Navarro, S. and Donahaye, E. [Eds.](1993) Proc. Int. Conf. Controlled Atmosphere and Fumigation in Grain Storages, Winnipeg, Canada, June 1992, Caspit Press Ltd., Jerusalem, pp. 449-460.

PHOSPHINE RESISTANCE IN STORED-PRODUCT INSECTS

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ABSTRACT

Fumigant resistance among strains of stored-product insects has been slow to develop. However, since the FAO Global Survey in 1972, resistance has been documented from a number of countries and control failures due to resistance have occurred in some areas. Even though it has been shown that stored-product insects have the potential to develop resistance to fumigants, there are only a small number of cases of resistance to methyl bromide and none to any of the controlled or modified atmosphere gases. Phosphine resistance, on the other hand, has increased both in scope and intensity since the first records from the FAO Global Survey. In practical terms, fumigant resistance among stored-product pests is synonymous with phosphine resistance. This paper will review some examples of phosphine resistance where control failures have occurred and speculate on strategies that might be used to control these resistant strains.

INTRODUCTION

Fumigants have been used in post-harvest pest control efforts for many years. For example, carbon disulphide came into general use as a grain fumigant in 1879 and hydrogen cyanide soon followed suit in 1886. Methyl bromide has been used commercially for over 60 years (Bond, 1983). Since then, a number of other products have come into being as grain fumigants and have been used extensively and effectively.

The first reported case of resistance to a fumigant was the well-publicized case of the San Jose scale to hydrogen cyanide in California in the early part of this century (Quayle, 1916). For many years after this incident, it was debated whether or not insects could actually develop resistance to toxic chemicals. And, indeed, resistance to fumigants was particularly slow to develop, a circumstance that added credence to the assumption that insects could not develop resistance to fumigants.

It was not until the publication of the FAO Global Survey of pesticide susceptibility in stored grain pests that we came to realize that fumigant resistance was indeed a world-wide reality and a phenomenon we would have to deal with (Champ and Dyte, 1976). The overall incidence of resistance to phosphine was 9.7% of the strains tested, as compared with only 4.7% to methyl bromide. However, up to that point, there had been no reports of control failures with any of the fumigants in use. This fact did not detract from the significance of the report, however, and fumigant resistance became a reality.

PHOSPHINE RESISTANCE

World-wide, only phosphine and methyl bromide remain in common use as grain fumigants. And although controlled atmosphere (CA) fumigation has been used as treatment for bulk and bagged grain and other commodities (Jay and D'Orazio 1984; Annis, 1989; Banks *et al.*, 1991), its scope is presently limited.

In the interim years since the FAO report, there have been no confirmed cases of resistance to methyl bromide nor to the gases used in modified atmosphere (MA) fumigation despite the fact that it has been shown that stored-product pests have a great potential to develop resistance to methyl bromide (Monro, 1964) and to MAs (Navarro *et al.*, 1985; Donahaye, 1990a; Donahaye 1991) (Table 1). Only slight levels have developed in the field (Table 2); however, many additional cases of phosphine resistance have been recorded from various parts of the world.

Table 1: Laboratory-selected fumigant resistance among species of stored-product insects.

Condition/ fumigant	**Species**	**Generation tested and resistance level**		**Reference**
Hypercarbia	*S. oryzae*	F10	X 3.3	Navarro *et al.* (1985)
	S. granarius	F7	X 3.3	Bond and Buckland (1979)
	T. castaneum	F40	X 9.2	Donahaye (1990a)
Hypoxia	*T. castaneum*	F40	X 5.2	Donahaye (1990b)
MeBr	*S. granarius*	F50	X 7.8-17	Bond and Upitis (1973)
	T. castaneum	F3	X 1.6	Winks (1979)
		F6	X 2	Rajendran (1992)
PH_3	*S. granarius*	F28	X 3	Monro *et al.* (1972)
	T. castaneum	F2	X 1.6	Winks (1969)
		F6	X 24	Rajendran (1992)
		F10	X 12	Kem (1975)
		F16	X 5.9	Saxena and Bhatia (1980)

After Champ (1986)

Table 3 (taken from Taylor, 1989) shows a compilation of the incidences of phosphine resistance in stored-product insects recorded by region and species. In addition to those reports cited by Taylor (1989), recent additions include data from Australia (Attia and Greening, 1981; Attia, 1983; Herron, 1990; White and Lambkin, 1990), Brazil (Sartori *et al.*, 1991), the US (Zettler, 1991), and the UK (Mills, 1986). It would appear from these data that phosphine resistance can be found wherever one looks for it.

CONTROL FAILURES FOLLOWING PHOSPHINE FUMIGATION

Despite the realization that fumigant resistance was prevalent around the world, not much was done to implement resistance management strategies in pest control programs until control failures began to appear. The first such report came from Bangladesh where whole stores were fumigated in warehouses with gas permeable walls (Tyler *et al.*, 1983). During fumigation of these storage structures, no phosphine remained after 96 hr and it was concluded that these repeated inadequate fumigations with a low dosage rate of 1.0-1.6 g phosphine/m^3 every 6 weeks for more than two years contributed to the high levels of resistance (Mills, 1983). Unfortunately, these inadequate fumigation practices remain commonplace in many parts of the world and resistance has been found in many countries (Taylor and Halliday, 1986).

Table 2: Field occurrences of methyl bromide resistance to pests of stored-products.

Species	**Areas of occurrence**	**Highest level recorded**	**Reference**
S. granarius	Malta	X 1.6	Howe (1962)
	US	X 1.1	Zettler (Unpublished)
T. castaneum	Australia	< X 1.5	Winks (1979)
T. confusum	Australia	< X 1.5	Winks (1979)
O. surinamensis	UK		Anon. (1981)

After Champ (1986)

When phosphine was introduced to developing countries in the early 1960s, it started a revolution in pest control and quickly spread the scope of fumigations throughout many remote areas not accessible previously to fumigation (Friendship *et al.*, 1986). Its ease of use eliminated many logistic problems and very little safety equipment was required during its application. Unfortunately, not much training was provided in the use of phosphine nor the conditions necessary to conduct a successful fumigation. Also, promotional information stressed that increased doses could compensate for improper or inadequate sealing of storages and that exposure periods of 2-3 days were sufficient to control pest species. These conditions ultimately led to the development of phosphine resistance.

REVISION OF TREATMENT SCHEDULES BASED ON PHOSPHINE RESISTANCE

Following a detailed examination of the resistance levels of phosphine-resistant insects from Bangladesh, Tyler *et al.* (1983) recommended that an adequate CxT product for phosphine-resistant strains would be 150 mg.hr/l for a minimum of 3 days. However, Winks (1980) had suggested earlier that a CxT product effective against resistant strains would be 150 for 7 days at 25°C or above. As seen from Table 4, this would be marginal for resistant strains of *C. ferrugineus* and *R. dominica* from Bangladesh, particularly if immature life stages were present and if the temperature was around 15°C.

A recent report from Brazil (Sartori *et al.*, 1991) indicated that there are some strains of *R. dominica* with very high resistance levels to phosphine, some sufficiently high to have caused control failures. Table 5 shows the response of some of these resistant strains of insects to phosphine at increased doses and exposure periods. Grain in the southern areas of Brazil is stored generally in bulk in large, flat storages open at the eaves. It is often fumigated without sheets or frequently with sheets in poor condition. These conditions, like those in Bangladesh, have led to the development of phosphine resistance in these insects. However, control of these strains could be effected at a CxT of 150 mg.hr/l for 7 days. Also, several phosphine resistant strains cited by Taylor (1989) would be controlled marginally by this dose (see Table 3).

DEALING WITH PHOSPHINE RESISTANCE

Given the economic costs required to develop pesticide chemicals to the point that they are accepted and registered for pest control, the likelihood that another fumigant with the characteristics of phosphine will be developed is remote at best. Given also the fact that phosphine fumigations are being carried out with improper techniques, resistance has increased both in scope and intensity, and there is every reason to expect that this trend will continue unless fumigation practices are improved (Friendship *et al.*, 1986, Winks, 1987). In addition, it is likely that resistant strains can be disseminated throughout the world in the grain trade (Taylor, 1991). Presently, phosphine resistance does not appear to be of such magnitude to preclude effective pest control. All resistant strains reported to date can be controlled with phosphine, provided that proper fumigation techniques are followed.

Table 3: Incidences of phosphine resistance by region and species.

Number of strains tested (T) and numbers resistant (R) of

Region	*Tribolium castaneum*		*Rhyzopertha dominica*		*Sitophilus* spp.		*Oryzaephilus* spp.		*Tribolium confusum*		*Cryptolestes* spp.		*Lasioderma serricorne*		*Plodia interpunctella*		*Cadra cautella*	
	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R
N. Africa	3	1	1	1	4	2	2	0	1	0								
Sub-Sahara	23	7	20	17	7	1	2	2			2	2						
South Asia	17	11	10	8	3	1	2	1										
Southeast Asia	12	0	16	9	3	0	1	0			2	1						
South America[1]	30	24	34	31	22	21	1	1			14	14						
Australia[2]	232	36	202	72	82	32	71	3	27	3								
U S[3]	59	22	21	8					17	3			20	8	7	4	18	3
UK[4]	14	5	2	0	39	17	54	3	4	1	30	4						

After Taylor (1989)

[1] Sartori *et al.* (1991)

[2] Attia and Greening (1981), Heron (1990), and White and Lambkin (1990)

[3] Zettler (1991)

[4] Mills (1986)

Table 4: Phosphine concentrations needed to control populations of resistant pests of stored-products.

Species	CxT (mg.hr/l) at 25°C	days	15°C	days
	Adults			
S. oryzae	13	7	17	7
O. surinamensis	42	7	86	7
C. ferrugineus	111	7	420	7
R. dominica	134	7	151	7
T. castaneum	30	3	30	3
	Immatures			
S. oryzae	94	10	574	14
O. surinamensis	38	6	110	6
C. ferrugineus	157	8	498	12
R. dominica	156	8	574	14
T. castaneum	38	6	54	6

From Mills (1986)

A successful fumigation is one in which a sufficient amount of the fumigant is confined in a sufficiently gas-tight enclosure to retain a toxic dose for all life stages of the pest present in the enclosure. Success is measured as complete control of all life stages of the pest, a situation that forestalls the development and spread of resistance. Economic control is something less (Banks and Annis, 1984). There are a number of improvements and alternatives that can be implemented to insure a successful fumigation.

LENGTHENING EXPOSURE TIME

Time is a critical parameter of dosage as it relates to phosphine toxicity for susceptible and phosphine-resistant insects alike. This is exemplified in susceptible insects by the natural tolerance of some of the immature stages (Hole *et al.*, 1976, Bell, 1976; 1977). The tolerance of the egg and pupal stage is considerably greater than that of larvae and adults (Winks, 1986a). However, the tolerant stages grow increasingly more susceptible as they age. Therefore, it is advantageous to lengthen exposure periods in order to allow sufficient time for tolerant stages to develop to less tolerant levels (Winks, 1987).

Table 5: Response of phosphine-resistant strains of stored-product pests to increased dosages and exposure periods.

		Discriminating dosage			**Increased dosage**		
Country	**Species**[1]	**CxT (mg.hr/l)**	**Exposure period (hr)**	**Percent mortality**	**CxT (mg.hr/l)**	**Exposure period (hr)**	**Percent mortality**
Brazil[2]	*R. dominica* (5)	3.6	120	39-86	50.4	168	99
	T. castaneum (2)	4.8	120	95	8	20	97
	S. oryzae (2)	4.8	120	89-100	16	40	99
	Cryptolestes spp.	7.2	120	84	24	40	90
Mali[3]	*R. dominica*				46.8	72	13
	R. dominica				24	120	38
	Cryptolestes				24	120	17
Pakistan[3]	*R. dominica*				28.8	72	96
	T. castaneum				28.8	144	89
Indonesia[3]	*R. dominica*				24	120	61
U. K.[3]	*Cryptolestes* spp.				64	72	98
					124	168	96
					30	168	97

[1] No. in parentheses represents no. of strains

[2] From Sartori *et al.* (1991)

[3] From Taylor (1989)

Winks (1986b) has pointed out that increasing the exposure time component of the CxT product is more important than increasing the dosage component at a fixed time exposure for a number of reasons. One is that the biological responses to pesticides, particularly to phosphine, are less variable within and among strains when the exposure time is extended. Another is that it is easier to achieve the longer exposure times required to control resistant insects than to achieve corresponding increases in concentrations (Winks, 1984; Winks and Waterford, 1986). In addition, since high concentrations of phosphine induce narcosis in insects such that tolerance may be increased as much as sixty-four fold (Winks, 1984), longer periods of exposure are required than would be expected from the response of the same strain at lower concentrations. Prolonged narcosis is toxic in itself. Thus, the key to controlling resistant strains is increasing the exposure time at concentrations sufficiently high to be toxic to the pests and sufficiently long to overcome the narcotic effect of the fumigant and to allow immature stages to develop to more susceptible stages.

IMPLICATIONS OF LENGTHENED EXPOSURE PERIODS

Exposure periods sufficiently long to control resistant insects require that a great deal of effort be put into making the storage structure gas-tight. Criteria for successful fumigations as outlined by Banks and Annis (1984), hinge mostly on the degree of gas-tightness of a structure. Winks (1987) compared the effectiveness of storage structures with various degrees of gastightness. He showed that in the control of resistant strains, it is futile to overdose a storage structure to compensate for leakage of the fumigant. For example, after 7 days in a leaky structure, little gas remained following a 10-fold increase in application rate. However, after 21 days in a gastight structure, considerable gas remained. In addition, the CxT product from the gastight structure even at 7 days was 2.5 times that of the leaky structure, sufficient to control resistant strains.

It is impossible economically to render many storage structures sufficiently gastight to achieve a successful fumigation of resistant insects. In fact, many structures cannot be made sufficiently gastight to achieve even an economic control. When these situations exist, these structures should not be fumigated at all with phosphine but rather some other method of control must be sought. Since all resistant strains to date have been shown to be susceptible to methyl bromide, fumigation with this alternative seems appropriate, especially as shorter exposure times would be required.

Therefore, when phosphine fumigations in leaky situations are carried out, supplementary measures must be implemented to reduce the leakage rate effectively. Gas-proof tarps can be used when appropriate to improve the gas-tightness of a structure. In addition, multiple or sequential dosing can be performed (Friendship *et al.*, 1986), whereby a structure under fumigation is fractionally-dosed several times during the course of the fumigation period such that the sum of the multiple doses approximates the desired single-dose total. Also, slow-release formulations of phosphine can lengthen effectively the exposure time during which lethal concentrations of gas are present. In some circumstances, it might prove necessary to use these measures in combination in order to produce an effective fumigation.

Another development in application technology is the use of gaseous phosphine from pressurized cylinders to dose a storage structure. One such system is the SIROFLO developed in Australia for fumigating silos (Winks, 1993). By introducing phosphine continuously into an air stream, this system provides positive pressure in the storage, thereby offsetting factors that otherwise would give rise to gas loss. It appears to be quite suitable for phosphine fumigations under leaky conditions. Another similar continuing dosing technique involves the use of 3% phosphine in liquid carbon dioxide (Bell *et al.*, 1993) that shows promise for fumigating flat storages.

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