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BENCHMARKING - WHAT MAKES A GOOD FUMIGATION?

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ABSTRACT

World over, insect pest elimination in stored products including food commodities is carried out by fumigation, particularly using phosphine. In the developing countries, food grains are traditionally stored in bags, and the bag-stacks are held indoors or outdoors. Fumigation of bag-stacks with phosphine apparently looks simple, but storage managers feel that the desired results (100% insect mortality) are not always achieved due to several reasons, including insect resistance. A good fumigation involves use of high quality gas-proof plastic sheets and excellent floor sealing so there is low gas loss (<10%, daily) and target insects are not exposed to sub-lethal levels of phosphine. Field trials on fumigation of wheat, milled rice and paddy rice stacks in India have been proven using revised target phosphine concentrations (500 - 1500 ppm) and exposure periods (5 - 15 days) according to pest species, their resistance status, and temperature conditions. In grain stacks in the open, due to the interaction of heat and wind forces, daily gas loss rates are inevitably high, - up to 30%. Monitoring of phosphine in grain stacks during the exposure period is emphasized as an important component of the fumigation process. A best-fumigation practice also includes checking of workspace gas concentrations to ensure safety of the workers in and around fumigation areas in grain storage centers, and monitoring control failures of the fumigation.

INTRODUCTION

The traditional method of storing foodgrains in bags and building them into stacks is still popular in most countries in Africa and Asia and to a limited extent in the other parts of the world. Foodgrains are bagged in jute sacks or in polypropylene bags, normally of 50 kg capacity. Grain stacks are built indoors (in warehouses or under sheds) or outdoors (wheat, paddy and maize only). For insect pest elimination in stored foodgrains fumigation plays a vital role. Phosphine from metal phosphide formulations, cylinderized formulations and from on-site generators is used for the protection of stored foodgrains under different storage situations in industrialized as well as developing countries. The developing countries are entirely dependent on phosphine as the fumigant for disinfesting grain stacks. Phosphine is cheaper, easy to apply grain, does not affect the quality even after repeated applications and the phosphine dust residue problem is insignificant. Although the application of phosphine is simple when compared with methyl bromide, insect mortality results are, however, reported to be unsatisfactory under practical applications. Phosphine fumigation of bag stacks of foodgrains has been discussed and described by several workers (Table 1). Also, fumigation experiments have been conducted on cereal stacks, mostly in developing countries: i) to determine the efficacy of phosphine treatment; ii) to study the performance of different types of gas-proof sheets; iii) to examine commodity sorption; iv) to assess floor sealing methods; and v) to evaluate sealed storage (Table 2).

TABLE 1

Reviews / status reports/ operations manual on bag-stack fumigation of food grains using phosphine

Reference	Topics
Friendship 1989b	Gas-proof sheets
van S Graver 1990	Requirements
van S Graver et al. 1992	Sub-standard fumigations
Taylor and Gudrups 1996; Rajendran 2000	Effective fumigation
Rajendran 2001	Resistance management
Gwinner et al. 1996; Friendship 1989a; FAO	Treatment procedure

Data on stack fumigations in developing countries, particularly under tropical conditions, are limited. In studies in Indonesia, Bengston et al. (1997) demonstrated sources of ineffective phosphine treatments of bag-stacks of milled rice in woven polypropylene bags. The authors showed that poor results could occur when sealing and other operating procedures are not up to the standard. Poor fumigation practice includes use of sheets having holes, and two or more sheets placed by simple overlap, rather than rolling together up to a meter length, leading to rapid loss of phosphine. In best-sealed stacks, the total loss of phosphine due to sorption, permeation through sheeting and leakage from day 4 onward was noted to be only 7% loss per day. In commercial fumigations of milled rice in Southeast Asia at the dosage of 2 g phosphine /tonne, Taylor and Harris (1994) observed phosphine levels ranging from 0.2 to 0.5 mg/litre over 100 h. However, in Tanzania in maize stacks fumigated at 2 g phosphine/ tonne under well sealed PVC sheeting, the terminal concentration at the end of 5 days was noted to be high (1.5 mg/l). Van S Graver (1990) analyzed factors that are responsible for unsatisfactory bag-stack fumigations such as lack of training and management awareness, failure to monitor gas and poor fumigation techniques. The insect resistance problem has been observed in most of the countries irrespective of the type of storage structures, i.e. silo or bag-stack system, which was used. However, the problem is acute in the developing countries in tropical regions where bagged storage is practiced and numerous cases of control failure have been reported. In view of the current crisis of the methyl bromide phase out, with development of insect resistance to phosphine and non-availability of suitable alternatives that are comparable to phosphine, there is a need to reappraise the fumigation practice with reference to phosphine for its best application. In this context, this paper discusses the components of best fumigation practice supported by data from field experiments.

TABLE 2
Phosphine fumigation experiments conducted on sealed bagged cereal stacks.

Commodity	Parameter examined	Reference
Indoor Stacks		
Paddy rice	Efficacy	Rajendran and Muralidharan 2001
		Cogburn and Tilton 1963
	Sorption	Annis 1990
	Sealed storage	
Milled rice	Efficacy	Bengston et al. 1997; Rajendran and Narasimhan 1994
	Sorption	Cogburn and Tilton 1963
	Sealed storage	Annis 1990
Wheat	Performance of gas-proof sheets and efficacy of phosphine preparations	Rajendran and Narasimhan 1994
	Floor sealing	Sonelal et al. 1993
	Efficacy	Lallanrai et al. 1964
Maize	Floor sealing	Taylor and Harris 1994
	Performance of gas-proof sheets	Valentini et al. 1996
	Sealed storage	
		Sabio et al. 1990;
		Annis 1990
Outdoor stacks		
Paddy rice	Efficacy	Rajendran and Muralidharan 2001
Wheat	Performance of gas-proof sheets	Vishwambharan 1969
	Efficacy	
		Rajendran et al. 2001

DOSAGE

A fumigant dosage comprises the amount of active ingredient (AI) placed in an enclosure which will generate a desired gas concentration in the free space of the enclosure and the duration of the treatment. It has been realized that the dosage of phosphine is not simple or straightforward because of the complicated interactions between phosphine and target insect pests (Annis, 2001). Disagreements about phosphine dosage, target concentrations and lower limit of temperature for effective fumigation exist. The dosage varies depending on temperature, commodity type, insect pest species and their resistant status, and gas-tightness level of the enclosure. EPPO (1984) recommended a general dose of 1g phosphine/m^3. For leaky structures and when resistant insects are present the dose must be increased by 2-3 times. A longer exposure period of 12 days for tolerant *Sitophilus* spp. and short exposure period (3-5 days) for several species including *Oryzaephilus surinamensis* (L.) and *Tribolium castaneum* (Herbst) at 20-30^o C was recommended. Based on laboratory studies with resistant insects, Mills (1986) observed that the EPPO recommendations on exposure period as well as dose may not be adequate for the control of resistant population of *Rhyzopertha dominica* (F.), *Cryptolestes ferrugineus* (Stephens), *T. castaneum* and *O. surinamensis*. The author suggested that application of sequential dosing and slow release formulation may be effective against resistant insects. Winks et al. (1980) also recommended phosphine application rates according to temperature conditions and level of gas-tightness. In view of the inadequate gas-tightness of bag-stacks, a high dosage of 5 g phosphine/m^3 (= 6.5 aluminium phosphide tablets/ tonne) with 7 days exposure period above 25^o C was recommended. The authors suggested that in the absence of *Sitophilus* spp, the exposure period could be reduced from 7 days to 5 days. In India, a dosage of 3 g phosphine/tonne (= 2.3 g PH_3/m^3), 5-7 days exposure period is commonly used for all cereal stacks. Gewinner *et al.* (1996) recommend an application rate of 3-6 g phosphine / tonne (=2.3-4.6 g phosphine / m^3) with exposure periods ranging from 6 (10-15^o C) to 4 days (> 25^o C) for sheeted bag-stack treatments.

The importance of commodity in selection of phosphine dosage has not been much considered. Comparison of phosphine concentration profiles of cereal stacks clearly shows that paddy is highly sorptive whereas sorption is less with wheat (Table 3). Annis (1990) stated that for paddy rice up to 10 g phosphine/ m^3 dose might be necessary depending on moisture content. In fumigation trials with paddy rice stacks held indoors and outdoors and applied at the rate of 2 –4 g phosphine/m^3, Rajendran and Muralidharan (2001) observed daily phosphine loss rate at 14.5% and 29.5% respectively and insisted on higher application rates for paddy stacks. Cogburn and Tilton (1963) reported higher sorption by paddy rice than milled rice.

Evidently, for phosphine treatments, adjustments with respect to dose and exposure period must take into consideration the biological (commodity and insect) and environmental factors (temperature and gas loss rate) .

TABLE 3

Gas concentration profiles for cereal stacks during phosphine fumigation

Elapsed Days	Phosphine concentrations in bag-stacks (ppm ± SD) [a]			
	Wheat	Parboiled rice	Raw rice	Paddy rice
1	>600 ± 92	>482 ± 2	>388 ± 6	443 ± 0
2	>600 ± 92	>482 ± 2	>388 ± 6	412 ± 3
3	>600 ± 92	>482 ± 2	>388 ± 6	359 ± 45
4	>583 ± 95	>482 ± 2	>388 ± 6	307 ± 41
5	>552 ± 103	477 ± 11	>388 ± 6	262 ± 42
6	>508 ± 104	451 ± 36	>368 ± 37	225 ± 40
7	463 ± 97	397 ± 42	304 ± 39	109 ± 39

[a] Mean of 8, 4, 6 and 3 indoor stacks of wheat, parboiled rice, raw rice and paddy rice respectively. Data after conversion to 1g phosphine/ tonne for 100 tonnes equivalent. (m.c. of the grain ranged from 10.5 – 13.5 %)

GAS CONCENTRATION

Phosphine has excellent diffusion characteristics; hence there has been little problem in achieving uniform concentration inside bag-stacks during fumigation. However, for a successful phosphine treatment, a minimum concentration has to be retained throughout the fumigation period. It has been noted that the recommended concentration goal or target concentration has increased over the years from 80 ppm (van S Graver et al. 1992) to 1000 ppm (Annis 2001) for achieving 100% mortality of susceptible insects (Table 4). The increase in target concentration has been due to our better understanding about the response of insects of field origin to phosphine. For resistant insects the recommended target concentration exceeds 1000 ppm (Fig. 1).

In commercial practice and in routine fumigations, ineffective levels of phosphine were reported in Australia (Collins et al. 1997), African countries (Taylor and Harris 1994), Southeast Asia (Taylor and Gudrups 1996) and in India (Rajendran 2001).

Rajendran observed that phosphine concentrations at the end of 5 days in routine stacks relative to experimental stacks were about 3 – 54% (Table 5).

TABLE 4
Target phosphine concentrations for effective fumigation of grains at 25° C and above.

Target PH_3 concentration (ppm)	Exposure period (days)	Reference
Susceptible insects		
> 80	7	van S Graver et al. 1992
100	7	van S Graver and Annis 1994
150	5	Friendship 1989a
360	7	FAO 2004
500	7	Rajendran (Unpublished data)
720	7	Winks and Hyne 1997; Collins et al. 2002
1000	8	Annis 2001
Resistant insects		
>1000	7	Rajendran 2001
>1300	6	Rajendran (Unpublished data)

In a laboratory study, Rajendran et al. (2000) found that it required terminal concentrations of 1200 ppm and 400 ppm for 100% population extinction of resistant *R. dominica* and *S. oryzae,* respectively. Nayak et al. (2002) determined a target concentration of 1450 ppm with 6-day exposure period or 720 ppm with 11 days for controlling resistant psocids. Sayaboc and Gibe (1997) determined an effective concentration of 640 ppm in a 7-day treatment against resistant *R. dominica* and stressed the need for extending the exposure period from the currently followed 3 days to 7 days. Although *S. oryzae* is considered to be the most tolerant species (excluding *T. granarium*) to phosphine, it has been found that *R. dominica* has developed the highest-level of resistance in India and elsewhere and hence it required higher target concentration (Bell 1986).

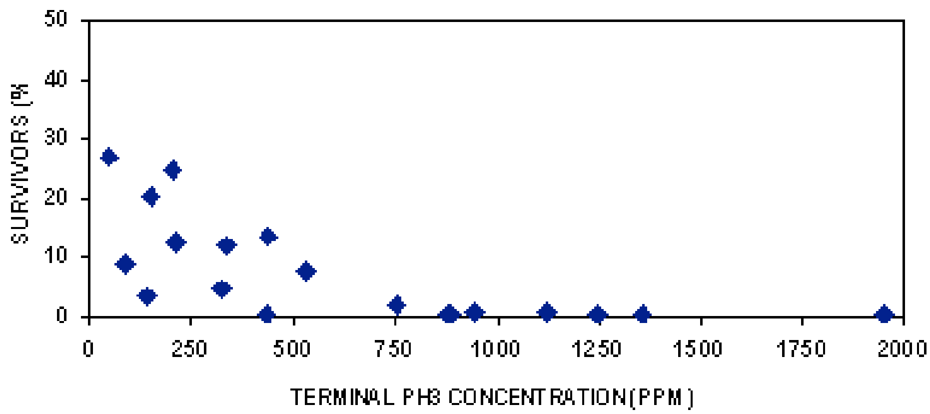

Figure 1. Survivors (%) in resistant *Rhyzopertha dominica* vs terminal concentration (ppm) of phosphine in cereal stacks in a 7-day treatment at 25ºC and above.

When aluminium phosphide tablet formulation is applied to a grain stack, the general trend is peak liberation of phosphine at 24 – 48 h after dosing followed by decay in gas concentration (e.g. Taylor and Harris 1994). However, if the tablets are hindered or prevented from decomposing rapidly by keeping them in cloth bags or in any other gas permeable barrier, the rate of release will be extended up to 96 h. Such a trend in gas liberation (delayed release) has been observed (Fig. 2) in the experiment on milled rice stacks dosed at 2 g phosphine / tonne for 6 or 7 days in Indonesia (Saryono *et al*. 1993; Bengston *et al*. 1997). The slow release-rate is advantageous for bag-stacks that show low to moderate leakage (Friendship *et al*. 1986). In China, aluminium phosphide tablets have been used in 0.03 to 0.06 mm thick polyethylene bags for slower release of phosphine for grain treatment (Liang Quan 1990). The slow release application has proved effective against highly tolerant mites in wheat in bulk storage (Qicuo *et al*. 1999). In laboratory experiments with mixed-age cultures of *R. dominica* and *S. oryzae,* Rajendran and Gunasekaran (2002) observed that application of phosphine in rising concentrations was more effective than constant or falling concentrations. In tests against resistant *C. ferrugineus,* Bell et al. (1990) observed that insect mortality was more with rising phosphine concentration than with falling concentration.

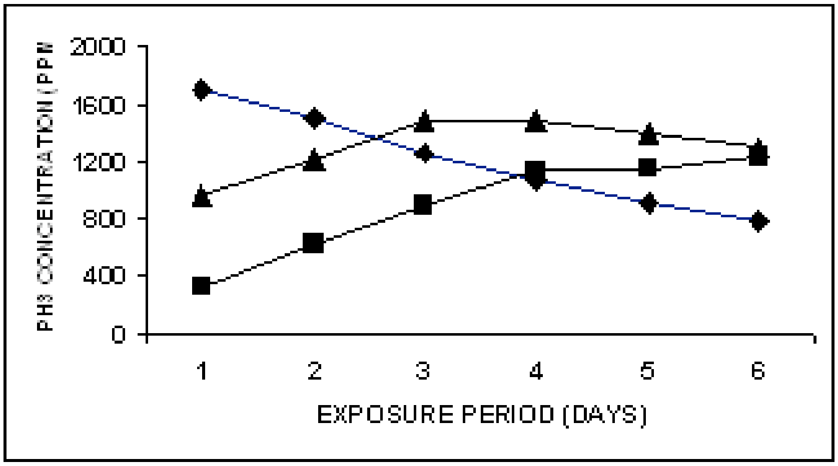

Figure 2. Phosphine concentration profiles during fumigation of milled rice (2 g PH_3/tonne) in India (-_- Rajendran, Unpublished) and Indonesia (-_- Saryono et al. 1993; -_- Bengston et al. 1997).

In laboratory experiments with resistant insects including *R. dominica* and *S. oryzae,* Price and Mills (1988) observed that a few individuals could survive a 14-day exposure period at 2 g phosphine/ m^3 at 15° C probably due to their low metabolic rate and reduced uptake of fumigant at that temperature. Kashi (1981) also noted a few survivors that could tolerate phosphine concentrations of 19 to 78 mg/l, in 12 h (*T. confusum*) or 24 h (*S. oryzae* and *S. granarius*) exposures at 25° C. In field experiments on outdoor wheat stacks, Rajendran et al. (2001) noticed that a few stray individuals of resistant *R. dominica* and *S. oryzae* survived 7-day treatments in spite of the terminal concentrations exceeding 945 ppm (*R. dominica*) and 885 ppm (*S. oryzae*) at 18-25° C. There is a need to carry out biochemical studies with such stray individuals to understand the mechanism of insect resistance to phosphine. The occurrence of survivors at longer exposure periods indicates that in addition to extended exposure period, higher dose/ concentration is required for resistant insects.

EXPOSURE PERIOD

When phosphine was introduced as a fumigant it was considered that an exposure period of 72 h was adequate. Subsequent studies, however, revealed that if the fumigant is to be effective against resistant as well as susceptible insects a longer exposure period (> 5 days) is required. Giving examples of extended duration of egg and pupae stages of insects at different temperatures, Winks and Ryan (1991) stated that even a 7-day exposure period might not be adequate to achieve the desired 100% mortality at low temperatures. Temperatures below 15° C affect the toxic action of phosphine against insect pests (Table 6). Authors vary in their recommendations on the minimum temperature below which phosphine fumigation should not be carried out. As phosphine is more effective at higher temperatures (> 25° C), Heseltine (1973) reported that phosphine is more suitable in the tropics than in the temperate regions. However, in tests against resistant *R. dominica*, it was noted that at certain concentrations, insect mortality was less at the higher temperature of 35° C than at lower temperatures (Hyne and Winks 1997). Psocids have a long egg period and hence required longer exposure periods (>10 days) for their control. In addition, phosphine resistant psocids needed higher target concentration for 100% mortality (Nayak et al. 2002).

TABLE 5
Average phosphine concentrations during fumigation (3 g phosphine/tonne) of bag-stacks under 0.25 mm thick polyethylene covers according to experimental and routine practice.

Commodity	Days elapsed	PH_3 concentration (ppm)		Concentration in routine stacks relative to experimental stacks (%)
		Experimental stacks [a]	Routine stacks [b]	
Indoor stacks				
Wheat	2	> 2000 [c]	>1750 [c]	87
	5	1812	985	54
Milled rice	2	>2000[c]	>1548[c]	77
	5	>2000[c]	977	49
Outdoor stacks				
Wheat	3	>2000[c]	57	3
	4	1726	132	8
Paddy rice	2	750	725	97
	5	235	8	3

[a] New covers and two rows of sand snakes used; average of 2-3 stacks.

[b] Previously used covers employed and single row of sand-snakes or mud plaster used; Mean of 2-8 stacks.

[c] One or more of the values exceeded the measuring range (1-2000 ppm) of Bedfont phosphine monitor.

GAS-PROOF SHEETS

Bag-stacks in many developing countries are fumigated under cover-sheets sealed to the floor, rather than in a sealed sheet enclosure because of the additional cost of bottom sheets and the need for a high degree of gastightness (Rajendran 2000). The preferred weight of fumigation sheet from the point of handling is 200 – 250 g/m^2 (Gewinner et al. 1986). The gas loss rate should be less than 1mg/day/m^2 (FAO 2004). Friendship (1989b) presented a list of factors such as cost, intended use, gas-permeability, weight per unit area, strength, handling characteristics and resistance to damage to be taken into consideration for the purchase of fumigation sheets. The author pointed out that long-term performance and durability of the sheet must be given priority over the cost factor. Gas permeability of a sheet material is likely to increase with use. The gas-proof sheets need to be checked at regular intervals for holes or other damage and they should be stored properly when not in use. In India, fumigation trials with new low density polyethylene (LDPE) covers, and covers that had been used several times revealed large differences in gas concentrations during fumigation of wheat stacks (Table 7).

TABLE 6
Suggested temperature limits for an effective phosphine treatment. Lower temperature limit

(°C)	Reference
5	Gewinner et al. 1996;
	Taylor and Gudrups 1996
10	EPPO 1984
15	Anon 1989; FAO 2004

In maize stack fumigation, Valentini *et al.* (1996) observed better retention of phosphine by polyvinyl chloride (PVC) sheet than polyethylene sheet although both were of the same (0.21 mm) thickness. Vishwambharan (1969) stated that when compared with rubberized fabric, LDPE sheet was cheaper. However, upon repeated use the number of holes developed in LDPE sheet was more than that of rubberized fabric and caused increased gas loss; thus the durability of LDPE sheet was poor and more expensive when considering gas losses. Different types of gas-proof sheets that are available in India were tested for gas-retention property as new sheets and after exposure to environmental conditions for 5 months. As new sheets, PVC and LDPE sheets showed highest phosphine retention. Following exposure to natural elements (sunlight, wind and rain) the sheets had lower retention than the unexposed sheets (Rajendran *et al*., 2003). Bengston *et al*. (1997) demonstrated that for bigger stacks, two or more sheets joined together by an up to 1 meter joint gave better results than when kept just by overlapping.

TABLE 7

Gas concentrations during fumigation (3 g PH_3/ tonne) of outdoor wheat stacks under new and used gas-proof polyethylene covers (0.25 mm thickness).

Days elapsed	PH_3 concentrations (ppm) [a] in stacks under	
	New cover	Cover used several times
1	>2000[b]	>1930[b]
2	>2000[b]	1401
3	>2000[b]	895
4	>1934	529
5	>1844	341
6	1685	206
7	1532	142
Ct (g h/m^3)	403	166

[a] Data are mean of 3-4 stacks fumigated at 24-34° C (day temperatures); grain m. c. range 10-12%.

[b] One or more of the concentrations exceeded the measuring range (1-2000 ppm) of Bedfont EC 80 phosphine monitor.

FLOOR SEALING

Efficient floor sealing is an important component of best fumigation practice. Use of sand snakes for weighting down the gas-proof sheet to the floor is the standard practice. The sand snake must be preferably 1meter length and 15-cm dia and filled with dry sand up to 80%. However, in some warehouses smaller sand snakes that are convenient to handle are used. The smaller sand snakes when used in a single row may not give adequate sealing of grain stacks. In such cases, use of sand snakes in double rows with overlapping joints between the two rows was noted to give effective sealing (Taylor and Gudrups 1996). In India, when there is inadequate supply of sand snakes, either loose sand or mud plaster is used. Use of loose sand damages sheet material, particularly the LDPE sheets. When mud is used for floor sealing, the mud dries up during fumigation period and develops cracks allowing phosphine to escape (Rajendran 1999). In some countries (e.g. Indonesia) metal chains are used for weighting down the edges of sheets. Another source of gas loss are the cracks in the floor area of a stack enclosure. Cracks should be sealed before undertaking fumigation.

TABLE 8

Phosphine concentrations in fumigated wheat stacks (dosage 3 g/ tonne) held indoors and outdoors (day temperatures 21-33° C and humidity 40-85%).

Elapsed time (days)	Phosphine concentrations in ppm (mean ± SD) in wheat stacks [a]	
	Indoor stacks	Outdoor stacks
1	1076 ± 73	1562 ± 91
2	>2000 ± 0 [b]	>2000 ± 0 [b]
3	> 2000 ± 0 [b]	>1967 ± 65 [b]
4	> 2000 ± 0 [b]	1549 ± 368
5	> 2000 ± 0 [b]	1162 ± 508
6	> 1972 ± 55 [b]	791 ± 333

[a] Data are average of 4 stacks each.

[b] One or more of the concentrations exceeded the measuring range (1-2000 ppm) of Bedfont EC 80 phosphine monitor.

Schneider *et al.* (2001) reported that half-loss time (HLT), i.e. the time taken for the loss of half of the original concentration of the fumigant from an enclosure due to leakage, is a good indication of the success of fumigation of shipping containers, food industry buildings and flourmills. The concept of HLT applicable for sulfuryl fluoride and methyl bromide treatments, has not yet been considered for phosphine fumigation. It has been claimed that based on the HLT data, fumigant can be added to compensate its loss during the fumigation process or the exposure period can be increased accordingly. In sealed storage, bag-stacks are fumigated after checking the standard of their gas-tightness (e. g. by pressure test) and continued under sealed enclosure for long-term protection against insect pests. However, in normal bag-stack treatments gas-tightness is not checked, since it is known that they have a loss rate of 10% and above.

GAS MONITORING

Gas monitoring involves measurement of phosphine concentrations inside a fumigation enclosure (to check the level of insecticidal concentration) and in the area around the fumigation enclosure (to determine leakage and safety of the work place). Digital electrochemical phosphine monitors are available for both the purposes. While monitoring phosphine in bag-stacks under fumigation, carbon monoxide interference of electrochemical sensor-based phosphine meters has been reported. In milled rice stacks in Indonesia, Bengston *et al*. (1997) recorded up to 64 ppm of carbon monoxide in 7 days. However, in India, Rajendran (unpublished data) only found up to 10 ppm during fumigation of milled rice stacks in 7 days. Simple devices like the Phoscard ® (Emery and Kotsas, 2002) may also be useful to check phosphine levels inside fumigated stacks; they are yet to be tested in bag-stack fumigations.

In India, there is an increased awareness about monitoring gas concentrations in grain stacks and in the work place. Gas monitoring is a regular practice during fumigation of tobacco stacks in the country. A similar practice is required for grain stacks so that the gas concentrations are recorded in stack-cards of individual grain stacks to monitor fumigation. Phosphine meters (1-2000 ppm measuring range) will soon be introduced into warehouses in India having 50,000 – 100,000 tonne storage capacity.

OUTDOOR STACKS

In China, paddy rice is stored in the open in jute bags, in bulk surrounded by grain bags and in bulk surrounded by reed matting. In India, paddy and wheat are held in jute sacks and stacked either inside warehouses (godowns) or in the open air. Whenever the conventional godowns are full, bag-stacks are built outdoors, typically as cover and plinth (CAP) storage, on raised concrete pads or at ground level on unused airstrips, on asphalted roads and other leveled surfaces. Rajendran and Muralidharan (2001) carried out phosphine fumigation trials on bag-stacks of paddy rice (89 – 132 tonnes) to study the differences in gas loss rates and concentration-time (C-T) products during the treatment of indoor and outdoor stacks. In outdoor stacks, phosphine levels were consistently lower than in indoor stacks. The average gas loss rate was 14.5% per day for the indoor stacks and 29.5% for the outdoor stacks. Similarly, during fumigation of wheat stacks, large differences in gas concentrations between indoor and outdoor stacks was noted (Table 8). Temperature and wind have been the major driving forces for gas loss and related control failures in outdoor storages. The outdoor stacks must be built on smoothly rendered plinths instead of brick floor. Stacking on bare earth is not advisable, as the stacks cannot be made gas tight for fumigations. Provision of a bottom plastic sheet is essential before stacking to render the bag-stacks suitable for fumigations (van S Graver and Annis 1991). Deployment of skilled labour in adequate numbers (one person per 1000 tonne or 8 stacks) is essential as CAP storage involves many operations including aeration, repair of covers, upkeep of drainage and salvage of damaged grain. There is a need to increase the current phosphine application rates (3 – 3.6 g phosphine/ tonne) for wheat and paddy rice stored outdoors to 4 and 5 g phosphine/ tonne respectively.

INSPECTION OF STACKS

Inspection of grain stacks is necessary during a fumigation period as well as after termination of the treatment. During the fumigation period, floor sealing with mud or loose sand is likely to be disturbed by labourers engaged in loading and unloading operations in the warehouse and by those involved in house-keeping of the store. In outdoor stacks, sealing is likely to be disturbed due to wind forces, particularly in the peripheral stacks. After termination of fumigation, the stacks have to be checked at regular intervals for the presence of survivors, if any, due to fumigation failure. Post-fumigation observations are critical to analyze factors responsible for control failures and to undertake suitable corrective measures. In the developing countries, stacks undergoing fumigation are seldom inspected except when there is a strong smell of phosphine due to leakage. However, post-treatment observations are undertaken for routine checking of infestation in the stacks. Unfortunately, any infestation observed in fumigated stacks is mistaken for cross-infestation. Post-fumigation incubation of samples from fumigated stacks for confirmatory tests for survivors is rarely carried out. Incubation of representative samples and checking for survivors by the “breeding out method” is an important part of best fumigation practice.

SAFETY CONSIDERATIONS

Fumigation without proper precautions leading to safety risks to others has been reported even in developed countries (Popp 2002). Phosphine concentrations exceeding the safety limit of 0.3 ppm, i.e. 0.17 – 2.11 ppm, were reported in warehouses in India. Also, the workers involved in fumigation showed transient phosphine poison symptoms (Misra *et al.* 1998). Under the current regulations, use of a personal phosphine monitor (1-20 ppm measuring range) is mandatory for commercial pest control operators in India. It has been noted that depending on the inert ingredient content of the formulation, spent aluminium phosphide tablets may form a finely powdered ash or a coarse lump. The appearance of the aluminium phosphide residues has often raised doubts about the active ingredient of the tablet formulation. However, in some cases at the end of a treatment period, partially decomposed tablets containing little active ingredient (i.e. aluminium phosphide content) were observed (Halliday, 1986). When trays are not used to dispense aluminium phosphide tablets, under the present system of placing tablets between bags, spent aluminum phosphide residues will remain on the bags. The spent powder may contain up to 5% active ingredient (aluminium phosphide). Safe disposal of the spent powder by dry or wet deactivation methods is part of best fumigation practices (Anon. 1989).

A minimum of 12 h ventilation of phosphine fumigated bag-stacks and a withholding period of not less than 2 days have been suggested (Anon 1989). It is necessary to check before entry into a fumigated area for clearance of the fumigant using personal monitors or indicator badges/ strips.

TRAINING

Several authors have stressed the importance of training the personnel involved in fumigation. By proper training, the technical staff could improve the fumigation practice and achieve 100% insect mortality. Taylor and Gudrups (1996) showed that in Kenya, after high level fumigation training, the commercial pest control operators could improve on the floor sealing technique resulting in a higher gas retention of 1224 ppm of phosphine in maize stacks after a dosage of 2 g phosphine /tonne at the end of 7 days. In India, training of grain storage staff at management level resulted in improved fumigation practices including revised exposure period from 5 days to 7 days, discontinuation of whole-store fumigation and introduction of gas monitors in storage centers. The training also created awareness among the storage managers about phosphine resistance in insects and the importance of longer exposure period for phosphine fumigation to kill resistant insects.

CONCLUSION

In summary, a good fumigation involves several operations to meet the demands of client, consumer and regulatory bodies. When the various steps in good fumigation are strictly followed, fumigators could prevent or delay the development of insect resistance, reduce the chemical contamination of the commodity as well as the environment and ensure safety of the fumigator and the work place. Experience gained so far, with phosphine with reference to occurrence of resistance and control failures, has increased awareness and interest to improve upon the current fumigation practices to ensure successful treatment of the commodities. It requires cooperation of the management to provide required facilities and manpower and sincere involvement of the technical/ quality control personnel to implement the best fumigation practices. Best fumigation practice also includes treatment of all the stacks in a storage unit at the same time for efficient control. Regular training of the fumigators has a significant role in best fumigation practice in the developing countries.

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