STRATEGIES FOR EFFECTIVE USE OF PHOSPHINE AS A GRAIN FUMIGANT AND THE IMPLICATIONS OF RESISTANCE

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Abstract:

Because of the large differences in the relative tolerance of the developmental stages of grain insects to phosphine, there are two basic approaches to the use of this fumigant: (i) high application rates achieving high concentrations which produce dosages sufficient to kill the most tolerant stage of the most tolerant species or (ii) low application rates achieving low concentrations but persisting long enough for the more tolerant eggs and pupae to develop to the less tolerant larvae and adults. The second approach requires a high standard of gastightness and yet appears to be the approach used for phosphine fumigations in many parts of the world even though the storages in which it is being used are not adequately gastight. Under these circumstances, survival of the more tolerant eggs and pupae is likely. Because of the difficulty in detecting these stages, they will probably go undetected in the early post-fumigation period and the fumigation judged a success. The consequences of this illusion of success are shorter storage periods before insects reappear and selection for phosphine resistance.

The increases in exposure period required to control phosphine-resistant strains, are smaller than corresponding increases in concentration and, hence, may be more acceptable on both commercial and environmental grounds. However, with conventional formulations, with or without recirculation, increases in exposure period of the magnitude required are possible only in structures that achieve a high standard of gastightness. In structures that are less gastight, the use of a positive-pressure, flow-through technique appears to offer the most effective way to achieve long exposure periods.

Introduction

Successful fumigation with phosphine is simply a matter of applying the right amount of phosphine for the right length of time in an enclosure of sufficient gastightness.

Three simple parameters - or are they?

For some years now there has been a progressive lowering of application rates, a continuing debate on minimum exposure periods and a response bordering on despair when gastightness of the enclosure is mentioned. Application rates have fallen from as high as 22 - 30 g/m^3

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(30 - 40 tablets per tonne) to less than 0.75 g/m^3 (one tablet per tonne); exposure periods used have been as short as 2 days and it is argued that economic constraints severely inhibit any efforts towards making grain storages gastight. While these changes may achieve a saving in the cost of material, accede to operational requirements and avoid capital expenditure or major modifications, they have had the effect of considerably increasing the frequency of failures. It is not really surprising that phosphine resistance has developed. Moreover, it can be argued with certainty that if practices do not change, phosphine resistance will spread.

For the most part, users are influenced by what they read on the labels of the various preparations. In this regard it is disturbing to learn that there is a tendency for some manufacturers to recommend exposure periods that are shorter than those recommended by other manufacturers for a similar formulation, simply to gain some commercial advantage i.e. it is suggested that in the minds of the consumer, if one product recommends a shorter exposure period than another, it must be a better product and will do the job faster. While the commercial pressures are understandable, it is difficult to believe that these pressures warrant jeopardising the future usefulness of perhaps the most useful fumigant we have and are ever likely to have.

It is appropriate to consider some of the underlying principles of phosphine toxicity, to evaluate how some of the current practices relate to these principles and to develop strategies for prolonging its effective life and preparing for the "phosphine-resistance era".

Principles of phosphine toxicity

Phosphine differs from other fumigants in terms of the magnitude of the differences in its relative toxicity to developmental stages. In most cases, the tolerance of the egg and pupal stages is considerably greater than that of either the larval or adult stage. This may be represented schematically as in Fig. 1. This diagram is based on data from Winks (1971), Lindgren and Vincent (1966), Bang and Telford (1966), Howe, 1973, Hole *et al*. (1976) and Nakakita and Winks (1981).

Whether the egg or pupal stage is the most tolerant is of little consequence. Both of these stages are considerably more tolerant of phosphine than the other stages. For example, from the data of Winks (1971) and Nakakita and Winks (1981), it may be deduced that the pupae and eggs of *Tribolium castaneum*, are up to 65 and 55 times more tolerant than 10-day larvae. The consequence of the differences in susceptibility is that the level of kill achieved in the more tolerant stages will determine the success or otherwise of the fumigation. Clearly, there are two ways of approaching the problem:

1. apply a high dosage sufficient to kill either eggs or pupae irrespective of whether development continues; or

2. retain the fumigant long enough for eggs to hatch and pupae to moult to adults and have a concentration at that time sufficient to kill these more susceptible stages.

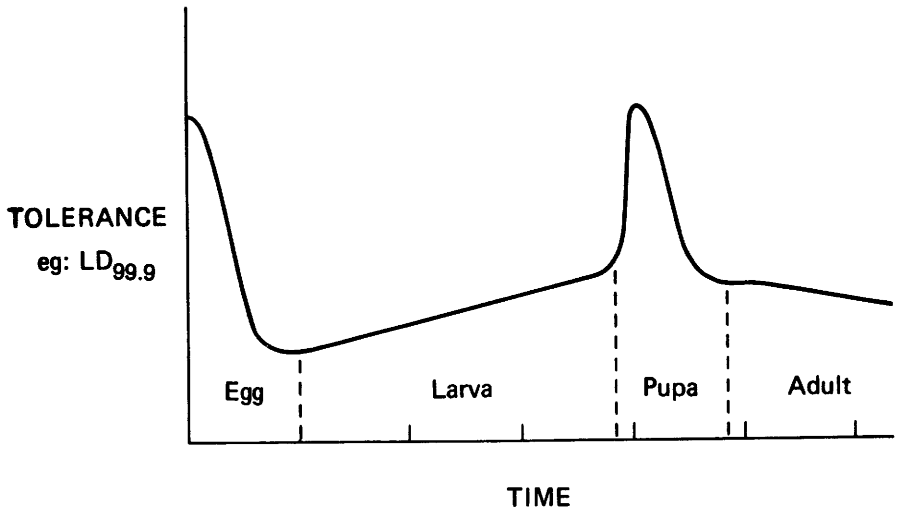

Fig. 1 Schematic representation of the change in tolerance to phosphine with development of many stored product insects.

In both approaches the period of exposure plays a part in determining the level of kill achieved but is of far greater significance in the second approach than it is in the first. The tolerance of both the egg and pupal stage decreases with time as their development proceeds. For example, the tolerance of the eggs of T. confusum (Table I) decreased nearly 19 fold from 1-day old to 6-day old (Lindgren and Vincent, 1966) and the tolerance of pupae of T. castaneum (Table II)

TABLE I. Estimates of Ct products (mg h/L) of phosphine required for a 99 per cent kill of Tribolium confusum eggs of different ages. Exposure: 16 h at 26.7°C.*

Age (days)	Ct product (mg h/L)
1	17.90
2	7.20
3	2.56
4	3.04
5	1.76
6	0.96

* from Lindgren and Vincent, 1966

decreased almost 11 fold from the early pupal stage to the late pupal stage (Nakakita and Winks, 1981). Moreover, it is clear that the tolerance of the pupae of Sitophilus granarius also decreases with time. The concentrations and times needed to achieve a 99.9% or complete kill

TABLE II. Dosages (mg h/L) of phosphine required to kill 99.9 per cent of different stages of Tribolium castaneum at 25°C, 60% r.h. with 6 h exposure periods. **

Stage	$LD_{99.9}$ (mg h/L)
15-day larvae	0.52
20-day larvae	0.29
early pupae	11.94
late pupae	1.12

** from Nakakita and Winks, 1981.

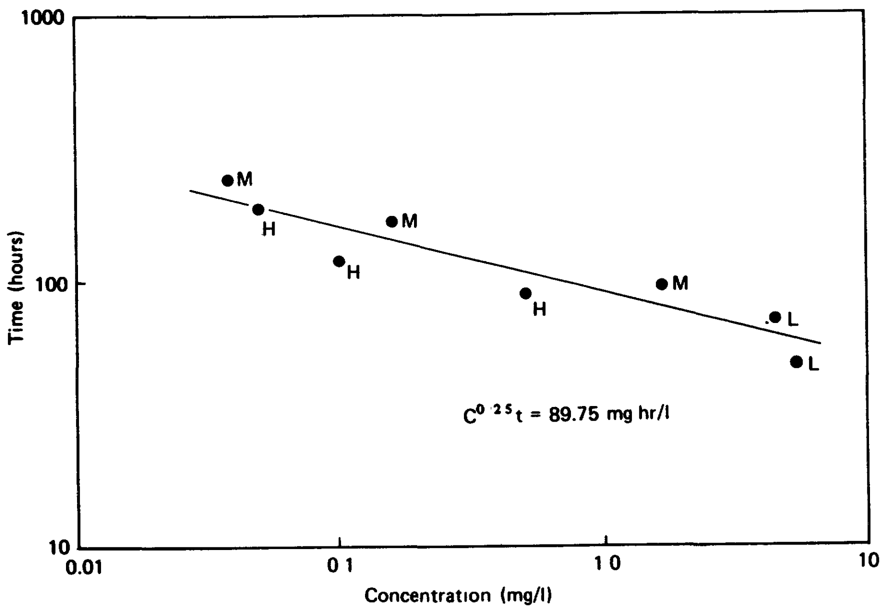

Fig. 2 The relationship between concentration and time derived from the data for high levels of kill (99.9%) or complete kill of Sitophilus granarius pupae exposed to phosphine. L = Lindgren and Vincent (1966); M = MAFF Inspectors Handbook (1974); H = Howe (1973).

of the pupae of this species, as reported by Lindgren and Vincent (1966), the MAFF Inspectors Handbook (1974) and Howe (1973), were plotted (Fig. 2) and a line of best fit calculated. The parameters of this line gave a relationship between concentration and time of $C^{0.25}t = 89.8$. From this relationship, concentrations and Ct products necessary to achieve high levels of kill were calculated for a range of exposure periods (Table III). Alhough the age of the pupae is not specified, it is reasonable to postulate that 7-day pupae are more developed than 1-day pupae and, therefore, that there has been a more than 300-fold decrease in tolerance from 1 to 7 days.

TABLE III. Concentrations and Ct products needed for high levels of kill of pupae of Sitophilus granarius with various exposure periods at about 25°C.

Exposure period (days)	Concentration (mg/L)	Ct product (mg h/L)
1	195.6	4694
2	12.2	587
3	2.4	174
5	0.3	38
7	0.08	14

Although many grain handling authorities would like to shorten phosphine fumigation periods, this is clearly very difficult to do when dealing with stages as tolerant as early pupae or, for that matter, young eggs. Furthermore, when time for development is obviously so important, fast release formulations, such as those based on magnesium phosphide, would seem to be of little value unless some attempt is made to increase application rates high enough to cope with young pupae or eggs and, at the same time, improve the rate of distribution.

From all of these data, it is apparent that there are advantages in longer exposure periods that allow time for the tolerant stages to develop to less tolerant stages that require a much lower dosage. Such an approach also allows sufficient time for the phosphide formulation to completely decompose and time for the gas to be distributed via natural convection currents. Longer exposure periods are even more important at low temperatures at which development will proceed slowly. However, it is implicit in the use of longer exposure periods that the standard of gastightness is high enough to permit the retention of an adequate concentration for the required time.

The curves of Fig. 3 show the dosages that could be expected from an application rate of 2 tablets/tonne in leaky storages both full and half full. The "full storage" curves would approximate fumigation under

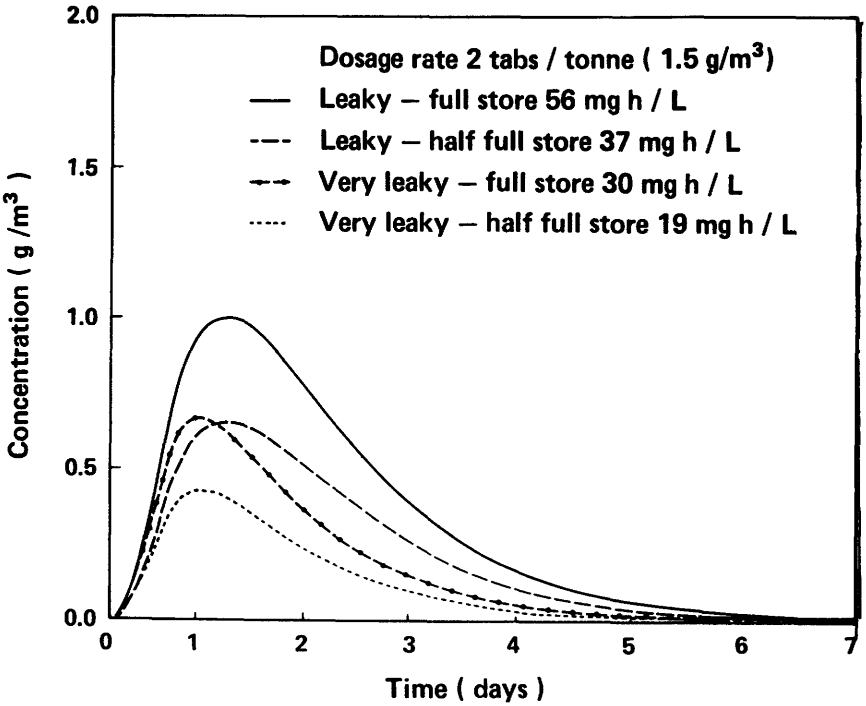

Fig. 3 Average phosphine concentrations and dosages expected in leaky storages following the application of aluminium phosphide tablets at a rate of 1.5 g/m3 (2 tablets/tonne).

damaged plastic sheeting while the "half full" curves would approximate fumigation of whole, leaky godowns in which there is a large headspace. All but the "leaky - full store" curve would allow some pupae of *S. granarius* to survive. It is important to note, moreover, that these are calculated curves that are designed to predict *average* concentrations and in turn produce an estimate of the *average* Ct product. They do not show the variation that could be expected in such leaky situations. In all such cases, pockets of low concentration would be found and in these, insects will survive, even those species that are less tolerant than *S. granarius*.

With a dosage of 1 tablet/tonne the situation is much worse (Fig. 4). Even the average concentrations shown in all of these curves are quite inadequate.

Under all of these circumstances, survival of the more tolerant eggs and pupae is likely. Because of the difficulty in detecting these stages, they will probably go undetected in the early post-fumigation period and the fumigation judged a success. The consequences of this *illusion of success* are shorter storage periods before insects reappear and selection for phosphine resistance.

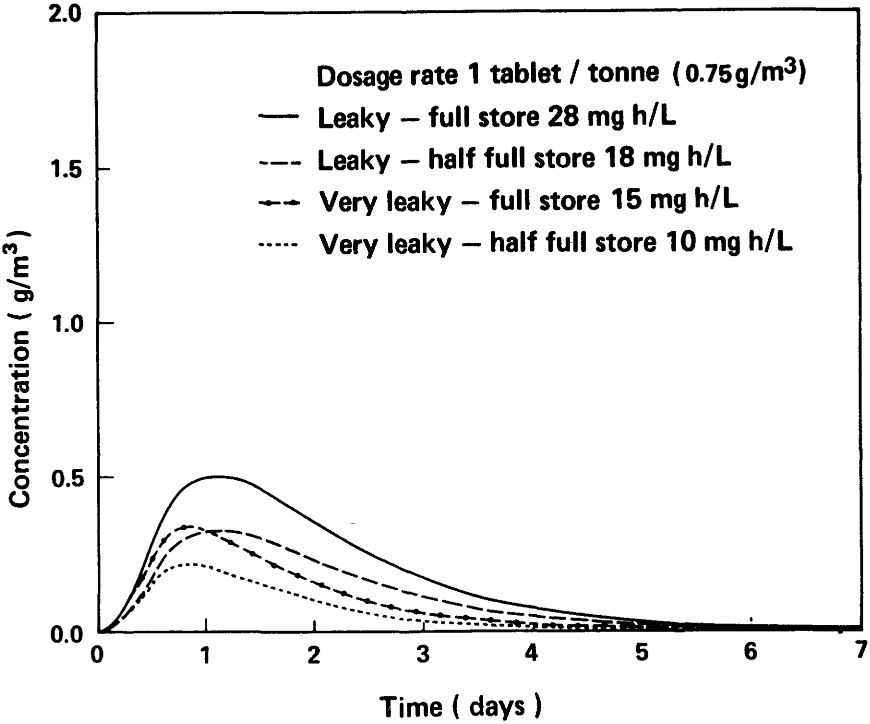

Fig. 4 Average phosphine concentrations and dosages expected in leaky storages following the application of aluminium phosphide tablets at a rate of 0.75 g/m3 (1 tablet/tonne).

Control of phosphine-resistant strains

Unless current practices are improved dramatically, it is likely that phosphine resistance will spread and, increasingly, the need will arise to control resistant strains. Resistance levels in strains studied to date suggest that it will be possible to continue using phosphine simply by adapting to a higher level of "natural" tolerance and modifying dosages accordingly. The key to successful control of phosphine-resistant strains with phosphine will be attaining high standards of gastightness or the development of new methods of application or both. Whichever approach is used the aim will be to retain an adequate concentration long enough for the more tolerant stages to develop to less tolerant stages. The strategy for controlling phosphine-resistant insects with phosphine will simply be an extension of that for phosphine-susceptible insects. Since the adult stage of most species is likely to be as least as tolerant as the late larval stage, it is appropriate to consider the implications of the tolerance of resistant adults on possible control strategies. From the data for adults of phosphine-resistant T. castaneum (Winks and Waterford, 1986) and for Rhyzopertha dominica (Winks and Waterford, in preparation) the increases in exposure period needed to achieve a 99% kill of the resistant strains would be smaller than corresponding increases in concentration (Table IV).

TABLE IV. The increases in either the concentration or exposure period necessary to achieve the same level of response (LD_{99}), in resistant strains of *Tribolium castaneum* and *Rhyzopertha dominica*. †

Dosage variable	Susceptible strain	Resistant strain	Increase necessary
Tribolium castaneum			
exposure period at 0.04 mg/L	10 h	30 h	x3
concentration at 20 h	0.02 mg/L	0.09 mg/L	x4.5
Rhyzopertha dominica			
exposure period at 0.04 mg/L	10 h	100 h	x10
concentration at 20 h	0.007 mg/L	0.16 mg/L	x23

† The concentrations and times chosen for this comparison are from about the middle of the range of concentrations and times where the response is least variable.

In theory, to achieve an LD_{99} in a practical fumigation of the strains shown, a minimum exposure of that shown plus the development time of either eggs or pupae, whichever is the longer, would be required. For example, to achieve an LD_{99} in the resistant strain of *R. dominica* referred to in Table IV the minimum exposure period at a concentration of 0.04 mg/L and a temperature of 25°C would be 4 days plus the maximum time for either eggs or pupae to complete their development. If the 'maximum' development time was taken as 7 days then the exposure period would need to be at least 11 days and a practical fumigation aimed at better than a 99% kill would need to be significantly longer than this. Even if an allowance were made for a slightly higher concentration and the fact that some poisoning would occur during pupal development, it would reduce this period only by a day or two. Clearly, fumigation in a leaky structure that retains gas for little more than 5 days is of little value.

The curves of Fig. 5 illustrate the significance of gastightness if conventional formulations are to be used to control resistant strains. A 10-fold increase in application rate in a leaky structure has been compared with a 3-fold increase in exposure period in a structure that achieves an adequate standard of gastightness. In spite of the large increase in concentration following the 10-fold increase in application rate in the leaky structure, there would be little gas left after 7 days. Again, it must be remembered that these are average concentrations and in such a leaky structure there would be pockets of

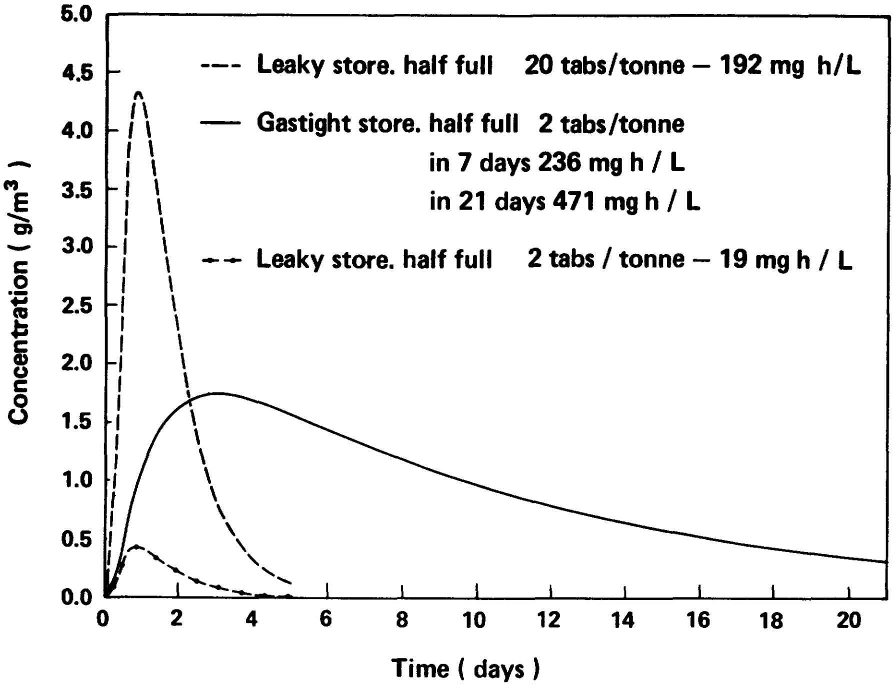

Fig. 5 Comparison of a 10-fold increase in application rate of aluminium phosphide tablets in a leaky storage with a 3-fold increase in the exposure period in a gastight storage.

much lower concentrations. Even in the areas of average concentration the fumigation would have failed to control the resistant R. dominica referred to above. By contrast, at 7 days in the gastight enclosure, the Ct product exceeds that in the leaky structure with a 10-fold increase in application rate. Furthermore, with a 3-fold increase in exposure period, a Ct product almost 2.5 times that obtained with the high application rate in the leaky structure is achieved. Moreover, there is still an effective concentration left after 21 days in the gastight structure so that, if necessary, the fumigation could be prolonged and a still higher Ct product obtained. In the gastight structure the resistant strains that we currently know about, could be controlled with phosphine. This would include strains from Bangladesh and those that have been selected in the laboratory.

Clearly, increased exposure periods will be the key to controlling phosphine-resistant strains. With conventional formulations, with or without recirculation, this will be possible only if a high standard of gastightness is achieved in the structure itself or with suitable gas-proof sheeting. In structures that are not sealed, an alternative method of application such as the flow-through or positive-pressure technique, that is currently under investigation, appears to offer the most effective way to achieve long exposure periods.

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