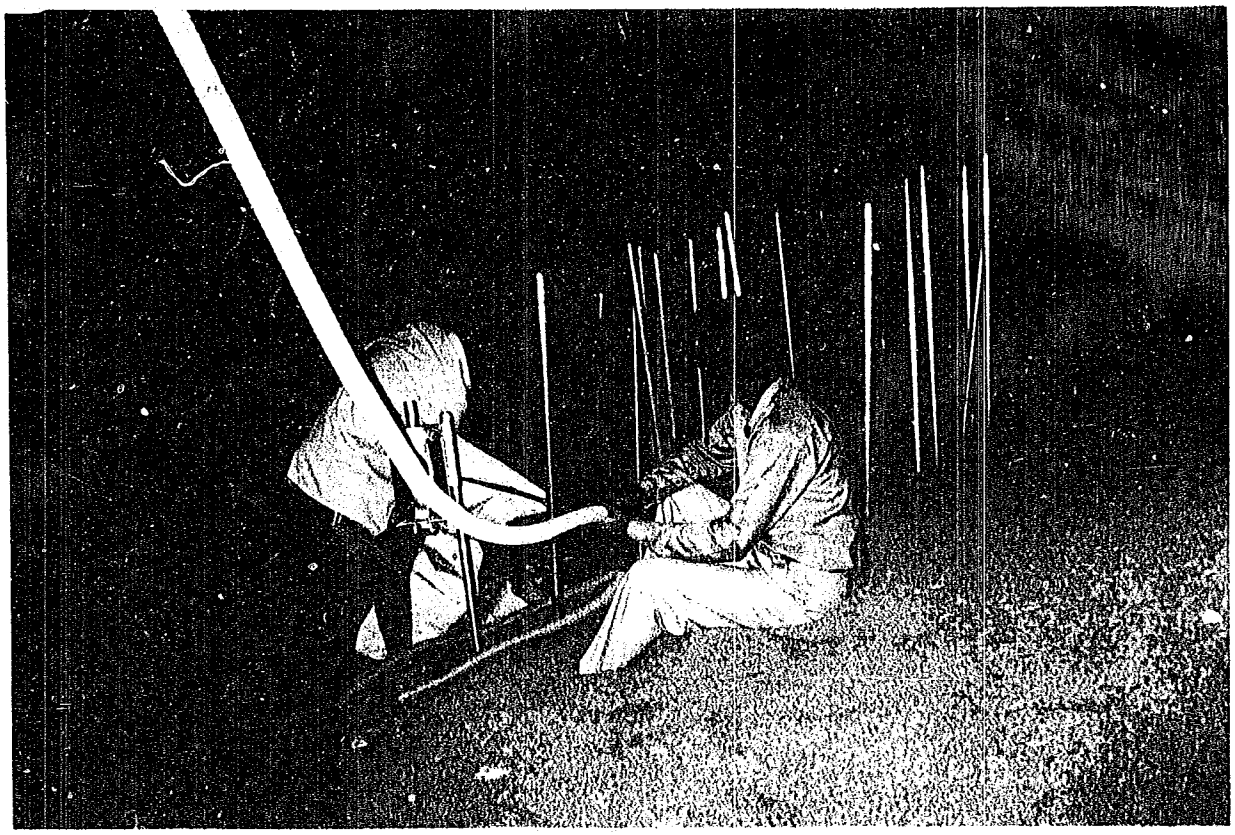

Figure 3. Collection of Grain Samples.

Figure 4. Packing Grain Samples in Polyethylene Bags.

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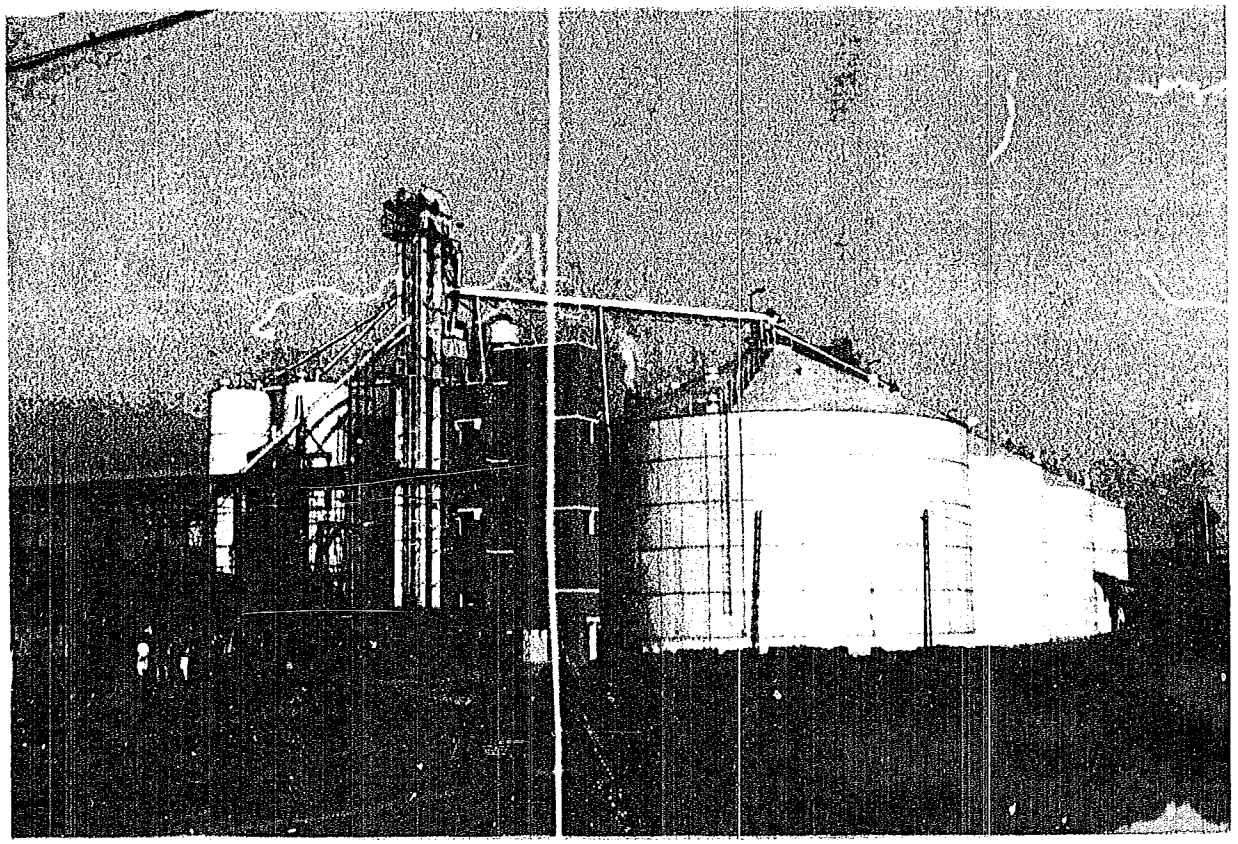

Figure 5. Steel Silo Complex at Multan.

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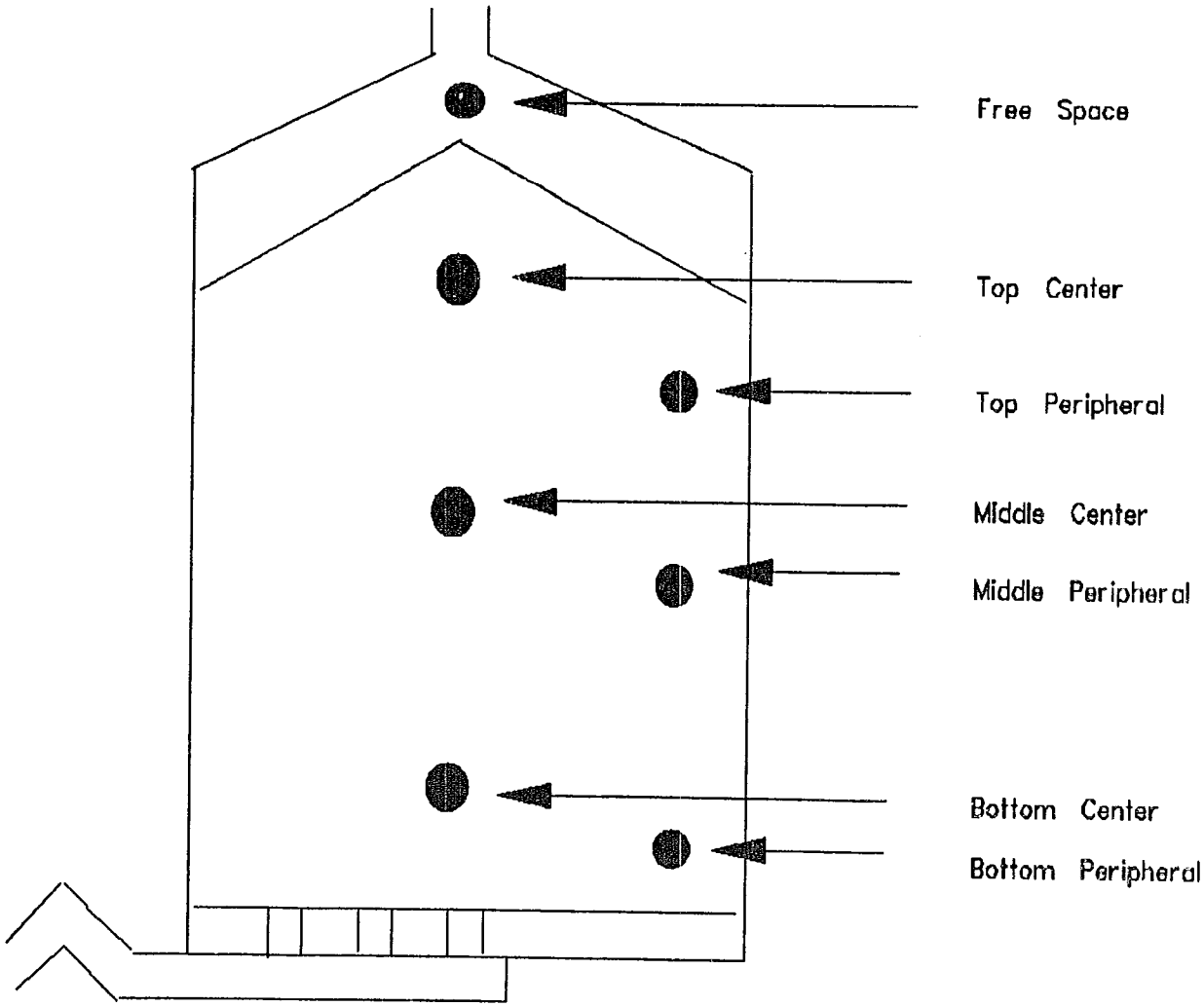

Figure 6. Phosphine Gas Monitoring Points in the Grain Mass.

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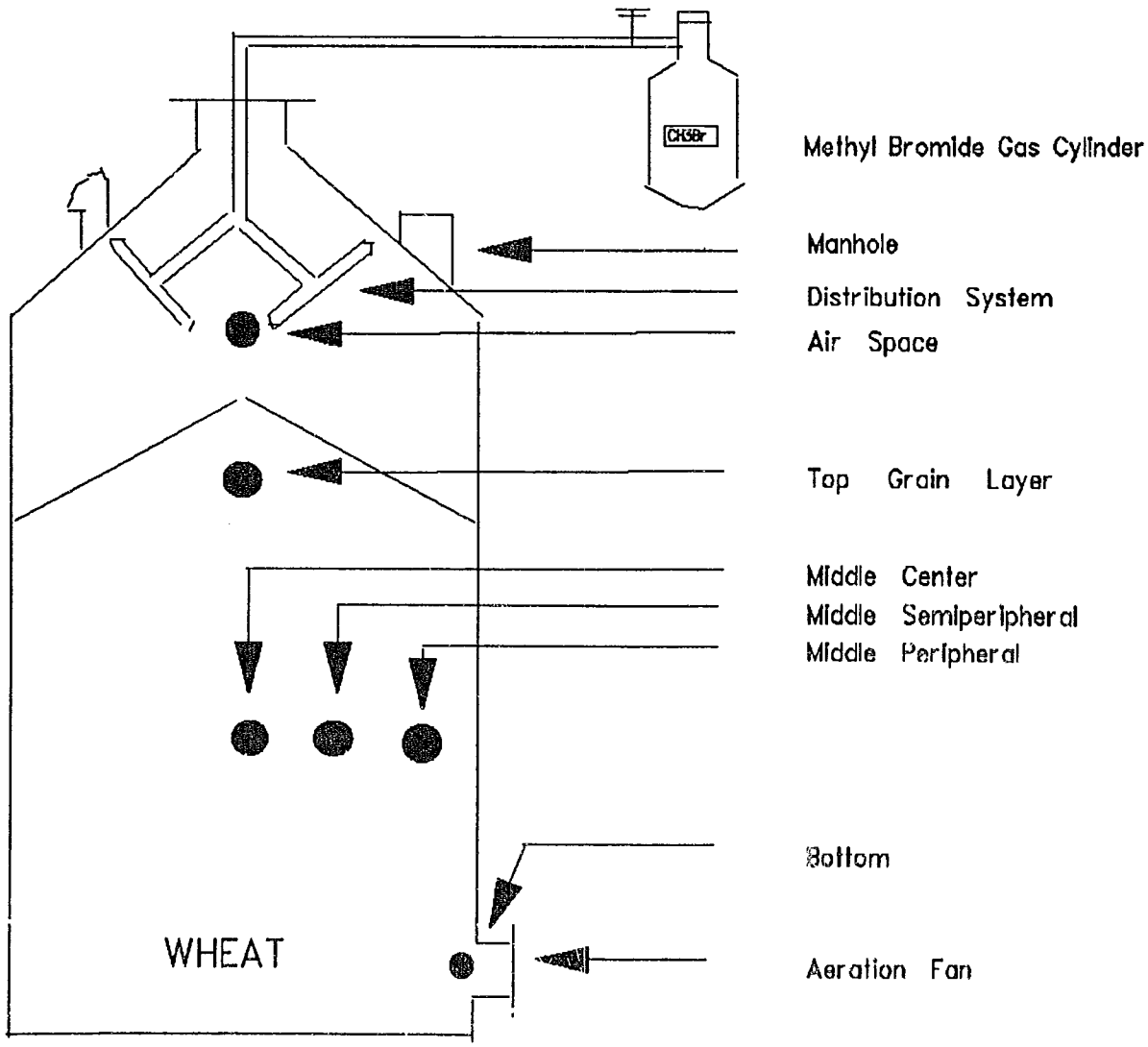

Figure 7. Methyl Bromide Distribution System and Gas Monitoring Points.

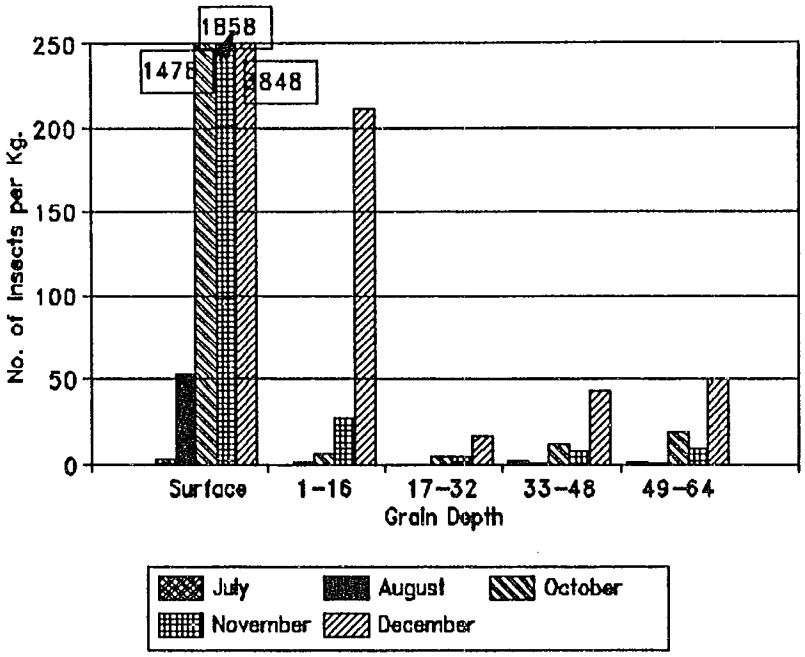

Figure 8. Total Population (before and after incubation, live and dead) of Trogoderma granarium (No. per kg of sample) in Different Grain Depths During the Study Period

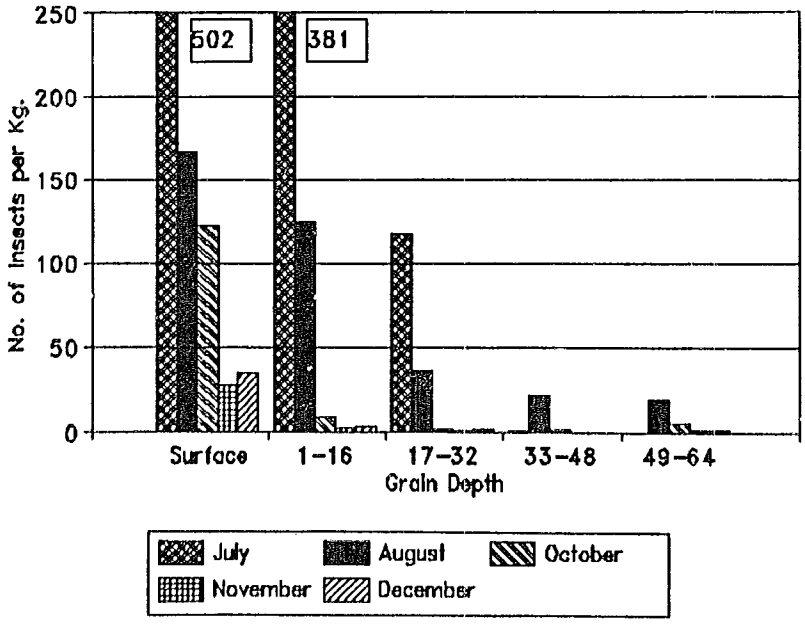

Figure 9. Total Population (before and after incubation, live and dead) of Rhizopertha dominica (No. per kg of sample) in Different Grain Depths During the Study Period

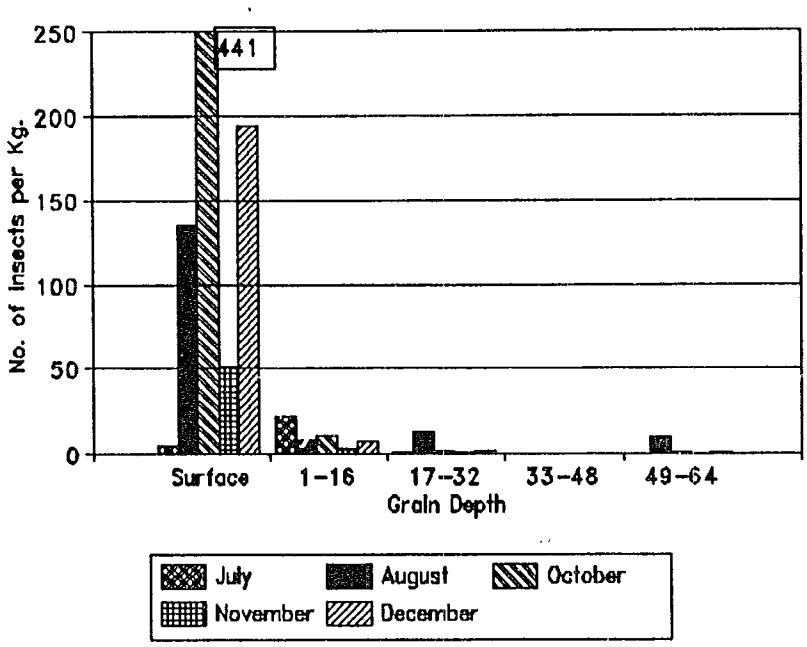

Figure10. Total Population (before and after incubation, live and dead) of Tribolium castaneum (No. per kg of sample) in Different Grain Depths During the Study Period

SECTION III

RESULTS AND DISCUSSION

Distribution of Insects

Different stored-grain pest species were encountered from various grain layers in the wheat-filled silo. The most important pest species were the khapra beetle, Trogoderma granarium; the lesser grain borer, Rhizopertha dominica; and the red flour beetle, Tribolium castaneum. Other pest species which were observed in very small numbers were the rice weevil, Sitophilus oryzae; the saw-toothed grain beetle, Oryzeaphilus surinamensis; and the rusty grain beetle, Cryptolestes ferruginous. These are not included in this report. Since the objective of the study was to determine the vertical distribution of insects in the silo, the number of the insects found from three sampling points (peripheral, semi-peripheral, and central) are averaged. The detailed distribution of the major insect pests is as follows.

The Khapra Beetle (Trogoderma granarium). Table 1 presents the distribution and abundance of this species present in different grain depths during the study period. The first grain sampling, carried out in July 1991, revealed a slight appearance of larvae and adults of this species on the grain surface and the upper 8 ft of grain layers. Some larvae were also found 52 ft deep in the grain mass. The rest of the grain mass was free from infestation by this species. In the next sampling (August), the number of insects increased considerably on the top and bottom grain layers. The middle part of the grain mass was comparatively free from insects. Phosphine fumigation was carried out in September 1991, and the grain was sampled after 25 days (October). Both live and dead insects were present in considerable numbers at various grain depths. At the grain surface, high numbers of dead insects were found, along with a significant number of live insects. Live insects were also present in the upper and bottom grain layers. In later months, both live and dead insects increased significantly on the grain surface and the deeper grain layers. The maximum number of live insects was recorded in December when they were distributed in the whole of the grain column (Table 1). Very high numbers of live adult and larvae were observed on the grain surface, while comparatively less were found in the upper layer of the grain up to 16 ft. The number decreased in deeper layers (32 to 64 ft) as shown in Figure 8.

After separating the live and dead insects, the samples were incubated for four weeks for eggs/pupae to hatch/moult into larvae and adults. Emergence of larvae and/or adult insects in the incubated grain samples represents the breeding activity of insects in the different grain layers. Insect data presented in Table 4 exhibits the number of eggs or pupae present at that particular place at the time of sampling. In July the breeding activity was restricted mostly to the grain surface and the 40 foot deep grain layer while it was more dispersed in the different depths in August. The maximum breeding activity of Trogoderma granarium was observed in the month of October on the grain surface, followed by the upper 8-foot layer, and in the bottom layers, in spite of phosphine fumigation in September. The appearance of insects after incubation indicated the tolerance of immature stages and/or brief exposure to phosphine gas.

Incubation data obtained in November showed the further distribution of breeding activity to almost all of the grain layers.

The Lesser Grain Borer (Rhizopertha dominica). Table 2 presents the distribution of the lesser grain borer at different depths of the grain bulk during the experimental period. In the first sampling (July 1991) live and dead insects were distributed up to 32 ft deep in the grain mass. The maximum number of insects was observed on the grain surface while comparatively fewer were observed in the deeper layers. In August the distribution of this species spread further into the deeper layers. After phosphine fumigation (in September), grain sampling in October resulted in a high number of dead insects on the surface and comparatively less in all of the deeper layers. Live insects were also found up to 24 ft from the top as well as in the bottom layer near the aeration duct. In November and December live insects were found on the grain surface and the top grain layers, while dead insects were present in most of the grain layers.

The lesser grain borer, Rhizopertha dominica is a primary stored-grain insect pest, both larval and adult stages damage the grain. Larvae of this insect stay inside the grain kernel and feed internally. Adults bore out of the grain kernels after maturity and feed externally. The determination of the insect's activity, therefore, was based upon the counting of adults only. After separating the insects, samples were incubated so that the immature stages (egg, larval, and pupal) may moult into adult stage. The data presented in Table 5 depicts the emergence of the adult Rhizopertha dominica after incubation. The maximum emergence was noted in July and August. In July the maximum emergence was found in the upper grain layers up to the 24-foot depth, while in August they were distributed randomly in all of the grain depths. In October the number of live insects before incubation decreased significantly due to phosphine fumigation in September (Table 2), but emergence of adult insects after incubation showed the incapability of this particular phosphine fumigation in controlling the immature stages (Table 5). In November the emergence of adult insects was perceived in different grain layers while in December it was restricted to the upper layers up to 24 ft from the grain top. The lower breeding activity in November and December may be due to the decline in temperature. Figure 9 shows the total insect load of this species in different grain depths throughout the study period.

The Red Flour Beetle (Tribolium castaneum). Table 3 shows the population of the red flour beetle, Tribolium castaneum distributed in different grain depths of the silo during the experimental period. The first sampling, done in July 1991, shows the presence of live and dead insects in upper grain layers up to 20 ft from the grain top. However, the maximum number was recorded at the 8-foot deep layer. In August the distribution of this species was more prominent at different depths. The maximum number of live insects in this month was found at the grain surface followed by the 52-foot deep grain layer. After phosphine fumigation (in September), grain samples were collected in October. These samples revealed a significant decrease in population of Tribolium castaneum at most of the sampled depths. The appearance of a significant number of live insects (24.16 per kg) on the grain surface indicated the partial success of phosphine fumigation. The high number of insects on the grain surface in October may be due to upward movement of the surviving insects from deeper parts of the grain mass. In December the maximum number of live insects was found on the

surface. Some live insects were also sampled from the 4- and 44-foot deep layers. Dead insects were noted in the whole vertical grain column.

Table 6 exhibits the emergence of adult red flour beetles. This table illustrates that in July, the breeding activity was mainly restricted to the upper grain layers while in August it was more distributed in the middle and bottom grain layers. In October the emergence of live insects was mainly in the middle grain layers (16 to 28 ft deep). The newly emerged insects probably distributed themselves on the top surface and other grain layers which were later sampled in November (Table 3). The breeding activity was restricted to the top grain layer and on the grain surface in November and December, respectively (Table 6 and Figure 10).

The presence of high numbers of insects on the grain surface is a well known phenomenon and was also observed in the present study. All major insect pests were populated on the grain surface and the highest number was found in the colder months (October through December). This may be due to more favorable environmental conditions by the presence of more free space above the grain top as the grain surface was 13 ft below the roof. The average temperature of the grain was 32 and 38^0 C at the top and deeper grain layers, respectively, while it was 19^0 C at free space. The moisture content of the surface grains was 10.18 and 12.52% in November and December, respectively, while comparatively less in the deeper grain layers (Table 7). The increase in the moisture level of the surface grain may be due to high infestation of Trogoderma granarium and/or moisture condensation. The high moisture content and relatively suitable temperature favor the building up of the other pest species, especially Tribolium castaneum.

Phosphine Fumigation by the Current Procedure

The sampling done (August 1991) before phosphine fumigation at the Chichawatni silo, showed the population of Rhizopertha dominica to be dominant at all sampling depths, followed by Tribolium castaneum and Trogoderma granarium. The maximum population of all species was concentrated on the grain surface and decreased with the depth of the grain mass. Live Trogoderma granarium were present mostly on the surface and at the 12-foot depth in the grain mass. They were also present (in small numbers) at the bottom zone where the aeration ducts were. Rhizopertha dominica and Tribolium castaneum were distributed in about all of the depths in varying numbers (Table 8).

Data in Table 9 shows the partial success of phosphine fumigation, because live insects were active throughout the grain depth. However, the number was comparatively less than the number before fumigation. The population of Rhizopertha dominica and Tribolium castaneum decreased significantly, while Trogoderma granarium increased in number at all grain depths, especially on the grain surface.

The survival of insects after phosphine fumigation may be due to the acquisition of tolerance against phosphine. The studies in the laboratory to control the Chichawatni strains indicated that a phosphine concentration of above 200 ppm is required for 12 days for Trogoderma granarium while other species required only five days for complete mortality (Mahmood et al., 1991b). The distribution and

survival of insects in different grain layers indicates the inadequate concentration and exposure time to phosphine gas. The results demonstrated that phosphine gas controlled the most susceptible strains, but it failed to control the resistant ones. Placing the AlP tablets in the aeration ducts proved useless as it did not control the insects in the bottom parts of the silo. It seems that phosphine gas generated in the aeration ducts leaked out through the aeration system soon after the application and created a haven for the surrounding insects.

The Chichawatni silos were constructed in 1983-84 and have been in use for wheat storage since that time. The only procedure adapted to disinfest the grain was phosphine fumigation by pre-described manner. This method of fumigation has already proved to be a failure in hexagonal bins (Mahmood et al., 1991a). The inadequate sealing, porosity of building materials, less dispersion of phosphine gas in the deeper parts of the grain mass, and other environmental factors made it difficult to maintain the required lethal gas concentration in the storage structures. This unwanted situation results in less effective fumigation and constant exposure of insects to sub-lethal doses of phosphine and causes selection pressure on the insect species that develop high tolerance to the toxic action of this gas (Bell, et. al., 1977).

The insects that survive in such operations can only be those which have a relatively high tolerance to phosphine. The survivors of further operations will thus become even more tolerant. Such selection will ultimately lead to the development of strains which may have hundreds of times more resistance to this gas than their ancestors. The development of resistance in insects is much faster because of their short life span compared to higher forms of animals.

The adverse effect of the appearance of resistant pest strains increases the cost of pest management. It will require higher dosage levels and repeated fumigation processes to control such pests. A more serious implication of the problem is making the fumigant useless as a pest management tool. There is no available substitute having similar properties to combat the pests. To retain the effectiveness of phosphine for as long as possible, alternative methods of grain protection are highly desirable. This becomes more pressing in situations where pests are resistant against phosphine. The complete control of resistant insects will help in making phosphine gas effective again in disinfesting stored grains. One way of achieving this objective is to maintain the lethal level of phosphine gas in the fumigated space over a comparatively longer period (Winks, 1986) which is only possible in structures having a high degree of gas-tightness. In non-gas-tight situations, phosphine will fail to achieve successful control of the resistant insect populations. Another way to keep the grain free from insect infestation is the application of grain protectants at the time of loading, but chemical residues and other factors restrict their use.

Methyl Bromide Fumigation

A proven method of controlling a phosphine-resistant pest is by methyl bromide fumigation. All phosphine-resistant strains are susceptible to this fumigant. Methyl bromide has demonstrated its effectiveness in disinfesting most agricultural commodities since its introduction in the market. The relatively shorter exposure period compared with phosphine is its major advantage. However,

difficulty of application and its sorption residue are the two major disadvantages of this fumigant. Methyl bromide is a colorless, odorless, and nonflammable gas at ordinary temperature. A lachrymal agent (chloropicrin) in the fumigant makes it easy to detect leakage or presence of the gas. The information related to penetration, distribution, and sorption have been discussed by Cotton and Walkden, 1951; Phillips, 1955, 1957; and Phillips et, al., 1959. Methyl bromide is mostly used for quarantine treatment and in situations where less time is available. Methyl bromide fumigation can be a tool to break the phosphine resistance in insects (Winks loc. cit.). Resistance to this compound has not yet been reported in Pakistan. Methyl bromide is a low-boiling point fumigant. It is available in the market as liquid under pressure in cylinders. The basic properties of this fumigant are:

Formula:	CH_3Br
Molecular Weight:	95
Boiling point (C):	3.6
Specific gravity (gas):	3.40 air = 1.0
Conversion factor (gm to ppm) at 30^0 C 1 atm:	260
Flammability limits in air (v/v):	13.5 - 14.5%
Solubility of liquid in water (v/v):	1.4

After the partial success of phosphine fumigation in the present study, the control of surviving resistant insects was highly desirable. This is to arrest the spread of insect resistance and to retain the effectiveness of phosphine for future use.

Live insects were present throughout the grain mass in all vertical layers before fumigation (Table 10). The population of three major species was highest on the grain surface and comparatively less in the deeper grain layers (Figures 8, 9, and 10). Trogoderma granarium was found to be more dominant than the other species in nearly all of the sampling zones. Visual observation inside the silo showed clusters of live Trogoderma granarium larvae on the peripheral region of the grain surface. They were also crawling on the walls of the silo. Populations of live Rhizopertha dominica and Tribolium castaneum were also prominent in the whole vertical grain column. The maximum strength of these species was present on the surface.

After fumigation, insect data presented in Table 11 showed no live insect at any depth. However, dead insects were found in varying numbers from each depth. No emergence of any larva or adult was noted in the incubated samples, which indicated the success of methyl bromide fumigation.

Concentration x time (Ct) product at different sampling points during 48 hours of exposure period are given in Tables 12 through 17. The maximum Ct product, 1325.55 gm. hr/m^3, was achieved in 48 hours at free space, followed by the middle peripheral, bottom (aeration duct), middle semi-peripheral, and top grain layers. The Ct product achieved at any sampling was well above the lethal level required to achieve complete mortality of stored grain insects. The lethal level of methyl bromide for most stored-grain pests is 150 gm. hr/m^3 at 25 ^{0}C, while it is 400 gm. hr/m^3 for Trogoderma granarium (Anonymous, 1989). The high Ct product achieved at the peripheral zones, as compared to the central zone of the grain

mass, may be due to the terminal openings of the gas distribution system directed towards the peripheral sides.

Phosphine Fumigation by the Flow-Through Method

To test this new procedure for phosphine fumigation of a filled silo, a trial was conducted on a wheat-filled steel silo at Multan. Gas monitoring data given in Table 18 showed that gas was generated in the central column of the grain mass throughout the whole depth of the silo and was distributed laterally soon after its application. The lethal concentration (above 200 ppm) of phosphine gas reached the peripheral zone of the grain mass after 24 hours. It was distributed more uniformly after the second day of application of the AlP tablets. The lethal concentration of gas was retained in the silo for five days due to leaky conditions of the silo under study. The daily average leakage rate was about 251 ppm. The maximum leakage was from the top zone (Table 18) while the middle and bottom portions were comparatively less leaky. Although the silo complex was rehabilitated a few months ago, there are still many gas leakage points present. Most of them were closed before fumigation. The main task of the present study was to improve the gas distribution in the whole parts of the grain mass. The gas retention period can be further improved by making the silo completely gas-tight by application of some sealant on the joints, cracks, and bolts.

Before fumigation, insect data showed the dominant population to be the khapra beetle, Trogoderma granarium; followed by the red flour beetle, Tribolium castaneum; and the lesser grain borer, Rhizopertha dominica (Table 19). The maximum number of live and dead khapra beetles was found on the grain surface. The red flour beetle was distributed in varying numbers in most of the grain depths while the lesser grain borer was observed on the grain surface and in the upper grain layers. Table 19 also represents the insect data after fumigation. The data showed the mortality of all three major insect species in different depths. No live insect was found in any depths, ascertaining the success of phosphine fumigation.

TABLE 1

DISTRIBUTION OF TROGODERMA GRANARIUM AT DIFFERENT DEPTHS OF A WHEAT-FILLED SILO BEFORE INCUBATION

Sampling depths (feet)	Devlp. Stage	SAMPLING MONTHS														
		July 1991			August 1991			October 1991			November 1991			December 1991		
		Live	Dead	Total	Live	Dead	Total	Live	Dead	Total	Live	Dead	Total	Live	Dead	Total
Grain Surface	Larvae	0.56	-	0.56	3.84	1.51	5.35	82.99	286.29	369.28	274.17	302.96	577.13	1039.75	1341.14	2380.89
	Adults	1.00	-	1.00	1.51	19.42	20.93	8.67	526.32	534.99	6.17	1243.98	1250.05	15.48	1403.55	1419.03
4	Larvae	-	-	-	-	-	-	2.69	3.12	5.81	8.12	23.30	31.42	40.94	285.42	326.36
	Adults	-	-	-	-	1.23	1.23	-	6.89	6.89	-	33.08	33.08	-	420.61	420.61
8	Larvae	-	-	-	-	-	-	0.57	0.87	1.44	1.30	3.28	4.58	0.30	4.20	4.50
	Adults	0.70	-	0.70	-	-	-	-	1.15	1.15	-	5.98	5.98	-	40.50	40.50
12	Larvae	-	-	-	0.63	-	0.63	-	1.54	1.54	3.58	6.38	9.96	0.28	7.88	8.16
	Adults	-	-	-	1.56	1.27	2.83	-	0.39	0.39	-	6.38	6.38	-	28.26	28.26
16	Larvae	-	-	-	-	-	-	-	3.36	3.36	5.10	3.92	9.02	0.48	7.39	7.87
	Adults	-	-	-	-	-	-	-	0.85	0.85	-	0.54	0.54	-	6.75	6.75
20	Larvae	-	-	-	-	-	-	-	1.92	1.92	0.23	6.04	6.27	-	5.80	5.80
	Adults	-	-	-	-	-	-	-	0.84	0.84	-	1.06	1.06	-	5.04	5.04
24	Larvae	-	-	-	-	-	-	-	2.83	2.83	-	4.76	4.76	0.25	4.35	4.60
	Adults	-	-	-	-	-	-	-	0.85	0.85	-	1.67	1.67	-	5.93	5.93
28	Larvae	-	-	-	-	-	-	-	2.85	2.85	-	1.74	1.74	-	4.45	4.45
	Adults	-	-	-	-	-	-	-	0.83	0.83	-	0.46	0.46	-	10.72	10.72
32	Larvae	-	-	-	-	-	-	0.73	6.25	6.98	-	1.75	1.75	0.31	10.02	10.33
	Adults	-	-	-	-	-	-	-	1.97	1.97	-	1.25	1.25	-	18.11	18.11
36	Larvae	-	-	-	-	-	-	-	2.72	2.72	-	4.72	4.72	0.26	9.23	9.49
	Adults	-	-	-	-	-	-	-	8.84	8.84	-	2.25	2.25	-	24.91	24.91
40	Larvae	-	-	-	-	-	-	-	2.13	2.13	-	2.38	2.38	-	8.35	8.35
	Adults	-	-	-	-	0.54	0.54	-	8.51	8.51	-	6.33	6.33	-	36.19	36.19
44	Larvae	-	-	-	-	-	-	-	1.30	1.30	0.19	2.48	2.67	0.30	13.68	13.98
	Adults	-	-	-	-	2.27	2.27	-	7.05	7.05	-	5.61	5.61	-	39.96	39.96
48	Larvae	-	-	-	-	-	-	0.44	1.97	2.41	0.19	5.13	5.32	0.30	5.64	5.94
	Adults	-	-	-	-	-	-	-	16.41	16.41	-	2.98	2.98	-	36.02	36.02
52	Larvae	1.23	-	1.23	0.49	-	0.49	-	6.34	6.34	-	2.67	2.67	1.03	13.67	14.70
	Adults	-	-	-	-	-	-	-	17.18	17.18	-	7.40	7.40	-	50.76	50.76
56	Larvae	-	-	-	-	-	-	-	2.54	2.54	-	5.34	5.34	-	7.54	7.54
	Adults	-	-	-	-	-	-	-	11.35	11.35	-	5.72	5.72	-	30.93	30.93
60	Larvae	-	-	-	0.71	0.71	1.42	0.41	2.61	3.02	-	2.54	2.54	0.75	7.37	8.12
	Adults	-	-	-	-	-	-	-	8.99	8.99	-	1.66	1.66	-	19.90	19.90
64	Larvae	0.63	-	0.63	1.45	0.70	2.15	5.28	8.40	13.68	2.04	5.04	7.08	1.15	14.43	15.58
	Adults	-	-	-	-	2.35	2.35	-	11.55	11.55	-	5.74	5.74	-	52.26	52.26

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TABLE 2

DISTRIBUTION OF RHIZOPERTHA DOMINICA AT DIFFERENT DEPTHS OF A WHEAT-FILLED SILO BEFORE INCUBATION

Sampling depths (feet)		SAMPLING MONTHS														
		July 1991			August 1991			October 1991			November 1991			December 1991		
		Live	Dead	Total	Live	Dead	Total	Live	Dead	Total	Live	Dead	Total	Live	Dead	Total
Grain	Surface	8.76	4.39	13.15	2.81	5.43	8.24	3.12	84.03	87.15	2.54	10.97	13.51	5.16	19.67	24.83
	4	5.72	3.34	9.06	1.08	2.75	3.83	-	2.69	2.69	0.22	0.22	0.44	-	6.58	6.58
	8	4.23	-	4.23	0.57	2.97	3.54	0.57	4.60	5.17	-	1.90	1.90	-	0.91	0.91
	12	4.14	-	4.14	2.19	5.32	7.51	0.39	5.28	5.67	-	3.17	3.17	-	2.06	2.06
	16	2.50	1.67	4.17	0.32	-	0.32	-	2.02	2.02	-	2.64	2.64	0.27	1.55	1.82
	20	2.40	2.40	4.80	-	-	-	0.54	0.84	1.38	-	-	-	-	2.49	2.49
	24	5.12	-	5.12	0.56	-	0.56	0.28	0.85	1.13	-	1.27	1.27	-	0.35	0.35
	28	-	0.88	0.88	-	1.79	1.79	-	0.94	0.94	-	0.92	0.92	0.69	1.37	2.06
	32	-	1.38	1.38	-	-	-	-	-	-	-	0.50	0.50	-	1.75	1.75
	36	-	-	-	-	1.81	1.81	-	0.47	0.47	-	0.15	0.15	-	0.31	0.31
	40	-	-	-	-	-	-	-	1.42	1.42	-	-	-	-	-	-
	44	-	-	-	-	-	-	-	1.16	1.16	-	-	-	-	-	-
	48	-	-	-	-	-	-	-	-	-	-	-	-	-	0.50	0.50
	52	-	-	-	-	-	-	-	0.84	0.84	-	0.14	0.14	-	0.68	0.68
	56	-	-	-	-	-	-	-	1.77	1.77	-	-	-	-	0.50	0.50
	60	-	-	-	-	-	-	-	0.70	0.70	-	1.00	1.00	-	1.00	1.00
	64	-	-	-	-	-	-	2.29	8.45	10.74	-	0.13	0.13	0.44	2.30	2.74

TABLE 3

DISTRIBUTION OF TRIBOLIUM CASTANEUMAT DIFFERENT DEPTHS OF A WHEAT-FILLED SILO BEFORE INCUBATION

Sampling depths (feet)		SAMPLING MONTHS														
		July 1991			August 1991			October 1991			November 1991			December 1991		
		Live	Dead	Total	Live	Dead	Total	Live	Dead	Total	Live	Dead	Total	Live	Dead	Total
Grain	Surface	0.56	-	0.56	5.91	102.82	108.73	24.16	417.21	441.37	11.52	38.62	50.14	117.08	52.51	169.59
	4	0.84	0.84	0.84	0.46	5.55	6.01	1.14	0.91	2.15	-	0.46	0.46	0.87	21.46	22.33
	8	22.58	-	22.58	-	1.05	1.05	-	-	-	-	3.21	3.21	-	1.71	1.71
	12	-	1.38	1.38	1.88	16.55	18.43	-	0.39	0.39	-	0.26	0.26	-	2.76	2.76
	16	-	0.83	0.83	0.32	0.93	1.25	-	0.41	0.41	0.20	0.38	0.58	-	2.72	2.72
	20	2.40	-	2.40	-	-	-	-	0.54	0.54	-	0.88	0.88	-	3.50	3.50
	24	-	-	-	-	-	-	-	0.29	0.29	-	0.25	0.25	-	1.21	1.21
	28	-	-	-	-	-	-	-	-	-	0.25	1.00	1.25	-	0.98	0.98
	32	-	-	-	0.47	1.95	2.42	-	0.64	0.64	-	0.50	0.50	-	1.17	1.17
	36	-	-	-	-	0.45	0.45	-	-	-	-	0.43	0.43	-	-	-
	40	-	0.95	0.95	-	0.54	0.54	-	1.79	1.79	-	-	-	-	0.77	0.77
	44	-	-	-	-	-	-	-	-	-	-	0.39	0.39	0.30	0.31	0.61
	48	-	-	-	-	0.51	0.51	-	-	-	-	-	-	-	0.20	0.20
	52	-	-	-	4.63	12.36	16.99	-	0.62	0.62	-	-	-	-	-	-
	56	-	-	-	-	-	-	-	1.77	1.77	0.23	0.15	0.38	-	0.73	0.73
	60	-	-	-	-	0.71	0.71	-	0.29	0.29	-	-	-	-	0.25	0.25
	64	-	-	-	0.91	0.45	1.36	-	0.77	0.77	-	0.10	0.10	-	2.94	2.94

TABLE 4

TOTAL NUMBER OF INSECTS PER KG OF WHEAT SAMPLE EMERGED FROM IMMATURE STAGES OF TROGODERMA GRANARIUM AFTER INCUBATION. THE SAMPLES WERE DRAWN FROM DIFFERENT DEPTHS OF A WHEAT-FILLED SILO.

Sampling depths (feet)		SAMPLING MONTHS July	August	October	November	December
Grain	Surface	1.27	26.07	573.67	31.05	48.33
	4	-	0.37	4.98	4.45	2.83
	8	-	0.28	0.71	2.06	-
	12	-	-	-	0.68	-
	16	-	-	-	-	-
	20	-	-	-	0.34	-
	24	-	-	0.71	0.34	0.94
	28	-	-	-	-	-
	32	-	-	0.71	-	-
	36	-	-	-	-	-
	40	8.54	-	-	0.34	-
	44	-	-	-	-	-
	48	-	-	-	0.34	-
	52	-	0.49	-	-	-
	56	-	-	1.42	0.92	-
	60	-	-	1.42	0.67	-
	64	0.49	0.76	0.71	-	-

TABLE 5

TOTAL NUMBER OF ADULT RHIZOPERTHA DOMINICA PER KG OF WHEAT SAMPLE EMERGED FROM IMMATURE STAGES AFTER INCUBATION. THE SAMPLE WAS DRAWN FROM DIFFERENT DEPTHS OF A WHEAT-FILLED SILO.

Sampling depths (feet)		SAMPLING MONTHS July	August	October	November	December
Grain	Surface	489.19	159.10	34.88	13.93	9.93
	4	455.99	260.22	7.12	1.70	0.93
	8	413.32	139.49	1.42	-	-
	12	342.86	25.30	8.54	0.34	0.00
	16	289.10	58.55	1.42	-	0.47
	20	146.12	4.00	2.13	-	0.47
	24	283.84	34.90	-	0.68	0.47
	28	4.41	94.60	0.71	-	-
	32	22.13	9.00	0.71	0.34	-
	36	-	37.26	-	-	-
	40	0.95	22.45	0.71	-	-
	44	-	5.45	0.71	-	-
	48	2.73	18.64	1.42	-	-
	52	-	45.57	-	0.34	-
	56	-	1.06	1.42	-	-
	60	0.70	6.35	3.55	-	-
	64	-	8.64	4.27	3.42	-

Table 6

TOTAL NUMBER OF INSECTS PER KG OF WHEAT SAMPLES EMERGED FROM IMMATURE STAGES OF TRIBOLIUM CASTANEUM AFTER INCUBATION. THE SAMPLES WERE DRAWN FROM DIFFERENT DEPTHS OF A WHEAT-FILLED SILO.

Sampling depths (feet)		SAMPLING MONTHS July	August	October	November	December
Grain	Surface	4.32	26.51	-	0.46	24.69
	4	4.18	1.48	-	4.45	-
	8	55.04	-	-	1.71	-
	12	-	0.64	-	0.34	-
	16	-	4.16	40.57	-	-
	20	-	-	0.71	-	-
	24	-	21.57	0.71	-	-
	28	-	24.16	2.85	-	-
	32	-	3.00	-	-	0.47
	36	-	0.47	-	-	0.47
	40	0.95	-	-	-	-
	44	-	-	-	-	-
	48	-	-	-	-	-
	52	-	-	0.71	-	-
	56	-	-	-	-	-
	60	-	0.35	-	-	-
	64	-	-	-	-	-

TABLE 7

AVERAGEMOISTURE CONTENT(%) OF GRAIN DURING THE STUDY PERIOD IN THE SILO

GRAIN DEPTHS (feet)	MONTHS July	August	October	November	December
Surface	8.58	8.64	9.49	10.18	12.52
1-16	8.65	8.96	9.01	9.40	9.30
17-32	8.18	8.73	8.81	9.29	9.29
33-48	8.26	8.73	8.74	9.35	9.36
49-64	8.13	9.38	9.23	9.71	9.56
Average	8.36	8.89	9.06	9.59	10.01

TABLE 8

NUMBEROF LIVE INSECTS PER KG OF WHEATSAMPLES AT DIFFERENT DEPTHS OF GRAIN MASS (BEFORE AND AFTER INCUBATION) **BEFORE PHOSPHINE FUMIGATION**

Sampling depths (feet)	Trogoderma granarium (larvae)			Rhizopertha dominica			Tribolium castaneum		
	B.Inc.	A.Inc.	Total	B.Inc.	A.Inc.	Total	B.Inc.	A.Inc.	Total
Surface	5.35	5.13	10.48	8.24	159.1	167.34	108.73	26.51	135.24
4	-	0.37	0.37	3.83	260.22	264.05	6.01	1.48	7.49
8	-	0.28	0.28	3.54	139.49	143.03	1.05	-	1.05
12	0.63	-	0.63	7.51	25.30	32.81	18.43	0.64	19.07
16	-	-	-	0.32	58.55	58.87	1.25	4.16	5.41
20	-	-	-	-	4.00	4.00	-	-	-
24	-	-	-	0.56	34.9	35.46	-	21.57	21.57
28	-	-	-	1.79	94.6	96.39	-	24.16	24.16
32	-	-	-	-	9.00	9.00	2.42	3.00	5.42
36	-	-	-	1.81	37.26	39.07	0.45	0.47	0.92
40	-	-	-	-	22.45	22.45	0.54	-	0.54
44	-	-	-	-	5.45	5.45	-	-	-
48	-	-	-	-	18.64	18.64	0.51	-	0.51
52	0.49	0.49	0.98	-	45.57	45.57	16.99	-	16.99
56	-	-	-	-	1.06	1.06	-	-	-
60	1.42	-	1.42	-	6.35	6.35	0.71	0.35	1.06
64	1.67	0.76	2.43	-	23.76	23.76	12.56	19.35	31.91

B.Inc. = Before incubation
A.Inc. = After incubation

TABLE 9

NUMBEROF LIVE INSECTS PER KG OF WHEATSAMPLE (BEFORE AND AFTER INCUBATION) **AFTER PHOSPHINE FUMIGATION**

Sampling depths (feet)	Trogoderma granarium (larvae)			Rhizopertha dominica			Tribolium castaneum		
	B.Inc.	A.Inc.	Total	B.Inc.	A.Inc.	Total	B.Inc.	A.Inc.	Total
Surface	369.28	573.67	942.95	87.15	34.88	122.03	441.37	-	441.37
4	5.81	4.98	10.79	2.69	7.12	9.81	2.15	-	2.15
8	1.44	0.71	2.15	5.17	1.42	6.59	-	-	-
12	1.54	-	1.54	5.67	88.54	94.21	0.39	-	0.39
16	3.36	-	3.36	2.02	1.42	3.44	0.41	40.57	40.98
20	1.92	-	1.92	1.38	2.13	3.51	0.54	0.71	1.25
24	2.83	0.71	3.54	1.13	-	1.13	0.29	0.71	1.00
28	2.85	-	2.85	0.94	0.71	1.65	-	2.85	2.85
32	6.98	0.71	7.69	-	0.71	0.71	0.64	-	0.64
36	2.72	-	2.72	0.47	0.00	0.47	-	-	-
40	2.13	-	2.13	1.42	0.71	2.13	1.79	-	1.79
44	1.30	-	1.30	1.16	0.71	1.87	-	-	-
48	2.41	-	2.41	-	1.42	1.42	-	-	-
52	6.34	-	6.34	0.84	-	0.84	0.62	0.71	1.33
56	2.54	1.42	3.96	1.77	1.42	3.19	1.77	-	1.77
60	3.02	1.42	4.44	0.70	3.55	4.25	0.29	-	0.29
64	13.68	0.71	14.39	10.74	4.27	15.01	0.77	-	0.77

B.Inc. = Before incubation
A.Inc. = After incubation

TABLE 10

NUMBEROF LIVE INSECTS PER KG OF WHEATSAMPLE (BEFORE AND AFTER INCUBATION) **BEFORE METHYLBROMIDE FUMIGATION**

Sampling depths (feet)	Trogoderma granarium (larvae)			Rhizopertha dominica			Tribolium castaneum		
	B.Inc.	A.Inc.	Total	B.Inc.	A.Inc.	Total	B.Inc.	A.Inc.	Total
Surface	2380.89	41.23	2422.12	24.83	9.93	34.76	169.59	24.69	194.28
4	326.36	0.93	327.29	6.58	0.93	7.51	22.33	-	22.33
8	4.50	-	4.50	0.91	-	0.91	1.71	-	1.71
12	8.16	-	8.16	2.06	-	2.06	2.76	-	2.76
16	7.87	-	7.87	1.82	0.47	2.29	2.72	-	2.72
20	5.80	-	5.80	2.49	0.47	2.96	3.50	-	3.50
24	4.60	0.94	5.54	0.35	0.47	0.82	1.21	-	1.21
28	4.45	-	4.45	2.06	-	2.06	0.98	-	0.98
32	10.33	-	10.33	1.75	-	1.75	1.17	0.47	1.64
36	9.49	-	9.49	0.31	-	0.31	-	0.47	0.47
40	8.35	-	8.35	-	-	0.00	0.77	-	0.77
44	13.98	-	13.98	-	-	0.00	0.61	-	0.61
48	5.94	-	5.94	0.50	-	0.50	0.20	-	0.20
52	14.70	-	14.70	0.68	-	0.68	-	-	-
56	7.54	-	7.54	0.50	-	0.50	0.73	-	0.73
60	8.12	-	8.12	1.00	-	1.00	0.25	-	0.25
64	15.58	-	15.58	2.74	-	2.74	2.94	-	2.94

B.Inc. = Before incubation
A.Inc. = After incubation

TABLE 11

AVERAGENUMBEROF INSECTS AT DIFFERENT GRAIN DEPTHS IN WHEAT-FILLED SILO AFTER **METHYLBROMIDE FUMIGATION**

SAMPLING DEPTHS (feet)	NUMBEROF INSECTS PER KILOGRAMOF WHEATSAMPLE					
	Trogoderma granarium		Rhizopertha dominica		Tribolium castaneum	
	Live	Dead	Live	Dead	Live	Dead
Grain Surface	-	2735.67	-	53.32	0.00	248.43
4	-	394.00	-	0.73	0.00	7.20
8	-	20.11	-	3.45	0.00	0.00
12	-	20.23	-	2.93	0.00	0.00
16	-	10.65	-	2.93	0.00	0.00
20	-	21.18	-	2.03	0.00	0.00
24	-	7.56	-	2.70	0.00	0.00
28	-	16.95	-	2.02	0.00	0.00
32	-	6.34	-	-	0.00	0.00
36	-	4.94	-	-	0.00	0.00
40	-	13.40	-	-	0.00	1.22
44	-	27.28	-	-	0.00	1.24
48	-	44.28	-	-	0.00	0.00
52	-	37.80	-	-	0.00	1.05
56	-	56.80	-	2.52	0.00	0.69
60	-	85.74	-	-	-	-
64	-	10.32	-	-	-	-

TABLE 12

CONCENTRATIONX TIME PATTERN OF METHYLBROMIDE AT THE AIR SPACE ABOVE THE GRAIN SURFACE DURING A 48 HOUR GAS RETENTION PERIOD

Sampling Time (hrs)	Time Step (hrs)	Concentration (gm/cu.m)	Ct (gm hr/cu.m)	Cumulative Ct (gm hr/cu.m)
0	-	-	-	-
4	4	34	-	0
8.1	4.1	41	153.07	153.07
20.6	12.5	32	422.76	605.83
23.9	3.3	24	91.45	697.28
27.9	4	25	97.97	795.25
31.65	3.75	28	99.21	894.46
44.48	12.83	25	339.44	1233.9
48.48	4	21	91.65	1325.55

TABLE 13

CONCENTRATIONX TIME PATTERN OF METHYLBROMIDE AT THE TOP GRAIN LAYERS DURING A 48 HOUR GAS RETENTION PERIOD

Sampling Time (hrs)	Time Step (hrs)	Concentration (gm/cu.m)	Ct (gm hr/cu.m)	Cumulative Ct (gm hr/cu.m)
0	-	-	-	-
4	4	24	-	0
8.1	4.1	18	85.21	85.21
20.6	12.5	20	237.17	322.38
23.9	3.3	15	57.15	379.53
27.9	4	16	61.96	441.49
31.65	3.75	15	58.09	499.58
44.48	12.83	10	157.13	656.71
48.48	4	8	35.77	692.48

TABLE 14

CONCENTRATIONX TIME PATTERN OF METHYLBROMIDE AT THE MIDDLE PERIPHERAL GRAIN LAYERS (20 FT DEEP FROM GRAIN SURFACE) DURING A 48 HOUR GAS RETENTION PERIOD

Sampling Time (hrs)	Time Step (hrs)	Concentration (gm/cu.m)	Ct (gm hr/cu.m)	Cumulative Ct (gm hr/cu.m)
0	-	-	-	-
4	4	14	-	0
8.1	4.1	13	55.31	55.31
20.6	12.5	32	254.95	310.26
23.9	3.3	28	98.78	409.04
27.9	4	30	115.93	524.97
31.65	3.75	34	119.76	644.73
44.48	12.83	41	479.02	1123.75
48.48	4	32	144.88	1268.36

TABLE 15

CONCENTRATIONX TIME PATTERN OF METHYLBROMIDE AT THE MIDDLE SEMI-PERIPHERAL GRAIN LAYERS (20 FT DEEP FROM THE GRAIN SURFACE) DURING A 48 HOUR GAS RETENTION PERIOD

Sampling Time (hrs)	Time Step (hrs)	Concentration (gm/cu.m)	Ct (gm hr/cu.m)	Cumulative Ct (gm hr/cu.m)
0	-	-	-	-
4	4	11	-	0
8.1	4.1	11	45.1	45.1
20.6	12.5	17	170.93	216.03
23.9	3.3	16	54.42	270.45
27.9	4	20	71.55	342
31.65	3.75	21	76.85	418.85
44.48	12.83	22	275.77	694.62
48.48	4	15	72.66	767.28

TABLE 16

CONCENTRATIONX TIME PATTERN OF METHYL BROMIDE AT THE MIDDLE CENTRAL GRAIN LAYERS (20 FT DEEP FROMTHE GRAIN SURFACE) DURING A 48 HOURGAS RETENTION PERIOD

Sampling Time (hrs)	Time Step (hrs)	Concentration (gm/cu.m)	Ct (gm hr/cu.m)	Cumulative Ct (gm hr/cu.m)
0	-	-	-	-
4	4	6	-	0
8.1	4.1	12	34.79	34.79
20.6	12.5	12	150	184.79
23.9	3.3	14	42.77	227.56
27.9	4	16	59.86	287.42
31.65	3.75	17	61.84	349.26
44.48	12.83	20	236.57	585.84
48.48	4	23	85.79	671.62

TABLE 17

CONCENTRATIONX TIME PATTERN OF METHYLBROMIDE AT THE AERATION DUCT AT THE BOTTOMOF THE SILO DURING A 48 HOURGAS RETENTION PERIOD.

Sampling Time (hrs)	Time Step (hrs)	Concentration (gm/cu.m)	Ct (gm hr/cu.m)	Cumulative Ct (gm hr/cu.m)
0	-	-	-	-
4	4	2	-	0
8.1	4.1	18	24.6	24.6
20.6	12.5	18	225	249.6
23.9	3.3	22	65.67	315.27
27.9	4	25	93.81	409.08
31.65	3.75	22	87.94	497.02
44.48	12.83	22	282.26	779.28
48.48	4	20	83.90	863.18

TABLE 18

CONCENTRATIONOF PHOSPHINE GAS AT DIFFERENT MONITORING POINTS IN WHEAT-FILLED STEEL SILO AT MULTAN. THE SILO WAS FUMIGATED WITH "AGTOXIN" AT A DOSE RATE OF 1.15 GM/CUBIC METER ON OCT. 6, 1992.

Days After Fumigation	Grain Top Peripheral	Grain Top Central	Grain Middle Peripheral	Grain Middle Central	Grain Bottom Peripheral	Grain Bottom Central	Free Space
1	963	>2000	195	1422	248	1448	1450
2	1190	1437	920	1192	995	1160	1162
3	682	804	688	762	692	705	732
4	410	298	570	365	504	360	310
5	275	235	335	230	300	290	202
6	168	145	215	195	195	148	107

TABLE 19

AVERAGENUMBEROF INSECTS PER KG OF WHEATSAMPLE DRAWNFROM DIFFERENT DEPTHS OF A STEEL SILO (MULTAN) BEFORE AND AFTER PHOSPHINE FUMIGATION BY FLOW-THROUGHMETHOD

Sampling Depths	Trogoderma granarium (larvae)				Rhizopertha dominica				Tribolium castaneum			
	Before		After		Before		After		Before		After	
	Alive	Dead	Alive	Dead	Alive	Dead	Alive	Dead	Alive	Dead	Alive	Dead
Surface	18.81	162.20	-	222.00	2.30	39.50	-	28.80	4.80	121.30	-	60.00
4	-	-	-	0.30	-	2.50	-	2.00	-	8.50	-	0.70
8	-	-	-	-	-	1.00	-	2.70	-	1.00	-	1.00
12	-	-	-	0.30	-	0.50	-	1.70	0.50	1.00	-	0.70
16	3.00	-	-	0.30	-	-	-	3.00	4.00	1.50	-	0.30
20	-	-	-	-	-	0.50	-	3.00	-	3.50	-	-
24	-	-	-	1.30	-	-	-	2.00	-	4.00	-	1.70
28	-	-	-	0.30	-	-	-	3.30	-	1.00	-	-
32	-	-	-	2.30	-	-	-	1.30	2.00	2.00	-	-
36	-	-	-	1.30	-	-	-	1.70	1.00	2.00	-	0.30
40	-	-	-	3.00	-	-	-	1.00	1.00	-	-	0.30
44	-	-	-	0.30	-	-	-	0.70	-	-	-	0.70
48	-	-	-	-	-	-	-	1.00	-	2.00	-	-
52	-	-	-	1.00	-	-	-	-	-	-		
56	1.00	-	-	32.00	-	-	-	5.00	-	4.00	-	-

SECTION V

CONCLUSIONS

The following conclusions are drawn from the present study.

1. Contrary to the general understanding, insects can live and breed in deeper layers of the grain filled silo. Although their number was much higher at the grain top and the grain bottom near aeration ducts, they were found in appreciable numbers in the middle grain layers throughout the vertical grain column.

2. Keeping in view the distribution of insects in the grain mass, the fumigant should be applied in such a way that the gas can uniformly penetrate the deeper layers of the grain-filled silo to achieve complete mortality.

3. The application method of AlP tablets for phosphine fumigation being used by PASSCO and PFD in silos (placing the AlP tablets on the grain surface) is ineffective as the gas cannot reach to the deeper parts of the silo in sufficient concentration to kill the insects.

4. Methyl bromide fumigation can provide a successful control of phosphine-resistant strains of stored grain insect pests. However, it cannot be a complete substitute for phosphine.

5. Phosphine fumigation of filled silos can be done successfully by the newly developed "Flow-through Method," provided the silo is well sealed and gas-tight. The phosphine gas can reach everywhere in the grain mass in sufficiently lethal concentration by using this technique.

SECTION VI

RECOMMENDATIONS

1. Methyl bromide fumigation can only be recommended in situations where phosphine proves ineffective due to the development of resistance in insects. In locations where such resistance has been detected, the insects should be controlled with methyl bromide fumigation once and then normal phosphine fumigation should be carried out.

2. More work should be conducted to improve the distribution of methyl bromide in bulk grain by mixing it with other gases like carbon dioxide and phosphine.

3. The current practice of phosphine fumigation of silos should be abandoned as it leads to the development of resistance in insect pests against this beneficial gas.

4. Phosphine fumigation in filled silos should be carried out with the newly developed "Flow-through method" as it proved successful in distributing the gas in the whole depth of the grain mass in sufficiently lethal quantity.

5. Phosphine fumigation is still beneficial for insect management in vertical silos, so emphasis should be on improving the gas-tightness of the silos by applying some suitable sealant on cracks, joints, and bolts for longer retention of phosphine gas.

6. Presence of dust and dockage with grain resists even distribution of gas by making channels through the grain mass in which the phosphine gas disperses through the grain having more intergranular spaces and avoids more compact (due to dust and dockage) portions. This results in survival of insects present in those particular portions. It is suggested, therefore, that clean grain should be stored in the silos.

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SECTION VI

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