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PHOSPHINE DOSAGE REGIMES REQUIRED FOR HIGH MORTALITY: A DATA-BASE APPROACH

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ABSTRACT

Phosphine has been in commercial use as a grain fumigant since the mid 1950s. It has developed and retained an important role in the control of storage pests since that time. More recently its use has expanded due to the phase-out of methyl bromide and marketing complications caused by grain protectant chemicals. This has challenged conventional phosphine use (aluminium/magnesium phosphide preparations) as the preparations were neither developed for nor suited to either the rapid fumigation of methyl bromide or the long-term unattended pest control of the grain protectants. Attempts to use phosphine under both these conditions are away from the dosage 'window' that was used most successfully for the earlier life of this fumigant. Over 70 individual papers have been published on dosage response of most stored-product insects to phosphine. Data from these papers have been collected into a database containing close to 3,000 records from which it is possible to define a boundary between survival and complete kill or high levels of mortality (>99%). This in turn allows a definition of the combinations of concentration and exposure time, which achieve effective fumigation under a range of conditions. The following combinations are the minimum required to achieve a very high level of kill in almost all stored-product beetles (excluding *Trogoderma* spp.), psocids and moths, excluding known resistant strains: 10,000 ppm for 1.5 days, 1,200 ppm for 2 days, 1,000 ppm for 8 days, 200 ppm for 10 days, 35 ppm for 20 days, 10 ppm for 30 days.

INTRODUCTION

Phosphine (PH_3) has been an important grain fumigant since the mid 1950s. In modern times it has become the treatment of choice for much of the world's grain, largely brought about by the progressive phase-out of methyl bromide (MB) and marketing complications associated with the use of grain protectant chemicals. The expanded role of PH_3 has been a challenge to the conventional formulations (aluminium/magnesium phosphides), as they were neither developed for the rapid fumigation times of MB nor the long-term unattended pest control of the grain protectants. Fumigation parameters for PH_3 at either very short or very long exposure times are outside the dosage window that has been used, usually successfully, for the earlier life of this fumigant. Modern usage requires much more understanding of the concentration/time/mortality response than was the case when PH_3 application was simply a matter of adding tablets to the grain stream on loading an unsealed silo. Fortuitously, much more control over the fumigation is now possible due to the availability of sealed storages, constant gas addition methods such as SIROFLO® and SIROCIRC®, and on-site generation and mixing methods. There is now the real possibility of being able to maintain any given target concentration for any length of time.

The huge flexibility in possible exposure periods and concentrations is particularly challenging for those trying to provide the data needed to define and justify application rates and their subsequent incorporation into recommended label rates. The work reported here was derived from such a challenge in Australia and was aimed at:

- Confirming existing label rates for sealed structures;
- Confirming SIROFLO® dosages;
- Investigating the problems of insects developing resistance; and
- Ensuring that any new recommendations have a traceable origin.

An extract of the current Australian label for gaseous PH_3 is shown in Table 1. The label rate for phosphide application gives more or less equivalent concentration end-points to the values in Table 1 when the treatment takes place in a suitably well-sealed structure.

TABLE 1
Extract of an Australian label (2000) for gaseous phosphine

Minimum concentration in ppm phosphine [PH_3]: to be maintained for the required period								
SIROFLO®, SIROFUME® and SIROCIRC™								
Species	Temperature	5 d	7 d	10 d	14 d	21 d	15 d	28 d
Tolerant species *Sitophilus* spp, *Rhyzopertha dominica,* *Lasioderma* & others with low level phosphine resistance	>20°C	na	700	200	35	20	35	15
	15-20°C	na	na	na	100	70	na	35

na = not available

Much has been written on the nature of the relationship between exposure period, concentration and the resulting mortality for PH_3 and other gaseous toxicants (e.g. Winks 1986; Annis 1998). Fully describing this relationship poses several interesting scientific/mathematical problems. But a general simplification of these is that as concentrations go down, the required exposure times increase and the converse also applies. It also seems likely that thresholds of action for both exposure time and concentration may also occur. Due to the hyperbolic nature of the relationship it may be difficult to confirm these threshold levels. For example, if 10 days at 100 ppm is required, the simple approximation that 1,000 days would be required at 1 ppm is not easily testable. This effectively means that 1 ppm is considered below the threshold of activity. The well-designed experiments and statistical analysis needed to pursue these details are exceptionally time and resource consuming, requiring at least a species by species approach, but more than likely also needing to include each stage and possibly several strains of each species. Some work to this end has been carried out. However most work has been carried out on adults of a few species in the window of concentration and time of conventional treatment, or as part of various screening methods for resistance.

Annis (1987) used a meta-analysis approach, with a wide range of concentration, exposure time and mortality data, to investigate controlled atmosphere treatment regimes. In that study, a wide range of relevant data was used to identify overall trends. This formed an adequate basis for rational dosage decisions without the need to complete all the multifactorial exposures required for a more rigorous and time-consuming approach. It was not possible to use an identical approach for PH_3 data as this comes from a more diverse set of sources and the data matching and consolidation steps were consequently more difficult. However there appeared to be adequate data to make some of the required judgments on dosage and response.

METHODS

Data were collected into a set of linked tables in a Microsoft ACCESS database. The main record data was contained in one table; secondary tables contained citation information, and species information. Data was extracted from a range of sources including: published journal literature, conference proceedings, publicly available reports and Stored Grain Research Laboratory (SGRL) laboratory data, some not yet published.

An initial literature search yielded about 800 items related to the use of PH_3 for insect control in general. Of these, 64 were sources of potential usable data, the citations of which are given at the end of this paper. About 2,800 usable records relating to 49 species were extracted from these sources and entered into a database. A usable record was defined as a single observation/result that gave the following pieces of information: temperature, mortality, concentration C, exposure time t, or Ct plus either C or t. This data was usually in the form of raw observations on a variety (sometimes undefined) of numbers of insects treated, but occasionally the data was a calculated Lt_x or LC_x. Additional information was also collected such as species, strain, stage, and whether resistance was proven or suspected.

The collected data was selected with various filters to produce relevant reports and these were displayed using the graphics in Microsoft Excel. The complexity of the data was such that no attempt was made to use the mortality observed quantitatively. Instead, it was used it as a threshold to define some survival (<100% mortality) or no survival (100% mortality) in the treatment.

RESULTS

The results of data base filtering are shown in Figures 1-4. The base data set for the current study was produced by filtering to remove data collected at <=15°C (because these lower temperatures are not common in Australian grain) or data from diapausing *Trogoderma* spp which are known to be uncharacteristically tolerant to PH_3 (Banks and Cavanaugh 1985). The first selective filtering of this base set included all observations where some susceptible insects survived (Fig. 1). A second selection included all observations where no susceptible insects survived (Fig. 2). These two sets were then used to define by inspection a boundary between survivors and non-survivors (Fig. 3). Current Australian label rates for gaseous PH_3 were then superimposed on this boundary diagram (Fig. 3). Finally a filtered set of data from surviving insects, that included only those that were known or suspected to be resistant to PH_3, were placed on the boundary diagram (Fig. 4).

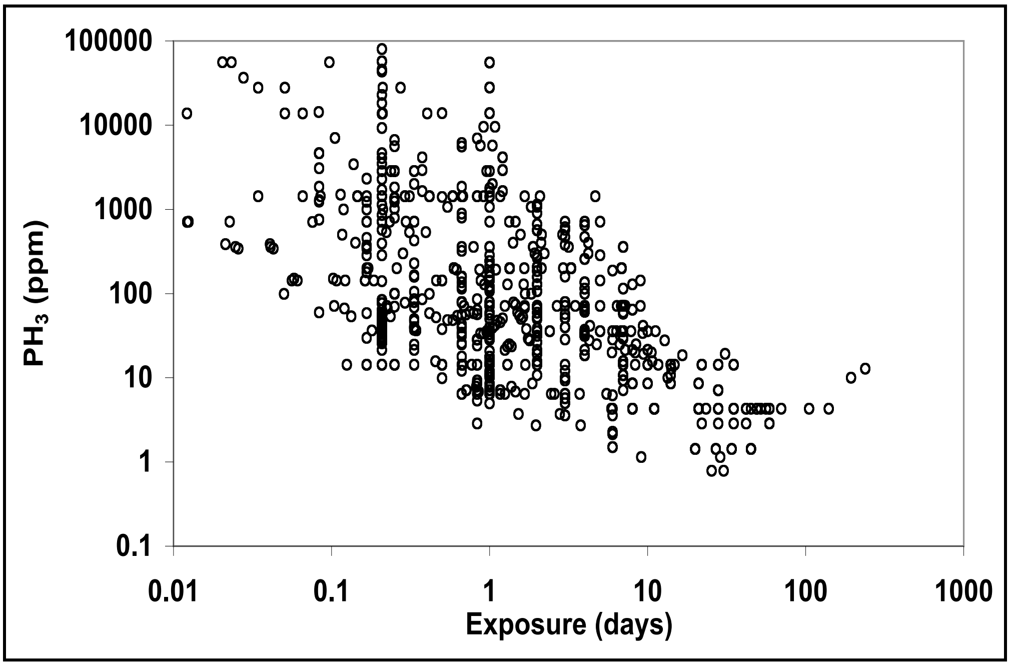

Fig. 1. Observations showing <100% mortality, all species, all stages, > 15°C, except diapausing *Trogoderma* spp.

DISCUSSION AND CONCLUSIONS

The data set above shows that the current (year 2000) Australian PH_3 label rate is consistent with the data obtained from non-resistant insects. In other words if the defined concentration and exposure time were met, any insects represented in the data would have died. The following are examples of combinations of concentration and minimum exposure time required to achieve a very high level of kill in almost all stored product beetles, psocids and moths, excluding known resistant strains and *Trogoderma* spp: 10,000 ppm for 1.5 days, 2,500 ppm for 2 days, 250 ppm for 8 days, 100 ppm for 10 days, 25 ppm for 20 days, 20 ppm for 30 days.

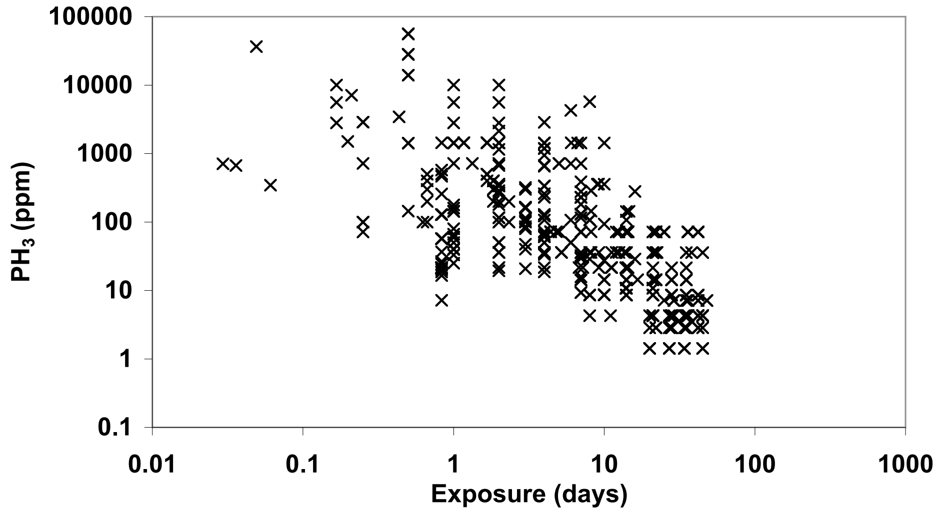

Fig. 2. Observations showing no survival, all species, all stages, > 15°C, except diapausing *Trogoderma* spp.

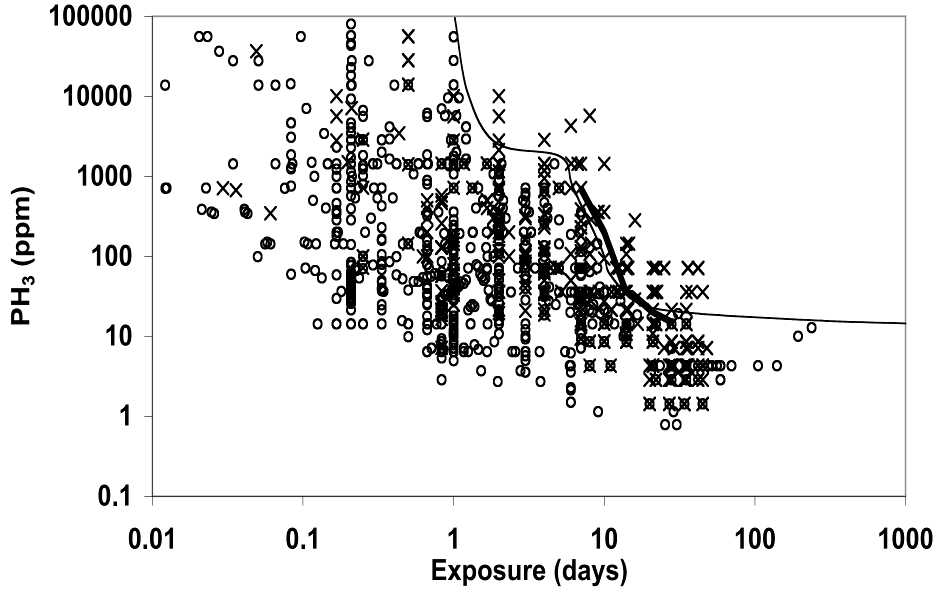

Fig. 3. Combined <100% mortality (□) and no survival (□), all species, all stages, >15°C, except diapausing *Trogoderma* spp. Light line, the boundary between survivors and no survivors. Bold line, the minimum concentrations indicated on the Australian gaseous phosphine label.

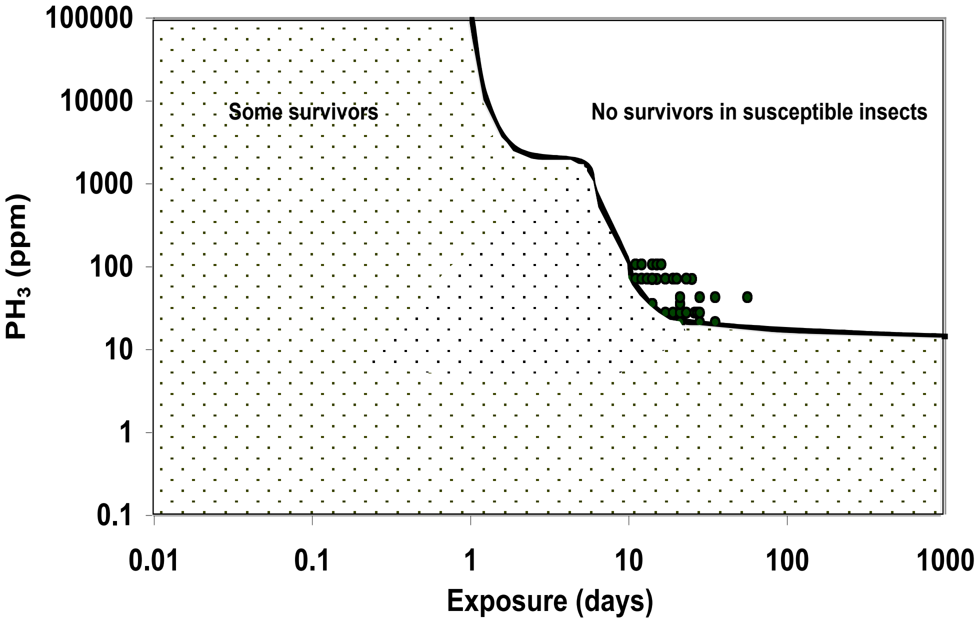

Fig. 4. Comparison of surviving resistant insects (•) with the boundary between survivors and no survivors in non-resistant insects, all species, all stages, > 15°C, except diapausing *Trogoderma* spp.

This does not assure that in an actual fumigation all insects would be killed. There remain questions of gas distribution, gas retention and the number of insects within the fumigation enclosure (it is important to remember that some records in the data may only represent 10 individuals killed out of only 10 treated). Higher level questions about the level of kill of a particular concentration/time combination, and the margin of confidence are not addressed in this analysis of these data. However, what is obvious from the inclusion of the resistant data set is that current resistance mainly affects the low concentration, long exposure part of the response curve. In practical terms, and from the data, this resistance can only be overcome by increasing the concentration, and not extending the exposure time. In terms of the original goals of the study, the following conclusions can be drawn by using the database approach:

- The recommended Australian exposure rate for gaseous PH_3 is consistent with data for non-resistant strains.
- The Australian phosphide label rates are also consistent with these data.
- A higher minimum concentration (>100 ppm) is required to deal with strongly resistant insects.

The database, as it stands, was adequate to draw the above conclusions. More extensive checking and validation, would be necessary before the database could be used by others as unrecognised errors or assumption about the data that were of little significance to this paper may be critical for other uses.

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REFERENCES

Annis, P.C. (1987) Towards rational controlled atmosphere dosage schedules: A review of current knowledge. In: *Proc. 4th Int. Working Conf. on Stored-product Protection*, (Edited by Donahaye, E., Navarro, S.), Tel Aviv. Caspit Press, 128-148.

Annis, P.C. (1999) The relative effects of concentration, time, temperature and other factors in fumigant treatments. In: *Proc. 7th Int. Working Conf. on Stored-product Protection,* (Edited by: Zuxun, J., Quan, L., Yongsheng, L., Xianchang, T. and Lianghua, G.), Beijing. Sichuan Publishing House of Science & Technology, **1,** 331-337.

Banks, H.J. and Cavanaugh, J.A. (1985) Toxicity of phosphine to *Trogoderma variabile* Ballion (Coleoptera: Dermestidae). *J. Australian Entomol. Soc.*, **14,** 179-186.

Winks, R.G. (1986) The biological efficacy of fumigants: time/dose response phenomena. In: *Pesticides and Humid Tropical Grain Storage Systems*, (Edited by Champ, B.R and Highley, E.), ACIAR Proceedings, **14,** 211-221.

Data sources used

Bang, Y.H. (1966) Effects of sublethal doses of fumigants on stored-grain insects. Technical Bulletin 50. Washington Agricultural Experiment Station. Washington State University, 22 pp.

Banks, H.J. and Cavanaugh, J.A. (1985) Toxicity of phosphine to *Trogoderma variabile* Ballion (Coleoptera: Dermestidae). *J. Australian Entomol. Soc.*, **14,** 179-186.

Barker, P.S. (1969) Susceptibility of eggs and young adults of *Cryptolestes ferrugineus* and *C. turcicus* to hydrogen phosphide. *J. Econ. Entomol.,* **62,** 363-365.

Barker, P.S. (1969) Susceptibility of the mushroom mite to phosphine and ethylene dibromide. *J. Econ. Entomol.* **62,** 145-146.

Barker, P.S. (1975) The response of eight strains of *Tribolium castaneum* (Herbst) to hydrogen phosphide. *The Manitoba Entomologist,* **9,** 39-42.

Bell, C.H. (1979) Limiting concentrations for fumigation efficacy in the control of insect pests. In: *Proc. 2nd Int. Working Conf. on Stored-product Entomology*. Ibadan 1978, 182-192.

Bell, C.H. (1977) Toxicity of phosphine to the diapausing stages of *Ephestia elutella, Plodia interpunctella* and other Lepidoptera. *J. stored Prod. Res.,* **13,** 149-158.

Bell, C.H. and Glanville, V. (1973) The effect of concentration and exposure in tests with methyl bromide and with phosphine on diapausing larvae of *Ephestia elutella* (Hubner) (Lepidoptera, Pyralidae). *J. stored Prod. Res.,* **9,** 165-170.

Bell, C.H. and Mills, K.H. (1983) Special factors affecting the toxicity of fumigants to insects. *Mitt. Dtsh. Ges. Allg. Angew. Ent.,* **4,** 120-122.

Bell, C.H. and Wilson, S.M., (1995. phosphine tolerance and resistance in *Trogoderma granarium* Everts (Coleoptera: Dermestidae). *J. stored Prod. Res.,* **31,** 199-205.

Bell, C.H., Hole, B.D. and Evans, P.H., (1977) The occurrence of resistance to phosphine in adult and egg stages of strains of *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae). *J. stored Prod. Res*., **13,** 91-94.

Bell, C.H., Hole, B.D. and Wilson, S.M., (1985) Fumigant doses for the control *of Trogoderma granarium*. Bulletin OEPP/EPPO Bulletin **15,** 9-14.

Bond, E.J. (1978) Toxicity of mixtures of methyl bromide and phosphine to insects. *J. Econ. Entomol.,* **71,** 341-342.

Bond, E.J. and Munro, H.A.U. (1961) The toxicity of various fumigants to the cadelle *Tenebroides mauritanicus*. *J. Econ. Entomol.,* **54,** 451-454.

Bond, E.J. and Upitis, E. (1973) Response of three insects to sublethal doses of phosphine. *J. stored Prod. Res*., **8,** 307-313.

Bowley, C.R. and Bell, C.H. (1981) The toxicity of twelve fumigants to three species of mites infesting stored grain. *J. stored Prod. Res*., **17,** 83-87.

Chaudhry, M.Q. and Price, N.R. (1990) Insect mortality at doses of phosphine which produce equal uptake in susceptible and resistant strains of *Rhyzopertha dominica* (F.) (Coleoptera: Bostychidae). *J. stored Prod. Res*., **26,** 101-107.

Clifton, A.L., Bell, C.H., Mills, K.A. and Savvidou, N. (1995) Control of grain pests with phosphine at temperatures below 10C. HGCA report No 105 Home Grown Cereal Authority, 62 pp.

Cox, P.D., Bell, C.H., Pearson, J. and Beirne, M.A. (1984) The effect of diapause on the tolerance of larvae of *Ephestia kuehniella* to methyl bromide and phosphine. *J. stored Prod. Res*., **20,** 215-219.

El-Lakwah, Von F. (1978) Tests on the efficacy of mixtures of methyl bromine and phosphine to Khapra Beetle (*Trogoderma granarium* Everts). *Anz. Schadlingskde pflanzenschutz Umwelschutz* **51,** 129-133.

Hashem, M.Y. and Reichmuth, C. (1989) The efficacy of phosphine against eggs of lesser grain borer *Rhyzopertha dominica* (Fab.) and the larger grain borer *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae). *Nachrichtenbl. Deut. Pflanzenschutz.* (Braunschweig) **41,** 159-163.

Ho, S. and Winks, R.G. (1995) The response of *Liposcelis bostrychophia* Badonnel *and L. entomophila* (Enderlein) (Psocoptera) to phosphine *J. stored Prod. Res*., **31,** 191-197.

Hole, B.D. (1981) Variation in tolerance of seven species of stored product coleoptera to methyl bromide and phosphine in strains from twenty-nine countries. *Bull. Ent. Res*., **7,** 299-306.

Hole, B.D., Bell, C.H., Mills, K.A. and Goodship, G. (1976) The toxicity of phosphine to all stages of thirteen species of stored product beetles. *J. stored Prod. Res.,* **12,** 235-244.

Howe, R.W. (1973) The susceptibility of the immature and adult stages of *Sitophilus granarius* to phosphine. *J. stored Prod. Res.*, **8,** 241-262.

Howe, R.W. (1974) Problems in the laboratory investigation of the toxicity of phosphine to stored product insects. *J. stored Prod. Res.,* **10,** 167-181.

Hyne, E.A. and Winks, R.G. (1997) The effect of temperature on some resistant stored-product insects exposed to phosphine. In: *Proc. Int. Conf. on Controlled Atmosphere and Fumigation in Stored Products.* (Edited by Donahaye, E.J., Navarro, S. and Varnava, A.), Printco, Nicosia, 31-43.

Ilic, B., Popovic, N. and Heller, G. (1979) Sensitivity of various insect species to reduced hydrogen phosphine concentrations. *Agrohemija,* **5-6,** 237-240.

Jalil, M., Ross, I.J. and Rodriguez, J.G. (1970) Methyl bromide and phosphine as fumigants for some acarid mites. *J. stored Prod. Res.*, **6,** 33-37.

Kalinovic, I. (1984) Efficiency of phosphine in the control of *Liposcelis bostrichophilus* Bad. Znann. Prak. Poljopr. Technol. 14/3-4/, 239-247.

Kashi, K.P. (1982) Dose-mortality response of five species of stored-products insects to phosphine. *International pest control* March/April, 46-49.

Kashi, K.P. (1981) Toxicity of phosphine to five species of stored-product insects in atmospheres of air and nitrogen. *Pesticide Scie*nce **12,** 116-122.

Kashi, K.P. and Bond, E.J. (1975) The toxic action of phosphine: role of carbon dioxide on the toxicity of phosphine to *Sitophilus granarius* (L.) and *Tribolium confusum* DuVal. *J. stored Prod. Res.*, **11,** 9-15.

Lindgren, D.L. and Vincent, L.E. (1966) Relative toxicity of hydrogen phosphide to various stored-product insects. *J. stored Prod. Res.*, **2,** 141-146.

Lindgren, D.L., Vincent, L.E and Strong R.G. (1958) Studies on hydrogen phosphide as a fumigant. *J. Econ. Entomol.*, **51,** 900-903.

Mills, K.A. (1983) Resistance to the fumigant hydrogen phosphide in some stored-product species associated with repeated inadequate treatments. *Mitt. Dtsch. Ges. Allg. Angew. Ent.*, **4,** 98-101.

Monro, H.A.U., Upitis, E. and Bond, E.J. (1972) Resistance of a laboratory strain *of Sitophilus granarius* (L) (Coleoptera: Curculionidae) to phosphine. *J. stored Prod. Res.*, **8,** 199-207.

Nakakita, H. and Winks, R.G. (1981) phosphine resistance in immature stages of a laboratory selected strain of *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidea). *J. stored Prod. Res.,* **17,** 43-52.

Pike, V. (1994) Laboratory assessment of the efficacy of phosphine and methyl bromide fumigation against all stages of *Liposcelis entomophilus* (Enderlein). *Crop Protection,* **13,** 141-145.

Popovic, I.B. (1975) Efficacy of hydrogen phosphide applied in very small concentrations on all stages of the grain weevil (*Sitophilus* sp). Environmental Quality and Safety Supplement 3 (Pesticides), 744-747.

Price, L.A. and Mills, K.A. (1988) The toxicity of phosphine to the immature stages of resistant and susceptible strains of common stored product beetles, and implications for their control. *J. stored Prod. Res.*, **24,** 51-59.

Rajendran, S. (1992) Selection for resistance to phosphine or methyl bromide in *Tribolium castaneum* (Coleoptera: Tenebrionidae). *Bull. Ent. Res,* **82,** 119-124.

Rees, D. (1994) Studies of distribution and control of Psocoptera (psocids or booklice) associated with the grain industry in Australia. CSIRO Entomology Report No 57, CSIRO Entomology Canberra, 23 pp.

Reynolds, E.M., Robinson, J.M. and Howells, C., (1967) The effect on *Sitophilus granarius* (L.) (Coleoptera, Curculionidae) of exposure to low concentrations of phosphine. *J. stored Prod. Res.*, **2,** 177-186.

Riudavets, J., Damcevski, K.A., Annis, P.C. (2001) Comparative response of a range of psocid (Psocoptera:liposcelididae) species to five alternative fumigants. In: *Proc. Int. Conf. Controlled Atmosphere and Fumigation in Stored Products,* (Edited by Donahaye, E.J., Navarro, S. and Leesch J.G.), Fresno, CA. 29 Oct. - 3 Nov. 2000, (these Proceedings).

Sartori, M.R., Pacheco, I.A. and Vilar, R.M.G. (1990) Resistance to phosphine in stored grain insects in Brazil. 1. In: *Proc. 5th Int. Working Conf. on Stored-product Protection,* (Edited by Fleurat-Lessard, F. and Ducom, P.), Bordeaux, France, 1990, Imprimerie Médocaine, Blanquefort Cedex, France, 1041-1049.

Sato, A. and Suwani, M. (1975) Studies on the characteristics of action of fumigants. III. Emergence of the Azuki bean weevil, *Callosobruchus chinensis* L., from Azuki beans fumigated with hydrogen phosphide at some developmental stages of ones. *Botyu-Kagaku,* **40,** 85-89.

Sayaboc, D.S. and Gibe, A.J.G. (1997) Resistance of *Rhyzopertha dominica* (Coleoptera: Bostrychidae) to phosphine in the Philippines. Proceedings of International conference controlled atmosphere and fumigation. In *Proc. Int. Conf. on Controlled Atmosphere and Fumigation in Stored Products.* (Edited by Donahaye, E.J., Navarro, S. and Varnava, A.), Printco, Nicosia, 513-517.

Storey, C. and Davidson, L.I. (1973) Relative toxicity of chloropicrin, phosphine, ED-CCl4, and CCl4-CS2 to various life stages of the Indian meal moth. ARS-NC-6 Agricultural Research Service U.S. D.A., 8 pp.

Taylor, R.W.D. (1989) phosphine - A major grain fumigant at risk. *International pest control,* Jan/Feb, 10-14.

Vincent, L.E. and Lindgren, D.L. (1977) Toxicity of methyl bromide and phosphine at various temperatures and exposure periods to the metamorphic stages of *Lasioderma serricorne. J. Econ. Entomol.,* **70,** 497-500.

Vincent, L.E. and Lindgren, D.L. (1972) Toxicity of phosphine to the life stages of four species of Dermestids. *J. Econ. Entomol.*, **65,** 1429-1431.

Vincent, L.E. and Lindgren, D.L. (1975) Toxicity of phosphine and methyl bromide at various temperatures and exposure periods to four metamorphic stages of *Trogoderma variabile. J. Econ. Entomol.*, **68,** 53-56.

Vincent, L.E. and Lindgren, D.L. (1972) Hydrogen phosphide and ethyl formate: fumigation of insects infesting dates and other dried fruits. *J. Econ. Entomol.*, **65,** 1667-1669.

Weller, G. (2001) Can SIROFLO® label rates control psocid infestations? In: *Proc. Australian Postharvest Technical Conference,* Adelaide, 1-4 Aug. 2000. (in press).

Winks, R.G. (1984) The toxicity of phosphine to adults of *Tribolium castane*um (Herbst): time as a dosage factor. *J. stored Prod. Res.*, **20,** 45-56.

Winks, R.G. (1996) New technique delivers improved stored grain protection. *Australian Grain,* April-May, 25-26.

Winks, R.G. (1986) The significance of response time in the detection and measurement of fumigant resistance in insects with special reference to phosphine. *Pesticide Science,* **17**, 165-174.

Winks, R.G. and Hyne, E.A. (1997) The use of mixed-age cultures in the measurement of response to phosphine. In: *Proc. Int. Conf. on Controlled Atmosphere and Fumigation in Stored Products.* (Edited by Donahaye, E.J., Navarro, S. and Varnava, A.), Printco, Nicosia, pp. 3-15.

Winks, R.G. and Hyne, E.A. (1994) Measurement of resistance to grain fumigants with particular reference to phosphine. In: In: Proc. *6th Int. Working Conf. on Stored-Product Protection* (Edited by Highley, E., Wright, E. J., Banks, H. J. and Champ, B. R.) Canberra, Australia, 17-23 April 1994, CAB International, Wallingford, Oxon, UK **1,** 244-250.

Winks, R.G. and Waterford, C.J. (1986) The relationship between concentration and time in the toxicity of phosphine to adults of a resistant strain of *Tribolium castaneum* (Herbst). *J. stored Prod. Res.,* **22,** 85-92.

Winks, R.G., Waterford, C.J., Cassells, J.A., Whittle, C.P. and Banks, H.J. (1992) Efficacy of SIROFLO® dosages against major storage pests. CSIRO Entomology Canberra, Limited access report.