MAXIMIZING BENEFIT : RISK RATIOS FROM INSECTICIDE

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Introduction

The assessment of the benefits and risks associated with the use of grain protectants is an integral part of the regulatory process. Maximum residue limits are established for grain protectants only where a benefit, such as insect control, has been demonstrated and only where there is an acceptable safety factor, i.e., where the ratio of the amount that causes a discernible effect on mammals to the amount expected on grain is high. In addition, this safety factor is kept as great as possible by establishing maximum residue limits at levels no higher than those required by good agricultural practice.

Implicit, therefore, in the establishment of maximum residue levels is evaluation of the ratio of gains to risks. It is the aim of this paper to demonstrate ways of increasing this ratio of gains to risks by utilization of knowledge drawn from disciplines, such as physical chemistry, insect demography, toxicology and engineering, that is, by integrated pest management (IPM).

Examples of IPM

Established procedures. Established sound agricultural practices, such as good warehousing procedures and control of moisture content, should properly be regarded as components of IPM. While everyone with experience in grain handling would agree that such practices are absolutely essential, there is an absence of sound published data on the effectiveness of such practices. This lack greatly increases the difficulties of those responsible for improving pest control.

The type of practical data needing publication can be illustrated by the following examples.

Poor Warehousing Procedures. I am aware of large quantities of grain in one country that are stored, badly contaminated, in a number of warehouses. The grain is unfit for human consumption but cannot be destroyed for political reasons. As a result, not only is the source of infestation a threat to insect control in other commodities in the warehouses, but the likely need for repeated treatments, often partially ineffective, will very probably result in the development of resistance to pesticides.

Worker Education. In Australia, the Bulk Grain Handling Authorities carry out a program of continuing worker education. These authorities occasionally assume responsibility for storages previously controlled by private traders, and continue to employ the same people. It takes at least until the second season of operation before the level of insect control in newly acquired storages reaches that obtained in comparable established storages, even though the same pest control procedures are employed (A Wilson, D Davis, personal communication).

Attention to Details of Protectant Application. In one exercise, I was asked to investigate a certain type of storage that had a record of serious insect infestation. I recommended that the spraying equipment be re-sited, to ensure better mixing of the pesticide with the grain. Insect control has improved markedly in the five years since this recommendation was adopted despite the fact that there has been a reduction in the level of pesticide applied. The ratio of gain to risks in the use of grain protectants has been increased as a result of re-siting the spray equipment. It is important that such 'non-scientific' causes of failure receive the attention they deserve.

Temperature-toxicity Relationships. Control of the temperature of grain treated with a grain protectant, affects insect populations in two ways. First, it affects the persistence and the lethal effects of insecticides, and second, it influences the reproductive rate and, to a lesser extent, the mortality, of adult insects.

The effect of temperature and time of exposure on the mortality of adult *Tribolium castaneum* (Herbst), strain CTC4, after exposure to natural pyrethrins synergized with piperonyl butoxide, 8:1, W/W, is shown in Fig. 1. In these experiments, two groups of insects, each of 50 adults on 140 g of wheat at 55% r.h., were removed after different exposure periods and the number of survivors were counted 14 days later. At 35°C mortality reached a plateau after a few days' exposure, whereas at 20°C mortality continued to increase with period of exposure (Fig. 1). Thus mortality after a 30 day exposure to 0.6 mg kg^{-1} pyrethrins at 20°C approximately equalled that obtained after a 30 day exposure to 2.5 mg kg^{-1} at 35°C.

The effect of temperature on the rate of reproduction of *T. castaneum* was assessed by exposing two groups of 50 adults each on 140 g of wheat, at 55% r.h., containing bioresmethrin, permethrin, IR-Phenothrin or natural pyrethrins, each synergized with 8 parts W/W of piperonyl butoxide. After an exposure of 14 days, adults were removed and progeny were counted 5 weeks later at 35°C and 8 weeks later at 25°C. Considerably more progeny developed at the higher temperature in all treatments (Fig. 2), and no progeny developed at 25°C after exposure to 5.0 mg kg^{-1} of any of the pyrethroids tested.

While the negative temperature effect of pyrethroids is demonstrated in Figs 1 and 2, quantitative measurement of the effects of pesticides on the intrinsic rate of development of insect populations cannot be determined from such data. The approach of Longstaff and Desmarchelier (1983) enabled such calculations to be made, for *Sitophilus oryzae* (L.), after exposure to low application rates of either pirimiphos-methyl or deltamethrin at 21, 27 and 32.3°C. Whereas deltamethrin was more effective at lower temperatures, pirimiphos methyl was more effective at higher temperatures (Table 1). Only approximately 0.4 mg kg^{-1} of pirimiphos-methyl is required to prevent population growth of *S. oyrzae* at 32.3°C and only approximately 0.1 mg kg^{-1} of deltamethrin is required to prevent population growth at 21°C (Table 1). These rates of application are only a small fraction of the rates of either pirimiphos-methyl (4 mg kg^{-1}) or deltamethrin (2 mg kg^{-1})

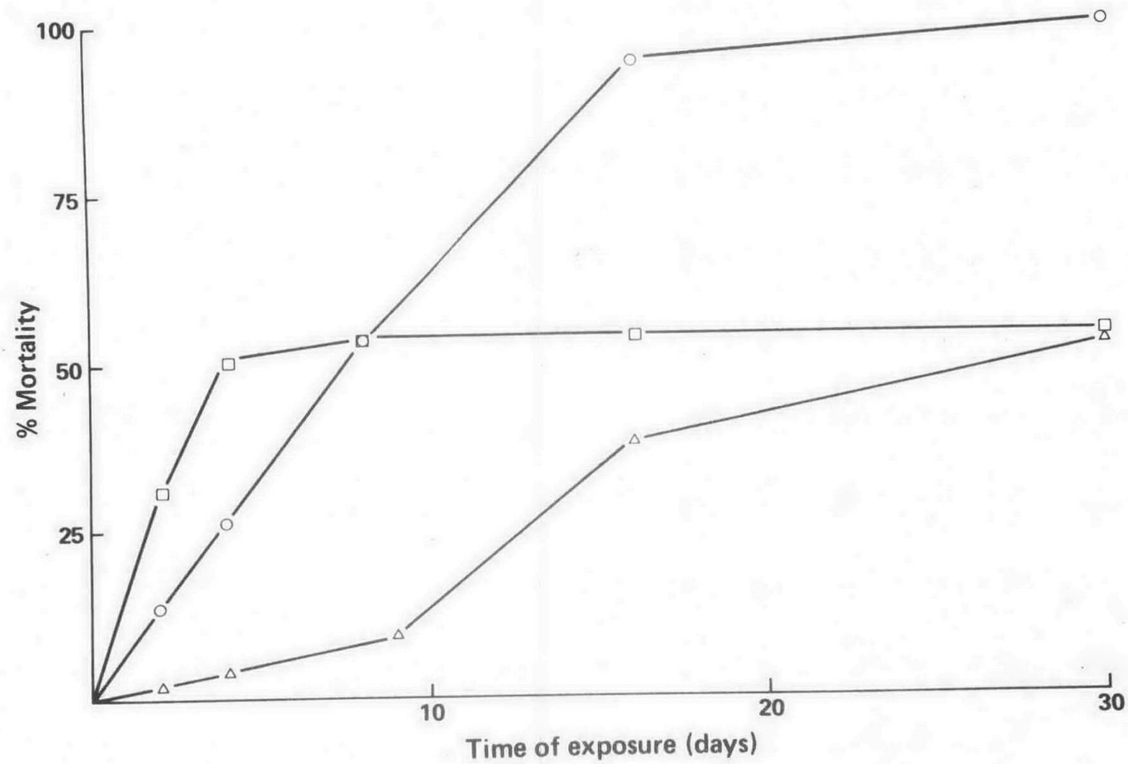

Fig. 1. Mortality of *T. castaneum* after exposure to synergised pyrethrins (□) 2.5 mg kg^{-1} pyrethrins at 35°C. (○) 1.2 mg kg^{-1} pyrethrins at 20°C. (△) 0.6 mg kg^{-1} pyrethrins at 20°C.

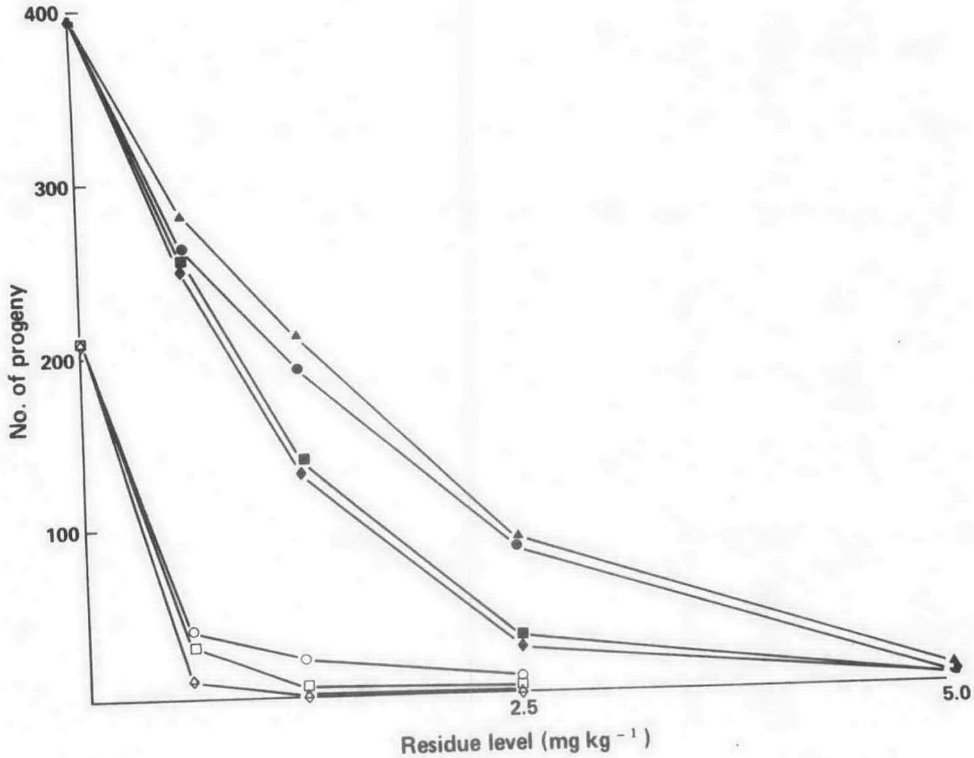

Fig. 2. Number of progeny of *T. castaneum*, after exposure to synergised pyrethroids (⊠) Control. (□) Bioresmethrin. (△) IR-Phenothrin. (○) Permethrin. (◇) Natural Pyrethrins. Open symbols = 25°C; closed symbols = 35°C.

recommended for control of stored product insects over the range of temperatures found on Australian wheat (Bengston and Desmarchelier, 1979). Thus if one has, or provides, a temperature that is less than optimal for the insect, and if one chooses an insecticide that is particularly effective at that temperature, a high level of control can be obtained.

Table 1. The intrinsic rate of increase per week of *S. oryzae* exposed to deltamethrin (0.1 mg kg^{-1}) or pirimiphos-methyl (0.4 mg kg^{-1}).

Temperature (°C)	Control	Deltamethrin	Pirimiphos-methyl.
21	0.336	0.083	0.285
27	0.679	0.452	0.241
32.3	0.465	0.247	-0.073

Cooling to Preserve Pesticide Residues. The effects of temperature on the stability of protectants on grain has been measured (Desmarchelier, 1978a, 1980; Desmarchelier and Bengston, 1979). It is possible to couple models of the stability of pesticides with models of cooling to derive a rate of application that will leave a minimum deposit after a given period of storage (Thorpe and Elder, 1980).

In Australia, fenitrothion is applied at three different rates of application, depending on climatic zone and anticipated time of storage, to leave a minimum effective residue at time of outloading. This is an example of an IPM procedure that is a considerable improvement, from the point of view of consumers, on a standard rate of application to cover all contingencies.

Another approach would be to apply a low rate of fenitrothion, and rapidly cool the grain to about 20°C, i.e. to a level low enough to prevent appreciable degradation of fenitrothion. Hunter, Wilson and Desmarchelier (unpublished results) achieved such a rapid cooling in summer in Victoria, using three methods to cool barley in 2000 t welded steel bin (Fig. 3). These included aeration with chilled air and ambient-air aeration at low (L) and high (H) rates of air flow. The chilled air unit operated continuously, whereas ambient-air aeration operated for the 12 coolest hours in a day.

The results, averaged from 4 bins for each regime, are shown in Fig. 3. Both average and maximum temperatures are recorded as well as the time required for the average and the maximum temperature to fall to 21°C. The cooling resulted in a decreased loss of fenitrothion to the negligible figure of 3% (Table 2).

From the results outlined in Fig. 3 and Table 2 it is concluded that Bulk Grain Handling Authorities could apply low rates of protectants and then cool grain quickly to about 20°C, where insect development is slow. Such rapid cooling, by preventing the build up of populations of immature stages, greatly reduces the selection pressure on insecticides, which is a major factor in the development of resistance. It also enables the immediate exploitation of the negative-temperature effect of pyrethroids (*cf.* Figs 2 and 3).

Rapid cooling plus use of insecticides has the considerable advantage as an IPM procedure of making grain management easier. Because only low amounts of protectant are applied, the grain is available for immediate shipment, if that is required. On the other hand, should the grain have to be held over, it can be further cooled during cooler periods, possibly by use of a mobile unit.

Table 2. Loss of fenitrothion on barley over a 4 month period from January in 2000 t steel bins at Murtoa, Victoria.

Type of Cooling	No. of bins tested	% loss of fenitrothion
None	2	28
Aeration, low flow	4	13
Aeration, high flow	1	3
Cooled aeration	4	3

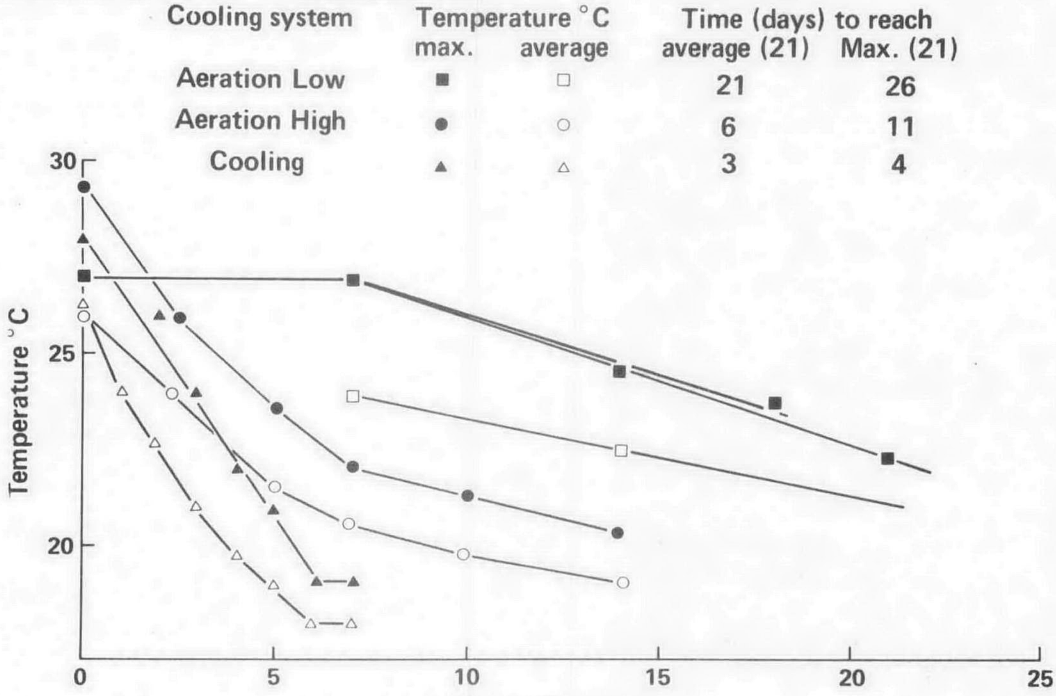

Fig. 3. Average and maximum barley temperatures in 2000 t bins plotted for three cooling systems against days of running.

A theoretical study of such "one-off" cooling by Thorpe and Elder (1980) demonstrated the benefits of such an approach for malathion and methacrifos. Levels of methacrifos required to leave a given deposit after storage for 6 months could be reduced by factors of betweeen 4 and 6, depending on location, relative to those required in uncooled storages.

Application Technology. At time of receival into Australian storages, grain typically contains about 20 insects per tonne (M. Bengston, personal communication) which could be controlled by microgram quantities of protectants, if all of the protectant reached only the target organisms. That fact that we apply gram quantities of pesticides per tonne is indicative of the huge inefficiencies in current application technology. The pest control industry is perhaps the only industry with an efficiency ratio that is measured in parts per million.

The types of processes that could be used to increase the amount of protectant that reaches target organisms are outlined in Fig. 4. Under current practice, pesticide is applied to grain (PG) which is then either directly transferred to insects (PG -> PI) or indirectly via vapour transfer (PG -> PV -> PI) (Desmarchelier, 1977, 1978b). Sometimes protectants are applied in carriers (PC), such as dusts, which can transfer protectants either to insects (PC -> PI) or to grain (PC -> PG), probably via the vapour phase (PC -> PV -> PG).

In the absence of carriers, Quinlan (1972) increased the ratio PV/PG of malathion by introducing it to grain as an 'aerosol,' via forced air flow. Desmarchelier *et al.* 1977 also performed a similar exercise with dichlorvos, and demonstrated that adults of dichlorvos-resistant *R. dominica*, CRD118, were controlled by an application, in the vapour phase, of 0.7 mg kg^{-1}, whereas an application of 18 mg kg^{-1} of dichlorvos as an emulsifiable concentrate to grain killed only 96% of adults from this strain. This increase in efficacy of a factor of more than 25 was shown to be due to an increase in the ratio PV/PG, and it was shown that dichlorvos applied to grain acts predominantly in the vapour phase (i.e. PG -> PV -> PI rather than PG -> PI). As the ratio PV/PG following application of dichlorvos on an emulsifiable concentrate is only approximately 1/10,000 (Desmarchelier, 1977), and as the logarithm of this ratio is proportional to air flow (Desmarchelier *et al.*, 1977), there is an enormous potential

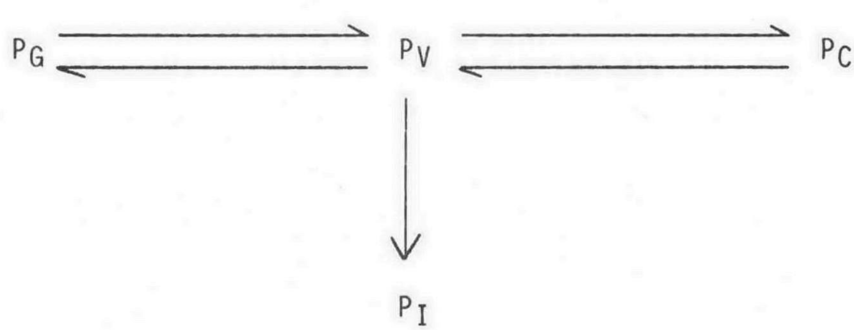

Figure 4. Protectant movement between grain (PG), vapour (PV), carrier (PC) and insects (PI).

to improve application technology and thereby reduce the amount of dichlorvos required to control insects. The system could presumably be integrated with the high air flows used in grain drying.

The idea of using slow release strips as carriers (PC) has potential. However, if persistent chemicals are used in these carriers it would be expected that residue levels on grain would increase with time, because of vapour transfer to grain (PC -> PV -> PG).

A possibility that has not been sufficiently investigated is to apply protectants in carriers (PC) that transfer protectant to insects (PC -> PI) but not to grain. The ability of carriers or supports, possibly impregnated with a liquid phase, to retain protectants has been investigated in so far as it is relevant to gas-liquid chromatography where retention times increase with the ratio PC/PV. Rather than attempt to measure this ratio directly, which would have been difficult, I applied 1 g of a carrier containing 1% of fenitrothion to 1 kg wheat and, after 3 months at 30°C, measured fenitrothion levels in aliquots of the wheat plus carier (PG + PC) and also in aliquots of the wheat after the carrier has been removed by sieving (PG). From these values I then calculated the ratio of the amount of fenitrothion in the carrier to that in the wheat (PC/PG). This ration varied between 0.03 and 20 for the carriers tested (Table 3). The value of 20 for Nuchar-Attaclay means that 20 parts of fenitrothion was removed with the Nuchar-Attaclay by sieving for every part left on the wheat. Thus if fenitrothion were applied to grain as a dust in carriers such as Nuchar-Attaclay, Steecoben, Steecomull or Halloysite (Table 3), the majority of the fenitrothion could subsequently be removed, along with the carrier, by sieving or by other cleaning procedures.

Recoveries on dust and wheat are also recorded in Table 3. The recoveries for dust refer to the measured fenitrothion concentration after 3 months storage of dust in a glass jar at 30°C, expressed as a percentage of the 1% value calculated to have been applied. Thus the recovery of fenitrothion from several of the 'residue-retaining' carriers such as Steecoben (96%) or Halloysite (101%) were comparable to those obtained from the commonly used dust, Talc (91%). On the other hand, recoveries were low on the proteinaceous carriers casein (40%) and gluten (26%).

It should be noted that the addition of 10%, W/W, of vegetable oil to alumina raised the recovery on dust from 59 to 88%, and increased the ratio PC/PG from < 0.05 to 0.45. One can, therefore, exploit the potential of co-additives that perform similar functions to the liquid phases used in glc.

Recoveries from wheat (Table 3) were calculated from the residue levels measured on uncleaned wheat after storage for 3 months at 30°C, expressed as a percentage of the calculated application rate, assuming that the carriers contained the nominal concentration of 1% fenitrothion, W/W. Loss of fenitrothion applied on 'residue-free' carriers was not greater than its loss after application on the standard carrier, Talc.

The success of 'residue-retaining' carriers depends not only on their PC/PG ratio, but also on their ability to transfer insecticide to insects (PC -> PI). Bioassays were accordingly carried out with fenitrothion-

Table 3. Recoveries of fenitrothion on dust, stored in a glass jar, and on dust mixed with wheat, after 3 months storage at 30°C. The ratio of pesticide on carrier to that on the grain, PC/PG, was calculated from levels on sieved and unsieved wheat.

Dust	Additive (10% W/W)	Recoveries on dust (% of applied)	Recoveries on wheat (% of applied)	PC/PG ratio
None	-	-	49	0.02
Chromsorb W	-	72	38	0.03
Alumina	-	59	12	<0.05
Talc	-	91	51	0.13
Talc	OV101	100	46	0.21
Talc	OV210	83	63	0.22
Fire-Clay	-	87	52	0.24
Dryacide	-	75	48	0.33
Alumina	Vegetable oil	88	48	0.45
Pyrophyllite	-	79	53	0.83
Filtercel	-	83	50	0.87
Cellulose	-	82	45	1.4
Casein	-	40	23	2.3
Gluten	-	26	39	2.5
Nuclo H	-	39	79	3.1
Silicar	-	89	51	6.3
Halloysite	-	101	45	8.0
Steecomull	-	89	72	8.0
Steecoben	-	96	55	8.1
Nuchar Attaclay	-	74	45	20

impregnated Talc, as a standard, and fenitrothion-impregnated Nuchar-Attaclay. This later compound was chosen as it had the highest PC/PG ratio of all carriers tested. At 4 mg kg^{-1} of fenitrothion, each dust gave 8 but not 12 weeks complete protection against *S. oryzae*, CLSD, on wheat at 30°C. At 6 mg kg^{-1}, each dust gave 12 weeks complete protection against this species and against *T. castaneum*, CTC4, again on wheat at 30°C.

In the experiments described above, dusts were mixed with wheat at the rate of 1 g kg^{-1}, a level too high for bulk handling. Such large amounts of dust are, however, not necessary: in laboratory experiments 50 mg of rice hull ash containing deltamethrin (0.05 mg) and piperonyl butoxide (2.0 mg) protected 1 kg of wheat against introduced *R. dominica*, CRD2, over the tested period of 3 months at 30°C, in that adult mortality was 100% and no progeny developed. This level of 50 mg of dust per kg of wheat would not greatly incease the current overall dust level.

It is hoped that a chemical company will take up the initiatives outlined above and develop and market 'residue-retaining' dusts. This has already been done to a degree, albeit probably by accident. In a formulation used by farmers in Australia and Papua New Guinea, Folithion C from Bayer Australasia Pty Ltd, 16% of fenitrothion is removed with the carrier by sieving (Desmarchelier and Smith, unpublished results). This figure of 16% could certainly be improved by use of other carriers.

It may be possible to develop residue-free carriers for bulk handling in the form of colloidal gels or wettable powders. The amount of carrier need not be great as it is theoretically possible to deposit 1 particle of size 20 microns per grain of wheat for a total amount of carrier of about 1 g per tonne.

Research to date on carriers has not increased the proportion of insecticide that reaches insects, although it has indicated methods that could be used to reduce the amount that reaches consumers, and by a factor of 20. What is now needed is development of ways to increase the transfer of insecticide from carrier to insect, i.e. the PI/PC ratio. David and Gardiner (1950) indicated several ways in which the efficacy of dusts could be improved. These include attention to particle size, particle shape, and the coaddition of mineral oil, which improved the efficacy of DDT in kaolin against *T. castaneum* and, to a lesser extent, *S. granarius*. David and Gardiner, also found that DDT in abrasive dusts was more toxic to insects than DDT in non-abrasive dusts, that the efficacy of DDT in dusts depended on the method of impregnation and that 'desiccant' dusts remained effective after the addition of oil. Such observations can certainly be taken as promising leads.

Discussion

Several ways of increasing the benefit : risk ratios in the use of insecticides have been demonstrated. The task ahead is to improve these procedures, and to make them manageable.

Once-off cooling coupled with low applications of either labile chemicals or pyrethroids is one procedure capable of immediate implementation, subject to fine tuning with regard to the estimation of the most appropriate application rate for the given circumstances.

At this international forum I would like to raise one topic that I think could greatly assist the world-wide implementation of IPM. That is the publication, possibly in monograph form, of practical data. I have in mind such things as storage design, sealing procedures and methods of protectant application. Such publications would, in my opinion, prevent many errors in practice, and delay the onset of resistance that is one result of the use of poor techniques.

'Residue-retaining' dusts are, I believe, at a stage where commercial development could begin and such formulations could be available for bulk grain in the foreseeable future.

It has been shown that the benefit : risk ratios can be increased by a factor of up to 10 by temperature control, by a factor of up to 20 by use of carriers with a high PC/PG ratio and by an unknown factor of x by use of carriers with a high PI/PC ratio. In combination, the ratio of benefit to risks could be increased by multiplying these factors, to give an 100-1,000 fold increase in the safety factor.

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