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Cover: *Rhyzopertha dominica* on severely damaged wheat.

Pesticides and Humid Tropical Grain Storage Systems

Proceedings of an international seminar
Manila, Philippines, 27–30 May 1985

Editors: **B. R. Champ and E. Highley**

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Foreword

THE concern of this seminar is the integrated use of pesticides to improve the safe storage of cereal grains and other secondary foodstuffs under the difficult environmental conditions of the humid tropics. It is a problem that has been given a high priority in this region and one that requires further research and development. Judging from the number attending this seminar, it is also a problem that has attracted a great deal of interest by those involved directly in grain storage.

Although pest management is only one component of the postproduction systems developed to ensure the safe storage of grain, it is an extremely important component, because insects and other pests are responsible for major losses during storage of grain and other foodstuffs, especially in the warm humid climates of this region.

In previewing the pest management problems identified by the ASEAN delegates attending this meeting, it is clear that most of these are common to the other countries in the region. Any differences that do occur are largely the result of the methods used, or the stage of development of the postharvest storage and handling facilities.

Some of the most important of the problems facing those involved in grain storage and handling, and the action required to resolve them, are as follows:

- the need for better prediction of losses due to insects and other pests infesting cereals and secondary food crops;
- pest buildup under conditions of long-term grain storage, especially paddy and milled rice held as buffer stocks and as strategic reserves;
- development of more effective grain protectants and other conventional and non-conventional fumigants for pest control and disinfestation of bag-stacked and bulk cereals and other grains;
- the need for a more integrated pest management approach involving the strategic use of chemicals as one of the inputs in the total storage system;
- the buildup and spread of insect resistance to commonly used pesticides, involving both cross and multiple resistance and the development of strategies to identify and combat this problem;
- the presence of pesticide residues on stored products and the need to develop procedures to minimise the risk to operators, the grain trade, and consumers generally;
- a better understanding of the benefits and costs of pest management procedures to ensure that the technology recommended is economically viable and socially acceptable;
- the urgent requirement for additional training and manpower development schemes to supply the demand for pest control and grain storage managers.

The research and development needed to tackle these and related problems are discussed at this seminar. The organisers, representing ACIAR, NAPHIRE, and the ASEAN Food Handling Bureau, designed a comprehensive program for this purpose. In addition, the seminar had the broader objectives of reviewing the extent and relevance of the current research activities in the region and identifying any gaps or new approaches required to assist in the resolution of these problems.

Research and development programs under the ASEAN umbrella have pioneered a new era of research cooperation and collaboration in this region. I know of no other part of the world where this sort of cooperation is so evident and has been so successful.

We are seeing in these ASEAN crops postharvest and food handling programs a new experiment in research collaboration and I am very pleased that ACIAR, along with other agencies, is able to play a part.

The seminar is an integral part of this collaboration and it is being held in mid 1985 to allow the participants to confirm the objectives of the research program, to examine the appropriateness and validity of the technology that is being developed, and to ensure that what emerges will be acceptable within the economic and social environments of the region.

In this sense it is an opportunity to pause and reflect on what is being done. Much of the technology being considered is under development in other parts of the world but its adoption and application in humid tropical environments present special problems. It requires a redefinition of the boundary conditions and functional relationships that apply in more temperate environments, to allow for the different crops and conditions under which they are harvested and stored, and the effect of these on the activities of the pests and on the chemicals used to control them.

While there is no doubt that there is a growing body of research talent available within this region to solve these problems, it can also be helpful and time saving if the collective wisdom of others can be co-opted to assist with these problems. Often in the process of adapting research to new problems in unfamiliar situations, new insights develop that can be helpful in improving the resolution of existing problems. It is this prospect of mutual benefit that attracts ACIAR and its collaborators, and others who are present at this meeting. It is a healthy motivation and an excellent basis on which to develop effective collaboration.

No single meeting of this nature can resolve all of the problems that must be tackled in an area such as pest management, but this one will serve to keep the program on course, to validate the objectives and update them as this becomes necessary with the rapid progress in technology, and to match the output against the expectations of the clients. Finally, it will help to achieve that special personal relationship between researchers which is the most important ingredient for good collaboration.

ACIAR would like to extend its thanks to the local organisers, to the paper presenters and to all the participants for making this a stimulating and productive meeting.

J. R. McWilliam
Director
ACIAR

Pest Problems
and
Current Use of Pesticides

Pest Problems and the Use of Pesticides in Grain Storage in Malaysia

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Abstract

Pest problems and pesticide use in various types of grain storages in Malaysia are reviewed. Paddy and milled rice account for most of the grain stored. Both bag and bulk storage are practiced. Various species of insects (*Sitophilus* spp., *Rhyzopertha dominica, Sitotroga cerealella*) are the main pests of stored paddy, while in milled rice rodents and birds are of major concern in addition to two insects species (*Sitophilus oryzae* and *Tribolium castaneum*). Studies revealed losses due to insects estimated at 3–7% in paddy and 5–14% in milled rice. The main use of pesticides at present, particularly insecticides and fumigants, is in milled rice godowns, horizontal, ventilated buildings of 1200–20 000 t capacity. The contact insecticides malathion and lindane are applied as residual sprays and by thermal fogging. For both water-based spraying and fogging, they are diluted to give doses of from 2–5% active ingredient, and are applied at rates of 5 l/100 m^2 and 1 l/1000 m^2, respectively. Fumigation under gas-proof sheeting is carried out using phosphine and, to a lesser extent, methyl bromide. It is suggested that more research needs to be done on ways of improving the choice and application of insecticides in bulk paddy and rice godowns, in the context of an integrated pest management program.

In Malaysia, the locally produced grain of major concern is rice, both in its unhusked form (paddy) and as milled rice. In 1983, the total area under paddy cultivation was 765 000 ha, producing an estimated 1.36 million t. This amount represented 72% of national needs, the balance being imported. The area sown to other grains (maize, pulses) is relatively marginal, with a total of less than 3000 ha (Anon. 1983). However, large quantities of wheat and maize are imported annually. Imports were estimated at 375 000 t and 10 500 t, respectively, in 1983. For various strategic reasons, all these grains have to be stored for a greater or lesser period in various forms and under variable conditions. Grains stored under humid tropical conditions are particularly susceptible to various factors causing deterioration, pest infestation being a major one. Measures to control pests are essential and the use of pesticides is currently the cheapest and most convenient and effective method to disinfest and protect stored grains.

The objectives of this paper are to provide a comprehensive review of storage practices, storage pests and the damage they cause, and pesticide use in stored grains, particularly milled rice in Malaysia. Problems associated with the current use of pesticides are discussed and the research needed to improve their efficacy outlined.

Malaysian Grain Storage System

The grain storage system in Malaysia is best described in terms of the various sectors involved. These are: (i) farm level; (ii) commercial mills/silos; and (iii) government's integrated complexes and godowns.

Farm-level Storage

Farmers normally sell 70–80% of their paddy immediately after harvest, the rest being stored mainly for domestic needs. This usually amounts to less than 1 t, which is stored in jute sacks or in bulk in different types of 'huts.' These are closed wooden structures (1–2 t capacity) with raised wooden floors, built near the farmer's house. The paddy is normally stored up to 6 months until next harvest.

Commercial Mills/Silos

The commercial sector purchases and mills 70% of paddy produced. This paddy is handled by more than 300 private millers throughout the country (Rohani and Shamsudin 1984). Paddy at their

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mills is commonly stored in jute bags in stacks of varying sizes inside the mill-cum-warehouses. The building fabric normally consists of corrugated asbestos or galvanised iron sheeted walls and concrete or wooden floors. The stack is supported by wooden dunnage or a layer of sacks containing paddy husk to avoid moisture seepage. Smaller mills normally keep about 5 t for a period usually less than 3 months (Shamsudin et al. 1981). In larger mills, the capacity ranges from 2000–10 000 t and the paddy may be stored for 3–6 months.

Bulk storage in the commercial sector takes the form of concrete silos which are normally used by grain importers. These silos are located at ports where grains, mainly wheat, maize, and soybeans, are hauled direct from ship by conveyers into silos of 1000–2000 t capacity. Under normal marketing, processing, or stockpile requirements, wheat is usually stored for 1–4 months, and maize for a maximum of 2 months.

Government's Storage Complexes/Godowns

Importation of milled rice is handled solely by the government through its operating agency the National Paddy and Rice Authority (LPN). Rice, which is commonly imported in bags, is transported by lorries direct from the port to rice godowns. There are 44 godowns with capacities ranging from 1200 to 2000 t. These are either owned or leased by LPN. The storages are of the horizontal type, ventilated at the main doors and along the bird mesh near the roof. In newer godowns, the building fabric normally consists of white-painted concrete or cement walls, concrete floors, and corrugated asbestos cement roofing material. Older buildings have the walls and roof made of corrugated galvanised iron or asbestos cement, with concrete or wooden basement floors.

Local or imported rice in 100 kg jute sacks is stacked in varying stack sizes to a height of 20–23 bags equivalent. Locally milled rice is packed in 50 kg polypropylene bags. To minimise problems associated with storage, particularly pests, current policy is to limit the storage period for all consignments, including stockpiled rice, to a maximum of 3 months. However, due to poor demand for certain varieties and grades of rice, storage periods up to 2 years are not uncommon.

Paddy purchased by LPN at its integrated complexes (drying, processing, and storage) is stored in bulk in either open, flat-bottomed rectangular bins, each of 750–1500 t capacity (up to 6 bins/complex) and equipped with aeration facilities, or vertical, concrete silos (closed/open), each of 750 t with total capacity of 6000 t in each complex. The storage period may be from a few weeks to 6–9 months depending on grain purchasing patterns and market demands in each season. Storage in jute sacks is also common in complex premises, particularly during peak harvest period.

Major Storage Pests and Associated Damage

Insects

So far about 40 species of insects have been recorded infesting stored paddy and rice in Malaysia (Singh 1972; Yunus 1980; Lim et al. 1980; Rahim et al. 1983). Insect pests of importance in paddy are *Sitophilus oryzae, Rhyzopertha dominica,* and *Sitotroga cerealella.* Major species encountered in large numbers in rice godowns and complexes are mainly secondary species such as *Tribolium castaneum, Corcyra cephalonica, Ephestia cautella, Oryzaephilus surinamensis,* and *Troctes entomophilus.* However, the species of major concern is the rice weevil, *S. oryzae.* It appears sporadically in the 44 government rice godowns in the country, occurring in abundance whenever it does. The appearance of *S. oryzae* (and subsequent total suppression of the population by fumigation) at a storage site is most likely associated with movement of rice stocks from one godown to another. More recently, the re-emergence and subsequent spread of *Trogoderma granarium* populations in various rice godowns and feedmills has warranted

Table 1. Summary of postharvest losses by insects to stored paddy and milled rice in Malaysia.

Storage method	Storage period (months)	Estimated % loss	Source
Paddy at farm level (in sack; bulk)	3	6.8	Rahim et al. 1983
	6	4.8	
Paddy at Farmers' Co-operative mill (in sack)	6	4.8	Rahim 1984
	9	3.2	
	12	3.0	
Milled rice in commercial stores	Unspecified	5–10	Yunus and Singh 1968
Milled rice in small plastic packings	2–4	7.3–14.2	Rahim and Jamiah 1983

formation of a national committee to monitor and rationalise optimum suppression measures.

There is at present a dearth of information on damage and losses to paddy and rice in large-scale storage (grain silos, storage godowns/complexes) due to pest infestations. Grain loss figures available so far are based on studies of farm-level storage where stocks are marginal. Evaluations of grain damage showed up to 6.8% grain loss due to insects after 3 months (Table 1). Subsequent assessments up to 6 months storage revealed losses of 4.2%, the reduction being mainly attributed to a decline in insect activity (Rahim et al. 1983). Paddy in jute bags of 40 kg each and stored in a cooperative rice mill, revealed a reduction of 3–4.2% in weight attributable to pests, mainly insects (Rahim, unpublished data). These reductions become substantial when translated into losses from paddy stored at LPN complexes or large private mills. Moreover, they do not take account of the qualitative deterioration in terms of lower milling recovery due to the occurrence of 'hot spots.' Losses to insects were estimated to be in the range 5–10% in commercial stores (Yunus and Singh 1968); whilst simulated loss evaluations under room conditions on 0.5 kg packages of rice showed that potential weight losses of 7.3–14.2% are possible after 2–4 months storage of rice infested with rice weevils.

Vertebrate Pests

The most common rodent species infesting stores and houses are *Rattus rattus diardii*, *Rattus exulans*, *Mus musculus*, and *Rattus norvegicus* (Tee et al. 1983). There is little information on the extent of damage caused by rodents in warehouses in Malaysia. However, they are known to damage storage structures and electrical installations. In addition, destruction of sacks and contamination by their faeces and urine can result in complete loss of stored rice. Birds, which are often found in large flocks in rice godowns, can cause excessive spillage and dislodging of stacked rice bags due to their feeding habits. Species that are considered pests are *Passer domesticus*, *Columbia livia*, and *Acridotheres tristis tristis*.

Fungal Species

Evaluations on fungi infesting farm-stored paddy over a 6-month period revealed that 50% of the grains were infected with one or more of 17 species identified (Rahim et al. 1983). Fungi of importance identified were *Calcarisporium sp.*, *Drechslera oryzae*, *Penicillium oxalium*, *Corynascus sepedonium*, *Aspergillus glaucus* group, and *Fusarium semitectum*, which together accounted for 56% of the grains infested. Studies on fungi infecting stored rice (0.5 kg plastic packings) revealed that the genus *Aspergillus* is the predominant group recovered. Fungal infection was found on 26% of the grains over 10 months storage. *A. candidus* was the dominant species, comprising 35% of the total fungi isolated. Other species included *A. aculeatus*, *A. niger*, *A. chevalieri*, *A. fumigatus*, and *A. flaxus* (Masdek 1980).

Chemical Control in Grain Storage

Early records on pest control in Malaysia reveal a variety of toxicants employed mainly in stored rice godowns. Corbett (1931) mentions the use of tuber root extracts for dipping empty rice sacks. Minerals such as lime (5% w/w), anhydrous magnesium oxide, and precipitated chalk (both 1% w/w) were also employed for control of rice weevils. After World War II, 5% DDT was used to dust dunnage, bagged rice, and rice sacks. Fuel oils such as 'Diesoline' were sprayed on the fabric of buildings. A mixture of pyrethrum extract and DDT in an oil base was used to suppress stored product pests, notably moths (Caldwell 1974). The sprayers used ranged from small hand atomisers to power-operated, compressed-air spray guns. In the 1950s, 'Gammexane' insecticide powder was used to disinfest godowns. Later, a spray of 1.3% w/v pyrethrins in heavy oil was recommended for bagged and boxed goods. In 1957, pybuthrin (a mixture of pyrethrins and piperonyl butoxide) was also recommended against flying insects, but was not popular because of its high cost relative to malathion. Dieldrex at 1% a.i. in water was suggested for spraying dunnage and used empty sacks. Singh (1972) reported spraying of stack surfaces at a government rice godown with a mixture of malathion and pybuthrin (568 ml : 284 ml in 4.5 L water). Residual spraying of stack surfaces and fogging with 20% BHC at the rate of 370 mg/L was done once a week. Fumigation with methyl bromide under gas-proof sheets was carried out once or twice a year at a dosage of 10–13 mg/t.

Current Situation

The pesticides currently in use are mainly fumigants and contact insecticides. They are in routine use in government, milled-rice godowns. Little if any chemical control is employed in farm-level storage. Although the benefit-cost factor favours the use of insecticides, the general opinion of farmers is that any artificial control is not necessary as the grain is kept mainly for domestic consumption.

Little information is available on the chemical control measures practiced at large commercial rice mills and warehouses. In most situations, pest problems encountered in these areas are handled by private pest operators (Tee et al. 1983). However, before imported grains found with insect infestations are loaded into commercial silos, they are sprayed with bioresmethrin at an application rate of 12 ppm a.i. The cost of this operation is M$10/t (during May 1985, 2.5 Malaysian dollars = US$1). A mixture of lindane and malathion is used to spray the fabric of warehouses storing wheat flour and stockfood (Tan, personal communication).

In spite of the large quantities of paddy that are stored for varying periods in bulk or bag form in government storage complexes, chemical control is virtually unknown. Several factors contribute to this situation:

- Lack of realisation of the potential losses in revenue in terms of direct weight loss and reduced milling recovery due to insect pest infestations.
- Hidden nature of pest infestations which thereby avoid detection and the attention of the relevant authorities.
- Lack of research information on grain losses.
- Uncertainty about the best pest control approaches and safety procedures in existing storage structures and under the present system.

In view of the prevailing situation, discussions in this paper on the status of pesticide usage in the government sector are confined to that practiced in milled rice godowns.

Insecticides

Emulsifiable formulations of malathion and lindane are currently used for reducing insect populations in rice storages. These contact insecticides are applied either as surface (residual spray) or space treatments (fogging). For surface treatment, malathion is more often used, although a mixture of the two is occasionally applied. The water-based spray is normally targeted on the fabric of the building and on dunnage and empty sacks and is applied at fortnightly intervals. The applicator commonly employed is the motorised knapsack mistblower (10 litres capacity). The application rate recommended is 5 l/100 m^2 at 2% a.i. However, in practice, the toxicant concentration used varies from 2–5% a.i. due to poor control provided by both malathion and lindane either as residual sprays or fogs.

Thermal fogging is employed to disinfest flying insects, the most active of which are *T. castaneum* and *C. cephalonica.* Fogging is done by the use of a 'Swing Fog.' Lindane, and to a lesser extent malathion, is diluted with 'Shellflex' or diesel oil at 2% a.i. per 4 l dilution and fogged at the rate of 100 ml/100 m^3 (20 mg a.i./m^3). Treatment frequency is usually weekly, but this can be increased whenever infestations are deemed heavy. Fogging or residual spraying is usually carried out between 1600–1700 hours, which is normally about the time insects start flying from stacks. The fog generated generally lasts 15–20 min within the confines of the godown, after which it has completely dispersed. Spraying or fogging is usually carried out on different days in most rice godowns, but in some cases, insecticide is applied by both methods on the one day, fogging in early morning at 0600–0800 hours when moths, especially *Corcyra cephalonica,* are usually active, and mist spraying in the evening, or vice versa.

The cost of chemicals for residual treatment at current application rates is M$1.20/100 m^2 for malathion and M$1.80/100 m^2 for lindane, which

Table 2. Comparative costs for surface treatment by residual spraying.

Insecticide	Formulation[a]	Application rate mg/m^2	Cost per 100 m^2 (M$)
Permethrin	w.p.	100	8.0
Bioresmethrin	e.c.	100	10.0
Deltamethrin	w.p.	50	9.0
Chlorpyrifos-methyl	e.c.	1000	9.0
Fenitrothion	e.c.	1000	3.5
Pirimiphos-methyl	w.p.	500	1.5[b]
Carbaryl	w.p.	1000	3.0[b]
Lindane	e.c.	1000	1.8
Malathion	e.c.	1000	1.2

[a] Wettable powder or emulsifiable concentrate.
[b] Estimate.

is cheaper than with alternative insecticides (Table 2). Fogging costs are M$0.39/m^3, including the cost of the 'Shellflex' diluent.

Contact insecticides are used in bagged milled rice godowns solely to reduce insect population pressure on the rice stacks. Several inadequacies are observable under present practices:

(i) *Insecticides.* There is a need for new insecticides, since widespread and continuous use of malathion and lindane over the years has resulted in the development of insecticide resistance (Champ and Dyte 1977). This is reflected in reports of their poor efficacy by pest control operators in rice godowns.

(ii) *Formulations.* Wettable powder formulations should be used whenever possible because of the filtration effect. Emulsified insecticides tend to be absorbed into fabrics of bags, and brick or cement walls, thereby limiting availability for controlling the insects.

(iii) *Pesticide application technique.* The coverage of the insecticide spray is often observed to be incomplete mainly because the spray swathe and distance covered by the knapsack sprayer is limited, leaving large sections of the godown's structure and fabric untreated. The upper portions of the walls and roofs, and the upper layers of the rice stacks are the most neglected areas. The correct choice of sprayer is critical. The machine must be able to provide good coverage over the entire targeted space or surface with minimal operational hazard.

(iv) *Management aspects.* Regular consultations, meetings, and training are essential among the staff involved in pest control operations. This would enhance technical know-how and management skills on the part of both supervisory staff and operators. Better regulation and monitoring of pest control operations would enhance performance and productivity.

Fumigation

This method of pest control is currently the most reliable for controlling pests of stored rice. It is particularly useful for disinfesting rice stacks of insects. The rice stacks, which also serve as hiding places for rodents, are fumigated with either phosphine gas or methyl bromide under gas-proof sheets, although the former is more popular since it is more convenient to apply. The application rate for phosphine is 2 g/t and for methyl bromide 28–32 g/t, for exposure periods of 72 and 24 hours, respectively. Fumigation is cheap: the fumigant alone is currently priced at M$0.40/t and M$0.36–0.42/t for aluminium phosphide and methyl bromide, respectively.

Fumigation does not provide residual protection to the rice stacks. Therefore, it is essential to reduce insect reinfestation from sources within or outside the fumigated stack(s) or godown. In addition to the use of contact insecticides to reduce this threat, certain management practices are desirable, such as ensuring all stacks within a godown or godown complex are *fumigated at the one time* whenever possible. Current practice is to fumigate stacks in batches, staggered over a few days or weeks. The yet-to-be treated or reinfested stacks often serve as primary sources of infestation to newly fumigated stacks. Though sometimes unavoidable, this practice should be avoided, in order to optimise benefits from fumigation.

Research Needs

It is envisaged that efforts to reduce losses in stored grains will continue to depend on the use of pesticides, given the need for a fast, reliable, and cheap means of pest control. However, pesticides must be employed in the context of overall pest control strategies, i.e. within the framework of an integrated pest management system (IPM). The immediate research priority is to investigate various aspects of the use of pesticides in the existing storage system. Long-term research needs may encompass areas pertaining to other components of IPM. Pesticides and other pertinent areas that need concerted research are briefly discussed in this final section.

1. Pesticides and Application Techniques

- *Choice of insecticide(s):* screening and verification of insecticides for residual grain treatment in bulk paddy. There is also a need for new insecticides to replace malathion and lindane as surface and space treatments in milled rice. Attention should also be given to the use of avicides and rodenticides.
- *Formulations:* emphasis on suitable contact insecticide formulations for specific application in rice godowns. There is also a need to explore innovative insecticide formulations that provide improved dispensing systems for both milled rice and paddy, e.g. controlled-release formulations.

- *Applicators:* evaluation of suitable insecticide applicator(s) that improve coverage and are adaptable to varied formulations and easy application.

2. Pest Monitoring Systems

- *To develop insect trapping techniques* (physical, mechanical, chemical) for monitoring effectiveness of control measures and to detect insect infestations.
- *Establishing 'treatment threshold'* based on trapping counts to guide pest control decisions (to fumigate, or apply space or surface treatments) in rice storage. Prevailing warehouse design allows continuous presence/reinfestation. Treatment threshold will space chemical treatments. Chemical control measures are to be taken only when the insect population index warrants treatment (expected damage = cost of control).
- *Ecological and biological studies* of pests and their environment are essential to improve understanding of insect behaviour and facilitate establishment of the treatment threshold.
- *Grain loss assessment studies* are essential for justifying control measures and formulating the treatment threshold.

3. Non-chemical Pest Control Methods

- Use of inert gases or airtight storage.
- Heat treatment methods (e.g. fluidised-bed, microwave, etc.).
- Use of ionising radiation.
- Physical barriers (insect-proofing godowns or rice stacks).

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Pest Problems and the Use of Pesticides in Grain Storage in the Philippines

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Abstract

Pest problems and the use of pesticides in grain storage in the Philippines are reviewed. The major pests attacking stored rice and maize are *Rhyzopertha dominica* (Fabricius), *Sitophilus* spp., *Oryzaephilus surinamensis* (L.), *Tribolium castaneum* (Herbst), and *Cryptolestes* spp. The lesser grain borer (*R. dominica*) is the predominant pest species damaging paddy, while *Sitophilus zeamais* is the main pest of stored maize. Estimates of weight losses due to insects in unprotected stored grain are 34% for maize stored for 8 months and 2.5% for milled rice stored for 3 months. Resistance to pesticides is a problem. A survey revealed that resistance to malathion in *T. castaneum* occurs nationwide. Cross-resistance to pirimiphos-methyl was also observed in some strains. Two types of resistance were also encountered in *R. dominica*: malathion-specific and cross-resistance to pirimiphos-methyl. *S. zeamais* was the dominant weevil in rice and the species remained susceptible to malathion and pirimiphos-methyl. The paper concludes with a listing of suggested priorities for research and development work on the use of pesticides to protect grains stored under humid tropical conditions.

OVER the years, the Philippine government has devoted much of its resources to raise food-productivity levels by embarking on various commodity production programs. These are designed not only to meet the growing requirements of its 54 million people but also to generate foreign exchange through export of surplus produce and at the same time save foreign exchange by reducing importations.

Recently, the Intensified Rice Production Program was launched to enable the Philippines to maintain a buffer stock of 45 days' supply. The government has also ventured into increased production of yellow corn through its Expanded Yellow Corn Production Assistance Program. Meanwhile, the National Soybeans Production Program has also been initiated to increase local production of soybeans and effect an import-free industry.

Other crops such as peanuts, mungbeans, cassava, and sweet potato are gaining attention from the government because they constitute a significant portion of the Filipino people's diet and are excellent sources of high-protein and energy food. Studies show that substituting cassava meal for half of the yellow corn imported annually in poultry ration alone could net a foreign currency saving of about US$1.4 million. Rootcrops are further utilised in the manufacture of starch and industrial alcohol, and as feed for livestock. Up to 10% cassava flour can be substituted for wheat flour in bread making with minimal changes in the quality of the product.

The intensification of crop production has led to many problems in the postharvest phase, of which pest infestation in storage has been a major concern. The situation is further aggravated by the growing attention devoted to the maintenance of buffer stocks to continuously provide food security for the country. Pest problems have concomitantly increased with the increase in the stockpile and longer duration of storage. Thus, in order to preserve the extra quantity of produce held in storage, as well as its quality, pest control technology must be continuously improved.

The Magnitude of Losses to Pests

It is estimated that maize loses about 34% of its weight when it is stored for eight months without protection from insects (Caliboso 1977). Based on

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the 1983 procurement of the National Food Authority (NFA), losses could be expected of about 40.8 million kg of maize valued at US$8.8 million if appropriate pest control measures were not adequately applied. This volume could easily fill about 22.5% of the country's import requirement for maize.[1] In milled rice, where the government must stockpile 783 million kg to constitute 45 days' consumption requirement, insect infestation that is left unchecked for three months can result in a loss of about US$6.2 million or 18.5 million kg.

A recent survey of government storages conducted by the National Post Harvest Institute for Research and Extension (NAPHIRE) revealed that under present conditions where warehouse designs are somewhat improved and chemicals are used to a certain extent to control insect infestations, signficant losses to insects still occur. Paddy stored for 7 months lost 5% of its weight, equivalent to 24.55 million kg valued at US$2.46 million.

Maize, on the other hand, lost 11 % of its weight in eight months storage. This is estimated to be around 13.21 million kg based on the volume of maize procured by NFA in 1983, with a value of US$1.06 million. Of the volume handled by the private sector, estimates of weight losses run to about 2%, at an average storage period of 74 days. With 61 million kg held by private processors, traders, and wholesalers, physical losses can run to 1.22 million kg, valued at US$98 278.

Rodents, likewise, present a serious problem in the preservation of stored grains. Sayaboc et al. (1984) reported that there are, on average about 111 rodents in a single warehouse. This population consumes around 2.6 kg of grain in a day and spills 27 kg more while feeding. Considering that there are 10 223 grain warehouses in the country, a daily loss between 39 000 to 312 000 kg can be realised.

Meanwhile, the dearth of information on the extent of damage and losses wrought by bird pests moved NAPHIRE to work on an initial study which shows that a single *Passer montanus* (Philippine weaver) consumes about 5.5 g of grain per day. Warehouses visited by the NAPHIRE research team sustained 50 to 400 birds each, so daily losses could range from 0.28 to 2.2 kg in each store.

Pest Complexes, Biology, and Ecology

Insects and Mites

The first systematic survey conducted in commercial storages for an inventory of major and minor insect pests of stored grains was undertaken by Labadan in 1957. Twelve species of beetles and four species of moths were recorded infesting stored grains. At present, a total of 43 species of coleopterous and lepidopterous insects and 16 species of mites have been recorded associated with stored grains in the Philippines. The various species of insects and mites occurring in different stored commodities are listed in Tables 1 to 4. These are based on the lists compiled by Capco (1957) and Baltazar (1968) and studies by Viado and Labadan (1960), Camarao (1971), Caliboso (1977), Gonzales (1979), Sabio et al. (1984), Tiongson (1984), and Sayaboc and Amoranto (1984).

The major insect pests of stored grains are *Rhyzopertha dominica, Sitophilus* spp., *Tribolium castaneum, Callosobruchus* spp., *Oryzaephilus surinamensis, Cryptolestes* spp., *Lophocateres pusillus, Tenebroides mauritanicus, Alphitobius* spp., *Latheticus oryzae, Palorus* spp., *Corcyra cephalonica, Sitotroga cerealella, Plodia interpunctella, Ephestia* spp., and *Thorictodes heydeni.*

Paddy, milled rice, and maize are the principal commodities stored. The grain is usually held in jute or plastic bags of 50 kg each. NFA, however, stores 5–10% of its stocks in bulk.

The lesser grain borer, *R. dominica,* has gained primary importance in the safe storage of rough and milled rice. On the other hand, the *Sitophilus* complex remains the most destructive and predominant pest of maize. *Callosobruchus maculatus* and *C. chinensis,* the bean weevils, are the most destructive species attacking stored mungbeans and soybeans.

Sitophilus zeamais is more predominant than *S. oryzae* as verified recently by Sayaboc and Amoranto (1984). Of the 38 strains collected by Sayaboc and Amoranto from 38 provinces, *S. oryzae* was found in only two provinces, namely Isabela and Batangas. A separate survey by Sabio of Metro Manila warehouses, revealed that *S. oryzae* also occurs in Manila, but is less abundant than *S. zeamais.* Rejesus found that of 50 samples examined from 17 provinces, 39 strains were *S. zeamais. Sitophilus oryzae* co-existed with *S. zeamais* in Batangas, Camarines Norte, Albay,

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[1] 1972–1984 Historical Summary of Importations, National Food Authority.

Table 1. Coleoptera recorded in stored grains in the Philippines

Species	Paddy	Milled rice	Rice bran	Maize	Sorghum	Soybean	Soybean meal	Wheat flour	Wheat	Mungbean
Anobiidae										
Lasioderma serricorne	x	x		x						
Cigarette beetle										
Anthribidae										
Araecerus fasciculatus				x						
Coffee bean weevil										
Bostrichidae										
Rhyzopertha dominica[a]	x	x	x	x	x	x	x	x		x
Lesser grain borer										
Dinoderus sp.				x						
Bamboo borer										
Bruchidae										
Callosobruchus maculatus[a]						x	x			x
Callosobruchus chinensis[a]						x	x			x
Bean or cowpea weevil										
Cleridae										
Necrobia rufipes			x	x						
Red-legged ham beetle										
Cucujidae										
Cathartus quadricollis				x						
Square-necked grain beetle										
Cryptolestes ferrugineus[a]	x	x	x	x	x	x	x			x
Rusty grain beetle										
Cryptolestes pusillus[a]	x	x	x	x	x	x	x			x
Flat-grain beetle										
Curculionidae										
Sitophilus oryzae[a]	x	x		x	x	x	x	x	x	x
Rice weevil										
Sitophilus zeamais[a]	x	x		x	x	x	x	x		x
Maize weevil										
Cryptophagidae										
Pharaxonothi kirschi				x						
Mexican grain beetle										
Dermestidae										
Attagenus piceus				x						
Black carpet beetle										
Dermestes ater				x						
Black larder beetle										
Dermestes maculatus				x						
Hide or leather beetle										
Trogoderma anthrenoides									x	
Larger carpet beetle										
Mycetophagidae										
Typhaea stercorea				x						
Hairy fungus beetle										
Nitudilidae										
Carpophilus dimidiatus		x		x	x					
Corn sap beetle										
Carpophilus pilosellus		x		x						
Dried fruit beetle										
Trogositidae										
Lophocateres pusillus[a]	x	x			x	x				x
Siamese grain beetle										
Tenebroides mauritanicus[a]	x	x	x	x	x		x			
Cadelle										

Table 1. (cont.) Coleoptera recorded in stored grains in the Philippines

Species	Paddy	Milled rice	Rice bran	Maize	Sor-ghum	Soy-bean	Soy-bean meal	Wheat flour	Wheat	Mung-bean
Silvanidae										
Oryzaephilus surinamensis[a] Saw-toothed grain beetle	x	x	x	x	x	x	x			
Ahasverus advena Foreign grain beetle		x		x						
Tenebroionidae										
Alphitobius diaperinus[a] Lesser meal worm		x	x	x			x		x	
Alphitobius laevigatus[a]		x		x				x		
Alphitobius piceus Black fungus beetle		x								
Coelopalorus foveicoliis Black beetle				x						
Gnathocerus maxillosus Slender horned flour beetle		x		x				x		
Latheticus oryzae[a] Long-headed flour beetle	x	x	x	x						
Palorus ratzeburgii[a] Small-eyed flour beetle		x		x						
Palorus subdepressus[a] Depressed flour beetle	x	x	x	x	x					
Tribolium castaneum[a] Red flour beetle	x	x	x	x	x	x	x	x	x	x
Thorictidae										
Thorictodes heydeni		x		x		x	x			

[a] Pest of major importance.

Table 2. Lepidoptera recorded in stored grain and its by-products in the Philippines

Species	Paddy	Milled rice	Rice bran	Maize	Sor-ghum	Soy-bean	Soy-bean meal	Mung-bean	Wheat
Galeriidae									
Corcyra cephalonica Rice moth[a]	x	x	x	x					
Gelechiidae									
Sitotroga cerealella Angoumois grain moth[a]	x			x					x
Pyralidae									
Anagasta kuhniella Mediterranean flour moth				x					
Ephestia cautella Fig or tropical warehouse moth				x					
Ephestia elutella Tobacco moth[a]	x	x		x					
Plodia interpunctella Indian meal moth[a]	x	x	x	x	x	x	x	x	
Pyralis farinalis Meal snout moth				x					
Pyraustidae									
Doloessa viridiz Green rice moth		x		x	x				

[a] Pest of major importance

Table 3. Miscellaneous insects recorded from stored grain and its by-products in the Philippines.

Order, Family	Paddy	Milled Rice	Maize	Sorghum	Soybean	Soybean meal	Rice bran	Wheat
Blattodea								
Blattidae			x				x	
Hemiptera								
Anthocoridae	x	x					x	
Hymenoptera								
Formicidae			x					
Unidentified parasitic wasps	x	x	x	x	x	x		x
Psocoptera		x	x		x			
Thysanura		x						

Table 4. Mites associated with stored products in the Philippines (Sabio 1983; Sabio et al. 1984).

Species	Paddy	Milled rice	Milled rice sweepings	Rice shorts	Regular rice bran	Rice bran (tiki-tiki)	Yellow corn	White corn-grits	Maize bran	Tahop	Sorghum
Acariformes											
Acaridae											
Aleuroglyphus ovatus[a]						x			x		
Caloglyphus berlesei[a]											
Lardoglyphus konoi[a]											
Glycyphagidae											
Aeroglyphus sp.[a]					x						
Suidasia pontifica[a]	x	x	x	x	x	x	x		x		
Cunaxidae											
Cunaxa sp.[a]											
Unidentified sp.[b]											
Cheyletidae											
Acaropsella sp.[b]											
Acaropsis sp.[b]											
Cheletomorpha Lepidoptorum[b]											
Cheyletus malaccensis		x	x	x		x	x	x			x

Table 4A. Mites associated with stored products in the Philippines (Sabio 1983; Sabio et al. 1984).

Species	Mungbean	Local soybean	Imported Soybean	Soybean meal	Mixed bran pollard	Soybean spillage	Flour	Flour Spillage	Peanut	Fish meal
Acariformes										
Acaridae										
Aleuroglyphus ovatus[a]										
Caloglyphus berlesei[a]									x	x
Lardoglyphus konoi[a]										x
Glycyphagidae										
Aeroglyphus sp.[a]									x	
Suidasia pontifica[a]					x				x	

Table 4A. (cont.) Mites associated with stored products in the Philippines (Sabio 1983; Sabio et al. 1984).

Species	Mung-bean	Local soy-bean	Import-ed Soy-bean	Soy-bean meal	Mixed bran pol-lard	Soy-bean spill-age	Flour	Flour Spill-age	Pea-nut	Fish meal
Cunaxidae										
Cunaxa sp.[b]							x	x		
Unidentified sp.[b]		x								
Cheyletidae										
Acaropsella sp.[b]		x								
Acaropsis sp.[b]						x				
Cheletomorpha lepidoptorum									x	
Cheyletus malaccensis	x	x		x		x	x	x		
Stigmaeidae										
Agistemus sp.[b]		x								
Tarsonemidae										
Tarsonemus fusarii										
Tydeidae										
Tydeus sp.		x								
Pronematus sp.				x						
Parasitiformes										
Ascidae										
Blattisocius sp.[b]	x		x							
Lasioseius sp.										
Uropodidae										
Unidentified sp.	x									

[a] Pests of economic importance.
[b] Predators.

Negros Oriental and Occidental, Leyte, Misamis Occidental, and Zamboanga del Sur. Both authors observed that in mixed populations, *S. zeamais* outnumbered *S. oryzae* (by a ratio of 3:1 according to Sayaboc and Amoranto). This phenomenon occurred even in populations gathered from paddy and milled rice samples. This further supports the conclusion that *S. zeamais* has replaced *S. oryzae* as a major pest of rice and maize.

The above finding can be explained by the fact that *S. zeamais* is 1.5x more fecund than *S. oryzae.* Santhoy and Morallo-Rejesus (1975) likewise observed that *S. zeamais* is more destructive than *S. oryzae* on maize and sorghum. Champ and Dyte (1976) further noted that *S. zeamais* is a pest in warm, moist climates with a distribution that is probably associated with maize production. This is because the maize weevil requires moister grain, as in ripening maize. The fact that oviposition of this species is inhibited on commodities of less than 12.5% moisture content strongly suggests that maize is stored locally at a higher moisture content. A study by Tiongson (1984) of maize deterioration at off-farm storages showed that maize is received and stored for 3–20 days by local traders at moisture levels of 14.4 to 15.5%. At the wholesaler's level, where maize is stored from 14–180 days, maize is held at an average moisture content of 13%.

The susceptibility of maize to damage by insect pests is evidenced by the value of the Economic Threshold Level (ETL) established by Sabio et al. (1984) on maize. At 2.94 months of storage, maize must be either fumigated or diposed of to prevent damage from attaining the Economic Injury Level (EIL), determined at 3.1 months in storage. In comparison, the ETL and EIL of rough rice were established at 5.17 and 7.6 months of storage, respectively.

Rhyzopertha dominica and *S. zeamais* multiply more rapidly on sorghum than on maize and milled or rough rice. However, *R. dominica* populations build up more quickly than those of *S. zeamais* on milled and rough rice (Morallo-Rejesus and Javier 1979). *Sitophilus* spp. and *R. dominica* initially attack both maize and sorghum in the field before harvest (Carino and Morallo-Rejesus 1976).

Of the numerous species of insect pests found in stored grains, only two have been the subject of biological studies, i.e. *S. oryzae* and *Doloessa viridis* (Arida 1974; Baldos 1979). The ecological succession of insects affecting stored seeds of upland crops was the subject of investigation by Camarao in 1971.

Data on stored product losses due to insect infestation are limited to a few laboratory (Viado and Labadan 1958; Morallo-Rejesus and Javier 1979) and two warehouse assessments (Caliboso 1977; Sabio et al. 1984).

Rodents

It was observed that private warehouses have the highest rodent populations (average of 223 per warehouse) with a daily consumption of 6.4 kg, four times that of modern government warehouses (see Tables 5 and 6). However, statistical analysis suggested that the levels of populations and their consumption do not differ significantly among these types of warehouses. This indicates that the levels of damage and loss due to rodents are comparable in all types of warehouses regardless of materials used in the construction of warehouses. Some provisions for rat-proofing in government warehouses did not significantly reduce infestation and subsequent physical losses, perhaps because they were not properly maintained.

Table 5. Classification of warehouse sites included in the field survey (Sayaboc et al. 1984).

Type	Ownership/ Management	Percentage concrete	Percentage GI sheet	Other features
I	government	80–100	—	Elevated floors, hanging stairs, equipped with centre weights, screened windows, gutters, and drainage
II	government	60	40	Floor at ground level, screened windows, gutters and drainage
IIIA	government-leased	100	—	Conventional design, no provision for rodent exclusion
IIIB	private	100	—	,,
IV	private	—	100	,,

Table 6. Average rodent population per warehouse according to type/design and daily consumption of paddy (Sayaboc et al. 1984).

Type of warehouse	Rodent population[a]	Consumption[a] (kg)
Type I NFA-GID	57	1.6
Type II NFA-GID	69	1.9
Type IIIA (NFA-leased)	89	2.5
Type IIIB (private)	119	3.4
Type IV (private)	223	6.4

[a] Non-significant at 1 and 5% levels.

It was found that 80% of the rodent populations consisted of Norway rats, *Rattus norvegicus* and 20% Philippine ricefield rats, *Rattus rattus mindanensis*.

The stomach contents of trapped rodents from modern government warehouses (Types I and II) were observed to have 99.5% grain component, while those collected from private warehouses (Types III and IV) contained 90% grains. This indicates that rats in government warehouses depend solely on stored grains for food. This further suggests that government warehouses have stable, local rodent populations or 'residents' while private godowns have 'immigrants' or 'transients'. The fairly closed design of modern government warehouses restricts movement into and out of them. Resident rats therefore depend solely on abundant food being stored for longer periods.

On the other hand, rats in private warehouses are able to move freely in and out of the loosely constructed warehouses and can thus exploit other food sources (such as feeds, grasses, fruits, and coconut). However, paddy remains their main food item.

Previous studies by the National Crop Protection Center (NCPC) on the Philippine ricefield rat revealed that the annual production of one female rat under field conditions averaged 32 offspring. By comparison, the same rat species has a higher annual production of around 35.21 individuals in storages. On the other hand, the female Norway rat produces 37.43 individuals annually. This indicates that the rodents infesting warehouses are more fecund and are therefore potentially more destructive than those found in the field.

At a pest density of 62 rats per day, sustained baiting or some other appropriate control strategy should be applied. In terms of spilled grain, control measures should be initiated when about 9 kg of spillage are observed. With a moderately sized warehouse (capacity of 4000 bags), the cost of protecting one bag of paddy from rodents over six months is around US$0.07, based on the 1984 price of the rodenticide warfarin.

Birds

The only bird pest species encountered in local warehouses surveyed by Genito et al. (1982) was *Passer montanus*, the Philippine weaver. In cage and field experiments, these birds were observed to consume the equivalent in grain of 30% of their body weight per day. The same study also revealed that private stores have higher bird populations than government warehouses. This is because NFA warehouses are better designed and therefore partly exclude birds. Grain comprised 91-97% of the gizzard contents of speciments collected from NFA and private stores.

Pesticide Use and Residues

Chemical screening tests have been conducted locally by sack treatment or dipping unhusked maize ears in DDT, malathion, DDVP, thiodan, methyl-parathion, carbaryl, and lindane for protection against insect pests of corn (Viado and Labadan 1958; Sanchez and Calora 1967; Calora and Derino 1964; Sanchez et al. 1970). Most of the recent tests on new compounds have been done by Morallo-Rejesus and associates. The toxicities of new compounds as compared with malathion were determined by topical or filter impregnation method using adults of maize weevil and red flour beetle as test insects.

The results of evaluations on grain (mainly on maize) showed pirimiphos-methyl, chlorpyrifos-methyl, synergised pyrethrins, and tetrachlorvinphos-methyl to be more effective than malathion (Cariño and Morallo-Rejesus 1976; Damasco-Verbo and Morallo-Rejesus 1975; Morallo-Rejesus 1973a, 1978a, b; Morallo-Rejesus and Cariño 1976; Morallo-Rejesus and Eroles 1976; Morallo-Rejesus and Javier 1978a, b; Morallo-Rejesus and Nerona 1973). The effectiveness of the insecticides varied with the method of application, formulation and concentration of the insecticides, insect species, grain species and type and duration of storage (Morallo-Rejesus 1978a).

A few residue analyses were made in the Philippines on pirimiphos-methyl, tetrachlorvinphos, and malathion in maize (Morallo-Rejesus 1975), and on malathion and pirimiphos-methyl in rice (Magallona and Celino 1977).

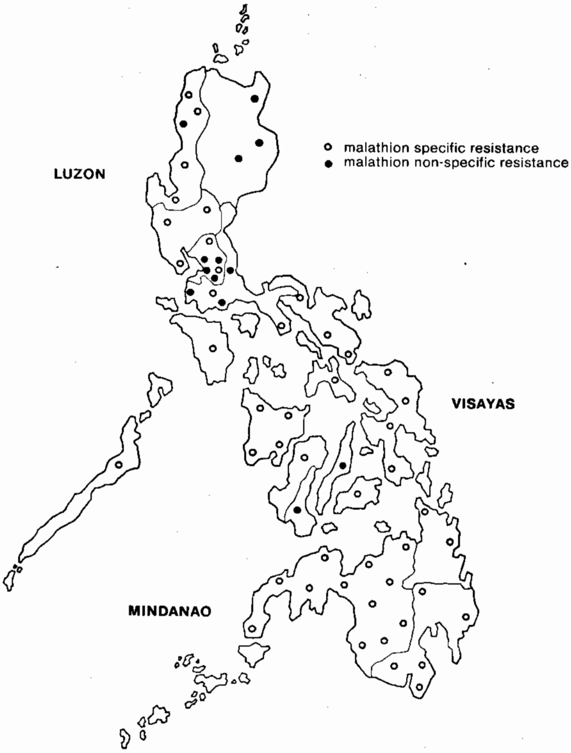

Fig. 1. Distribution of malathion-resistant strain in *Tribolium castaneum*.

Among the various sectors of the local grain industry, only the government and large food and feed processors (such as feed millers, flour millers, and seed companies) practice pest control. Virtually no measures are undertaken in village rice and maize mills to control pests because insects are not regarded as a serious problem in the preservation of these commodities. This is due to the fact that there is a fast turnover of stocks in private mills. Paddy is usually stored for one to two months in raw form. Milling only commences when there is an assured market for the milled rice.

For sectors which apply measures to control pests, pest suppression has for a long time been synonymous with the use of pesticides. Chemical control has been the cornerstone of NFA's pest control program. Similarly, pesticides play a major role in checking pest populations in food and feed processing plants. Sanitation and other basic storage principles, if at all applied, are relegated to supplementary or minor roles. Annually, NFA spends some US$53 045 to protect 300 million kg

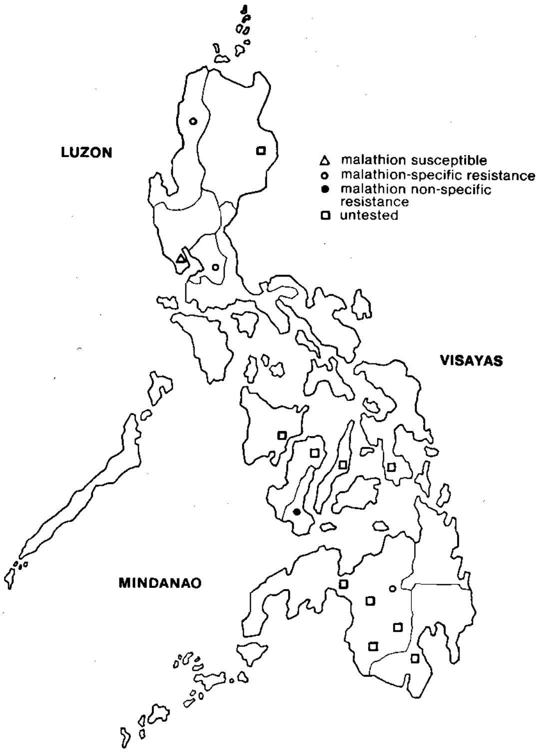

Fig. 2. Occurrence of malathion-resistant strain in *Rhyzopertha dominica.*

of commodities from insects and rodents alone. Of the amount spent for pesticides, fumigants consume 67%, insecticides constitute about 32%, and rodenticides 1%. The only two fumigants used are phosphine, which accounts for 95% of the expenditure on these materials, and methyl bromide.

The insecticides in current usage are malathion, dichlorvos, pirimiphos-methyl, bioresmethrin, permethrin, fenitrothion, and tetrachlorvinphos. These are mainly applied in the form of sprays for stacks and structures, thermal fogs, and non-thermal fogs or aerosols (ULV).

Insect Resistance to Pesticides

The occurrence of resistance to pesticides in stored grain insects in the Philippines was first detected in *Sitophilus* spp., *R dominica,* and *T. castaneum* by Champ and Dyte (1976). Almost all strains of the aforementioned species were resistant to lindane. Malathion resistance, however, occurred only in *R. dominica* and *T. castaneum.* The malathion-resistant strains exhibited a malathion-specific type of resistance.

The results of the local surveys of insecticide resistance (Morallo-Rejesus 1973b; Morallo-Rejesus and Javier 1978d; Morallo-Rejesus and Virrey 1978a, b) indicated that *Sitophilus* spp., and *R. dominica* are resistant to DDT, lindane, and carbaryl, but susceptible to malathion.

The current investigation of pest resistance to insecticides being carried out by NAPHIRE in collaboration with the Queensland Department of Primary Industries (QDPI) and supported by the Australian Centre for International Agricultural Research (ACIAR), revealed the development of a non-specific type of resistance to malathion in *T. castaneum* and *R. dominica.* Twenty-two percent, or 13 of 60 strains of *T. castaneum* tested demonstrated cross-resistance to pirimiphos-methyl. Malathion non-specific resistance was also detected in one strain of *R. dominica.* It is interesting to note that strains showing cross resistance were found in places where other types of insecticides are readily available in the local market.

Varietal Resistance to Insects

The attractiveness of finding resistant varieties that can tolerate pest damage cannot be overemphasised. A resistant variety will need less chemical to protect it from pests.

Some maize and sorghum varieties have been found to be resistant to *Sitophilus* spp., (Bernardo 1971, 1972; Bernabe-Adalla and Bernardo 1976a, b). In mungbean, Malit (1973) and Epino (1980) examined several accession lines of mungbean for susceptibility or resistance to the bean weevil *(C. chinensis).* Resistance in maize, sorghum, and mungbean varieties is due to non-preference for oviposition sites and antibiosis.

Biological Control

The use of insect growth regulators as an alternative method of pest control has been studied in maize and rice. Dimilin (chitin synthesis inhibitor), methoprene and Bowers JH (synthetic juvenile hormones), and Attacus JH isolated by Paguia and Morallo-Rejesus (1977), were found to be effective against *C. cephalonica, P. interpunctella, Sitophilus spp.,* and *R. dominica* (Fajardo and Morallo-Rejesus 1980; Morallo-Rejesus and Javier 1978b).

No studies have so far been made on the use of parasites, predators, and microorganisms for the control of insects.

Other Methods of Control

Gamma Radiation

The effects of gamma radiation on the survival of *Sitophilus* spp., *O. surinamensis,* and *L. serricorne* have been reported (Viado and Manoto 1963; Manoto 1969; Rejesus and Lapis 1975; Lapis et al. 1975).

Inert Dusts

Viado and Labadan (1959) tested three inert dusts at rates of 5 and 10 g/kg of shelled maize for the control of insects. Maquiling clay or 'white earth' was more effective than rice hull ash and sugar cane bagasse ash. The rice hull ash was more effective than the sugarcane bagasse ash.

Research and Development Needs

The following are essentially the collective concerns and recommendations of a group of experts convened by NAPHIRE in an in-house workshop addressed to the development of an Insect Pest Management Research, Training and Extension Program to be pursued primarily by the Institute. Represented were the ASEAN Crops Post-Harvest Programme, National Food Authority, National Crop Protection Center, and NAPHIRE.

Research

1. Inadequate information and understanding of major pests and other important insect species

a. Generation of unified information on the biology and ecology of other important pests which are frequently abundant but have not been studied in stored grains. These are *Cryptolestes* spp., *Oryzaephilus surinamensis, Lophocateres pusillus, Tenebroides mauritanicus, Latheticus oryzae, Palorus* spp., *Corcyra cephalonica,* and *Sitotroga cerealella.* An investigation of the nature and extent of their damage to other less-studied commodities (such as sorghum, mungbean, soybeans), their ability to compete or interact with other major pests, and the implications of their potential rise to predominant pest status must be pursued.

b. Periodic monitoring of pest occurence, relative importance of each species, their distribution in relation to pest control, and warehouse management practices. This will update existing knowledge on pest complexes, provide surveillance and thus prediction of pest outbreaks, resurgence, etc. that will in turn serve as a database for modifying pest control strategies or establishing research priorities.

c. Regular field assessment of actual losses arising from pest infestations will also monitor progress, and indicate success or failure from adopting certain pest control strategies. A related issue here, in the case of loss assessment in paddy, is the determination of dry weight loss of usable milled rice from assessment of dry weight loss of rough rice. This could be estimated after standardised milling of damaged and sound samples. The information from the foregoing exercise will provide a basis for further improvement of the pest management system being employed.

d. Resistance profile of other economically important pests. This is also necessary in developing comprehensive and integrated pest control strategies, particularly in screening potential grain protectants.

e. Development of detection techniques for early or hidden infestations, especially those involving species which are subject to quarantine and difficult to detect. The data could also be used in correcting loss estimates which are based on loss assessment methods that yield significantly inaccurate results when such infestations are present.

f. Thirty-five to 45% of the marketable surplus of paddy is held by the private sector at the farm or village level. A study should be undertaken to determine the level of pest damage and corresponding food losses and also catalogue existing pest control practices in temporary farm storages and by millers and traders (including transportation facilities). This is needed to clearly define the magnitude of the problem at this level, and to determine if control measures are necessary and the point at which pest control is wanting and insect population build-up is evident.

g. After obtaining damage potentials and the corresponding economics of control, the Economic Threshold Level (ETL) should be calculated for different storage pests and various stored commodities. This will help improve the accuracy and practicability of action for rational management of stored commodities.

h. More knowledge and deeper understanding of pests in bulk stores in view of the expressed plan by the government to gradually shift to bulk storage within the next 10 years.

2. Further studies on chemical control:

a. Continuous search for alternative insecticides, in conjunction with periodical diagnosis of the resistance status of various economically important species. The selection of suitable candidate materials should be influenced not only by their efficacy and safety to consumers but also by their effects on beneficial organisms.

b. Establishment of the most appropriate dosages and exposures for fumigant application under local field conditions

c. Improved techniques, methods, and equipment for application of insecticides

3. Development of an integrated pest management system that will ultimately result in greater pest control efficiency and reduced dependence on chemical pesticides

a. Evaluation of insect growth regulators, pheromones, parasites, and predators to determine their potential as biological control agents used either singly or in combination with each other or with chemical insecticides

b. Pilot-testing of various known methods of modified storage atmosphere-chemical control combinations, namely: dehumidified storage with fumigation, aeration with insecticides, and CO_2 enriched atmosphere with fumigation under tropical humid storage conditions. The socioeconomic aspects of these technologies should also be evaluated.

c. Potential use of indigenous plant extracts possessing insecticidal properties

d. Evaluation of the relative susceptibilities or tolerances of various locally grown varieties and accession lines to major insect pests of stored grains. The data generated should be included as a factor in influencing national and local recommendations for the use of new varieties and active selection by plant breeders to produce new varieties with high tolerance to storage pests.

e. Appropriate warehouse design is a basic requirement for safe storage of grains. To this end, the modification and improvement of existing warehouses to make them more suitable for holding grains must be pursued.

Despite the availability of information on pest control technologies, many sectors of the industry have failed to adopt any of these. A study should be undertaken to identify and establish the degree of influence of various socioeconomic and technical factors affecting the adoption and non-adoption of pest control technologies. With this as baseline information, strategies can then be developed and pilot tested to effect more widespread adoption of the technology.

Training and Extension

a. Seminar for top management officials to influence their decisions for pest control resource allocation;

b. Intensive training and workshops for farmers, warehousemen, traders, processors, extension agents, pest control technicians, and quarantine officers on storage and pest control principles and techniques. Insect recognition capabilities of pest control officers, researchers, quarantine officials, and warehousemen should also be upgraded;

c. Exchange of experts at regional and international levels;

d. Graduate degree program for junior and senior researchers;

e. Regular seminar-workshops at the local level to promote interaction between various sectors of the postharvest industry, thus maintaining relevance of research and extension programs of agencies involved in such activities;

f. Periodic regional and international seminars to promote exchange of information;

g. Publication and dissemination of extension materials for various sectors of the industry.

Conclusions

It appears that our basic understanding of insect pests of stored grain is still inadequate and therefore studies of their ecology and effects on foodstuffs need to be pursued.

Chemical pesticides will continue to play a major role in the control of insect pests. Suitable alternative insecticides must therefore be actively sought.

At the same time, the development of other pest control technologies involving non-chemical methods must be vigorously pursued with a view to formulating an integrated pest management system. The success of any control undertaking depends on the ability to integrate principles, methods, and techniques advanced by various disciplines into a coherent and comprehensive program.

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Pest Problems and the Use of Pesticides in Grain Storage in Thailand

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Abstract

Postharvest pest problems and control measures in Thailand are reviewed. Some seventy species of insects and various types of rodents have been recorded infesting stored grain and other agricultural products. *Sitrotroga cerealella, Rhyzopertha dominica,* and *Sitophilus* spp. are the dominant pests of stored paddy, while the most abundant species found in milled rice are *Sitophilus* spp., *Tribolium castaneum*, and *Corcyra cephalonica.* The *Sitophilus* spp. group are the only major pests of stored maize, sorghum, and wheat. *Rhyzopertha dominica* has become more important than *Sitophilus* spp. as a pest of stored barley, while in grain legumes the major pests are *Callosobruchus maculatus* and *C. chinensis*, with the former being more abundant. Estimates of percentage losses due to insects vary between 1 and 25%. A recent study in which 20 varieties of paddy seed were stored unprotected for 10 months revealed losses between 2 and 24%, with an average of 4.5%. Although some insecticides have been recommended for use in grain storages, their application has been limited to seed and for treatment of the storage structure: they have not been applied directly to bag or bulk grain. On the other hand, fumigation with methyl bromide or phosphine is general practice in commercial stores. Methyl bromide is preferred, because of the shorter exposure periods needed.

THAILAND is one of the major rice growing countries of the world. About 10.02 million hectares are under cultivation and annual production is 19.55 million tonnes. Rice is grown in all parts of the country, from the southern border with Malaysia to the northern border with Laos and Burma, a distance of about 1600 km. Most of the rice grown is of irrigated varieties dependent upon rainfall. There are very few upland rice varieties. About 20% are floating rice varieties which may grow in water several metres deep. Rainfall is the most variable climatic factor affecting rice cultivation. The average annual rainfall for the whole country is 1550 mm (about 60 inches). In the north-eastern region, lower annual rainfalls of about 1000 mm are common, while in the south the usual rainfall is about 2000 mm and may reach 2500 mm.

Besides rice, Thailand also produces maize, sorghum, mungbean, soybean, cassava, etc. Table 1 gives areas planted and yields of the principal crops in 1983–84.

Table 1. Area planted and production of principal crops.

Commodity	Area planted (ha)	Production (t)
Rice	10 015 360	19 549 000
Maize	1 688 311	3 552 391
Cassava	1 404 720	19 985 327
Mungbean	483 442	288 337
Sorghum	265 096	327 057
Soybean	161 357	179 126
Groundnut	125 270	146 550

Source: Office of Agricultural Economics, Ministry of Agriculture & Co-operatives. Agricultural Statistics No. 213 (1984): Agricultural Statistics of Thailand, Crop Year 1983/84. 244 p.

Most farmers do not store grain in large quantity, but only small amounts for their own consumption and some for seed. They generally sell the grain either before harvesting or during threshing for rent or cash requirements. Nearly all the grain and other agricultural products are therefore stored in the mills, warehouses, or silos ready to be released to the local markets or exported. At this stage, fumigation is necessary and is generally practised. For the farmers, however, losses due to storage pests, particularly insects, have significance and most of them do nothing to protect the grain from insect infestation. Since no problem is perceived at farmers'

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Table 2. List of insect pests of stored products in Thailand.

Order/Family	Scientific name	Common name
Coleoptera		
1. Family Anobiidae	*Lasioderma serricorne* (Fabricius)	Cigarette beetle
	Stegobium paniceum (Linnaeus)	Drugstore beetle
2. Family Anthicidae	*Anthicus* sp.	—
3. Family Anthribidae	*Araecerus fasciculatus* (Degeer)	Coffee-bean weevil
4. Family Bostrichidae	*Apate submedia* (Walker)	—
	Dinoderus minutus (Fabricius)	Bamboo borer
	Prostephanus truncatus (Horn)	Larger grain borer
	Rhyzopertha dominica (Fabricius)	Lesser grain borer
5. Family Bruchidae	*Bruchus pisorum* (Linnaeus)	Pea weevil
	Bruchidius murinus (Boheman)	—
	B. varius (Olivier)	—
	B. lividimanus (Gyll.)	—
	B. trifolii (Motsch.) f. *alfierii* (Pic.)	—
	Callosobruchus analis (Fabricius)	—
	C. chinensis (Linnaeus)	Cowpea weevil
	C. maculatus (Fabricius)	Southern cowpea weevil
	C. rhodesianus (Pic.)	—
	Caryedon gonagra (Fabricius)	—
	C. serratus (Olivier)	Groundnut borer
	Spermophagus subfasciatus (Boheman)	—
	Spermophagus sp.	—
6. Family Carabidae	*Dioryche* sp.	—
	D. indochinensis (Bates)	—
7. Family Cleridae	*Necrobia ruficollis* (Fabricius)	Redshouldered ham beetle
	N. rufipes (Degeer)	Redlegged ham beetle
	Thaneroclerus buqueti (Lefevre)	—
8. Family Cucujidae	*Cryptolestes pusillus* (Schönherr)	Flat grain beetle
	C. turcicus (Grouvelle)	—
9. Family Curculionidae	*Sitophilus oryzae* (Linnaeus)	Rice weevil
	S. zeamais (Motschulsky)	Maize weevil
10. Family Dermestidae	*Anthrenus fasciatus* (Herbst)	—
	A. pimpinellae (Pic.)	—
	A. vorax (Waterhouse)	Carpet beetle
	Attagenus gloriosae (Fabricius)	—
	Chelonarius indicum (Grow)	—
	Dermestes ater (Degeer)	Black larder beetle
	D. maculatus (Degeer)	Hide beetle
	D. peruvianus (Castelnau)	—
	Thaumaglossa rufocapillata (Redt.)	—
11. Family Hysteridae	*Carcinops quattuordecimstriata* (Stephens)	—
12. Family Lyctidae	*Lyctus brunneus* (Stephens)	Powderpost beetle
13. Family Mycetophagidae	*Typhaea stercorea* (Linnaeus)	Hairy fungus beetle
14. Family Nitidulidae	*Carpophilus dimidiatus* (Fabricius)	Corn-sap beetle
15. Family Silvanidae	*Ahasverus advena* (Waltl)	Foreign grain beetle
	Cathartus quadricollis (Guerin)	Square-necked grain beetle
	Oryzaephilus mercator (Fauvel)	Merchant grain beetle
	O. surinamensis (Linnaeus)	Sawtoothed grain beetle
16. Family Tenebrionidae	*Alphitobius diaperinus* (Panzer)	Lesser meal worm
	A. laevigatus (Fabricius)	Black fungus beetle
	Cynaeus angustus (Leconte)	Larger black flour beetle
	Latheticus oryzae (Waterhouse)	Long-headed flour beetle
	Martianus dermestoides (Fairmaire)	—
	Mesomorphus vitalisi (Chatany)	—
	Palorus foveicollis (Blair)	—
	P. subdepressus (Wollaston)	Depressed flour beettle
	P. ratzeburgii (Wissman)	Small-eyed flour beetle
	P. shikhae (Sarup, Chatterji & Menon)	Depressed flour beetle
	Tenebrio molitor (Linnaeus)	Yellow mealworm

Table 2. (cont.) List of insect pests of stored products in Thailand.

Order/Family	Scientific name	Common name
Coleoptera — cont.		
	Tribolium castaneum (Herbst)	Rust-red flour beetle
	T. confusum (Jacquelin du Val)	Confused flour beetle
17. Family Thorictidae	*Thorictodes heydeni* (Reitter)	—
18. Family Trogositidae	*Lophocateres pusillus* (Klug)	Siamese grain beetle
	Tenebroides mauritanicus (Linnaeus)	Cadelle
Lepidoptera		
1. Family Blastobasidae	*Blastobasis ochromorpha* (Meyri)	—
	Blastobasis sp.	—
2. Family Galleriidae	*Corcyra cephalonica* (Stainton)	Rice moth
3. Family Gelechiidae	*Sitotroga cerealella* (Olivier)	Angoumois grain moth
4. Family Phycitidae	*Ephestia cautella* (Walker)	Tropical warehouse moth
5. Family Pyralidae	*Doloessa viridis* (Zeller)	Green rice moth
6. Family Tineidae	*Melasina* sp.	—

level, there is no doubt that much more work has been devoted to pests attacking crops in the fields rather than to pests of stored products.

Pests of Stored Products

Seventy species of beetles and moths have been recorded in association with grain and other agricultural products in Thailand. They are listed in Table 2. Only a few cause major economic damage. The major pests can be grouped according to feeding behaviour as follows:

Paddy:
- *Sitophilus oryzae* (Linnaeus) (rice weevil)
- *Sitotroga cerealella* (Olivier) (Angoumois grain moth)
- *Rhyzopertha dominica* (Fabricius) (lesser grain borer)
- *Lophocateres pusillus* (Klug) (Siamese grain beetle)
- *Cryptolestes pusillus* (Schönherr) (flat grain beetle)

Rice:
- *Sitophilus zeamais* Motschulsky (maize weevil)
- *S. oryzae* (Linnaeus) (rice weevil)
- *Tribolium castaneum* (Herbst) (rust-red flour beetle)
- *Corcyra cephalonica* (Stainton) (rice moth)
- *Oryzaephilus surinamensis* (Linnaeus) (sawtoothed grain beetle)
- *Cryptolestes pusillus* (Schönherr) (flat grain beetle)

Maize and sorghum:
- *Sitophilus zeamais* (Motschulsky) (maize weevil)
- *Tribolium castaneum* (Herbst) (rust-red flour beetle)
- *Carpophilus dimidiatus* (Fabricius) (corn-sap beetle)
- *Corcyra cephalonica* (Stainton) (rice moth)
- *Ephestia cautella* (Walker) (tropical warehouse moth)

Pulses:
- *Callosobruchus maculatus* (Fabricius) (cowpea weevil)
- *C. chinensis* (Linnaeus) (southern cowpea weevil)
- *Ephestia cautella* (Walker) (tropical warehouse moth)

Cassava:
- *Araecerus fasciculatus* (Degeer) (coffee bean weevil)
- *Rhyzopertha dominica* (Fabricius) (lesser grain borer)
- *Lasioderma serricorne* (Fabricius) (cigarette beetle).

Various species of cockroaches and rodents are also recorded in stored products (Tables 3 and 4).

Insects are considered to the most destructive of the pests of grain and grain products. Therefore, only insects and insecticides will be discussed in this paper.

As mentioned earlier, insect infestation of stored products has not yet been recognised as a major problem in Thailand. This is because farmers keep the grain either as food or seed in small quantities and the percentage of damage is

Table 3. Species of cockroaches found in storages in Thailand.

Scientific name	Common name
Periplaneta americana (Linnaeus)	American cockroach
P. brunnea (Burmeister)	Large-brown cockroach
P. australasiae (Fabricius)	Australian cockroach
Neostylopyga rhombifolia (Stoll)	—
Supella supellectilium (Serville)	Brown-banded cockroach
Pycnoscelus surinamensis (Linnaeus)	Surinam cockroach
Blattella germanica (Linnaeus)	German cockroach
Nauphoeta cinerea (Olivier)	Lobster cockroach
Phoetalia pallida (Brunner)	—

Table 4. Species of rodents found in storages in Thailand.

Scientific name	Common name
Rattus exulans (Peale)	Polynesian rat
R. rattus (Linnaeus)	Roof rat
R. norvegicus (Berkenhout)	Norway rat
Mus musculus (Linnaeus)	House mouse

insignificant to them. In general, the grain is not treated in any way during storage, except for seed where the farmers may use one of the agricultural by-products or inert dusts. Ashes, for example, may be mixed with or dusted on the seed. Salt or plant materials are also used to treat seed to keep it free from insects. Lastly, insecticides which are cheap and available locally may be bought for treating the seed.

Losses Due to Insect Infestation

The percentage of losses is very difficult to determine and the figures vary from as little as 1% to as much as 25%. Official figures released by the five ASEAN countries stated that the member nations lost about 25% of their paddy crop during harvesting and other postharvest practices including storage and transportation, and that the loss represents 10.5 million tons of paddy. In 1977, FAO reported losses of rice within the postharvest system for Thailand ranging from 8 to 14%.

In Thailand itself, there is no official report on losses due to insect infestation. The estimation of losses is based only upon experiments. For paddy, some investigators reported losses in weight of 1.14–3.41% following 8 months storage on-farm, and more than 5% for commercial storage, while the author has reported grain losses from 0.05–10.48% after one year of storage. A recent report from the Thai Rice Institute notes that when 20 varieties of paddy seed were stored untreated for 10 months, the losses varied from 2.06 to 24.30% with an average 4.54%. Other grain crops, eg. maize, sorghum, and pulses, are not only subject to field infestation by insects but are also stored under poor conditions. When grain has no protection, insect populations will build up rapidly. Losses and damage by insect pests are therefore related to the duration of storage. Unfortunately, there are no records on losses of these crops but it has been observed that the severe damage will occur within a few months of storage and may reach up to 50% for 6 months storage. This is one of the reasons why farmers do not keep grain in large quantities or for long periods.

Currently, quantity loss is not as important a factor as the loss of goodwill in international trade. The loss of good will between traders and farmers or between importers and exporters in international trade can be a serious matter as regards future marketing. In the past, some major exporters of grain had the embarrassment of some shipments being declared distressed cargoes. This was due to the presence of a quantity of insecticide on the grain which may be a health hazard to human beings. Commercial losses can also occur due to the reduction of quality through adulteration or insect attacks.

Pesticides Used in Storage

Thailand is one of the pesticide-importing countries in the region. The value and quantity of pesticide imports are shown in Tables 5 and 6. Of the insecticides imported in 1983, around 15.54% were recommended mostly for household and storage pests. Approximately two-thirds were used for control of household pests and field insects and the balance (90% are fumigants) for storage insects. Rodenticides totalled 0.19% whereas fungicides for seed purposes were 10.43% of total fungicides imported.

Generally, insecticides have no role in control of insects in farm storage. The reasons are firstly, that farmers do not recognise the damage caused by infestation and secondly, that residues can appear in foodstuffs after treatment. In contrast, farmers feel a need to use insecticide on seed by admixing with any cheap locally available insecticide. There

Table 5. Value of pesticides imported into Thailand, 1980–83 (million baht)[a].

Pesticide	Year			
	1980	1981	1982	1983
Insecticides	784.51	791.81	691.80	631.38
Fungicides	121.46	148.90	132.63	156.33
Herbicides	321.88	460.95	460.77	333.63
Total	1227.85	1401.66	1977.08	1121.34

a. During May 1985, 20 Thailand baht (THB) = US$1.

Table 6. Quantity of pesticide imported into Thailand, 1980–83 (t).

Pesticide	Year			
	1980	1981	1982	1983
Insecticides	10 045.42	6 625.11	5 587.31	6 718.32
Fungicides	3 024.74	2 863.72	2 219.45	3 903.58
Herbicides	7 001.49	9 441.92	6 466.00	6 106.44
Total	20 071.65	18 930.75	14 272.76	16 728.34

Table 7. List of insecticides recommended for use on seed in Thailand.

Common name	Trade name
Chlorpyrifos	Lorsban
Chlorpyrifos methyl	Reldan
Etrimphos	Satisfar
Fenitrothion	Folithion, Sumithion
Phoxim	Baythion

Table 8. List of insecticides recommended for use on grain or seed in Thailand.

Common name	Trade name
Pirimiphos methyl	Actellic
Malathion	Malathion
Methacrifos	Damfin
Cypermethrin	K-orthene
Deltamethrin	Ripcord

is no doubt that DDT and carbaryl are widely used for seed application. In commercial seed production, seed must be treated with both insecticide and fungicide. Here, malathion is the insecticide most often used, and captan the fungicide. The insecticides used for seed treatment are listed in Table 7.

Some insecticides have been tested and recommended for use on stored grain (Table 8), but none has been applied to stored grain or grain products, either bagged or in bulk. Insecticides such as malathion and phoxim may sometimes be used for spraying the walls, floors and ceilings of warehouses or godowns in order to deal with residual infestations. In commercial grain storage involving both local traders and exporters, fumigants play an important role in controlling the grain insects during storage. The only fumigants used are methyl bromide and phosphine. In practice, however, methyl bromide is preferred because grain needs shorter periods of exposure to it.

For commodities other than grain, such as tobacco, the insect growth regulator methoprene has been introduced to control the cigarette beetle in storages where fumigation is difficult to apply.

It may be concluded that despite the fact that large amounts of stored grain and grain products in Thailand are infested by insects, insecticides are not used in bagged or bulk grain. Their use is limited to treatment of seed. In commercial storage, fumigants are widely used and fumigation is practised in all types of structures.

Pest Problems and the Use of Pesticides in Grain Storage in Indonesia

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Abstract

Postharvest practices and problems in Indonesia are reviewed. Stored product pests cause considerable loss and damage each year. In milled rice stored for 6 months, for example, it is estimated that the loss due to insect infestation is between 0.5 and 2%. The major storage pests of milled rice are *Sitophilus* spp. and *Tribolium castaneum*, with *Corcyra cephalonica, Ephestia kuehniella, Rhyzopertha dominica,* and some other secondary pests causing lesser damage. The application of pesticides is generally considered as the best method of protecting grain from insect infestation. Pirimiphos-methyl in emulsifiable concentrate formulation is the most extensively used pesticide for spraying, while phosphine and methyl bromide are in common use for fumigating storages and ships. Pesticide application is part of an Integrated Storage Pest Management (ISPM) program initiated in the early 1970s and now considered to be working well. The program has five components: improvement and provision of storages; proper insecticide application; physical control strategies; training of pest control and storage managers; and collaborative research and development work in the area of storage pest management. Current work includes studies directed towards combatting insects such as psocids (*Liposcelis* spp.) and controlling pests of secondary crops.

DURING the last 5 years the Government of Indonesia has been able to accelerate its agricultural production significantly. Rice production, for example, has increased at a rate of 4–6% per annum, which is above the average production increase in most developing countries. Total rice production in Indonesia during 1984 reached 25.8 million t.

Successes in rice production and agricultural development, however, have also brought about problems which need to be solved as soon as possible. The postharvest problem is one of the urgent matters that the Government of Indonesia has to deal with. Losses as high as 15–20% occur almost every year during harvesting, threshing, transport, and storage.

Improper treatment of rice after harvest causes subsequent problems in storage. Quality deterioration and weight loss are quite common during storage. These can be attributed mainly to insect infestation and, to a lesser degree, the activities of rodents and birds.

The National Logistics Agency (BULOG) is the sole government agency handling food grains in Indonesia. Its main function is to stabilise prices and it maintains stocks of grains in order to achieve this. The quantity of grains (especially rice) stored in its godowns varies from time to time, but there is a tendency for it to increase each year (Table 1), because whilst production is increasing, consumption remains more or less the same.

The largest outlet for BULOG's rice in recent times has been 'budget groups' (civil service, armed forces, and government-owned plantation

Table 1. Rice production in Indonesia and stocks held by BULOG (1979–1984).

Year	Production (Mt)	BULOG stock (Mt)
1979	17.9 (2.3%)[a]	0.886
1980	20.2 (12.4%)	1.242
1981	22.3 (10.4%)	1.591
1982	22.8 (2.2%)	1.031
1983	24.0 (5.3%)	1.417
1984	25.8 (7.5%)	2.502

[a] Increase in production over the previous year.

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estates), which acquire about 1.5 million t per year. Direct sales to the rice market (popularly called 'market operation') have decreased markedly in the last 2 years. These circumstances have lengthened the storage time for rice. Maximum storage periods used to be 4–6 months: now they are often more than 12 months and sometimes up to 24 months. Another problem is that the major portion of BULOG's stock is milled rice, a commodity which is particularly susceptible to insect infestation.

In conditions such as these, pesticides play an important role in controlling insects in grain storage, and the application of pesticides has increased markedly over the last two decades. However, with the increasing awareness of the problems that may arise from pesticide use, BULOG is seeking other measures to control insect pests.

In this paper, the use of insecticides in grain storage in Indonesia is reviewed briefly along with the various insect control options which will be implemented by BULOG in the near future.

Problems of Stored Product Pests

Insects

The storage insects found in Indonesia are the same species as are found in association with stored products in most parts of the world. Insect pests either alone or in combination usually occur in stored products such as paddy, milled rice, maize, beans, dried cassava, etc. It is quite common for one species to predominate over others in a particular commodity such as milled rice but to become less important in another such as paddy (or rough rice).

Haines and Pranata (1982) made a detailed survey of the species of storage insects associated with stored products in different types of storages throughout Java. The numbers of species found in the various taxonomic groups were: Coleoptera, 56; Lepidoptera, 9; Psocoptera, 5. The predominance of a wide variety of Coleoptera among storage pests is well known. It is also widely recognised that lepidopteran pests are second in importance to the Coleoptera.

Rice is the primary grain stored by BULOG, more than 70% of it in the form of milled rice, which is readily infested by stored product pests. There are no precise data about actual weight losses caused by insect infestation during storage. However, according to Sugiarto et al. (1977), the percentage weight losses of milled rice in BULOG's warehouses may reach 0.35% after 6 months storage. This value is much lower than weight losses from milled rice infested with insects in laboratory conditions. Sidik (1979), using 54 kg drums filled with rice and infested with *Sitophilus zeamais*, recorded weight losses as high as 22% after 6 months. Husain (1982) recorded a weight loss from milled rice due to *S. zeamais* infestation of 14.8% in 3 months.

There are several factors affecting the extent of weight losses from milled rice caused by insects during storage. These include the variety of the rice involved, storage conditions, and pest control practices. Husain (1982) noted that the order of susceptibility to insect attack of varieties of rice stored in Indonesia was: Cisadane, IR. 36, Cimandiri, and IR. 32. Both Cisadane and IR. 36 are high-yielding varieties of rice which are widely grown in this country and apparently suffer more severe damage than any other varieties. Therefore, it can be predicted that insects contribute great loss and damage to stored, milled rice in Indonesia.

Among the various storage insects, those most commonly encountered and considered as being most important in terms of losses and damage to stored grains in Indonesia are as follows.

Sitophilus spp. are recognised as the major, primary pests of whole cereal grains. It is now becoming more widely known that *Sitophilus zeamais* is the dominant species on most cereals, especially maize and rice, in the tropics. As a result, it has been assumed that in Indonesia the *Sitophilus* found on maize and all forms of rice are *S. zeamais*. *S. zeamais* does indeed appear to be dominant over *S. oryzae* on milled rice and maize in Java, but not completely so (McFarlane 1978; Haines and Pranata 1982). *S. oryzae* has also been found infesting green gram and black soya, and the observed frequency of occurrence of *S. oryzae* on pulses indicates that a pulse-feeding strain is quite common in Java.

Tribolium castaneum (rust-red flour beetle) is a significant pest but is possibly more of a scavenger on polished rice than a primary pest of whole cereal grains or flour (McFarlane 1978). On undermilled rice, it will probably feed actively and productively on the residual bran and may also attack the embryo region. Haines and Pranata (1982) reported that *T. castaneum* was not often found in farmers' stores, presumably because of the preponderance of rough rice in these stores.

The high frequency of occurrence of this beetle in the stores of private traders is the combined result of relatively long-term storage of cereals in these stores and the quality of store management.

A number of other species of grain storage insects are known to occur in Indonesia.

Rhyzopertha dominica (lesser grain borer) is potentially a very damaging pest because of the unusual extent of adult feeding over and above that of the larvae. It is a major pest of rough rice but appears to be relatively uncommon on milled rice.

Other beetle species, *Oryzaephilus* and *Cryptolestes,* for example, may become established in place of *Tribolium castaneum.* The factors leading to this may warrant further investigation. Climatic factors, especially grain temperature, are likely to play a part, but other factors, including the packaging materials used for bagged stored commodities, may be important.

Most other beetles, including *Ahasverus advena, Alphitobius* spp., and *Tenebroides mauritanicus,* do not warrant consideration as major pests of stored products. They are abundant only where infestation by other insects has already produced a high level of damage. *T. mauritanicus* and *Alphitobius* spp. are regarded as signs of a long-term infestation problem and/or of poor warehouse sanitation. *Callosobruchus maculatus* is commonly found in stored green gram and soybean. *Trogoderma granarium* has been recorded on imported milled rice not yet unloaded from ship (Sukardi 1978).

Corcyra cephalonica (rice moth) causes 'clumping' of rice grains through the silk webbing produced by the larvae. The larvae attack the grain at the site of the embryo, consuming this if it is present, as well as feeding on the other surfaces and any residual bran layer.

Ephestia cautella (tropical warehouse moth), like *Corcyra,* is prevalent in milled rice, particularly if there is a high percentage of broken grains. The infestation is characterised by the presence of aggregations of grains.

Sitotroga cerealella (Angoumois grain moth) is an important pest of rough rice, but appears to be unimportant on milled rice. On milled rice, although each emerged adult can cause considerable damage and spoilage the low multiplication potential makes this insect insignificant as a pest, except perhaps on under-milled rice (McFarlane 1978).

Psocids (Psocoptera) are primarily scavengers and in milled rice they probably feed mainly upon minute grain fragments and the dust produced by the feeding of other insects. Nevertheless, they can multiply to very large numbers on milled rice in bag stacks. The active migration of these insects throughout a warehouse can constitute a severe nuisance to storage workers. *Liposcelis entomophilus* is the most common psocopteran in many types of warehouses in Java. Haines and Pranata (1982) reported that the occurrence of *L. entomophilus* in samples collected from BULOG warehouses was high compared with other types of warehouses. Whether this is due to association with large-scale storage of milled rice or to the regular use of insecticides in these stores remains uncertain. There is circumstantial evidence to support both hypotheses.

Fungi

Fungal infections not only bring about deterioration and spoilage of stored products, but also produce highly toxic substances called mycotoxins. In a detailed study on mycotoxin-producing fungi in rice, Suriawiria (1976) recorded the occurrence of 10 species of *Aspergillus,* 4 of *Penicillium,* and 5 of *Fusarium.*

Rodents

Soekarna et al. (1977) recorded four species of rodents associated with stored products: *Rattus norvegicus, Mus musculus, Rattus rattus diardii,* and *Suncus murinus.* Rodent infestation of stored rice usually occurs when food becomes short in the surrounding fields. In certain areas such as the northern part of West Java (Cirebon, Indramayu), rodents caused great losses to milled and rough rice in storage.

Other Pests

Mites and birds have been cited as causes of damage to stored grains. As regards mites, Haines and Pranata (1982) recorded *Caloglyphus* spp., *Tyrophagus putrescentiae,* and *Blattisocius* spp. from stored grains. The real significance of bird infestation in terms of actual damage remains uncertain, but there is no doubt that large numbers of small birds, particularly *Passer montanus* (house sparrow), have been found to be a problem in inadequately screened rice storages.

Current Use of Pesticides in Grain Storage

As noted in the introduction to this paper, pesticides play an important role in controlling grain storage pests in Indonesia. The application of insecticidal materials for grain preservation in this country was probably practiced long before 'modern' insecticides were actually invented. In the past, farmers have used various methods to protect their agricultural products such as paddy or maize from insect infestation. The admixture to the grain of ash from burnt coconut shells, maize cobs, or rice husks could provide temporary protection against insect attack. Also, farmers traditionally used smoke from burning woods to dry and preserve their maize.

Modern methods of pesticide application to stored grain were introduced in the early 1970s when BULOG set up the Bureau of Maintenance and Stock Control. Since then, the application of pesticides in grain storages owned by BULOG has become a part of grain preservation system.

The two basic methods of chemical pest control practiced in grain storage are spraying and fumigation.

Spraying Spraying entails the application of insecticides (either emulsifiable concentrates or wettable powders) to storage buildings and/or stacks of rice. This treatment is intended to kill insects on the surface of the stacks and storage and also to provide protection against reinfestation.

Since 1975, intensive spraying programs have been carried out in almost all BULOG storage complexes throughout the country. Milled and rough rice storages are sprayed every 2 and 3 weeks, respectively.

Pesticides used in grain storage have, in general, to comply with Indonesian pesticides regulations. Before they can be used, insecticides are evaluated for chemical residue and toxicological aspects by the Indonesian Pesticides Committee. If an insecticide meets all requirements, the Committee recommends its use, and eventually the chemical will be incorporated in what is called a 'white list.' Table 2 lists all insecticides recommended for controlling stored product pests and applied in BULOG storages.

With the introduction of malathion in the 1960s, the use of insecticide in grain storage markedly increased. This pesticide gained wide acceptance in the 1970s and was extensively used in BULOG storages to control *Sitophilus* spp., *Tribolium* spp., and other stored product pests. However, the use of malathion for postharvest pest control began declining after there were indications of insect resistance to it. Other organophosphorus insecticides, such as dichlorvos, fenitrothion, and pirimiphos-methyl, have replaced malathion for use in grain storage. The area sprayed is increasing each year, especially over the past 3 years as storage periods for milled rice have increased. Total area sprayed in BULOG storages increased from almost 14 million m^2 in 1977–78 to over 51 million m^2 in 1983–84. More

Table 2. Recommended pesticides and fumigants used in grain storage by BULOG.

Pesticide formulation	Active ingredient	Purpose	Application rate	Frequency of application
Methyl bromide	Methyl bromide 98%, Chloropicrin 2%	Fumigation	21 g/t	Subject to the level of insect infestation
Phostoxin tablet	Aluminium phosphide 56%	Fumigation	2 g PH_3/t	Subject to the level of insect infestation
Gastoxin tablet	Aluminium phosphide 55%	Fumigation	2 g PH_3/t	Subject to the level of insect infestation
Detia Gas Ex B	Aluminium phosphide 57%	Fumigation	2 g PH_3/t	Subject to the level of insect infestation
Dedevap 50 E C	Dichlorvos 647.1 g/l.	Spraying	30 ml/m^2 (1%)	Routine basis every 3 weeks
Nuvan 50 E C	Dichlorvos 500 g/l.	Spraying	30 ml/m^2 (1%)	Routine basis every 3 weeks
Gardona 24 E C	Tetrachlorvinphos 240 g/l.	Spraying	30 ml/m^2 (1.5%)	Routine basis every 4 weeks
Damfin 950 E C	Methacrifos 950 g/l.	Spraying	30 ml/m^2 (3.3%)	Routine basis every 6 weeks
Silosan 25 E C	Pirimiphos-methyl 250 g/l.	Spraying	30 ml/m^2 (1.5%)	Routine basis every 3 weeks

Table 3. Volume in litres of insecticides used in grain storage in Indonesia, 1979–84 (source: BULOG).

Insecticide	1979	1980	1981	1982	1983	1984
Pirimiphos-methyl	12 900	18 600	16 000	16 600	14 000	18 975
Dichlorvos — Dedevap	4 435					
— Nuvan	1 500	1 600	1 500	10 300	11 140	11 740
Propoxur	13 260	—	—	—	—	—
Methacrifos	—	—	—	—	1 000	3 500
Tetrachlorvinphos	—	—	—	—	—	2 000

than 50% of the spraying program is carried out by BULOG pest control operators, and the rest by private pest control companies.

Pirimiphos-methyl appears to be the most common insecticide used in storages, followed by dichlorvos (Table 3). In storage trials conducted by BULOG in collaboration with the manufacturer of pirimphos-methyl, this insecticide gave good protection against the major stored product pests found in Indonesia for a period of 6 months. However, in actual storage conditions pirimiphos-methyl is less effective in controlling *Rhyzopertha dominica* and psocids *(Liposcelis* spp.). Psocids, although not considered as grain pests, cause considerable nuisance to storage workers. BULOG has not yet been able to find a good method for controlling psocids. Methacriphos (another organophosphorus insecticide) is sometimes quite effective against these insects but more often fails to give a good control, especially if the population is high and this pesticide has been used repeatedly.

BULOG has recently begun to use admixture of insecticides, especially for preserving maize and other secondary crops. A pirimiphos-methyl (and soon permethrin) dust formulation to control *Sitophilus* spp., *Tribolium* spp., and other storage pests is mixed with the grain using mechanical grain mixing equipment.

Fumigation Fumigation has been used quite extensively in Indonesia as an alternative to spraying for insect control. Although it needs special skills and techniques to apply, it is still one of the most popular methods for quickly disinfesting stored grain of all stages of insects.

Methyl bromide and phosphine are in common use as fumigants in grain storage in Indonesia. Methyl bromide was probably introduced in the early 1960s, whereas phosphine was first used 10 years later. Methyl bromide is usually preferred whenever short exposure periods are necessary, such as in ship fumigation before unloading, or if the grain has a high moisture content. The use of methyl bromide seems to have declined since the introduction of phosphine, generally because fumigation using methyl bromide needs more complicated equipment.

During the 5 years from 1979 to 1984, the amount of methyl bromide used as a fumigant ranged between 10 and 70 million grams per year. In other words, between 0.5 and 3.5 million t of milled rice each year had been fumigated with this material. Phosphine (which has three different trade names, Detia gas ex B, Phostoxin, and Gastoxin) was used for fumigating between 0.9 and 3.3 million t per year of milled rice over the same period. Total phosphine and methyl bromide use for each year during the period is shown in Table 4.

Fluctuation in fumigant use is very much influenced by the amount of rice procured by BULOG. The more rice bought by the government, the greater will be the use of fumigants. Stored rice is usually fumigated every 3 months, although a survey or inspection is conducted beforehand to check the level of insect infestation in the storage. Fumigation will be carried out whenever the level of infestation has reached moderate levels (as determined by a method based

Table 4. Fumigant use (kg) in grain storage in Indonesia, 1979–84 (source: BULOG).

Fumigant	1979	1980	1981	1982	1983	1984
Phosphine	1 920	4 954	6 171	5 685	5 976	6 455
Methyl bromide	10 621	47 955	70 157	51 720	51 720	60 981

Notes: 1. Standard dosage per tonne of commodity is 2 g phosphine or 21 g methyl bromide.
2. Fumigation is carried out four times per year.

on the FAO survey method). Plastic covers are often used for fumigating rice in storage, whereas total space fumigation is necessary in ship fumigation to eradicate khapra beetle.

Options for Insect Control in Grain Storage

As mentioned previously, insecticides have now been in intensive use in grain storage practice in Indonesia for 10 years. Despite their good results, however, the emergence of insect resistance to them seems likely. Indications of pesticide resistance were reported by Haines and Pranata (1982). Realising the problem, BULOG, as a part of maintaining grain quality during storage, has launched an Integrated Storage Pest Management (ISPM) program for controlling insect pests. Under this program, the use of pesticides is integrated with various physical control strategies and other measures such as 'new methods' of controlling insects, provision of good storage conditions, etc.

Since 1975, the Indonesian Government has been constructing new storage complexes throughout the country. The standard capacity of such storage is 3500 t and so far almost 3 milllion t capacity of new storage has been completed.

One of the promising methods of insect control which has been tested in collaborative work with CSIRO and TDRI is the use of carbon dioxide (CO_2). This method is basically a modified atmosphere where the balance of gases inside sealed stacks is changed to achieve conditions which are lethal to insects, and if possible, microorganisms. Since most of the rice in Indonesia is stored in bags, it is quite expensive to seal the whole storage. Sealing of individual stacks has therefore been selected.

This method was examined 2 years ago with good results (Annis and Sukardi 1983) and beginning in 1985, BULOG has decided to implement the system in large-scale operations. So far more than 30 000 t of milled rice has been treated with CO_2 and the total may reach 200 000 t by the end of 1985, if the investigation currently underway shows the system to be robust.

The main physical control method currently being applied is ambient aeration. Basically this involves cooling of bag stacks of milled rice under plastic covers by forced circulation of 'dry air' through the stacks. The air flow is driven by an axial exhaust fan placed on top of each stack. The procedure has been shown to be efficacious in the control of moisture migration, preservation of grain quality, and a reduction in insect populations and the use of pesticides. A critical factor in its implementation is the effectiveness of the fumigation carried out before the fan is turned on. Spraying all air inlets is recommended to avoid insect penetration to the stack. Further investigations are being conducted in one of BULOG's storages in central Java. The main objectives of these studies are to find out the best time to run the fan, and to assess the economics of the method.

There is no doubt that there are many options for insect control. However, as a business-oriented organisation, BULOG has to justify the applicability of methods in large-scale operation. New methods suggested as alternatives to pesticide use in grain storage, must be economically as well as technically feasible. In this context, collaboration among research institutes, universities, and other groups is essential in order to speed up the process of achieving the goal. Priority should be given to finding other options to control insects in grain storage which meet the above 'requirements.'

Summary and Conclusions

The successful agricultural development program launched by the Government of Indonesia has markedly increased rice production. However, rice now has to be stored longer and is more prone to insect infestation.

Among the storage insect pests which are commonly found in stored milled rice, *Sitophilus* spp. and *Tribolium* spp. are the most predominant species and they cause greater loss to the rice than any other species.

To overcome pest problems in grain storage, BULOG still relies on pesticides. Intensive spraying using several pesticides such as pirimiphos-methyl, dichlorvos, methacriphos, etc. has been carried out since the 1970s. Fumigation using phosphine or methyl bromide is also conducted regularly to eradicate all stages of insect pests of stored products.

In 1975 BULOG set up a program called Integrated Storage Pest Management, following the detection of insect resistance to certain pesticides. Under this plan, various control measures and supporting activities such as training, provision of good storage, etc. are integrated to achieve better control over insect pests.

Two of the alternatives which have been tested successfully for insect control and are now being implemented by BULOG are modified atmosphere and ambient aeration techniques. The modified atmosphere technique is applied to sealed stacks, basically by purging them with CO_2. This system will become an important insect control method for long-term storage in Indonesia.

Regardless of the methods of controlling stored grain insects now being used, there is no doubt that efforts to find better control measures are needed. In this context, national and international collaboration between research institutes, universities, and other groups is needed in order to speed up the research and development process.

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Problems Relating to Pest Control and Use of Pesticides in Grain Storage: the Current Situation in ASEAN and Future Requirements

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Abstract

The constraints to safe storage of cereals and secondary food crops in ASEAN member countries are outlined in relation to the estimated levels of losses incurred from storage pests. The species of pests (predominantly insects and mites) which are most often encountered, the commodities they infest, and estimated losses based on laboratory and limited field evaluations, are tabulated to give an indication of the severity of the problem with respect to storage type and duration. In order to identify the main areas of concern, a comparative analysis of the pesticide schedules recommended for use, principally by the national grain agencies, is made. Among the problems discussed are those relating to insect identification, methods of assessing losses in storage, pesticide resistance and related control failures, cost effectiveness of pesticide applications, warehouse sanitation and management, inherent susceptibility of the improved varieties, and long-term storage of strategic reserves. The discussion serves to focus on grain protection in storage as an integral part of the post-production system. Other methods of pest control that can be integrated into the present storage system in ASEAN, and which have been or are being investigated as means of lessening reliance on pesticides to effect adequate control, are outlined. Recommendations for the future direction of regional research and development projects in stored grain pest control, as well as the immediate need for training and extension programs, are also discussed in detail.

ALL the crop-growing members of the Association of Southeast Asian Nations (ASEAN), have made concerted efforts over the past decade to expand production of the main staple food and feed grains, to the point of self-sufficiency or export surplus, either of which would markedly reduce the burgeoning foreign exchange deficits that are presently being experienced. Increasing areas are being brought under irrigation, and existing and new irrigation areas are being more intensively managed, through the use of high-yielding varieties (HYVs) in multiple cropping systems (Russell 1980). Increasing the area sown to crops as an adjunct to enhancing productivity is limited by the amount of arable land available in Southeast Asia.

Increased production therefore hinges very dramatically on intensification technologies and hence the widespread adoption of HYVs (Vogen 1978; Anderson 1978). Pomeranz (1982) stated that 'increasing crop productivity is the key to feeding the world's expanding population', and this becomes more evident with realisation of the disproportionate increase in population that is occurring in the developing world, compared with the industrialised nations.

Multiple cropping, simply translated, means that at least one crop is grown during the monsoon season, creating problems and difficulties in harvesting, threshing, drying, and storing, and resulting in rapid biological deterioration. In addition, the HYVs shatter easily, are generally softer, and when harvested, tend to have a wider range of kernel maturity than the traditional nonimproved varieties. The dilemma that exists in enhancing productivity using HYVs is the associated problems that are now so prevalent in the postproduction system, where traditional systems of storage and handling already considered inappropriate, are now more so with the HYVs than they were with traditional varieties.

One of the most challenging problems of the eighties is to reduce losses caused by pests, especially insects, during the food production,

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storage, and processing operations. Without exception, greater benefit would be derived if greater efforts were directed towards conservation and quality maintenance of what is already being produced, rather than on energy-intensive methods to produce more. This was exemplified by the United Nations Environment Programme (UNEP) Guidelines for Post-Harvest Food Loss Reduction Activities (1983). In many cases, the amount of grain imported barely covers the amount of locally produced grain that is consumed by pests after harvest. It must be recognised that no single method of pest control will ever become a panacea, as pesticides were once considered to be. Various techniques are available or are being developed. In addition, there is a need to implement some of the most basic principles of pest control which are not being followed, or at best only superficially. Stock management and the need for physical cleanup of stores are prime examples.

It must also be recognised that pest control is an integral part of postproduction handling system. The history of the grain before entering storage has a definite influence on subsequent quality deterioration and weight losses, and is modified by the type of storage system employed. Harein (1976) listed the most important pre-storage factors that determine the susceptibility of a crop to subsequent infestation in storage as:

(1) the amount of pre-harvest infestation;
(2) amount of kernel damage during harvesting and threshing;
(3) the drying efficiency in terms of both moisture loss and uniformity of drying, as well as kernel damage during the drying phase; and
(4) grain variety.

The field infestation potential of maize before harvest by major pests such as *Sitophilus zeamais* and *Sitotroga cerealella* is well documented (Cotton and Wilber 1983; Champ 1983). *Rhyzopertha dominica* is also known to infest cereals in the field (Carin and Morallo-Rejesus 1976), but is mainly restricted to maize, paddy, and sorghum which has been left drying after harvest and before threshing. Rahim et al. (1983) have also indicated the extreme infestation potential of farm-stored paddy in the Tanjung Karang/Sebak Bernam paddy region, Malaysia, from field infestations at the threshing sites. The infestations consisted predominantly of *R. dominica* and *Sitophilus oryzae, R. dominica* with the higher populations, but *S. oryzae* occurring more frequently. Other species encountered included *S. cerealella, Cryptolestes ferrugineus* and *C. pusillus, Tribolium* sp., *Ahasverus advena, Lophocateres pusillus,* and psocids which were either present in large numbers or not at all.

Table 1. Selected commodities at risk to attack by stored-products insects in the ASEAN region.

Code number[a]	Commodity and form attacked
1	Rice *(Oryza sativa)* (rough rice/paddy: milled rice bran and milled by-products)
2	Maize (corn) *(Zea mays)* (on ear/cob: shelled: grits)
3	Wheat *(Triticum aestivum)* (whole wheat: flour)
4	Sorghum *(Andropogrum sorghum)* (ear: shelled: milled)
5	Coconut *(Cocos nucifera)* (as copra)
6	Tobacco *(Nicotiana tobacum)* (leaves or finished product — cigarettes, cigars)
7	Coffee *(Coffea* sp.*)* (beans)
8	Cacao *(Theobroma cacao)* (beans)
9	Garlic *(Allium sativum)* (bulbs)
10	Pulses and grain legumes (seeds)
	a) Mungbean blackgram *(Phaseolus mungo; P. radiatus)* goldengram *(Vigna radiata; V. aureus)* greengram *(Phaseolus aureus)*
	b) Peas *(Pisum sativum)*
	c) Cowpea *(Vigna siensis, V. ungiculata)*
	d) Chickpeas/garbanzos *(Cicer* spp., *C. arietinum)*
	e) Soybean *(Glycine max)*
	f) Peanuts *(Arachis hypogaea)*
	g) Broadbean *(Vicia faba)*
	h) Lentil *(Lens culinarus)*
	i) Beans *(Phaseolus* spp., *P. vulgarus)* (lima, navy)
11	Cassava *(Manihot esculenta)* (flour, chips)
12	Sweet potato *(Ipomoea batatus)*
13	Commodities high in moisture and contaminated by moulds.
14	Commodities harbouring scavengers and causal intruders; woodborers. Associated insects not damaging stored commodities as listed.
15	Fishmeal
16	Spices

a. Notation used for host range and associated insects in Table 2.

The foregoing emphasises the need for reviewing pest control methods in storage in the context of the existing system, in which both pre- and postharvest operations have a profound effect on the magnitude of losses that are likely to occur in the absence of any form of control.

Stored Grain Pests of ASEAN Countries

Insects and Mites

The stored grain insects that have been identified in ASEAN countries, and the commodities they infest, are given in Tables 1, 2 and 3. In some instances during survey work, insect species were recovered from commodities that they do not normally infest, or are not commonly associated with. However, previous records have shown that certain strains of *S. oryzae* are capable of attacking and breeding on pulses and legumes such as split peas (Coombs et al. 1977) and carob pods (Pemberton and Rodriguez (1980), and a pulse-feeding strain has been recorded and cultured on mungbeans (greengram) in Indonesia (Haines and Pranata 1982).

Both *S. oryzae* and *S. zeamais,* as well as *Tribolium castaneum* and *Oryzaephilus surinamensis,* are frequently encountered in large numbers in the ASEAN region. In the Philippines, *S. zeamais* is dominant over *S. oryzae* in maize and sorghum. *R. dominica* appears to have displaced *S. oryzae* as the dominant species on paddy (Sabio et al. 1984). Haines and Pranata (Haines 1982; Haines and Pranata 1982) have demonstrated that *S. oryzae* remains the dominant weevil on paddy in Indonesia, but that *S. zeamais* has attained dominance on maize and milled rice. In on-farm storage in Malaysia, *S. oryzae* and *R. dominica* were the dominant species on paddy, followed by *S. cerealella* which was more localised in its occurrence (Rahim and Tee 1981; Rahim et al. 1983). These three species constituted approximately 70% of the total monthly insect population over a storage period of 6 months. *S. zeamais* has been reported as the most destructive pest of stored maize in Thailand (Sukprakarn 1984) and *S. cerealella* as a major and destructive species in paddy (Sukprakarn 1983).

Tribolium castaneum and *Corcyra cephalonica* appear to be the most abundant species infesting milled rice in the Philippines (Sabio et al. 1984), and these species together with *S. oryzae* have been reported as the major pests in milled rice godowns in Malaysia (Lim et al. 1980). Various moth species, such as *Ephestia cautella* and *Doelessa*

Table 2. Insect and mite pests associated with stored commodities in ASEAN.

Pest	Host range[a]	Occurrence[b]	References
INSECTS			
COLEOPTERA			
Anobiidae:			
Lasioderma serricorne	2, 6, 8, 9	Philippines	Baltazar 1969; Mollasgo 1982
cigarette beetle	1, 2, 11	Indonesia	Haines and Pranata 1982
	6	Indonesia	Atmosudirdjo 1981
		Thailand	Sukprakarn and Tauthong 1981
Stegobium panecium		Thailand	Sukprakarn and Tauthong 1981
drugstore beetle		Indonesia	Haines and Pranata 1982
	16	Indonesia	Atmosudirdjo 1981
	6	Philippines	Baltazar 1969; Mollasgo 1982
Anthribidae:			
Araecerus fasciculatus	2, 11	Indonesia	Mangoendihardjo 1981; Atmosudirdjo 1981
coffee bean weevil			
	11	Thailand	Sukprakarn and Tauthong 1981
	2, 7, 8, 11, 12	Philippines	Capco 1956; Sabio et al. 1984
	10, 10a, 10f	Philippines	Mollasgo 1982
	1, 2, 4, 10a, 10i	Indonesia	Haines and Pranata 1982
	2, 7, 16	Malaysia	Lim and Tan 1981
		Regional	Morallo-Rejesus 1979
Araecerus simulator	10	Malaysia	Lim and Tan 1981
Araecerus levipennis	7	Philippines	Morallo-Rejesus 1981
Araeocorynus cumigni		Indonesia	Haines and Pranata 1982

Table 2. (cont.) Insect and mite pests associated with stored commodities in ASEAN.

Pest	Host range[a]	Occurrence[b]	References
Bostrychidae:			
Rhyzopertha dominica	1, 2, 4, 10a	Philippines	Sabio et al. 1984
lesser grain borer	1, 2, 4, 11	Indonesia	Atmosudirdjo 1981; Mangoendihardjo 1981
	1, 2, 4, 10a, 10i, 11	Indonesia	Haines and Pranata 1982
	1	Thailand	Sukprakarn and Tauthong 1981
	1, 2, 3, 4	Philippines	Morallo-Rejesus 1979
	1, 10h	Malaysia	Salim 1981; Lim and Tan 1981
		Regional	Morallo-Rejesus 1979
Apate submedia		Thailand	Sukprakarn and Tauthong 1981
Dinoderus bifoveolatus	1, 2, 4, 11	Indonesia	Haines and Pranata 1982
Dinoderus minutus	1, 2, 11	Indonesia	Haines and Pranata 1982
bamboo borer		Malaysia	Morallo-Rejesus 1979
		Thailand	Sukprakarn and Tauthong 1981
Heterobostrychus aequalis		Indonesia	Haines and Pranata 1982
Sinoxylon anale	11	Indonesia	Atmosudirdjo 1981
Xylopsocus capucinus		Indonesia	Haines and Pranata 1982
Prostephanus truncatus	2	Thailand	Sukprakarn and Tauthong 1981
larger grain borer			
Bruchidae:			
Acanthoscelides obtectus	10	Philippines	Baltazar 1969
bean weevil	10	Malaysia	Tee et al. 1983
Callosobruchus Chinensis	10, 10a, 10e	Philippines	Sabio et al. 1984
cowpea weevil	1, 10a, 10i	Indonesia	Haines and Pranata 1982
	10a, 10e	Indonesia	Atmosudirdjo 1981
	10	Malaysia	Lim and Tan 1981
	10	Thailand	Sukprakarn and Tauthong 1981; Tauthong and Wanleelag 1981
		Regional	Morallo-Rejesus 1979
Callosobruchus maculatus	10, 10a, 10e	Philippines	Camarao 1971; Sabio, et al. 1984
southern cowpea weevil	10	Thailand	Sukprakarn and Tauthong 1981
		Indonesia	Haines and Pranata 1982
	10	Malaysia	Tee et al. 1983
		Regional	Morallo-Rejesus 1979
Callosobruchus theobromae		Indonesia	Haines and Pranata 1982
Callosobruchus analis	10, 10e, 10f	Indonesia	Haines and Pranata 1982
Caryedon sp.		Indonesia	Haines and Pranata 1982
Caryedon serratus	10f	Thailand	Sukprakarn and Tauthong 1981
[= C. gonagra]			
Cleridae:			
Necrobia rufipes	2, 5	Philippines	Morallo-Rejesus 1975, 1981
redlegged ham (or copra) beetle	1, 2, 11	Indonesia	Haines and Pranata 1982
	5	Indonesia	Atmosudirdjo 1981
	5	Thailand	Sukprakarn and Tauthong 1981
Necrobia ruficollis		Thailand	Sukprakarn and Tauthong 1981
redshouldered ham beetle			
Cucujidae:			
Cryptolestes ferrugineus	1, 2, 4	Philippines	Mollasgo 1982; Morallo-Rejesus 1975, 1981
rusty grain beetle			
	1, 2, 4, 11	Indonesia	Haines and Pranata 1982
	1	Malaysia	Rahim et al. 1983
		Regional	Morallo-Rejesus 1979

Table 2. (cont.) Insect and mite pests associated with stored commodities in ASEAN.

Pest	Host range^a	Occurrence^b	References
Cryptolestes pusillus	1, 2, 4, 10	Philippines	Morallo-Rejesus 1981
flat grain beetle	1, 2, 4, 11	Indonesia	Prevett 1975; Haines and Pranata 1982
		Thailand	Sukprakarn and Tauthong 1981
	1	Malaysia	Rahim et al. 1983
		Regional	Morallo-Rejesus 1979
Cryptolestes turcicus		Thailand	Sukprakarn and Tauthong 1981
Curculionidae:			
Sitophilus oryzae rice weevil	1, 2, 3, 4, 5, 10	Philippines	Capco 1956; Mollasgo 1982; Baltazar 1969
	1, 2, 4, 10a, 11	Indonesia	Haines and Pranata 1982
	1, 2, 4	Thailand	Sukprakarn and Tauthong 1981
	1	Malaysia	Lim and Tan 1981
		Regional	Morallo-Rejesus 1979
Sitophilus zeamais maize weevil	1, 2, 4, 11	Indonesia	Prevett 1975; Haines and Pranata 1982
	1, 2, 3, 4	Philippines	Santhoy and Morallo-Rejesus 1975; Mollasgo 1982
	1, 2, 4	Thailand	Sukprakarn and Tauthong 1981
		Regional	Morallo-Rejesus 1979
Cylas formicarius	12	Indonesia	Atmosudirdjo 1981
Languriidae:			
Pharaxonatha kirschi Mexican grain beetle	2	Philippines	Baltazar 1969; Morallo-Rejesus 1979
Cerylonidae:			
Murmidius ovalis	1, 13	Indonesia	Haines and Pranata 1982
Colydiidae:			
? *Myrmechixenus* sp.		Indonesia	Haines and Pranata 1982
? *Murmidius segregatus*		Malaysia	Morallo-Rejesus 1979
Dermestidae:			
Attagenus megatoma *[= Attagenus unicolor]* black carpet beetle	2	Philippines	Morallo-Rejesus 1975
Attagenus spp.	1	Indonesia	Haines and Pranata 1982
Dermestes ater	2	Philippines	Morallo-Rejesus 1975, 1981
hide beetle	15	Philippines	Sabio et al. 1984
	1, 10e	Indonesia	Haines and Pranata 1982
		Thailand	Sukprakarn and Tauthong 1981
Trogoderma anthrenoides larger carpet beetle	2	Philippines	Baltazar 1969; Morallo-Rejesus 1981
Attagenus gloriosae *[= Attagenus fasciatus]*		Thailand	Sukprakarn and Tauthong 1981
Thorictodes hydeni	1, 2, 10	Philippines	Sabio et al. 1984
	1, 2	Indonesia	Haines and Pranata 1982
		Malaysia	Morallo-Rejesus 1979
		Thailand	Sukprakarn and Tauthong 1981
Trogoderma granarium	1, 2, 10i, 11, 15, 16	Philippines	Morallo-Rejesus 1979
khapra beetle	1	Indonesia	Sukardi 1978
		Malaysia	Rahim, these proceedings
		Malaysia	Morallo-Rejesus 1979
		Thailand	Sukprakarn and Tauthong 1981; up until 1979

Table 2. (cont.) Insect and mite pests associated with stored commodities in ASEAN.

Pest	Host range[a]	Occurrence[b]	References
Anthrenus fasciatus		Thailand	Sukprakarn and Tauthong 1981
carpet (or museum) beetle			
Anthrenus pimpinellae		Thailand	Sukprakarn and Tauthong 1981
Anthrenus vorax		Thailand	Sukprakarn and Tauthong 1981
Chelonarius indicum		Thailand	Sukprakarn and Tauthong 1981
Dermestes maculatus	5	Thailand	Sukprakarn and Tauthong 1981
hide beetle	15	Philippines	Sabio et al. 1984
Dermestes peravianus		Thailand	Sukprakarn and Tauthong 1981
Thaumaglossa rufocapillata		Thailand	Sukprakarn and Tauthong 1981
Palembos dermetoides		Malaysia	Morallo-Rejesus 1979
Lathridiidae:			
Corticaria sp.	1, 13	Indonesia	Haines and Pranata 1982
plaster beetle			
Mycetophagidae:			
Typhaea stercorea	1, 13	Philippines	Morallo-Rejesus 1975
hairy fungus beetle		Indonesia	Haines and Pranata 1982
		Thailand	Sukprakarn and Tauthong 1981
Merophisiidae:			
Holoparamecus depressus		Indonesia	Haines and Pranata 1982
Nitidulidae:			
Carpophilus dimidiatus	1	Malaysia	Salim 1981; Lim and Tan 1981
corn sap beetle		Thailand	Sukprakarn and Tauthong 1981
	2	Philippines	Baltazar 1969
	1	Indonesia	Haines and Pranata 1982
		Regional	Morallo-Rejesus 1979
Carpophilus pilosellus	1, 2, 4	Indonesia	Haines and Pranata 1982
dried fruit beetles	2	Philippines	Morallo-Rejesus 1975, 1979, 1981
Carpophilus hemipterus	4	Indonesia	Haines and Pranata 1982
Carpophilus mutilatus	1	Indonesia	Haines and Pranata 1982
Carpophilus obsoletus	2	Indonesia	Haines and Pranata 1982
Silvanidae:			
Ahasverus adrena	1, 7	Malaysia	Lim and Tan 1981; Rahim et al. 1983
foreign grain beetle		Thailand	Sukprakarn and Tauthong 1981
		Indonesia	Haines and Pranata 1982
	1, 2, 13	Philippines	Baltazar 1969
		Regional	Morallo-Rejesus 1979
Oryzaephilus mercator	1, 2	Indonesia	Prevett 1975; Haines and Pranata 1982
merchant grain beetle			
	5	Thailand	Sukprakarn and Tauthong 1981
	5, 16	Malaysia	Lim and Tan 1981
Oryzaephilus surinamensis	1, 5	Philippines	Morallo-Rejesus 1979, 1981
sawtoothed grain beetle	1, 2, 4, 10a, 10e	Philippines	Sabio et al. 1984
	1, 2, 10a	Indonesia	Prevett 1975; Haines and Pranata 1982
		Thailand	Sukprakarn and Tauthong 1981
	1, 2	Malaysia	Lim and Tan 1981
		Regional	
Monanus ?concinnulus		Indonesia	Haines and Pranata 1982
Nausibius clavicornis	1	Philippines	Morallo-Rejesus 1979, 1981
Cathartus quadricollis	1, 2	Thailand	Sukprakarn and Tauthong 1981
square-necked grain beetle			
Silvanus sp.		Indonesia	Morallo-Rejesus 1979

Table 2. (cont.) Insect and mite pests associated with stored commodities in ASEAN.

Pest	Host range[a]	Occurrence[b]	References
Scolytidae:			
Hypothenemus hampei	7	Philippines	Morallo-Rejesus 1981
coffee berry borer			
gen. and sp. indet.	14	Indonesia	Haines and Pranata 1982
Tenebrionidae:			
Alphitobius diaperinus		Thailand	Sukprakarn and Tauthong 1981
lesser mealworm	1, 2	Malaysia	Lim and Tan 1981
	1, 2, 3, 13	Philippines	Baltazar 1969; Sabio et al. 1984
	1, 2, 11	Indonesia	Haines and Pranata 1982
		Regional	Morallo-Rejesus 1979
Alphitobius laevigatus		Thailand	Sukprakarn and Tauthong 1981
black fungus beetle		Malaysia	Rahim et al. 1983
	1	Philippines	Baltazar 1969
	1, 2, 10e, 10i, 11	Indonesia	Haines and Pranata 1982
		Regional	Morallo-Rejesus 1979
Coelopalorus foveicollis	1, 2	Philippines	Baltazar 1969
black beetle		Thailand	Sukprakarn and Tauthong 1981
	1, 2, 11	Indonesia	Haines and Pranata 1982
Coelopalorus carunatus		Indonesia	Haines and Pranata 1982
Cynaeus angustus	1, 2	Thailand	Sukprakarn and Tauthong 1981
larger black flour beetle			
Gnathocerus maxillosus	1, 2, 4	Philippines	Baltazar 1969
slenderhorned flour beetle	1	Indonesia	Haines and Pranata 1982
Gnathocerus cornutus		Indonesia	Haines and Pranata 1982
broadhorned flour beetle			
Latheticus oryzae	1	Philippines	Morallo-Rejesus 1975; Sabio et al. 1984
longheaded flour beetle			
	1, 2, 4, 10, 11	Indonesia	Haines and Pranata 1982
		Thailand	Sukprakarn and Tauthong 1981
Palorus ratzeburgii	1, 2	Philippines	Baltazar 1969
smalleyed flour beetle		Thailand	Morallo-Rejesus 1979
		Thailand	Sukprakarn and Tauthong 1981
	1, 2, 4, 10e, 11	Indonesia	Haines and Pranata 1982
Palorus subdepressus	1, 2	Philippines	Morallo-Rejesus 1975; Sabio et al. 1984
depressed flour beetle			
		Thailand	Sukprakarn and Tauthong 1981
	1, 2, 4, 10e, 11	Indonesia	Haines and Pranata 1982
		Regional	Morallo-Rejesus 1979
Palorus genalis	1, 2, 10e, 11	Indonesia	Haines and Pranata 1982
Palorus ficicola		Indonesia	Haines and Pranata 1982
Palorus cerylonoides	1, 2	Indonesia	Haines and Pranata 1982
Palorus beesoni	1	Indonesia	Haines and Pranata 1982
Palorinus humeralis		Indonesia	Haines and Pranata 1982
Tribolium castaneum	1, 5, 8	Malaysia	Lim and Tan 1981
rust-red flour beetle		Thailand	Sukprakarn and Tauthong 1981
	1, 2, 4, 10e, 11	Indonesia	Mangoendihardjo 1981; Atmosudirdjo 1981; Haines and Pranata 1982
	1, 2, 3, 4, 5, 10a, 10e	Philippines	Baltazar 1969; Sabio et al. 1984
		Regional	Morallo-Rejesus 1979
Tribolium confusum	1, 2, 3, 4, 5	Philippines	Baltazar 1969
confused flour beetle		Thailand	Sukprakarn and Tauthong 1981
	1, 2	Indonesia	Prevett 1975; Atmosudirdjo 1981
Gonocephalum sp.	2, 4	Philippines	Camarao 1971
Uloma sp.	2, 4	Philippines	Camarao 1971
Martianus dermestoides		Thailand	Sukprakarn and Tauthong 1981

Table 2. (cont.) Insect and mite pests associated with stored commodities in ASEAN.

Pest	Host range[a]	Occurrence[b]	References
Trogossitidae:			
Lophocateres pusillus	1	Malaysia	Rahim et al. 1983
Siamese grain beetle		Thailand	Sukprakarn and Tauthong 1981
	1, 2	Philippines	Baltazar 1969
	1, 2, 4, 10e	Indonesia	Haines and Pranata 1982
		Regional	Morallo-Rejesus 1979
Tenebroides mauritanicus	1, 2	Philippines	Sabio et al. 1984
cadelle		Thailand	Sukprakarn and Tauthong 1981
	1, 2, 4	Philippines	Capco 1956
	1, 2, 11	Indonesia	Haines and Pranata 1982
		Regional	Morallo-Rejesus 1979
Dytiscidae:			
gen. and sp. indet.	14	Indonesia	Haines and Pranata 1982
Histeridae:			
gen. and sp. indet.	14	Indonesia	Haines and Pranata 1982
Lyctidae:			
gen. and sp. indet.	14	Indonesia	Haines and Pranata 1982
Lyctus brunneus	14	Thailand	Sukprakarn and Tauthong 1981
powderpost beetle			
Rhizophagidae:			
gen. and sp. indet.	14	Indonesia	Haines and Pranata 1982
Anthicidae:			
gen. and sp. indet.	14	Indonesia	Haines and Pranata 1982
LEPIDOPTERA			
Gelechiidae:			
Sitotroga cerealella	1, 2	Thailand	Sukprakarn and Tauthong 1981
Angoumois grain moth	1	Malaysia	Salim 1981; Lim and Tan 1981
	1, 2, 3, 9	Philippines	Baltazar 1969
	1, 2, 4, 10a	Indonesia	Haines and Pranata 1981
		Regional	Morallo-Rejesus 1982
Pyralidae:			
Subfamily Phycitinae:			
Ephestia cautella	1, 8, 10a	Malaysia	Lim and Tan 1981; Rahim et al. 1983
tropical warehouse moth	2, 4	Thailand	Sukprakarn and Tauthong 1981
	2	Philippines	Capco 1956
	1, 2, 10e	Indonesia	Haines and Pranata 1982
		Regional	Morallo-Rejesus 1979
Ephestia kuehniella	2	Philippines	Capco 1956: Morallo-Rejesus 1981
Mediterranean flour moth			
Ephestia elutella	1, 2, 6, 9	Philippines	Capco 1956; Morallo-Rejesus 1981; Baltazar 1969
tobacco moth			
	1	Indonesia	Prevett 1975
Plodia interpunctella	1, 2, 4, 10	Philippines	Capco 1956; Morallo-Rejesus 1975, 1981
Indian meal moth			
	1	Indonesia	Haines and Pranata 1982
	1	Malaysia	Lim and Tan 1981
Subfamily Pyralinae:			
Pyralis farinalis	2	Philippines	Capco 1956; Morallo-Rejesus 1979
meal moth			

Table 2. (cont.) Insect and mite pests associated with stored commodities in ASEAN.

Pest	Host range[a]	Occurrence[b]	References
Subfamily Galleriinae:			
Corcyra cephalonica	1	Thailand	Sukprakarn and Tauthong 1981
rice moth	1, 2, 3, 4	Philippines	Cariño and Morallo-Rejesus 1975; Sabio et al. 1984
	1, 2	Indonesia	Haines and Pranata 1982
	1, 7	Malaysia	Lim and Tan 1981
	2, 11	Indonesia	Mangoendihardjo 1981; Atmosudirdjo 1981
		Regional	Morallo-Rejesus 1979
Doloessa viridis	1, 2, 11	Indonesia	Atmosudirdjo 1981; Mangoendihardjo 1981; Haines and Pranata 1982
green rice moth			
	1	Philippines	Baltazar 1969
	1	Malaysia	Lim and Tan 1981
Tineidae:			
Setomorpha rutella	6	Philippines	Baltazar 1969
tropical tobacco moth		Malaysia	Morallo-Rejesus 1979
		Indonesia	Haines and Pranata 1982
Tinea pellionella	1	Indonesia	Haines and Pranata 1982
casemaking clothes moth			
PSOCOPTERA			
Liposcelidae:			
Embidopsocus sp.	1, 10e, 13	Indonesia	Haines and Pranata 1982
Liposcelis entomophilus	1, 2, 10a, 13	Indonesia	Haines and Pranata 1982
		Malaysia	Morallo-Rejesus 1979
Liposcelus bostrychophilus	1, 2, 11	Indonesia	Haines and Pranata 1982
Psquillidae:			
Rhyopsocus sp.	Indet.	Indonesia	Haines and Pranata 1982
MITES			
gen and sp. indet.	1, 2, 4, 10a, 10e, 10i	Indonesia	Haines and Pranata 1982
Acaridae:			
Aleuroglyphus sp.	1, 15	Philippines	Sabio et al. 1984
Aleuroglyphus ovatus		Indonesia	Haines and Pranata 1982
Caloglyphus hughesi		Indonesia	Haines and Pranata 1982
Caloglyphus oudemansi		Indonesia	Haines and Pranata 1982
Cardoglyphus konoi		Indonesia	Haines and Pranata 1982
	1, 2, 14	Philippines	Sabio et al. 1984
Suidasia pontifica	1, 2	Philippines	Sabio et al. 1984
Suidasia medanensis oudemans		Philippines	Haines 1981
Tyrophagus putrescentiae		Indonesia	Haines and Pranata 1982
Cosmoglyphus laarmani	1	Philippines	Morallo-Rejesus 1979
Glycophagidae:			
gen. and sp. indet.		Indonesia	Haines and Pranata 1982
Uropodidae:			
Leiodinychus sp.	13	Indonesia	Haines and Pranata 1982
	1	Singapore	Haines 1981
Leiodinychus krameri		Indonesia	Haines and Pranata 1982
gen. and sp. indet.	1, 13, 15	Philippines	Sabio et al. 1984

a. Numbers refer to listing in Table 1. The occurrence of insect species does not confirm it is a pest of that commodity.
b. Some species may occur regionally but have not been identified.

Table 3. List of parasites and predators positively identified in surveys conducted in ASEAN countries.[a]

Parasite/predator	Country	References
Class Arachnida		
Subclass Acarina: (Acari – mites)		
Order Prostigmata: (Acariformes)		
Suborder Actinedida:		
Pyemotidae:		
Pyemotes sp. (indet.)	Indonesia	Haines and Pranata 1982
Acaropsis sp.	Philippines	Sabio et al. 1984
Cheyletidae:		
Cheyletus malaccensis	Indonesia	Haines and Pranata 1982
	Philippines	Sabio et al. 1984
Tarsonemidae:		
Tarsonemus fusarii	Philippines	Sabio et al. 1984
Tydeidae:		
Tydeus sp.	Philippines	Sabio et al. 1984
Order Mesostigmata (Parasitiformes)		
Suborder Parasitoidea (Gamasina):		
Ascidae:		
Blattisocius dentriticus	Indonesia	Haines and Pranata 1982
Blattisocius keegani	Indonesia	Haines and Pranata 1982
Blattisocius tarsalis	Indonesia	Haines and Pranata 1982
Blattisocius sp.	Philippines	Sabio et al. 1984
Agistemus sp.	Philippines	Sabio et al. 1984
Lasioseius sp.	Philippines	Sabio et al. 1984
Subclass Pseudoscorpiones		
Cheliferidae:		
gen. and sp. indet.	Indonesia	Haines and Pranata 1982
Withius subruber	Indonesia	Haines 1981
Subclass Aranea (Araneae)		
Thoridiidae:		
Thoridion sp.	Singapore	Haines 1981
fam. indet.	Indonesia	Haines and Pranata 1982
Subclass Opiliones:		
fam. indet.	Indonesia	Haines and Pranata 1982
Class Insecta:		
Order Hemiptera – Heteroptera		
Reduviidae:		
gen. and sp. indet.	Philippines	Sabio et al. 1984
Peregrinator biannulipes	Indonesia	Haines and Pranata 1982
? Vesbius sp.	Indonesia	Haines and Pranata 1982
Lyctocoridae:		
Xylocorus? flavipes	Indonesia	Haines and Pranata 1982
Order Hymenoptera		
Braconidae:		
Bracon hebator	Indonesia	Haines and Pranata 1982
Chalcididae:		
Euchalcidia sp.	Indonesia	Haines and Pranata 1982
Pteromalidae:		
Anisopteromalus calandrae	Indonesia	Haines and Pranata 1982
Chaetospila elegans	Indonesia	Haines and Pranata 1982
Dinarmus laticeps	Indonesia	Haines and Pranata 1982
Bethylidae:		
Cephalonomia tarsalis	Indonesia	Haines and Pranata 1982
Cephalonomia waterstoni	Indonesia	Haines and Pranata 1982

Table 3. (cont.) List of parasites and predators positively identified in surveys conducted in ASEAN countries.[a]

Parasite/predator	Country	References
Holepyris hawaiiensis	Indonesia	Haines and Pranata 1982
Plastanoxus (?) *munroi*	Indonesia	Haines and Pranata 1982
Rhabdepyris seae	Indonesia	Haines and Pranata 1982
Order Coleoptera		
Carabidae:		
gen. and sp. indet.	Indonesia	Haines and Pranata 1982
Dioryche sp.	Thailand	Sukprakarn and Tauthong 1981
Dioryche indochinensis	Thailand	Sukprakarn and Tauthong 1981
Cleridae:		
Thanoclerus buqueti	Indonesia	Haines and Pranata 1982
	Thailand	Sukprakarn and Tauthong 1981
Histeridae:		
Carcinos troglodytes	Indonesia	Haines and Pranata 1982

a. Parasites and predators have rarely been unequivocally associated with their specific hosts. This list records the presence only of recognised parasites and predators.

viridis are regionally distributed, but *Plodia interpunctella* appears to be on the decline, especially in the Philippines (Morallo-Rejesus 1979).

Sabio et al. (1984) found little difference between storage types with regard to the species of pests present, mainly due to the uniformity of commodities stored. In Indonesia, on the other hand, Haines and Pranata (1982) found significant differences between storage type and the complex of pests encountered.

Tribolium castaneum was found to be very common in commercial as well as BULOG, cooperative, and private stores. This is indicative of the relatively long-term storage of cereals and byproducts, as well as a lack of adequate store management in some instances. *Tribolium castaneum* was less abundant in retail outlets because of competition from other tenebrionid species present. Neither is it common in farm storage, since at this level rice is stored as paddy.

The psocid *Liposcelis entomophilus* was found to be common in BULOG stores, less so in commercial stores, and completely absent from farmers, cooperative, and retail stores. When it does occur, it is extremely abundant, and almost exclusively associated with government rice stocks which are frequently treated with pesticides. There is some evidence to suggest that its resurgence is associated with the demise of the cheyletid predator *Cheyletus malaccensis.*

Most of the surveys focusing on insect distribution and abundance have demonstrated relationships between species found, types and varieties of commodities stored, and the type of storage. However, data about some pest/commodity associations are still lacking.

The major insect pests infesting pulses and soybeans in the Philippines are *Callosobruchus maculatus* and *Callosobruchus chinensis* (Sabio et al. 1984). These species are recognised as major pests in the other ASEAN countries. However, *Callosobruchus analis* appears quite frequently and in abundance in Indonesia, and has been recorded in Thailand.

The major pests of stored cassava chips are *Araecerus fasciculatus, R. dominica,* and *Lasioderma serricorn* (Parker and Booth 1979; Sukprakarn and Tauthong 1981), but in the territory of Yogyakarta, Indonesia, *S. oryzae* and *T. castaneum* also contribute significantly to the large losses that are regularly incurred (Mangoendihardjo 1981). *Araecerus fasciculatus* is also frequently associated with stored coffee beans in Malaysia (Tee et al. 1983).

Necrobia rufipes is the major pest of stored copra and, in Malaysia, *L. serricorne* attacks copra cakes in oil mills (Tee et al. 1983). *Oryzaephilus mercater* and *Desmestes maculatus* are the common pests of copra in Thailand (Sukprakarn and Tauthong 1981). *Lasioderma serricorne* and, to a lesser extent, *Ephestia elutella* are the main tobacco pests and *L. serricorne* and *E. cautella* are the common pests of stored cacao beans and chocolate confectionary (Tee 1982).

Vertebrate Pests

The most common rodent and bird species infesting grain storages in ASEAN are given in Table 4. The most common rodent pests throughout the region appear to be *Rattus norvegicus*, different subspecies of *Rattus rattus*, and *Mus musculus*. Rahim et al. (1983) have shown that rodent infestation in the Tanjung Karang area of Malaysia is quite variable in farm storage. However, heavy infestations were recorded at three farm storages that were evaluated. Between 32% and 46% of traps set during an 8-week assessment period caught rodents.

In the Philippines, *R. norvegicus* and *R. rattus mindanensis* were the most dominant in storage, constituting 80 and 20% of the total rodent population, respectively, in a study of grain storages conducted by the National Post-Harvest Institute for Research and Extension (NAPHIRE), a subsidiary of the National Food Authority (NFA). Average daily food consumption of rodents was estimated at 10% (range 7–15%) of

Table 4. The most commonly encountered species of rodents and birds infesting grain storages in the ASEAN region.

Pest	Occurrence	References
RODENTS		
Muridae:		
Rattus norvegicus	Philippines	Caliboso 1982b
Norway rat	Malaysia	Tee et al. 1983
	Indonesia	Soekarna et al. 1977
Rattus rattus diardii	Malaysia	Tee et al. 1983
Malaysian house rat	Indonesia	Soekarna et al. 1977
Rattus rattus mindanensis	Philippines	Caliboso 1982b
common ricefield rat	Philippines	Sayaboc et al. 1984
Rattus argentiventer	Philippines	Caliboso 1982
	Malaysia	Shamsuddin et al. 1981
Rattus exulans	Malaysia	Tee et al. 1983
little house rat (Burmese, or Polynesian rat)		
Mus musculus	Malaysia	Tee et al. 1983
house mouse	Philippines	Caliboso 1982b
Mus musculus castaneus	Indonesia	Soekarna et al. 1977
Suncus murinus	Indonesia	Soekarna et al. 1977
BIRDS		
Order Passeriformes:		
Suborder Tyranni:		
Pipridae: (Manakins)		
Lonchura sp.	Philippines	Caliboso 1982b
Lonchura leucogastra white-breasted manakin	Philippines	Caliboso 1982b
Lonchura punctulata nutmeg manakin	Philippines	Caliboso 1982b
Lonchura malacca chestnut manakin	Philippines	Caliboso 1982b
Suborder Oscines:		
Ploceidae = (Weavers and Sparrows)		
Padda oryzivora Java sparrow	Philippines	Caliboso 1982b
Passer montanus tree or house sparrow	Philippines	Caliboso 1982b
Passer domesticus house sparrow	Malaysia	Tee et al. 1983
Acridotheres tristis tristis common mynah	Malaysia	Tee et al. 1983
Order Columbiformes		
Columbidae:		
Columbia livia feral pigeon	Malaysia	Tee et al. 1983

body weight, while grain consumption varied from 90% of food intake in private warehouses to 99.5% in government warehouses (Sayaboc et al. 1984). It was further estimated that rodents cause spillage of as much as 7.5 times the amount of grain consumed. This can be recovered, but at an additional cost for processing. Grains contaminated with rodent hairs, faeces, and urine were infected with storage fungi such as *Aspergillus flavus* and *Aspergillus ochraceous*, as well as bacteria responsible for food poisoning, and these probably constitute the major form of loss and hazard.

The main bird species present in grain storages throughout the region are members of the sparrow genus *Passer*. The importance of bird infestations has not been quantified, but they pose problems similar to those of rodents. They damage bagged commodities by their feeding, cause excessive spillage and hazards to workers by the bags they dislodge (Rahim 1979), and contaminate the storage environment and commodities with their droppings which are likely to be infected by food-poisoning *Salmonella* spp.

Primarily a seed-eater, *Passer montanus* has been shown to consume 30% of its body weight per day, with grain comprising 91–97% of the diet of birds trapped in private and NFA stores (Caliboso 1982b). Daily consumption was estimated at 5.6 g per bird weighing 20 g, but again spillage constituted the major form of physical loss.

Losses Due to Storage Pests

The results of some of the loss assessment studies and laboratory evaluations that have been conducted in ASEAN grain storage systems are given in Table 5.

Table 5. Estimates of losses due to pests in various stored products in ASEAN, based on field and laboratory evaluations.

Commodity	Estimated weight loss[a] (%)	Cause	Remarks	References
Philippines				
maize (shelled)	43	insects, rodents	NFA storage, 13 months	Caliboso 1977
native rice	26	"	"	"
China rice	24	"	"	"
Thai rice	13	"	"	"
white and yellow maize (grits)	24	"	12 months storage	Semple et al. 1983
milled rice	0.1	*S. zeamais*	laboratory storage, 6 months	Morallo-Rejesus and Javier 1979
paddy	0.5	"	"	"
maize	6.6	"	"	"
sorghum	5.5	"	"	"
milled rice	5	*R. dominica*	"	"
paddy	3.6	"	"	"
maize	1.6	"	"	"
sorghum	3.3	"	"	"
maize	10.7	insects (29.95%) damaged kernels	8 months storage, 200 bagged tonne stacks; 7.6–9.8% moisture content	Sabio et al. 1984
maize	2.4	insects	3–10 months (EIL; calculated)[b]	"
maize	2.3	insects	2.94 months (ETL; calculated)[c]	"
paddy	5	insects 6.68% insect-damaged kernels	200 t bagged stacks; 9.8–11.2% m.c., 7 months storage	"
paddy	1.8	insects	5.17 months (ETL; calculated)	"
paddy	2.9	insects	7.57 months (EIL; calculated)	"

Table 5. (cont.) Estimates of losses due to pests in various stored products in ASEAN, based on field and laboratory evaluations.

Commodity	Estimated weight loss[a] (%)	Cause	Remarks	References
white maize (whole)	1.1	insects 6.25% insect-damaged kernels	miller's storage	Unpublished Report, ASEAN-Australia Project 1985
Indonesia				
maize	3–6	insects, rodents	BULOG central storage up to 9 months	Semple, unpublished data
legumes	5	”	unspecified storage	
rice	2–5	all causes	storage	Anon. 1978
cassava (dried)	10–12	insects, water loss	annually	Mangoendihardjo 1981
maize	26–29	insects only	9 months storage, bags and bamboo baskets	Paransih Isbagijo 1981
paddy	12	all postharvest losses	farm level, East Java wet season	FAO survey, Damardjati et al. 1984
paddy	11	”	dry season as above	”
paddy	25 (5.5% storage)	”	BULOG estimate	Pratomo et al. 1979
paddy	0.9–5.9 Ave. 0.65	insects, rodents	maximum range and average for Sth. Kalimantan; Sth. Sulawesi; W. Java; and Aceh provinces (losses in quantity only)	Anon. 1982
paddy	4–23 (% quality loss only)	discoloured, damaged and broken kernels	average range of 4 provinces (as above), and average of all quality losses, 6 months storage, KUD DOLOG and farm level	Anon. 1982
Malaysia				
rice	5	all causes	farm storage	Anon. 1978
cassava (chips)	16	*A. fasciculatus* *L. serricorne* *R. dominica*	2 months storage	Tee et al. 1983
paddy	2–5	all causes	3 months storage; small mill; Tanjung Karang	Rohani and Samsuddin 1984
paddy	14–38	same, mainly hot-spots and yellowing	large mills 2000–10 000 t cap.; bulk Tanjung Karang; 3–9 months storage	”
paddy	1–34	same, mainly hot spots and yellowing (vertical concrete bins)	LPN complexes Tanjung Karang; 6000 t cap., bulk aeration at 0.3 m^3/t min. reduced yellowing to 1.5%; long-term storage 9 months	”
milled rice	3.9–7.7	*C. cephalonica*	laboratory evaluation (larval development period at 4 moisture contents)	Osman 1984
millet	13–16	”	laboratory evaluation (larval development period at 4 moisture contents)	”
Thailand				
soybeans	12–15	insects, rodents	farm storage	
rice	1.5–3.5	all causes	on-farm storage	Anon. 1978

Table 5. (cont.) Estimates of losses due to pests in various stored products in ASEAN, based on field and laboratory evaluations.

Commodity	Estimated weight loss[a] (%)	Cause	Remarks	References
paddy	5.1	insects, rodents and birds	6–12 months storage	
paddy	1.1–3.4	insects	farm storage, 8 months	Kajarnvech and Wilpanit 1971
paddy	5	"	commercial storage, 12 months	"
paddy	0.05–10.5	"	12 months storage	Sukprakarn 1976
soybeans	0.6–68	all causes	central storage	Anon. 1978
groundnuts	0.3–16	"	"	"
All Developing Countries				
staple cereals	12	"	farm level storage using improved varieties	Huysmans 1982
staple cereals	3 (but generally 5–8)	"	farm level storage; traditional with unimproved varieties	Calverley 1984; Greeley 1980

[a] Rounded off to two significant figures.
[b] EIL = economic injury level.
[c] ETL = economic threshold level.

The accurate determination of storage losses due to various agencies is often performed simply to justify changes to the existing system, or the injection of high technology and sophisticated control techniques. Postharvest losses in farm level storage by traditional methods appear quite low, but the introduction of HYVs has taxed the ability of traditional handling, drying, and storage systems to cope with the larger quantities being produced, especially during the wet season harvest. The low benchmark of losses encountered in traditional, unimproved farm level storage systems should be recognised as the acceptable level of loss attainable. Low-cost control methods become more relevant in this form of storage and care should be exercised that the improved technologies often advocated do not put the farmer at a disadvantage (Tyler 1982). At the national and commercial levels of storage, capital intensive but cost-effective control measures assume greater importance, since reserves or carry-over buffer stocks are often stored for more than 12 months, and losses in this type of storage can be extremely high.

The accuracy and comparability of loss assessment methods are difficult to ascertain. Due to lack of standardisation of methodology and the variable climatic conditions under which commodities are grown, harvested, stored, processed, and handled, estimates are extremely variable from commodity to commodity and from country to country or even different parts of the same country (Tyler 1982). Storage losses have, however, been quantified more accurately by an accounting and inventory system (Caliboso 1982a; Caliboso and Teter 1983), which is being field evaluated in Iloilo, Philippines for paddy, and two NFA warehouses in Cebu and Manila for yellow corn (maize). Further evaluations of the concept are anticipated for the remaining ASEAN countries (Anon. 1985).

Morallo-Rejesus (1982b), using the loss estimates of Caliboso (1977) for maize (see Table 6), calculated that 71.27% of the increased production of maize in 1977 over 1976 was lost to insects during storage. Schulten (1982) listed several constraints to the effective implementation of postharvest loss reduction in tropical Africa. They appear, in principle, to be just as applicable to ASEAN countries. Schulten's constraints include:

(1) lack of coordination among the various national institutes/agencies involved in loss prevention;
(2) lack of trained personnel in research, warehouse management, quality control, and extension;
(3) lack of information on postharvest technologies that have proved effective elsewhere;
(4) lack of accurate information on the magni-

Table 6. Active ingredients and formulations of pesticides used in or recommended for use in the ASEAN grain storage system.

Active ingredient	Formulation	Chemical name
Organophosphorus Insecticides		
Pirimiphos-methyl	50% EC 25% EC	2-diethylamino-6-methyl pyrimidin-4-yl-dimethyl phosphorothioate
Phoxim	5% dust	a-cyanobenzylidineamino diethyl phosphorothioate
Chloropyrifos	20% EC	diethyl 3,5,6-trichloro pyridyl phosphorothioate
Malathion	57% EC 96% tech. grade (fogging)	S/1,2,-di(ethoxy carbonyl) ethyl/dimethyl phosphorodithioate
Tetrachlorvinphos	24% EC (Ind) 75% W.P. (Th)	2-chloro-1-(2,4,5-trichloro phenyl) vinyl dimethyl phosphate
Fenitrothion	100% EC, 50% EC (25% WP avail)	3-methyl-4-nitrophenyl dimethyl phosphorothioate
Dichlorvos	93% EC (fog) 50% EC	dimethyl 2,2-dichlorovinyl phosphate
Chloropyrifos-methyl	50% EC	3,5,6-trichloropyrid-2-yl dimethyl phosphorothioate
Methacrifos	95% EC	0-(2-methoxy carbonyl prop-1-envyl)-0,0-dimethyl phosphorothioate
Etrimphos	50% EC	0-6-ethoxy-2-ethyl-pyrimidin-4-yl 0-0-dimethyl phosphorothioate
Synthetic pyrethroids		
Bioresmethrin	0.2% RM 5% EC, (10:1 PPB) 20% EC	5-benzyl-3-(furylmethyl (+)-*cis, trans,* chrysanthemate
Permethrin	5% dust 25% WP	3-phenoxybenzyl (RS)-*CIS, trans*-3-(2,2,-dichlorovinyl)-2,2-dimethyl cyclopropane carboxylate
Cypermethrin	15% EC	(RS)-alpha-cyano-3-phenoxybenzyl (IRS)-cis, trans-3-(2,2-dichlorovinyl)-2,2 dimethyl-cyclopropanecarboxylate
Deltamethrin	2.5% EC	Alpha-1-cyano 3-phenoxybenzyl *cis,* 2,2-dimethyl (2,2-dibromevinyl) cyclopropane carboxylate
Carbamates (Singapore only)		
Bendiocarb		2,3-isopropylidenedioxyphenyl methyl carbamate (I)
Propoxur	20% EC	2-isopropoxyphenyl N-methyl carbamate

tude of losses in different operations within the postharvest system;
(5) lack of appropriate loss assessment methods;
(6) lack of storage capacity;
(7) lack of an effective transport and distribution system;
(8) lack of grades and standards that can be applied in the field for assessing quality; and
(9) lack of differential pricing of the various grades to create incentives for farmers to deliver better quality grain, and for the investment in improved facilities such as dryers at the neighbourhood, association, or cooperative level and appropriate storage systems that facilitate the implementation of suitable pest control strategies.

As reiterated by Tyler (1982), there must be a national commitment towards identifying the major causes of loss, their extent, and where they occur, and developing a coordinated national plan of action to reduce these losses, in conjunction with productivity programs under way. Various working groups have now been formed, such as the Committee for the Coordination of Post-Harvest Research and Evaluation of Post-Harvest Technology in Thailand, and the National Committee on Food Crops Post-Harvest Programme in Indonesia to coordinate postharvest research and development activities (Anon. 1985).

Losses cannot be considered in isolation.

Studies must be linked with assessments of the benefits of loss reduction activities to determine the extent of loss reduction activities that is economic. The cost-effective course may be to accept all or part of current losses.

Pest Control Methods

Use of Pesticides

A comprehensive listing of the various insecticides and fumigants being applied to food, feed, and seed grains in ASEAN is given in Table 7.

These schedules are principally the ones being used by the national grain agencies. They therefore represent only what is recommended and not necessarily the use of pesticides in this sector, the commercial sector, or on-farm. The proprietary names and formulations being used are given in Table 6.

Admixture of grain protectants for food, feed, and seed is recommended only in Thailand. These materials, however, are not used for farm storage

Table 7. Pesticide schedules (dosage and frequency) of the national grain storage agencies of ASEAN.

Purpose and insecticide used (a.i.)	Country									
	Philippines		Malaysia		Thailand		Indonesia		Singapore	
	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)
1) Protective spray for bag stacks (1 l/20m^2; or 600 ml/20 m^2 for Indonesia)										
— Malathion	1	x4/ month	0.5–2.0 400 ml–1 l/20 m^2	—	—	—	—	—	—	—
— Pirimiphos-methyl	0.5	every 3 weeks	—	—	—	—	1.5	every 3 weeks; used frequently	—	—
— Bioresmethrin	0.2	x2/month	—	—	—	—	—	—	—	—
— Permethrin	0.1	x2/month	—	—	—	—	—	—	—	—
— Methacrifos	being evaluated		—	—	—	—	3.3	every 6 weeks; used frequently	—	—
— Deltamethrin	—	—	—	—	—	—	—	—	2.5	occasionally
— Tetrachlorvinphos	—	—	—	—	—	—	2.2	every 4 weeks; used frequently	—	—
— Fenitrothion	—	—	0.5–2.0 (400 ml–1 l/20 m^2)	—	—	—	—	—	—	—
— Dichlorvos (DDVP)	—	—	(400 ml–1 l/20 m^2)	—	—	—	1.0	every 3 weeks; infrequently	—	—
2) Structural treatment (1 L/20 m^2 or 600 mL/20 m^2 for Indonesia)										
— Permethrin	0.1	x1/3 monthly	—	—	—	—	—	—	—	—
— Propoxur	—	—	—	—	—	—	—	—	2.5–5	x1/2 monthly
— Dichlorvos (DDVP)	2	x1/3 monthly	0.5–2.0	—	—	—	1.0	every 3 weeks; infrequently	—	—
— Fenitrothion	not now used		0.5–2.0	—	—	—	—	—	—	—
— Bendiocarb	—	—	—	—	—	—	—	—	15g/5L	x1/2 monthly

Table 7. (cont.) Pesticide schedules (dosage and frequency) of the national grain storage agencies of ASEAN.

	Country									
	Philippines		Malaysia		Thailand		Indonesia		Singapore	
Purpose and insecticide used (a.i.)	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)
— Tetrachlorvinphos	2	x1/3 monthly	—	—	—	—	2.2	every 4 weeks; infrequently	—	—
— Malathion	—	—	0.5–2.0	—	—	—	3.3	every 6 weeks; used frequently	—	—
— Methacrifos	being evaluated		—	—	—	—	3.3	every 6 weeks	—	—
— Azamethiphos	being evaluated		—	—	—	—	—	—	—	—
— Azamethiphos	trials planned		—	—	—	—	—	—	—	—
— Pirimiphos-methyl	—	—	—	—	—	—	1.5	every 3 weeks	—	—
3) Sack impregnation										
— Chlorpyrifos (20% EC)	—	—	—	—	0.4	—	—	—	—	—
— Phoxim (2% Dust)	—	—	—	—	1.0	—	—	—	—	—
— Pirimiphos-methyl (50% EC)	—	—	—	—	1.0	—	—	—	—	—
— Malathion (57% EC)	—	—	—	—	1.0	—	—	—	—	—
— Tetrachlorvinphos (75% WP)	—	—	—	—	1.0	—	—	—	—	—
4) Grain admixture										
a) For food and feed										
— Pirimiphos-methyl (50% EC)	—	—	—	—	5–10 mg/kg	—	being evaluated on corn		—	—
— Permethrin	—	—	—	—	—	—	being evaluated on corn		—	—
— Tetrachlorvinphos (75% WP)	—	—	—	—	15–30 mg/kg	—	—	—	—	—
— Malathion (57% EC)	—	—	—	—	20–30 mg/kg	—	—	—	—	—
— Methacrifos (50% EC)	—	—	—	—	5–10 mg/kg	—	—	—	—	—
— Deltamethrin (2.5% EC)	—	—	—	—	0.25–0.5 mg/kg	—	—	—	—	—
— Cypermethrin (15% EC)	—	—	—	—	1.5–2.0 mg/kg	—	—	—	—	—
b) For seed (6 months protection)										
— Chlorpyrifos-methyl (50% EC)	—	—	—	—	10–20 mg/kg	—	—	—	—	—
— Malathion (57% EC)	—	—	—	—	20–30 mg/kg	—	—	—	—	—
— Etrimphos (50% EC)	—	—	—	—	5–10 mg/kg	—	—	—	—	—
— Tetrachlorvinphos (75% WP)	—	—	—	—	15–30 mg/kg	—	—	—	—	—
— Chlorpyrifos (20% EC)	—	—	—	—	10–20 mg/kg	—	—	—	—	—
— Baythion (3% Dust)	—	—	—	—	15–20 mg/kg	—	—	—	—	—
— Fenitrothion (50% EC)	—	—	—	—	20–25 mg/kg	—	—	—	—	—
— Pirimiphos-methyl (50% EC)	—	—	—	—	5–10 mg/kg	—	—	—	—	—

Table 7. (cont.) Pesticide schedules (dosage and frequency) of the national grain storage agencies of ASEAN.

Purpose and insecticide used (a.i.)	Country									
	Philippines		Malaysia		Thailand		Indonesia		Singapore	
	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)
5) Fogging										
— Malathion	2 (390 ml/ 500 m³)	as needed	—	—	—	—	—	—	—	—
— Dichlorvos	0.2 (400 ml/ 500 m³)	x1/month	—	—	—	—	—	—	—	—
Bioresmethrin (ULV)	0.2 (150 ml/ 500 m³)	x1/ month	—	—	—	—	—	—	—	—
(Those being tested in Thailand, Sukprakarn, 1983)										
— Pirimiphos-methyl (50% EC)	—	—	—	—	10 ml/ 50 ml diesel to 50 m³	1 week before loading bulk; 4–7 months protection against *S. cerealella*	—	—	—	—
— Chlorpyrifos-methyl (50% EC)	—	—	—	—	”	”	—	—	—	—
— Cypermethrin (15% EC)	—	—	—	—	20 ml/ 50 ml diesel 50 m³	”	—	—	—	—
— Deltamethrin (2.5% EC)	—	—	—	—	”	”	—	—	—	—
6) Fumigation										
— Methyl bromide, 98% and Chloropicrin, 2%	1–2.5 lb per 1000 ft³ or 16–40 g/m³, 24–48 hr exposure	once every 3 months or as needed	24 g/m³	—	2 lb/ 1000 ft³ or 325 g/m³, 24 hr exposure	Just before export	21 g/t; 16 g/m; 24 hr exposure	Subject to level of infestation	2.5 lb/ 1000 ft³ or 40 g/m³; 24 hr exposure	every 2–2½ months entire w/house; treated in total
Phosphine generating formulations: — Phostoxin (aluminium phosphine, 56%)	15–45 tablets/ 1000 ft³; approx. 0.5–1.5 g/m³, 72 hr exposure	once every 3 months	—	—	3–5 g/t or 2 g/m³, 72 hr exposure	Mainly at export terminal before shipment	6 g phosphide/t; 2 g/t; 72 hr exposure	Applied subject to population level	Not used	
— Detia gas (aluminium phosphide, 57%)	3–5 bags/ 1000 ft³; or 1–2 g/m³; 72 hr exposure	once every 3 months	—	—	MOF up-country storages, maize in silos 3 g/t as above		5.7 g phosphide/t 72 hr exposure (2 g/t)	Applied subject to population level	—	—

Table 7. (cont.) Pesticide schedules (dosage and frequency) of the national grain storage agencies of ASEAN.

Purpose and insecticide used (a.i.)	Country									
	Philippines		Malaysia		Thailand		Indonesia		Singapore	
	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)	D (%)	F (%)
— Gastoxin (aluminium phosphine, 55%)	—	—	—	—	as above		2 g/tonne 72 hr exposure	Applied subject to population level	—	—
— Celphos	—	—	—	—	as above		—	—	—	—
7) Rodenticides:										
Anticoagulants										
a) Hydroxycoumarin group:	—	—	—	—	—	—	—	—	—	—
— Coumatetralyl (Racumin)	—	—	as bait 1:20 0.75%	—	—	—	as bait 1:20 0.75%	—	not used	
— Coumachlar (Ratilan)	—	—	ready mixed black 0.25%		—	—	ready mixed black 0.25%		—	—
— Difenacoum	0.005 as needed		—	—	—	—	—	—	—	—
— Bromdifacoum	—	—	—	—	—	—	—	—	—	—
— Warfarin	0.025 as needed		—	—	—	—	—	—	—	—
b) Indane-dial group:										
— Chlorophacinane	—	—	0.005	—	—	—	—	—	—	—

and the Marketing Organisation for Farmers (MOF) uses only fumigation in maize storages. Similarly, commercial traders rely solely on fumigation just before export. One private mill uses malathion and baythion for fabric treatments, and the Department of Agriculture uses malathion for seed treatment.

In Indonesia, the National Logistics Agency (BULOG) is planning to evaluate both permethrin and pirimiphos-methyl as grain protectants for maize. Although grain admixture is not practised in Indonesia, Pranata et al. (1983) have demonstrated the efficacy of a single application of permethrin at 5 ppm, in controlling *R. dominica, S. oryzae,* and *S. zeamais* in paddy and milled rice for 6 months. *Tribolium castaneum* were slow to die but their reproduction was almost completely suppressed. *Liposcelis* spp., on the other hand, remained abundant, being seemingly unaffected by the insecticide and enjoying the lack of competition from other species.

Sack impregnation in preference to treating the bagged stack in situ is at present recommended only in Thailand. In the Philippines, Cariño and Morallo-Rejesus (1976) have shown that application of tetrachlorvinphos and pirimiphos-methyl as a preharvest spray to sorghum which was then stored in sacks impregnated with these insecticides as well as malathion (at 2 and 4%) gave protection from *S. zeamais, R. dominica,* and *T. castaneum* for a period of 6 months. Dipping or spraying all sack surfaces with a 2% solution of malathion or pirimiphos-methyl offered better protection for 12 months against *R. dominica, T. castaneum, C. cephalonica,* and *S. oryzae* than simple spraying of two surfaces of the sack (Morallo-Rejesus and Javier 1981).

Looking at the formulations available for use in grain storage, it appears that little attention has been given to the superiority of wettable powder (W.P.) formulations over emulsifiable concentrates (E.C.) for fabric treatment of porous surfaces, particularly concrete. The ‘filtration’ effect is appreciated and well documented (Parkin 1966; Watters and Grussendorf 1969). W.P. formulations of azamethiphos and deltamethrin have been shown to be effective structural treatments especially on concrete, and against O.P.-resistant *R. dominica* (Williams et al. 1982, 1983). Permethrin is the only insecticide used in W.P. formulation throughout the region.

Differences in efficacy also exist when insecticides are applied to the surfaces of commodity stacks composed of either polypropylene or jute bags. Webley and Kilminster (1980) have shown that fenitrothion, malathion, pirimiphos-methyl, and permethrin were less persistent on polypropylene and resulted in higher grain residues than on jute sacking. However, bioassays showed that the higher deposits on jute were generally unavailable. Therefore, the best insect control coupled with low grain residues will be achieved with a W.P. formulation of a less mobile insecticide of low volatility. Similar differences were observed with methacrifos and pirimiphos-methyl when applied on jute and polypropylene sacks at 1 g/m^2 active ingredient (Sabio et al. 1984). The higher residues of pirimiphos-methyl on jute and polypropylene as compared with high grain residues in treated jute sacks indicate pirimiphos-methyl is better suited to sack impregnation.

Grain fumigations using methyl bromide have generally been recommended at higher than normal dosages which is indicative of some control failures in Singapore, and rejections of export commodities from Thailand. Because survivors, particularly of *T. castaneum* in milled rice exported from Thailand after fumigation with methyl bromide, are re-exposed to further treatments on receival at the International Trading Company's (INTRACO) warehouses, resistance could develop, although this has not been confirmed. Other factors such as poor fumigant distribution (through lack of recirculation), incorrect dosing and exposures, and inadequate sealing leading to rapid gas loss are probably contributing to the lack of control.

The pest resistance profile of insect species to residual contact insecticides is poorly defined in most ASEAN countries. In Thailand, where malathion use is widespread and the insecticide is applied at higher dosages than those recommended, resistance to malathion is widespread, particularly in *T. castaneum*, and in *S. oryzae* (Sukprakarn, personal communication). In Indonesia, Osman and Morallo-Rejesus (1981) detected resistance to malathion in 87.5% of samples of *T. castaneum* collected from BULOG and commercial godowns, Village Unit Cooperative (KUD) stores, and on-farm storage. None of the samples tested was resistant to pirimiphos-methyl.

In the Philippines, malathion resistance in *T. castaneum* is widespread with 75% of the strains tested showing resistance specific to malathion and the remainder a non-specific resistance which included pirimiphos-methyl. All strains of *S. zeamais* were susceptible to both malathion and pirimiphos-methyl, while 80% of strains of *R. dominica* were resistant to malathion with only 20% also resistant to pirimiphos-methyl. However, the number of strains evaluated in these studies was too low for definitive interpretation (NAPHIRE, unpublished data). Commercial millers in the Philippines importing wheat and maize usually store it in vertical, concrete silos. Malathion is applied to the grain as it travels via conveyor belt from barges to the silos. It is unlikely that this procedure is achieving adequate protection or control. If the resistance profile of the strains of the major target species warrants it, trials should be undertaken to identify suitable techniques and replacement protectants or combinations of protectants. The aim would be to restrict dosage rates and costs while achieving broad spectrum protection, if the resistance profile of the strains of the major target species warrants this approach.

Integration with Other Control Methods

Sayaboc et al. (1984) have demonstrated the cost effectiveness of a rodent control regimen consisting of poison baiting, warehouse trapping, and maintenance of maximum levels of warehouse sanitation, both in and around the structure. This strategy reduced losses due to rodents by as much as 87%. Similarly, the same authors established that the potential monetary returns from fumigation with phosphine-generating formulations in both paddy and maize, and maintenance of maximum levels of warehouse sanitation, in terms of reduced losses by insect pests, are greater than the costs of implementing the control techniques.

At the farm level, control measures are more traditional in nature. In Thailand, admixture of ricehull ash at 10 g/kg of maize grain, rock phosphate at 15–20 g/kg, and castor oil of 5 ml/kg have been used (Sukprakarn 1984). Extracts of black pepper have been evaluated in the Philippines (Javier and Morallo-Rejesus 1982) and neem in Malaysia (Rahim 1984). Other vegetable oils such as palm oil, bran oil, peanut oil, and corn oil at 5–15 ml/kg have provided insect control for 4 months on legume seed without affecting seed viability (Sukprakarn and Tauthong 1981).

For large-scale application, other forms of insect control by grain irradiation, and by fluidised bed and microwave heating have been described in

Malaysia (Lim et al. 1980). The use of CO_2 disinfestation of bagged milled rice under sealed plastic sheets that remain in place has been demonstrated as a most cost effective and practical method for long-term (18–24 months) storage in Indonesia (Sukardi and Martono 1983; Suharno 1984). A preliminary trial conducted in 1984 was inconclusive because of inadequate sealing of the enclosure.

Singapore is developing a technology of integrated control involving initial disinfestation of milled rice using methyl bromide fumigation in plastic enclosures in open ventilated warehouses, transferring milled rice to rigid, well-sealed compartments under CO_2, thorough cleaning to remove living or dead insects or insect fragments, frass, rodent hairs, etc., and then packing rice in 5 kg PVC bags for distribution. The new storage facility at Pepys Road, Singapore consists of two blocks with a total storage capacity of 19 400 tonnes of milled rice. One block consists of 10 compartments (15.7 x 34 x 7 m high) each holding 1200 t of bagged milled rice, while the second block consists of 5 similar compartments and floor area for the packaging plant and storage of packaged, insect-free rice prior to distribution. Initially, an output of 200 t per day (i.e. 6 days to clear each compartment) is expected. This will be doubled after a year if the storage and packing strategy proves successful.

The facility was developed because of the Singaporeans' strong demand for premium quality (usually fragrant) milled rice. Because of previous control failures involving methyl bromide, it is planned to eventually phase out this operation in all warehouses (Anon. 1985).

Lembaga Padi dan Beras Negara (LPN) in Malaysia is also investigating long-term storage of bagged milled rice in a ventilated, dehumidified environment in a 2000 t capacity concrete warehouse in Senawang, Negri Sembilan. The facility is also fitted with a system for dispensing and recirculating methyl bromide. Conditions of 70% r.h. and 30°C were maintained in initial trials as opposed to 80% r.h. and 30°C in conventional uncontrolled ventilated warehouses (Dhiauddin et al. 1984). An infestation involving mainly *T. castaneum* underlined the requirement for an effective disinfestation technique to be performed at the beginning of the storage period. In this instance, the concrete structure had not been sealed to the level that is deemed necessary for successful fumigation and, consequently, the Government of Malaysia has allocated funds through LPN to allow the building to be sealed before any additional trials are undertaken using methyl bromide or, in future, phosphine or carbon dioxide.

Similarly, BULOG in cooperation with the Tropical Development Research Institute (TDRI) have evaluated phosphine fumigation in 200 tonne stacks of bagged milled rice under permanent sheeting. It was found that safe storage can be extended to only 4 months, after which aeration by Low Volume Suction Ventilation (LVSV) is needed to dissipate heat and moisture (Locke et al. 1983). The use of phosphine and ventilation for medium-term storage, in combination with long-term storage under carbon dioxide, seems an economic proposition.

Problems in Pest Control and Use of Pesticides

The prevention (or at least minimisation) and control of pest infestation in storage have been listed as priority areas of concern for possible regional collaborative effort at the Donor-ASEAN Consultation meeting held in Singapore, 25–27 April 1985. This has reconfirmed priorities that have been previously established by the ASEAN Crops Post-Harvest Programme, and by the ASEAN-EEC Consultation Meeting held in January 1984.

The specific problems related to grain storage pests and their control have been categorised by Haines (1982) and Morallo-Rejesus (1982a, b), and were re-emphasised at an inter-agency working group meeting sponsored in the Philippines by NAPHIRE in September 1984 to develop an integrated pest management program for NFA.

The problem areas are still valid even though certain research projects now under way are focusing directly on establishing practical methods for alleviating the problems. The main categories of concern are:

1. Lack of Information and Understanding of the Pest Problem in Storage.

— Lack of recognition and therefore inaccuracy in recording closely related insect species in the field.

— Lack of understanding of pest biology, ecology, and the factors leading to grain deterioration in storage. This is related to the interactive effects of the major pest species on all commodities and to several secondary pests, classified as minor species, that are commonly found in abundance on paddy.

— Lack of accurate information for different commodities on losses due to pest infestation in different storage situations, such as on-farm, in villages or in the private sector at all levels, as well as in national government storage.

— Pre- and post-harvest farming practices such as partial drying by allowing the crop to stand uncut in the field, and then completing the drying process by stacking after cutting but before threshing. Traditional threshing such as foot trampling and beating against a bamboo frame or with sticks increases the chance of mechanical damage to the protective husk, allowing access to grain by both primary and secondary grain feeders.

— Lack of inclusion of post harvest varietal susceptibility as a factor influencing national recommendations for the introduction of new varieties, and the lack of long-term selection by plant breeders to produce varieties that have both preharvest resistance and low susceptibility to storage pests.

Very little attention has been focused on secondary pests such as *Lophocateres pusillus* and *Cryptolestes* spp., especially *C. ferrugineus* and *C. pusillus,* whose importance on milled products is acknowledged, but which also occur frequently and in abundance on paddy, sometimes significantly outnumbering the primary pests. They are considered to cause little damage, but the early instar larvae of these beetles are able to gain entry to the grain through the same sorts of physical defects used by *R. dominica.* Because of their abundance, it is assumed they are using whole paddy, and the extent of damage and loss may be quite significant, especially in long-term storage. The same applies to mites and psocids associated with stored commodities in the humid tropics. Levels of losses inflicted are not known and they are generally discounted because of their small size.

Only limited studies have been performed on the inherent susceptibility of the HYVs of paddy to storage insects in Southeast Asia. Hussein et al. (1983) have shown that *S. oryzae* possesses a strong advantage over *S. zeamais* on paddy, while the reverse is true on milled rice, based on the averaged Index of Susceptibility of four HYVs (IR-32, IR-36, Cisadane, and Cimandiri) commonly grown in Indonesia. These observations support the view of species dominance that has been observed from field surveys (Haines and Pranata 1982). When these varieties were compared in milled rice form, Cisadane and IR-36 were more susceptible, with IR-32 consistently being the least susceptible. However, in paddy form, IR-32 suffered the greatest weight loss followed by IR-36, based on the observation that these HYVs had a higher proportion of grains with incomplete (gaping) and thin husks which allowed higher oviposition and adult emergence.

Morallo-Rejesus and Dimaano (1984) compared the susceptibility of 20 varieties of milled rice to *S. zeamais* and *T. castaneum.* IR-36 was highly resistant, while IR-29, IR-38, IR-42, IR-46 were highly susceptible to *C. zeamais.* IR-32 was highly resistant to *T. castaneum,* completely suppressing adult emergence, and IR-4570, IR-46, and IR-29 were, in decreasing order, the most susceptible. Apparently, the main differences in susceptibility were attributed to antibiosis (on insect development) and inhibited oviposition, or a combination of both. Other varietal characteristics such as protein content were not significant contributory factors to resistance in this study.

2. Lack of Adequate Storage Facilities

In the tropics, 80–90% of grain is stored in rural areas. About 60% is farm-stored in Indonesia, and 40–60% in the Philippines (Ebron et al. 1979). In Malaysia, however, Rohani and Samsuddin (1984) have shown that only 10% of paddy harvested in the Tanjung Karang area of Selangor State is farm-stored, with 51% of farmers not storing at all. Approximately 90% is stored commercially, and of this, 70% is handled privately and the rest by LPN. Rahim et al. (1983) stated that 23% of the harvested crop in the Sebak Bernam paddy region in Tanjung Karang is farm-stored in structures with capacities around 0.8 t. Throughout Malaysia, approximately 30% is farm-stored (Shamsuddin et al. 1981).

Regionally, farm storage capacities are small (1–5 t) and storage times from 3–6 months duration, depending on whether single or multiple cropping is practised. Around 70% is for home consumption, 24% for later sale, and 6% for seed. Storage systems include traditional raised wooden or bamboo granaries, either rectangular or circular in shape, and with palm leaf or tiled roofs. The paddy is stored in bulk in piles on a mat, or in tins, containers, or jute and polypropylene sacks, as well as small capacity (1–2.5 m^3) bamboo baskets kept inside the dwelling. Insecticides are not applied, sanitation is minimal, inspection irregular or nonexistent, and first-in-first-out principles difficult to apply unless the granary is completely emptied. These traditional storages are well ventilated, but are usually not rodent-proof, moisture-proof, or gastight. The application of a mixture of cowdung and mud to bamboo baskets, lining with a 0.0406 cm polythene film (Acasio et al. 1982), or a linseed oil and ash paste applied on both the inside and outside surfaces (Tripathi et al. 1981) prevented moisture absorption, and created a fumigable structure at low cost. Anything more sophisticated is unlikely to gain acceptance at this level. Farmers still consider that insects appear spontaneously and rodents are counted as the major agent of loss. The potential losses that can accrue from hidden infestations of insects are not comprehended.

Rural traders and millers may possess stores with concrete or compacted soil floors for bagged rice storage. These are poorly ventilated but remain fairly cool. Sanitation is inadequte, management of stocks poor, and structures generally unsuitable for fumigation. National storages normally of 3500–5000 t capacity are generally better designed. They are usually well ventilated but little attention is given to maintenance or to rodent and bird proofing. They are usually made of concrete and steel, with corrugated iron walls and roofs. Storage is in bags which allow easy entry of insects through the seams and stitches. Malaysia and Thailand also have considerable government and commercial storage capacity in bulk in vertical concrete cells and horizontal warehouses. The requirements for adequate aeration and turning facilities at LPN's 33 storage and milling complexes have been examined, while the modifications needed to allow use of steel silos in the tropics have also been investigated with eight units installed at the LPN complex in Bukit Kenak, Trengganu (Shamsuddin et al. 1984). However, the system proposes the installation of wooden liners inside the metal bins to compensate for moisture migration and for moisture ingress through sheering bolts where the neoprene washers were damaged or missing. This is a poor substitute from an entomological point of view for applying a more extensive and perhaps expensive sealant and reflective finish to the outside surfaces. Rohani and Shariffah (1984) investigated the feasibility of several storage systems incorporating 1 tonne cylindrical metal bins. They concluded that hermetic storage was a feasible alternative to traditional bulk storage granaries at the farm level, with daily costs amounting to M$0.12.

3. Lack of Information on Adequate Methods of Control

The use of insecticides, rodenticides, and fumigants remains the primary source of stored grain pest control in ASEAN especially at the national storage level. The associated problems related to the total reliance on pesticides to effect control are:

— pest resistance

— pest resurgence and reinfestation after treatment

— lack of cost effectiveness based on inadequate application methods applied on a calendar basis

— lack of standard codes of practice for the efficient use of methyl bromide and phosphine, with regard to proper dosing and application, adequate exposure periods, adequate levels of sealing, as well as gas detection and monitoring/safety equipment

— screening and selection of replacement grain protectants as well as the most appropriate formulations for specific situations

— lack of information on the practical application of biological control agents such as parasites and predators (see Table 3) and disease organisms such as *Bacillus thuringiensis* and sporozoans as well as insect growth regulators (IGRs) and pheromones.

— lack of information on the practical use of inert dusts, vegetable oils, and botanical pesticides such as extracts of neem and black pepper that would be relevant in small-scale farm and rural storages.

4. Lack of Adequate Store Management

Farmers and private warehouse managers are often under the misguided impression that adequate storage facilities and drying are all that are necessary to prevent insect infestation. High levels of sanitation are required but are rarely seen at this level, and indeed the use of recommended insecticides and fumigants does not achieve the same reduction in damage and loss that it does when sanitation is included. The problem is compounded in many instances by the lack of appropriate chemicals in rural areas or their prohibitive cost in relation to insecticides used in field crop protection. If they are available, they are often not packed in convenient sizes reasonably priced for small-scale use. Phosphine-generating formulations are a prime example (Morallo-Rejesus 1982).

Bagged commodities are often poorly stacked, sometimes directly on the floor without dunnage, and new grain is mixed with leftover and often heavily infested stocks. A first-in-first-out policy is almost impossible to implement. Facilities are often overstocked, thus making fumigation impossible as well. In most cases, practical grading standards and price incentives do not exist to improve quality and implement adequate pest control at this level. There is also rapid turnover of stocks.

The dispatch of grain from one storage to another, often infested and untreated, only hastens the spread of insects from one province or region to another. The same applies to empty bags which are a major source of reinfestation. This is particularly relevant to quarantine and damaging insect pests such as *T. granarium.*

Methods of transportation such as road transport and river barges are not subject to cleaning or pesticide treatment, and consequently all the quality controls implemented in previous storage become wasteful, although loss has been minimised up to that point. Mills and ancillary equipment, such as the wooden elevators that are common in village-level or cooperative mills in Thailand, are also insect havens allowing further infestation to develop in packaged, milled rice.

It is quite obvious, therefore, that a systems analysis approach must be devised to minimise infestation. This must be coupled with economic appraisal of pest control methods and financial incentives, if substantial improvements in grain storage practice are to be made.

Recommendations for Research, Development, Training, and Extension

1. Pest Species, Pest Biology, and Ecology

— Accurate estimates of losses, in medium and large scale storage in Southeast Asia, in both rice and maize. The precision of current loss assessment methods needs further clarification. Different loss estimates can be generated simply as a result of the method adopted (Sidik and Pederson 1984).

— Studies on the biology and ecology of storage pests that are commonly encountered and in abundance. This includes psocids such as *L. entomophilus* which are becoming increasingly common throughout the region.

— Further studies along the same lines as those of Hodges et al. (1984) on methods for detection and estimation of population levels by trapping including establishing correlations with direct sampling methods (spear sampling). If estimates of population densities of free-living insects within the warehouse gave an accurate representation of the pest complex and densities within the commodity, predictive modes to improve the timing of control measures could be built.

— Insect modelling and population dynamics, including bio-energetics, as described by Sinha and Campbell (1975) and Sinha (1982) to accurately predict losses with storage time. This will also allow improvement in the accuracy of the warehouse inventory method.

2. Pest Control

(a) Chemical Control

— Improvement of rural storages to minimise losses due to insect attack and to make them suitable for fumigation.

— Improved formulations of stable insecticidal dusts, in ready-to-use packages suitable for small-scale use. The same applies to phosphine tablets and pellets, although small packages (3–5 tablets) are now being produced and may be commercially available in the near future.

— More accurate information on Economic Threshold Levels (ETLs) of various pest control techniques or combinations (to include sanitation) based on storage duration, as an incentive to implement control methods.

— Development of a diagnostic laboratory unit capable of performing continuous evaluation of insecticide and fumigant resistance in field strains collected throughout each ASEAN country. This unit should be attached to research institutes of the national grain agencies. Predicting when grain protectants should be phased out based on control failures through resistance, and a more logical selection of new compounds for introduction to prevent rapid cross-resistance, is considered essential.

— Studies on the most appropriate dosages and exposures of grain protectants and fumigants based on research work being conducted elsewhere, such as in Australia, where recommendations for phosphine consist of a dosage rate of 1.5 g/m^3 for an exposure period of 5 or 7 days (if *Sitophilus* spp. are present) for temperatures of more than 25°C, and in well-sealed enclosures, irrespective of formulation. Exposures for phosphine and methyl bromide are much longer than those being recommended by the manufacturers.

— Development of suitable pest control strategies for bulk storage in vertical concrete bins based on adequate cleaning and residual treatment with insecticides before inloading, admixture of grain protectants on inloading, possibly using a gravity feed, constant head system applying undiluted concentrates non-uniformly to the grain stream, and fumigation, where necessary, if surface application is proved effective. Recirculation methods to enhance downward dispersion in tall, narrow structures should be investigated.

— Application of a protective chemical treatment to bagged stacks before sheeting for fumigation rather than after the fumigation has been completed and sheets removed. Any spillage that is deemed recoverable and is being kept for further conditioning, *should* be fumigated at the same time to reduce cross-contamination.

(b) Biological Control

— Identification of the most effective natural plant extracts, their methods of extraction, and residual activity for small-scale use.

— Effects of natural enemies (parasites and predators) on pest populations.

— The practicality of using insect growth regulators and pheromones in pest control strategies.

— Creating awareness for the need for incorporating inherent varietal resistance or tolerance to postharvest insect attack as a priority area of concern for plant breeders. Studies on varietal susceptibility to a wide range of insect pests and species complexes therefore need support.

(c) Physical and Non-chemical Control

— Determination of the effects of current drying technology on insect survival.

— Utilisation of wood or rice hull ash and other sorptive dusts and their effectiveness in insect control at the village level.

(d) Sealed Storage and Controlled Atmosphere Storage Technology (CAST)

These research priorities are being investigated by ACIAR and the BULOG/TDRI Grain Storage Management Project. Further emphasis is needed on:

— alternative methods of sealing plastic enclosures.

— effects of prolonged low concentrations of CO_2 and micro-organisms.

— methods for externally generating the desired controlled atmosphere.

— dosages and exposures required under humid tropical conditions.

— comparisons of single purging with CO_2 versus purging plus the addition of 'maintenance' CO_2 during the desired storage period keeping CO_2 concentrations greater than 35%.

— methods for remote sensing of grain quality, moisture, and CO_2 concentrations in sealed enclosures.

— use of vacuum containerisation.

— holding of semi-wet (approximately 20% m.c.) grain prior to drying.

— grain storage in sealed plastic enclosures in the open. Initial disinfestation can be achieved by either phosphine or CO_2.

— moisture movement by natural convection in sealed enclosures.

— application of storage techniques with sealed plastic enclosures to a wider range of commodities (it has proved successful for small volumes (9 t) of coffee beans).

3. Training and Extension

— Improved accuracy of pest recognition by inspectors and grain storage personnel. A simple but accurate and comprehensive pocket-size key is required that can be useful in the field.

— More emphasis should be placed by extension personnel on appropriate storage practices at the farm level. The fact that insects are major contributors to loss and that they *can* be controlled requires emphasis.

— When codes of practice on store management, and application of insecticides and fumigants have been developed, these should be widely disseminated.

— On-the-job training of pest and quality control personnel on a more widespread and regular basis.

— Upgrading the capability of universities in the region that have identified strengths in various disciplines involved in postharvest technology to overcome the shortage of adequately skilled and trained technologists which is one of the major constraints against achieving excellence in postharvest technology. This includes graduate and faculty research addressed to real world problems, faculty exchange and curriculum development programs, the development of linkages with internationally recognised universities, as well as extensive scholarship/fellowship support.

— Strengthening of national postharvest institutes, such as NAPHIRE's Research and Training Centre, Muñoz, Central Luzon; LPN's National Research and Training Centre at Anak Bukit, Malaysia; BULOG's Food Technology Research and Training Centre at Tambun, Indonesia; and the Klong Luang Training Centre in Thailand.

— Upgrading of library facilities for national training centres, and their integration with computer retrieval systems.

— Identification of suitable regional training facilities.

— Development of training support materials such as manuals, audio-visual aids, and publications.

The strengthening of national postharvest institutes and linkages with identified universities has previously been advocated by FAO, with the formation of regional networks to stimulate development, to facilitate the exchange of research information, and to assist in the coordination of research, development, training, and information activities in the region. The Regional Network of National Institutes for Post-Harvest Research and Development, an FAO/UNDP undertaking in the 3-year project 'Inter-Country cooperation in Post-Harvest Technology and Quality Control of Food Grains,' has been developed, culminating in the Drying and Handling of Wet Paddy Regional Workshop in the Philippines in 1984. Warehouse management and pest control was also one of several specific proposals identified for inter-country cooperation in the Consultation Meeting in Bangkok 1983 but has not yet been implemented. This type of regional activity is strongly supported for continued regional cooperation.

Conclusions

The control of stored grain pests in Southeast Asia, at the national storage level, is heavily reliant on the application of insecticides and fumigants. Large commercial traders and millers use methyl bromide fumigation but in most other instances, the application of pesticides and good warehouse management practices are virtually non-existent. The rapid turnover of stocks and lack of financial incentives through workable grades and standards have stifled any attempts to introduce appropriate pest control techniques at this level. Unless a penalty is imposed for insect-infested and damaged grain, premiums are given for higher quality, and the cost-effectiveness of appropriate pest control strategies to suit specific situations is demonstrated, any strategies to generate improvements in conservation and maintenance of quality in storage will not be met with any great success.

Resistance to residual insecticides is becoming increasingly commonplace. Control failures involving methyl bromide and phosphine fumigation in ASEAN and attributed to resistance have not been adequately defined. However, they underline the requirement for use of fumigants in well-sealed situations, and for much more stringent monitoring of the fumigation procedure with regards to gas loss and C.t products, and laboratory evaluation of field strains where only partial mortality has been achieved. (To maintain effectiveness, the introduction of additional fumigant to compensate for decays in concentration is an established practice for good fumigation.)

For long-term storage, there is an increasing trend for the national grain agencies (NGAs) to store rice in the milled form for rapid disposal to consumers. The protective husk of paddy has been replaced by storing under gastight fumigation enclosures or in rigidly constructed sealed compartments or warehouses, after initially disinfesting the commodity with CO_2. Evidence suggests that this offers the most immediate and practical method for lessening on 'calendar-based' application of pesticides with its associated resistance and residue problems.

The NGA's current and future approach to pest control should be based on maintenance of maximum levels of storage hygiene and cleanliness, with more judicious use of insecticides and fumigants, applied in the most effective manner, and integrated with CAST. Monitoring of pest build-up through appropriate inspection procedures is considered essential in establishing the timeliness of these control techniques.

Tolerance to high concentrations of carbon dioxide has been induced in adults of *S. oryzae* in laboratory evaluations (Dias and Navarro 1983) but it is not likely to invalidate the technology for field application. However, failures will occur if insufficient attention is given to the sealing requirements and exposure periods that have already been specified for dry grain storage, and extrapolated and now being evaluated under typical storage conditions in the humid tropics.

The problems of pest control in the humid tropics are serious and continuous. The technology for adequate disinfestation and long-term control is either known or is being developed to suit humid tropical climatic conditions. However, implementation of suitable technology at all storage levels remains a socioeconomic phenomenon. In the larger stores, pest control is often not practised simply because of ignorance on the part of store management as to the benefits that can be achieved if an investment in pest control is made.

It is therefore the financial benefits of pest control technology that must be verified. To achieve this, losses that are presently being experienced due to pest infestation in storage of cereals and grain legumes, must be estimated as accurately as possible by known standard techniques before appropriate intervention is taken. This will help elucidate where the major losses are being incurred within the system, and what strategy is best suited to improving the situation, both in terms of weight loss reduction and maintenance of quality. This becomes increasingly important in situations where prices once controlled by parastatal authorities are deregulated and production approaches self-sufficiency levels or even export status. Larger marketable surpluses equate to longer storage durations, and therefore the requirement for introducing improved storage technology and pest control in preference to simply modifying traditional methods.

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Session Chairman's Summary
Pest Problems and Current Use of Pesticides

E.D. Magallona*

THE main points or issues arising from this session were as follows:

1. Governments in almost all tropical countries consider the maintenance of food stockpiles important and this has brought about the need to protect these materials from pests. Farmers and the commercial sector also maintain stockpiles, but these are not as extensive as those in government storages.

2. Stored products are attacked by a number of pests. Among the insects, *Sitophilus oryzae, S. zeamais, Tribolium castaneum* and *Rhyzopertha dominica* are the most important. Fungi, and vertebrate pests such as rats and birds, are also important.

3. Country estimates of stored products pest damage point to the potential contribution of adequate pest control to food supplies. Losses can go as high as 35%, which is a cause for serious concern, particularly when these are added to preharvest losses.

4. Pesticides have been used to control many of these pests, especially the insects. This is in recognition of the positive cost-benefit assessment generally obtained with their use, as well as their convenience of application.

5. On the other hand, pesticide usage also poses problems which must be overcome if we wish to continue to reap the benefits which accrue. The most important problems associated with pesticide use appear to be (a) development of resistance, (b) hazards to applicators, and (c) residues.

6. The use of pest management in storage systems is being proposed partly to avoid the problems with pesticide usage, and partly to capitalise on other preventive and suppressive control measures that appear quite promising.

7. Research, development, and extension efforts are necessary to realise the potential of these methods as well as use of pesticides.

8. As part of this effort, some work may be necessary on the correct identification of the pests in each country, on monitoring of pest populations with the idea of applying control measures at the optimal time, and on proper pesticide use.

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Some Constraints to Use of Pesticides

Management of Pest Control in Grain Storage Systems

D. Halliday* and D.J.B. Calverley*

Abstract

Ideally, cereal grains should be handled and stored under conditions that minimise the opportunities for insects and other pests to cause economic damage. This may be achieved by good design and maintenance of stores, good inspection and quality control of stored commodities and good stock control, activities which together constitute what is known as good storage practice. However, in the conditions encountered in developing countries, the use of fumigants and contact insecticides is often necessary if serious losses are to be avoided. The most appropriate ways of using these, at both farmer and central storage level, are discussed, with particular reference to problems in using contact insecticides to protect grain stored on farms and the development of resistance to phosphine in insects.

THE ready availability of a wide range of chemicals to combat all pests which are likely to be encountered in grain storage systems has led to the mistaken belief in many quarters that they are an essential component of procedures for minimising damage caused by such pests. In fact, whilst chemicals often *are* needed to keep losses within manageable proportions, this might well not have been the case had proper attention been given in the first place to all those factors which are generally referred to collectively as 'Good Storage Practice'. Far too often today chemicals are used in an attempt to remedy problems caused by inattention to good storage practice or to provide a cosmetic impression that pests are being properly controlled.

The Principles of Good Storage Practice

Good storage practice covers those simple precautions that are essential in storage situations to minimise the natural presence of insect pests so that losses are kept to economically acceptable proportions without the use of chemicals. Store and environment cleanliness and the disposal of rubbish are key elements (Anon. 1979). Nonetheless, sustaining an insect-free environment without the use of chemicals is a difficult task which requires good management and meticulous attention to detail by farmers, storekeepers, and other staff working in stores.

The principal factors which need to be borne in mind when designing and operating storage systems to minimise pest management problems include:

The Design and Maintenance of Stores

Stores should, as far as possible, be designed to minimise the opportunities for entry of rodents and birds, to facilitate cleaning, and to make control of insects as simple as possible. Bird screens should be fitted to ventilation panels, the doors should be well-fitting, and there should be no defects in the roof or walls to allow pests to enter. The interior should be designed to minimise structures which provide harbourage for pests or make pest control operations difficult to carry out.

Clearly, store design is necessarily a compromise between what is ideal and the standards to which the building contractor can be persuaded to work. There are still far too many instances of stores being built in developing countries which are inadequate due to poor design and lack of understanding rather than lack of money. Poor or even lack of maintenance of stores after they are built is a common problem and is tolerated without recognition of the difficulties it makes in pest control management and in the considerable losses which result.

Store Physical Hygiene

It has often been said that the man with the

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brush and shovel is the best form of pest control in produce stores. While this is clearly an over-generalisation, it is certainly true that effective pest control is most easily achieved in clean and well maintained stores. It is absolutely essential that produce in bags is arranged to facilitate pest control operations, that spillage of produce should be promptly swept up and removed from the store and disposed of, and that walls and roof supports are regularly cleaned.

It is difficult to keep stores insect free by such measures if they are situated in areas where produce is being handled and stored nearby. Many insect pests of stored grains have considerable flight activity and very rapidly cross-infest clean stores from those which are infested (Giles 1969). Locke (1971) described ways in which this problem was tackled at the port of Mombasa in Kenya where high value commodities such as coffee were being cross-infested from other, less valuable commodities. A special insect-free area was established in the port in which high value commodities might be held.

Inspection and Quality Control

Obviously, there is little advantage in paying attention to store hygiene if infested produce is subsequently loaded into the store. All produce, therefore, needs to be carefully inspected. Inspections for insect pests can be concurrent with that needed to ensure compliance with the standards of quality, i.e. moisture content, admixture, etc. Procedures for small grains have been developed that are simple and quick to apply. Paddy rice presents more problems, as do quality standards that are complex and time consuming. In such situations, proper procedures may be bypassed and inspection standards lapse, permitting inferior and infested grain to be accepted into store.

Infestation in produce delivered to stores may originate from a number of sources. These include field infestation immediately before and after harvest, cross-infestation on the farm, infested residues in lorries or railway wagons, cross-infestation from infested produce adjacent to it, and being held in dirty transit stores. All these factors require attention if the level of infestation on delivery to store is to be minimised. This emphasises the need to treat the problem of infestation as one involving the whole system of handling, storage, and marketing, rather than limiting it to the storage component.

Stock Control

Pest management problems may be minimised by careful control of the movement, storage, and disposal of commodities. The most obvious way to do this is to ensure that those stocks which have been longest in store are disposed of first. However, this is not always immediately attractive in economic terms as it is often cheaper and easier to divert consignments directly to outlets without their being brought into store at all. Also, the stacking of commodities in stores may make it much easier for storekeepers to issue more recently received stocks which are nearer to the doors. Irrespectively, stock which is deteriorating needs moving quickly whatever its age.

Adequate pest management may be achievable by a reorganisation of supply arrangements. Friendship (1984) cites an example of wheat flour imported into Sri Lanka by the Government in large consignments which often had to be stored for periods of up to 1 year or more before issue to the public. This resulted in the buildup of heavy infestations of *Tribolium* spp. necessitating frequent fumigations with phosphine and considerable diminution in quality. Bakers and consumers complained bitterly about the poor quality of the flour and the bread made from it. The establishment of a new flour mill at Trincomalee in 1982 made it possible for the production of flour to be carefully matched to consumption forecasts. A coding system for production batches was also introduced to ensure that no consignments were accidentally put aside. Rigid adherence to this procedure has resulted in a dramatic reduction in damage caused by *Tribolium* without the use of chemicals of fumigants. This has been associated with an equally dramatic improvement in the quality of bread sold in Sri Lanka.

Hermetic Storage

Many workers have shown that storing infested grain under hermetic conditions will cause the insects to die. The technique and its practical application is widely covered in the literature (Dendy and Elkington 1920; Oxley and Wickenden 1963; Hyde et al. 1973; and Shejbal 1980). There is no doubt that hermetic storage is an effective method of controlling insect pests. However, the practical difficulties of maintaining an airtight environment have led to a decline of interest in this method of pest control in developing countries (de Lima 1980). It seems likely there are more effective and cheaper methods of pest control.

The ability to seal stores has led to the development of storing grain in an atmosphere of inert gases, usually nitrogen or carbon dioxide. The technique is widely practised in Australia where much of the work on commercial storages has been done (Ripp 1984; Shejbal 1980). Trials are continuing outside Australia, as described by Annis and Graver (these proceedings), but it is likely to be some time before the technique can be extended safely to the humid tropics.

The use of plant extracts acting as insecticides, ovicides, or simply as deterrents is a subject of interest for grain protection on farms. Similarly, admixture with sand, ashes or a range of seed sizes provide a physical barrier to insect activities on a small scale.

Use of Chemicals

Obviously, the application of good storage practice cannot be relied on always to provide the answer to problems of pest control management. Management and technical failures are likely to occur to varying degrees in systems for handling and storing commodities. Also, good storage practices per se are likely to be inadequate in certain situations. The overall cost of commodity and storage systems must always be considered and it may be that in some instances it is more economic to make use of chemicals to control pests than to face the probability of economic loss or alternative capital expenditure.

The chemicals normally used to control pests of stored grain are fumigants, contact insecticides, and rodenticides. Microflora can be controlled by the use of fungicides. Considerable advances have been made in the storage of cereal grains for livestock feed using organic acids, but the resulting taint and appearance of the grain renders it quite unacceptable for human consumption. Moulds are, therefore, best controlled by drying, preferably as soon after harvesting as possible. The ways in which fumigants and contact insecticides can be used depend very much on the type of system. In particular, it is necessary to distinguish between the type of storage at the level of the small farmer and centralised storage controlled by traders of parastatal commodity marketing organisations.

It is generally considered that about 20% of grain remains on farms in most developing countries, although in ASEAN countries the proportion is likely to be lower. The relative amounts of grain handled in the public or private sector markets will obviously vary from country to country depending on national policies. Despite the amount of grain stored on the farms, the opportunity for intervention to reduce losses with chemicals is easiest and greatest in central storage situations. Nonetheless, all grain originates and is stored on farms, even if only for short periods. It is here that infestation, found later in central stores, may largely have originated. Perhaps it is here that greater attention should be given to the control of insect infestation.

Farmer Level Storage

Farmers in developing countries grow grain principally for the subsistence of their families. Grain after harvest is therefore normally stored in a wide variety of small, traditional structures appropriate to the indigenous agricultural system and using such materials as may be locally available (Hindmarsh et al. 1978). Such materials typically include mud and various forms of woven baskets. Containers made from basket work allow drying to continue after harvest but also allow access by insect pests. Mud containers may provide better protection against entry by insects but do not allow drying. Very little attempt is normally made to prevent traditional storage structures being invaded by rodents.

Contact Insecticides

Attempts have been made in various parts of the world, particularly where maize is grown as a subsistence crop, to develop the use of contact insecticides for the protection of grain in traditional farm stores. However, it has been recognised in recent years that in unimproved agricultural systems losses of grain are normally too small to justify the expense of using insecticide (Adams and Harman 1977). Once traditional agricultural systems are changed by modifying cropping patterns and using new high-yielding varieties, the use of contact insecticides is justified and indeed necessary unless storage periods are quite short (Golob and Muwalo 1984). Another recent example where the use of contact insecticides to protect farmers' stored grains is quite essential is in combating the recent outbreak of *Prostephanus truncatus* (the larger grain borer) in

Tanzania (Golob 1984), where it is without any indigenous natural checks and controls.

In addition to economic considerations, there are technical problems to be considered when using contact insecticides in small farm stores (Webley 1979). The first and perhaps most important, but one which is often sadly neglected, is that of providing to the farmer a good quality formulation which is efficient in controlling the total pest complex. The type of formulation which has proven most convenient for the farmer to use in Africa is a dilute dust containing up to 2% of active ingredient. He can simply sprinkle the dust on maize cobs as he is loading his crib or admix it with the threshed grain using a shovel (Anon. 1977). The use of insecticides to protect paddy rice stored on farms in South East Asia has been little researched but there could well be instances where insecticide dusts might be used to control *Rhyzopertha dominica* and surface sprays to control *Sitotroga cerealella.*

A problem with most of the active ingredients in dilute dusts developed for this purpose is that, because they are organophosphorus compounds (such as malathion, fenitrothion, and pirimiphos methyl), they are notoriously difficult to formulate as stable dusts at very low concentrations. The more reputable suppliers can and do produce low-concentration dusts of adequate stability which can be stored for quite long periods before use. However, the high proportion of the inert carrier present makes it uneconomic to formulate dusts in developed countries for export to the developing countries. There is, therefore, pressure to formulate locally from imported concentrates and locally available carrier materials. The local materials may be less suitable for producing stable products and technical control of product quality may be diminished.

The situation is exacerbated by marketing practices which increase the length of time between formulation and use by the farmer. There are, consequently, far too many cases of dilute dusts of poor stability being offered to farmers. Apart from the economic loss, farmers may in consequence face food shortages and become disillusioned about the efficiency of chemical treatments.

These difficulties are being overcome in the current Larger Grain Borer Control Programme in Tanzania by importing the complete 0.5% permethrin dust from reputable suppliers. The concentration of active ingredient in consignments of the dust stored up-country is monitored regularly to ensure that its efficiency is maintained.

A second problem associated with the use of insecticide dusts by farmers is that of packaging and marketing the small quantities required. Packaging and marketing costs may increase the purchase price to the farmer by three or four times the import cost. However, it is still not a commercially profitable operation and few insecticide supply companies are interested.

The final problem in using insecticide dusts for protecting stored grain is that of ensuring that the treatment provides adequate protection over a reasonable period of time. Protection is often needed for periods up to 10 months after harvest, i.e. at the beginning of the next rainy season when conditions are favourable for the development of insect pests. This requires that the active ingredients are not lost from the grain too rapidly after application and that they provide an adequate period of protection to grain stored in a wide variety of containers and under a broad spread of climatic conditions.

Obviously, any active ingredient should be of sufficiently low mammalian toxicity that any residues remaining on the grain after proper application do not present a hazard to consumers. This, together with the other factors already mentioned, severely restricts the range of active ingredients which can be used for the protection of stored grains by direct application to a few organophosphorus compounds and, more recently, some of the synthetic pyrethroids.

Fumigation

The most serious problem encountered in using fumigants to disinfest farmer-stored grains is that of ensuring gastight conditions. Without these the fumigation will be ineffective and, subject to where the grain may be stored, the fumigant gas could contaminate living areas. The fumigation of small quantities of grain contained in polythene sacks has been suggested (Proctor and Ashman 1972; Giles 1976), while adapted water tanks have been found to be useful sealable containers for maize stored in Southern Africa and Central America (Harris 1970; Giles 1976). However, most storage bins on farms in developing countries will remain unsuitable for fumigation.

Packaging of the small quantities of fumigant needed to protect the one or two tonnes of grain which farmers typically have in store presents further problems. The normal packs of aluminium phosphide are unsuitable for small farmers. They contain in an aluminium tube sealed with a plastic plug, enough tablets (20–30) to treat 10 tonnes of grain. Smaller packs of 3 to 5 tablets have been produced experimentally by two major suppliers and it is hoped that these may be available in the near future. The only current widespread use of fumigants at farm level is in parts of India where ampoules of ethylene dibromide are supplied commercially to farmers (T.S. Krishnamurthy, personal communication). However, it is difficult to know how effective this treatment is. It is also noteworthy that in other countries the use of ethylene dibromide is discouraged because it is considered dangerous to health.

Central Storage

The scope for using chemicals in centralised storage installations is much greater than on the typical small farms of developing countries. Fumigants can be used more safely and effectively while contact insecticides can be applied as emulsions or as suspensions of wettable powders.

Bulk storage installations are only gradually becoming more common in developing countries. Most grain is handled and stored in gunny bags and pest control operations must then be carried out in stores on stacks of bags. The main weapon at the disposal of the pest control officer is fumigation with either phosphine or methyl bromide. Phosphine is easy to apply as a solid aluminium or magnesium phosphide based formulation but suffers from the disadvantage of needing very long exposure periods of up to 7 days for complete effectiveness (Halliday et al. 1983). Methyl bromide has to be applied from cylinders through pipes and nozzles but can, if applied properly, fumigate effectively over periods of between 24 and 48 hours.

Fumigations of bag stacks are traditionally carried out under gasproof sheets because it has been considered impossible to seal stores sufficiently to retain adequate concentrations of gas for long enough periods. Problems of inadequate gas retention have arisen through the use of poor quality sheets, which do not retain gas properly, or inadequate fumigation periods, especially when phosphine is used. Under these conditions there is a superficial impression of having obtained good kills, but immature stages of insects may survive and give rise to a need for refumigation some few months later. To prevent rapid reinfestation from either adjacent untreated stacks or the structure of the store, it is essential that good housekeeping be practised in the whole store. The walls and floors must be treated with contact insecticides and, if possible, all bag stacks should be fumigated simultaneously.

It is a very common and widespread practice to spray large quantities of contact insecticides onto bag stacks after fumigation in the belief that this prevents reinfestation. There is very little evidence to support the contention that such treatments are indeed effective and it is likely that this is a complete waste of time and materials. Contact insecticides are most effective when used for structural spraying. Protection of bag stacks from reinfestation after fumigation is perhaps best achieved (if needed) by permanent coverage with plastic sheets (Prevett 1961) or with cloth impregnated with insecticide (Gilman 1982). The use of such techniques must, however, take into account potential mould problems associated with moisture movement in the bag stack under closed conditions.

The ideal way to control infestation of grain in bag stores is by fumigating the whole store. Small stores can be entirely covered by gasproof sheets but this is a laborious technique which can only be used occasionally in special circumstances, e.g. for the elimination of infestations of *Trogoderma granarium*. It is possible to make warehouses gastight by the extensive applications of sealants but, for the time being, this would be expensive and very difficult to achieve in most developing countries. It is therefore to be considered that for the present in these countries stores cannot normally be made sufficiently gastight to retain concentrations of fumigant for sufficiently long periods to carry out effective fumigations. The Tropical Development and Research Institute (TDRI) is now developing a technique of applying phosphine in multiple doses rather than a single initial dose. The technique may enable whole store fumigations to be carried out with phosphine in situations where the leakage rate is not more than 40% per 24 hour period. It is hoped to undertake trials with this system in Africa and Asia during 1985–86 to enable definition of the conditions under which this approach can be used.

A most serious consequence of carrying out phosphine fumigations for many years under unsatisfactory conditions has been the development of resistance to phosphine by certain common species of insect pests of stored grains in some areas of the world. The problem seems to be worst on the Indian subcontinent (India, Pakistan, and Bangladesh), where highly resistant strains of *Rhyzopertha dominica* are now commonly found. For example, work carried out by a TDRI team in Bangladesh during 1982 (Tyler et al. 1983) observed that bad fumigation techniques used for many years had resulted in the development of strains of *R. dominica* which were so highly resistant to phosphine that they were now difficult to control even when good fumigation practice was employed. Other instances of high resistance to phosphine are reported by Dyte and Halliday (1985), while recent studies by TDRI have shown strains of *R. dominica* from Pakistan to be highly resistant to phosphine (A.H. Harris, personal communication). Clearly, the situation will need to be monitored very closely and a major effort must be mounted to improve the efficiency of phosphine fumigations in developing countries.

Bulk storage installations in the form of silo complexes in developing countries are normally used as transit facilities in port areas rather than for long-term storage of grain. The techniques for pest control in these are well established and facilities to carry these out are often built into the system. For example, insecticide emulsions may be sprayed onto grain as it passes on a conveyor belt under a fixed spray nozzle, or tablets of alumium phosphide may be added by a dispenser at the same point. Problems which have emerged include the poor gas retention of many silos, particularly concrete silos built some years ago. This could well cause pockets of grain to receive sublethal doses of fumigant unless recirculation devices are installed (Sullivan 1985). Spraying of grain with contact insecticides also causes problems of customer acceptability and the development of resistance to particular active ingredients by some species of insect pests. Australian wheat exports are treated with a mixture of two active ingredients (a synthetic pyrethroid and an organophosphorus compound) to increase efficiency at acceptable rates of application so as to reduce both residues and the risk of the development of resistance by insect strains.

The scope for using fumigants to control infestation of bulk cargo in ships' holds or in cargo containers is limited by considerations of safety to ships' crews. However, the treatment of bulk grain in ships' holds with phosphine has now become established practice, particularly in the United States (Zettler et al. 1984) while cargo containers which can be well sealed can be effectively and safely fumigated with phosphine or mixtures of methyl bromide and phosphine with carbon dioxide (Harris 1984; Wainman et al. 1983).

Future Problems for Developing Countries

This brief survey of pest management in grain storage systems and the scope for using pesticides to control infestations highlights certain problems, some of which have been with us for many years and a few which have emerged more recently.

A general problem is how fumigants and insecticides should be used in storage systems to produce the maximum effect at the minimum of cost. There is little doubt that considerable sums of money are currently wasted by inefficient fumigation technology and the application of contact insecticides to little effect. Better training of pest control teams and a better understanding of the principles of pest control by management seems to be the key to solving this problem.

The second major problem, which is a consequence of the first, is the quite alarming development of resistance to phosphine by pests such as *Rhyzopertha dominica.* If this resistance continues to spread and no alternative fumigants are developed, we could well be forced to rely on 'Good Storage Practice' to minimise insect infestation. This is a good thing in theory but is likely to be unachievable in practice.

More than ever do we need to put a high priority on those practices and techniques which inhibit the development of pest populations that can infest produce from the field through to the consumer. We need to exploit the use of natural controls and checks and to integrate these with the minimal use of chemicals commensurate with adequate control and reasonable cost.

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Safety Considerations in Insecticide Usage in Grain Storage

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Abstract

Only those insecticides that have been specifically approved should be used on and around stored grain. The choice of insecticides that may be used is limited by the very strict requirements that must be enforced to ensure safety for operators, consumers, the grain trade, and livestock. Absolute safety for consumers of these important basic food commodities is a prerequisite in the choice of insecticide. The requirements for selection for use as a grain protectant are enumerated. About 20 insecticides have been evaluated and most of them have been found suitable and acceptable. The nature and extent of the studies carried out to determine the toxicological properties of candidate insecticides and to evaluate the potential effect on humans and livestock are described. The safety of insecticide-treated grain to consumers and livestock also depends upon the fate of the insecticide deposit during storage, processing, and cooking of the grain and grain products. The importance and value of studies of residues and of metabolism for providing reassurance on safety are summarised.

GRAINS such as wheat, rice, maize, and millet, and legumes such as beans, lentils, and peas, form a large part of the diet of the world's population. These commodities are stored as dry seeds and form the only real reserve of food. Furthermore, they provide the means by which food supplies can be replenished in future seasons through the planting of a portion of the viable seed. However, all of them are subject to attack by a variety of insects that cause great amounts of damage and loss of nutritious foods, and thus give rise to one of the causes of malnutrition in many lands.

Until comparatively recently there was a tendency to regard the association of insects with food as inevitable. However, no longer is any recognisable part of an insect accepted in our foods and the highest degree of purity, including freedom from pests or their remains, is now expected. In many countries the required purity is legally controlled. The improvement in food hygiene which has been effected during the past 20 years can, to a very great extent, be attributed to the development and usage of synthetic pesticides, which pest control research has stimulated.

The use of chemicals to control insects in stored products is usually not a matter of choice. It devolves into a question of whether infestations and losses in commodities are to be tolerated. Some authorities consider that use of chemicals is undesirable but because of the efficacy of selected insecticides and the low hazard to consumers, chemical control of stored product pests is by far the lesser evil when compared with losses that may occur without their use.

There is no doubt that insecticides make a great contribution to the conservation of our food stocks and to the maintenance of their quality and purity. Therefore, unless there is to be an unexpected acceptance of foods contaminated by insects, or some alternative economic form of pest control that is free from all hazards to operators and consumers is put forward, we must rely on these chemicals.

Chemical control is required for the major pest species only. Minor species can and should be managed by attention to hygiene and control of moisture content. Use of chemicals under conditions where these minor species are important is wrong in principle and will lead to side effects, such as chemical resistance in major pests.

Chemical control must thus be placed in its correct perspective. It is necessary to reiterate the framework on which practical infestation control

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programs are based. Practical infestation control is an integration of the following:

1. adequate drying of the commodity to be stored;
2. use of suitable storage facilities and if necessary their improvement to an acceptable standard;
3. use of aeration and other physical control methods if practicable;
4. good warehouse keeping;
5. regular inspection for infestation or other causes of deterioration;
6. use of commodity protectants;
7. use of residual insecticides;
8. fumigation, where infestations become established; and
9. if appropriate, changes in varieties of grain produced and changes in harvesting techniques.

Grain Protectants

A pesticide is any substance that is used to kill, destroy, eliminate, control, or repel any organism, including insects, mites, spiders, fungi, bacteria, weeds, rodents, birds, vermin, etc. Because most of the pesticides which are used in conjunction with stored grain are insecticides, the term insecticide will be used for chemicals applied for the protection and treatment of grain against insect pests and for the control of pests in and around grain storage facilities.

Grain protectants are insecticides that, when applied to grain, prevent infestations from becoming established. They are not intended to control heavy infestations present in the commodity at time of treatment. These should be controlled by fumigation as a separate operation. In practice, grain protectants will control light infestations present at the time of treatment. However, because the treatment of populations of insects will accelerate the selection of resistant strains, it should be avoided.

Only those insecticides that have been specifically approved for use on and around grain should be used. The choice of insecticides that may be used is limited by the very strict requirements that must be enforced to ensure absolute safety of important food commodities. To qualify for selection as a possible candidate grain protectant for use on grain, the insecticide must fulfill the following requirements (FAO 1982):

1. it must be effective at economic rates of use;
2. it must be effective against a wide variety of insect pests;
3. it must be capable of being used without hazard to operators;
4. its use must be acceptable to health authorities;
5. it must present no hazard to consumers of grain and grain products;
6. it must not affect the quality, flavour, smell, or handling of grain;
7. it must not be flammable, explosive, or corrosive; and
8. its method of use must be compatible with established grain-handling procedures.

Although the scientific literature contains many references to the effectiveness against stored-product pests of a large number of insecticides, the number registered for application to stored grain and for which maximum residue limits are established is limited. Of these, only a few have yet been adopted commercially, though the rate of adoption appears to be increasing. The following compounds are currently being used for treating stored grain and probably other stored commodities (FAO 1982): bioresmethrin, bromophos, carbaryl, chlorpyrifos-methyl, dichlorvos, fenitrothion, malathion, pirimiphos-methyl, piperonyl butoxide, and pyrethrins.

The following compounds have been subjected to extensive study, and most appear capable of fulfilling the criteria for approval as grain protectants: deltamethrin, etrimfos, fenvalerate, methacrifos, methoprene, permethrin, and phenothrin.

Several insecticides which have been extensively studied appear to be unsuitable or less suitable than available materials. These include: diazinon, iodofenphos, lindane, phoxim, and tetrachlorvinphos.

Fumigants

Hydrogen cyanide and hydrogen phosphide are approved and widely used as grain fumigants in many countries. The basis of approval is that their use does not result in residues in cereal-based foods.

Although carbon disulphide, carbon tetrachloride, chloropicrin, ethylene dibromide, ethylene dichloride, ethylene oxide, methyl bromide, and trichlorethylene are approved for use as fumigants in most countries, international maximum residue limits have not been established as there is a deficiency of information available on the chronic toxicity, metabolism, and level of residues following accepted practice. Until recently, the available analytical methods were either not specific or not sufficiently sensitive to determine the level and nature of the residues of these fumigants or their fate during processing and storage. Recent studies carried out at the instigation of the FAO Working Party of Experts on Pesticide Residues have provided a basis for establishing useful limits for fumigant residues but it appears certain that some, at least, of these liquid grain fumigants are going to be condemned and probably prohibited because of toxic manifestations. This development will increase the importance of alternative pest control procedures, including the use of insecticides.

Safety

Before going any further, we should pause to consider the word 'safety.' It is a most unsatisfactory, vague and, at best, relative term. It means different things to different people and its meaning differs vastly with each situation in which it is used. To those of us who spend our lives dealing with chemicals it involves the concept of hazard or risk, i.e. the likelihood of some adverse effect resulting from a certain set of circumstances, including the approved use of a chemical or any possible misuse.

There is a great dichotomy of views among different segments of society. Some people wish to be reassured that there is absolutely no risk to anyone, anywhere, at any time, irrespective of circumstances, conditions, or the practical realities of the world around us. On the other hand, some people seem to think something is safe if there is only an even chance of something disastrous happening under the best of circumstances.

Hazard in the use of pesticides may be defined as the likelihood that injury could result from the use of or exposure to the product. Many people use the terms toxicity and hazard as though they mean one and the same thing. If you examine the respective definitions, you will see that they refer to distinctly different concepts.

Toxicity measures the actual harm which results if the product is absorbed. *Hazard* takes into consideration the likelihood of contact or absorption. Extensive practical experience has shown that highly toxic substances may be handled continuously over long periods without any harm simply because precautions have been taken to prevent contact or absorption. Under these conditions the hazard is negligible.

On the other hand, it is well known that many substances with a relatively low toxicity have injured workers and innocent members of the general public simply because adequate precautions were not taken to avoid exposing people to them. For example, people were injured when DDT powder was used in mistake for flour in the preparation of food. In another case, pesticides carried on a ship loaded with grain (which is illegal) leaked into the grain causing numerous deaths among people who used the grain for food. Storing or transporting pesticides along with food represents an unacceptably high risk or hazard.

It would not be possible to define all the hazards that might arise from the handling of toxic substances in the course of efforts to control pests and prevent damage to grain. It must be emphasised that the pesticides that have been selected for use on or close to grain have been chosen with greatest possible care to ensure that the health and welfare of consumers are never in doubt. Persons applying these substances can be endangered only if precautions and commonsense are deliberately ignored.

Although the space sprays and contact insecticides permitted for use in grain handling are remarkably safe, the list of fumigants includes several of the most toxic substances in general use today.

Hazards

The hazard that needs special and repeated emphasis above all others is the risk to innocent persons that could arise through gross contamination of grain or cereal products with toxic substances. If through carelessness or misadventure such contamination remains undetected until the food is consumed at some later date or in some distant place, the consequences could be serious. It is the responsibility of everyone engaged in the handling, inspection, and storage of grain to ensure that they and all those associated with them are adequately informed about the correct procedures, and that fail-safe procedures are followed to guard against the remote possibility of any such contamination occurring, particularly during storage and transport.

The following are the more important hazards involved in the use of pesticides in and around grain. Precautions should be taken to eliminate the risks involved.

(a) Acute Hazards

(i) Oral intake

- Eating the substance or contaminated food
- Drinking the substance or contaminated food
- Eating or drinking from contaminated utensils
- Eating or handling food with contaminated hands
- Blowing or sucking to clear a blockage in equipment

(ii) Dermal absorption

- Handling concentrates without protection
- Splashing concentrates onto skin
- Spillage of concentrates
- Contaminated clothing, tools, or work places
- Lack of protective clothing
- Lack of personal hygiene
- Carelessness in mixing and spraying

Many pesticides including malathion, dichlorvos, methyl bromide, liquid grain fumigants, and hydrogen phosphide are rapidly absorbed through the skin. The greatest quantity is absorbed during the first hour after exposure. All exposed skin, especially face, head, and neck, should be promptly and thoroughly washed with soap and water, certainly within a half hour of becoming contaminated. Clothing that has become seriously contaminated should be removed immediately.

(iii) Inhalation

There is a risk of absorption through the lungs:

- During fumigation
- Due to insufficient ventilation in work area
- During aeration of treated grain
- During mixing and spraying contact insecticides.

A number of the most toxic substances, including methyl bromide, have little or no smell. Persons working in contaminated atmospheres rapidly lose the ability to recognise the odour of the material they are using.

(b) Chronic Hazards

These can result from faulty practices repeated over extended periods.

- Familiarity and failure to observe precautions
- Poor personal hygiene
- Poor ventilation
- Inadequate protective clothing
- Faulty equipment
- Repeated exposure to spray or dust (particularly organophosphorus insecticides)

Detailed instructions about the safe and correct use of pesticides are issued by the following authorities.

- Grain handling authorities
- Departments of Agriculture
- Departments of Health
- Chemical manufacturers
- World Health Organization

Failure to observe and practise any of these safeguards must be looked upon as culpable negligence on the part of anyone involved in the handling, inspection, and storage of grain.

Precautions

The following precautions will reduce the potential risks arising from use of pesticides:

(a) Bystanders

Unauthorised persons should not be allowed into an area where pesticides are being applied. Spray drift should be avoided. Pesticides, especially concentrates, should not be left where children can reach them. Remember that over 80% of all cases of illness due to chemicals involve children under five years old.

Never measure, mix, carry, or store pesticides in drinking, eating, or cooking utensils or in containers normally used for food or drink. Never store pesticide concentrate or the diluted spray in an unlabelled vessel. When using fumigants take the utmost care to ensure that innocent or unauthorised persons are not in or do not enter the area being fumigated.

(b) Symptoms

Poisoning by insecticides will give rise to symptoms which may be easily recognised by intelligent people who take the care to become familiar with the typical indications.

If you are dealing with pesticides, remember that any one symptom on its own is not proof that the person has been affected by the material being used. It is, however, a warning to be on the lookout for further indications. Two or more symptoms must be considered serious, warranting removal from further exposure and possibly medical attention.

(c) First Aid

Everyone using insecticides, and particularly supervisors responsible for operators handling insecticides, should be thoroughly familiar with the symptoms of poisoning with the compounds in use. First aid instructions should be readily available and should be understood by all personnel involved. In the case of an accident, time is critical. First aid treatment applied immediately is often better than medical treatment applied later.

First aid instructions should be printed on every label of every pesticide. These would normally be provided by the manufacturer but as an added safeguard they are required by law to be clearly shown.

(d) Grain and Food

The handling of pesticides close to grain involves special responsibility. The utmost care must be exercised to be sure that grain or grain products do not become contaminated with pesticides. If an accident occurs it should be reported immediately. In cases of doubt, it is best to remove and destroy all grain that might have become contaminated.

Pesticides must not be transported in vehicles carrying grain. They must be stored under lock and key well away from grain, grain handling equipment, sacks, or other provisions.

(e) The Environment

Domestic animals, wildlife, and especially fish are sensitive to many pesticides. The pesticides should be confined to the areas being treated. Ditches, drains, watercourses, rivers, and any open body of water must be protected from possible contamination. Do not pour unwanted materials or washings into drains, sinks, lavatories, ditches, or stormwater channels. Such unwanted materials should be poured into a hole dug in absorbent ground and covered with 45 cm of soil.

Toxicity and its Determination

Toxicity is a measure of the tendency of any substance introduced into an organism in a relatively small amount to act upon the tissues to produce serious injury or death.

Everything is poisonous; it is only the quantity which determines whether injury will result from exposure to any given substance. Depending upon the nature of the exposure, a chemical may be taken orally (by being eaten or drunk), absorbed dermally (through the skin without necessarily injuring the skin or causing any local sensation), percutaneously (by injection or by penetration of the skin which has become broken or injured), or by inhalation (being breathed as a gas, vapour, fog, aerosol, dust, or smoke).

The quantity absorbed depends upon the nature of the substance, its concentration, the period of exposure, the degree of contact, temperature, and physical barriers.

Every form of life has many biochemical functions similar to those of other, distinctly different life forms. Some of the chemical processes that allow plants to grow and develop have their counterparts in insects and higher forms of animal life. Many of the biochemical and physiological functions essential to life in insects have their counterparts in higher animals, including man. The study of the effects of foreign substances (chemicals or poisons, including pesticides) on these functions is referred to as 'toxicology.'

(a) Toxicity to Laboratory Animals

The toxicity of any substance to any given species may be determined by applying known amounts to individual animals or to groups of animals maintained in laboratories under strict conditions designed to suit the habits and requirement of the particular species. The quantity of insecticide required to kill is known as the lethal dose (LD). The quantity required to kill the most sensitive of any large number of animals is known as the minimum lethal dose (LD/I). The quantity of chemical required to kill the whole (100%) of any given population is known as the maximum lethal dose (LD/100).

The differences between LD/I, LD/50, and LD/100 can be quite considerable because in any population there are some members that are quite susceptible and some that have an ability to tolerate the poison to a greater degree. In toxicity tests on animals, usually mice, rats, guinea pigs, rabbits, hamsters and, occasionally, larger animals, such as cats, dogs, and monkeys, a large number of animals must be used to be certain that the tests measure the effect upon a given population rather than on an individual, which might be either susceptible or tolerant. Great care has to be exercised to ensure that all of the animals are of a similar age, size, and weight, that they are free from disease, and that they are maintained under stress-free conditions. An adequate supply of food, water, air, light, and space for movement must be provided.

The substance under test may be administered in single doses by way of a stomach tube or capsule, or a predetermined amount may be incorporated in the diet. In other tests, the material may be injected or applied to the skin, or the animals may be exposed for a given time to a known concentration of the substance produced in the form of a gas or vapour that the animals breathe along with normal air.

Two distinctly different types of toxicity determinations are usually carried out: acute and chronic. Acute toxicity experiments determine the effect of known amounts of the substance given in a single dose by one or all of the above routes. The effect of the substance is observed over a period of a few hours to several days following administration. A graded range of doses is employed with a different group of animals receiving each successively higher dose. By this process it is possible to determine, with precision, the quantity required to kill the most susceptible, the most tolerant, or the average individual in a population. The symptoms of poisoning may be observed and should be recorded. The effect of the substance on vital organs such as heart, liver, kidneys, lungs, and brain is observed from postmortem examinations.

Chronic toxicity tests measure the effect of continuous exposure to relatively small quantities of the substance over a long period. The period chosen for such tests usually extends to 18 months in the case of mice and 2 years in the case of rats, the approximate lengths of their life spans. Groups of animals receive a carefully measured dose of the substance in their daily food and each group receives a successively higher dose. At least one dose must be high enough to produce a toxic effect.

In chronic toxicity experiments, the object is generally to determine the maximum amount of substance that may be tolerated by the test animals without producing any observable toxic effect. Other tests may be arranged in such a way as to determine the possible effects upon reproduction, on the unborn, or on the possible production of tumours.

(b) Toxicity to Domestic Animals

Where domestic livestock are unlikely to be exposed to pesticides, it is usual to estimate the possible toxic dose from that tolerated by laboratory animals because of the cost of carrying out extensive toxicity trials on large creatures. In the case of substances that are likely to come into contact with livestock, acute and subacute studies must be performed on each species of animal.

Experiments are sometimes made to determine the dose which farm animals will tolerate. In such experiments, it is usual to take only a small group of animals for testing. Tests may be carried out on chickens, ducks, sheep, goats, pigs, and cattle, which vary greatly from one to another in their ability to tolerate chemicals.

(c) Toxicity to Man

Because of legal and moral objections, it is not possible to carry out toxicity experiments on humans, even volunteers, except with substances that are intended for administration to humans for therapeutic purposes. The toxicity to man cannot be calculated from experiments on laboratory or domestic animals, though these give a very good indication of the probable relative toxicity (low, moderate, high, very high).

Extensive practical experience in the use of a particular chemical does not necessarily measure its toxicity, though it is a good indication of potential hazard to users. Information gathered from investigations of accidents involving operators and other personnel, or attempts at suicide, provide an indirect indication of toxicity. However, it must be emphasised that all chemicals before being released for use in the control of pests are, by government regulation, required to be first subjected to extensive toxicological studies involving a variety of laboratory animals. Products with a high toxicity must be labelled with adequate directions to warn the user and to reduce the possibility of injury to persons coming into contact with the product either casually or in their daily work.

Safety of Operators

The insecticides selected for use as grain protectants all have a relatively low acute toxicity and represent a low hazard to operators. Under normal conditions operators should not be exposed to significant quantities of these protectants but nevertheless all personnel involved in the handling and use of such insecticides should be instructed and supervised in proper safe handling practices.

Remember that all pesticides are not equally dangerous; neither are they equally safe. Treat all chemicals with respect and common sense and do not fail to heed directions and precautions set out on labels, in technical literature, and in operator's manuals.

Store pesticides in a well ventilated room or shed that can be securely locked. Unauthorised persons, especially children, should not be allowed into such stores. Be sure that labels do not become damaged. Place the container so that the label is clearly visible.

The concentrated materials present the greatest peril to operators. Do not pour or measure concentrates unless wearing rubber gloves. In the case of more hazardous materials, the operator should be protected with full coverage clothing and face shield. Splashes in the eyes or around the mouth can be dangerous. Wash off immediately with soap and water, any contamination by concentrate.

Wettable powder concentrates may contaminate the operator during weighing out and initial preparation of the spray. When pre-mixing wettable powder sprays, do not add the water to the powder; tip the powder gently into the water and allow it to sink before commencing to stir.

People engaged in mixing or spraying pesticides should wear a wide brimmed, washable hat, long sleeved overalls done up to the neck, and boots. Change into clean clothing for meal periods and again as soon as work is finished for the day.

If an accident should happen or if an operator becomes ill seek medical advice immediately.

The following rules should be learned and remembered,

(i) Carefully read the label, especially the safety precautions, before use.
(ii) Use all products as recommended on the labels and do not use persistent chemicals when there are effective, less persistent alternatives.
(iii) Safely dispose of all used containers. Directions for disposing of containers and unwanted chemicals should be provided to operators.
(iv) Never transfer pesticides into other containers, especially beer and soft drink bottles.
(v) Close any partly full containers and return to a locked store away from grain, animal feeds, and out of reach of children and unauthorised persons.
(vi) Avoid contact with concentrates; wear gloves and protective clothing when directions indicate.
(vii) Prepare in the open air or in a well-ventilated toom.
(viii) Measure accurately.
(ix) Mix thoroughly but not with the hands.
(x) Avoid spilling or splashing.
(xi) Clean up spillages promptly.
(xii) Change contaminated clothing immediately and launder before wearing again.
(xiii) Wash hands, arms, face and neck thoroughly with soap and water before smoking, eating, or drinking.
(xiv) Wash exposed parts of the body thoroughly when the job is completed.
(xv) After each day's spraying, wash protective clothing including hat.
(xvi) Do not smoke when applying pesticides.
(xvii) Be careful not to become doused with insecticides when cleaning blocked nozzels or repairing spray hoses. Wash immediately if this happens. Never clear blocked spray nozzels with the mouth.

Whilst those handling concentrated insecticides and those applying grain protectants and fumigants are instructed to take appropriate care to avoid possible risk to their health and the health of fellow workers, there is no need for similar concern over the safety of the residual deposit on the grain itself.

There is little or no risk that workers handling treated grain could absorb quantities of insecticide sufficient to produce injury or even to give rise to detectable reaction. This does not mean that common sense should not be used or that workers should avoid proper hygiene during and at the end of work each day.

Insecticidal powders containing low concentrations of selected insecticides have been developed for use under village conditions, for application to farm-stored grain, and for treating small quantities of stored grain and seeds. Such powders offer several advantages, among them convenience, effectiveness, low cost, and simplicity in application, including safety to operators. The use of insecticidal powders may increase in the near future, encouraged by their safety to users.

Practical experience with malathion, fenitrothion, bioresmethrin, and pyrethrum under Australian conditions over more than 20 years has not indicated any hazard to operators, many of whom have handled extremely large quantities of these protectants in the course of treating stored grain.

Safety of Consumers

The anxiety felt by individuals and government agencies about possible risks to health from the prolonged ingestion of small amounts of chemicals deliberately added to food as pest control agents is understandable. However, competent scientists in many countries have emphasised that there is no evidence to suggest that the general population — who benefit considerably from the judicious use of insecticides — is at all adversely affected by residues in foods when insecticides have been applied in accordance with recommended practice. Nevertheless, the effective control of any residues is the proper concern of the public health officials in every country.

There is general agreement among toxicologists and other health experts that the level of human exposure should be as low as possible. Consequently, restrictions on pesticides not only require that residues must be safe, but also that they must be no higher than is actually needed for good agricultural practice.

Residue limits must, of course, be acceptable toxicologically. Modern toxicology stands on the tenet that 'the dose makes the poison.' Indeed, without specifying amounts, the word 'toxic' is meaningless. Thus, an estimate is required of a level of pesticide residue intake below which the risk to health is too small to be of concern. This level of intake is normally referred to as the acceptable daily intake (ADI) which is defined as the amount of a chemical which can be consumed every day for an individual's entire lifetime with the practical certainty, on the basis of all the known facts, that no harm will result. This concept was introduced by the Joint Meeting of Experts on Pesticide Residues (JMPR), a meeting of experts of international repute in their respective fields, invited by the World Health Organization or the Food and Agriculture Organization, to consider the residues of various pesticides occurring in foods in international trade. Many pesticides now have ADIs assigned to them by the JMPR.

ADIs are derived from the results of long-term studies with laboratory animals. The studies encompass an assessment of carcinogenic, mutagenic, and teratogenic potential. The possibility that a residue might be neurotoxic or have an effect on reproduction is also considered. The intake causing no toxicologically significant effect in animals when given daily over their life span is determined, and the ADIs are derived by the application of generous safety factors (usually at least 100).

The ADI is expressed in terms of milligrams of the residue ingested per kilogram of body weight per day. In this context, man is usually reckoned as having a typical weight of 60–70 kg. It should perhaps be stressed that in appraising residues in foods one is virtually never concerned with short-term or 'acute' toxic hazard — residues arising from good agricultural practice never reach levels anywhere near those that could pose an acute hazard. Rather, one is concerned with possible longer-term effects from ingestion of very small amounts over a lifetime.

If the amount of residue found in food following approved use of the pesticide is less than the amount which has been calculated from animal feeding studies to be safe for man if consumed in his food for an entire lifetime, then the maximum residue limit is fixed at the level of residue found in food following such approved use of the chemical. No matter how innocuous the chemical might appear from the toxicological studies on laboratory animals, the legal limit will not be fixed on a substantially higher level than that shown to occur when good agricultural practice has been followed.

'Good agricultural practice' means the recommended usage of a pesticide which is essential for the control and prevention of pests under all practical conditions and which takes into account:

- the quantities necessary to adequately control the pest, leaving the smallest possible amount of residue;
- the toxicological and environmental hazards involved;
- differences in the amount and frequency of the pesticide required as a result of differences in ecology, husbandry, climatic conditions, and severity of pest-control problems.

The 'recommended usage' should comply with the procedures (including the formulation, dosage rates, frequency of application, and the interval between treatment and harvesting) recommended by appropriately trained specialists. It is the usage that has been registered, approved, or otherwise accepted to the purposes by the relevant official department and which is normally included on the label. Recommended methods of application should be based upon supervised trials and other experimental work and should take into account variations in climate, storage practice, and incidence of pests under the practical conditions in which pesticides may be used. Good agricultural practice includes practice in the control of pests during the storage, transport, marketing, and processing foods.

No maximum residue limits have been provided to cover accidental contamination or the misuse of pesticides nor is it anticipated that these residues will be accorded legitimate status. Every effort must be made to prevent such accidents.

The deliberate application of insecticides or fumigants for the destruction of insects in stored grain or for protection against insect attack presents quite distinctive problems when it comes to consideration of residues.

Residues resulting from use of pesticides before or during the growth of the crop occur only occasionally and then only at relatively low levels so that the intake of residues in the diet is relatively insignificant. When chemicals are deliberately added to stored grain, the chances are that all or most of the grain will be treated and that the residues will be at a relatively high level. The intake in the diet could therefore theoretically be highly significant. Toxicologists and health authorities require greater assurance and more extensive evidence of safety before authorising the deliberate addition of potentially toxic substances to food.

These authorities are conservative and unless the scientific data which are available are conclusive and leave no room for doubt, no recommendation for use or for a maximum residue limit will be made.

During the research work leading to the acceptance of insecticides for use on stored grain it has to be demonstrated by studies under laboratory and practical conditions that the amount of residue in food at the time of consumption will be less than the amount of the acceptable daily intake.

Among the misconceptions of those who have expressed concern over the addition of insecticides to grain there is one that has been difficult to dislodge. This is the assumption that the intake of residues will be sufficient to cause a potential hazard, if not actual injury, to consumers. The misconception arises from the practice of assuming that the whole of the amount of insecticide applied to the raw grain is present in the food as consumed.

Apart from the significant loss and degradation which occurs while the treated grain is in storage, there are further losses during milling, processing, and cooking that result in the amount of residue in the food as consumed being much less than 10% of the amount in the raw grain. This is the figure that should be used in calculating the theoretical consumption, not the level in the raw grain, and certainly not the legal maximum residue limit which is usually higher still.

Unfortunately, some of the officials in developing countries who do not have access to comprehensive technical information and advice are seriously disturbed by the alarmist publicity in the news media about the alleged danger of chemicals, particularly pesticides. Since they take their responsibilities seriously they are reluctant to accept the use of grain protectants lest there should be adverse effects upon consumers, particularly in countries where raw grain is converted into food with a minimum of preparation and cooking.

The monographs of the JMPR contain extensive data and references to many studies which demonstrate that residues of each of the approved grain protectant insecticides are substantially removed before the food reaches the consumer. The information available is summarised in Table 1. The loss is, to some extent, dependent upon the amount of processing. Because of this, wholemeal bread will contain somewhat more than white bread because the bulk of the residue is removed with the bran during the preparation of white flour. However, the work of Lockwood et al. (1974) showed that even when wheat, rice, and sorghum were subjected to traditional preparation and wet methods of cooking, such as are used in India, there was complete loss of malathion, fenitrothion, and tetrachlorvinphos. Dry cooking methods used in preparing chapatties from wheat and sorghum resulted in losses of 51–75%. Further work along these lines is needed to determine the fate of residues under traditional methods of food preparation and cooking.

It is recognised that unsophisticated people, particularly small farmers and village storekeepers, might not be able to apply grain protectants as safely as they are applied in industrialised countries with central grain storage facilities. However, experience has shown that provided the grain protectants are formulated as dilute dusts and that these dusts are pre-packed into small sachets, sufficient for one bag, basket, or

Table 1. Percentage reduction of residues brought about by various steps in processing raw grain for human consumption.

Insecticide	Wheat to wholemeal	Wheat to white flour	Wheat to wholemeal bread	Wheat to white bread	Rice in husk to husked rice	Rice in husk to polished rice	Rice in husk to cooked rice	Barley to malt	Barley to wort
Bioresmethrin	0	35	100	100	85	93	97	90	99
Bromophos	0	76	72	90	/	/	/	/	/
Carbaryl	57	98	75	99	93	98	99	97	100
Chlorpyrifos-methyl	(67)b	(94)b	(83)b	98	/	/	/	95	99+
Deltamethrin	0	80	30	80	/	/	/	/	/
Dichlorvos	50	80	95	100	90	96	100	/	/
Etrimphos	0	70	80	95	/	/	/	/	/
Fenitrothion	40	92	80	99	92	97	99	80	99+
Fenvalerate	0	88	30	90	/	/	/	/	/
Malathion	20	75	80	95	90	97	98	98	99+
Methacriphos	50	87	100	100	90	97	99	93	99+
Permethrin	0	88	68	94	/	/	/	/	/
Phenothrin	0	82	46	87	90	97	98	83	99+
Pirimiphos-methyl	0	73	53	88	85	93	97	100	100
Pyrethrins	/	/	100(?)	100(?)	/	/	/	/	/

NOTE: / = No information available; (?) = Assumed to be destroyed by cooking but no information available; b = to be checked.

standard container, the least sophisticated people can apply them safely and effectively.

Notwithstanding the long-standing and extensive use of malathion as a grain protectant, the scientific data on the nature, level, and fate of the deposit on all types of grain and stored commodities in various types of storage are probably not yet widely available. It is therefore understandable why government officials in some countries have appeared more than a little reluctant to embrace the idea of grain protectant insecticides under conditions which prevail in their country. More data on each of the grain protectant insecticides are sorely needed. To collect these data is not particularly glamorous work and it certainly will not lead to great discoveries, but the work must be done and must be published if we are to receive the support and approval of health officials in grain producing and grain importing countries.

The work needs to be repeated and extended under a wide variety of practical conditions to provide the experience and reassurance that is so necessary to dispel any misgivings about the value, safety, and acceptability of grain protectants treatments. Studies designed to demonstrate the fate of the deposit during storage, processing, and cooking are particularly valuable, especially when they are carried out under conditions that are distinctly different to those prevailing in countries with central grain handling systems. The paper by Lockwood et al. (1974) describes the results of work typical of the type that is badly needed. Also, one hopes that the work of La Hue (1978) will be extended with all speed so that the value of tailor-made dusts to developing countries can be proven and exploited.

In several countries where grain protectant insecticides are used exclusively or extensively for the protection of grain, total diet studies have confirmed that the intake of residues of these insecticides by consumers is within the ADI.

Trade Difficulties

Trade might be defined as supplying what the customer wants at a price which is economically viable to the supplier. The buyers of agricultural products dictate not only the demand and price, but also the quality. In order to meet the high standards demanded by overseas markets or set by foreign competitors, producers must employ modern technology to prevent blemish from pests and diseases. In so doing, it is absolutely essential to avoid visible residues and to control invisible residues to ensure that at no time do these exceed the limits fixed by legislation or convention in the market place.

Whether by accident or by design, chemical residues, including those of a wide range of agricultural chemicals, have become a hazard to international trade in food commodities and in a number of instances have become barriers to free trade in important foodstuffs.

Those who have not been personally involved in an incident in which a consignment of an agricultural commodity destined for a foreign market was rejected because of chemical residues will find it impossible to imagine the complications and repercussions that ensue.

When a consignment is rejected in a foreign market the value of that consignment is lost and the resulting publicity can often damage the future prospects for the exporter and for others engaged in similar trade. If the loss of the consignment means that the shipper can no longer meet contractual obligations, substantial damages may be claimed by the importer and the exporter is likely to face a considerable increase in insurance premiums on future shipments. It is not unlikely that such an incident could result in protracted negotiations at a government to government level.

Having once encountered such a situation, exporters become extremely sensitive, usually reacting by demanding that farmers who supply them with grain cease using pesticides. Those involved can count themselves fortunate if the news media do not seize upon the incident to provoke public concern.

All of this is justified if there has been misuse of a pesticide, if the food commodity is contaminated to the point where it might present a potential risk to consumers, or where the producer or exporter has violated the law of the exporting country. More often than not, however, the incident occurs because one or other of the following circumstances prevails in the importing country:

(a) there is not yet a legal limit for the particular residue in that food commodity;
(b) the limit is set at a slightly lower value;
(c) the definition of the residue is different to some minor extent;
(d) sampling and analytical problems have resulted in an apparent violation of the laws.

The number, variety, and complexity of such issues is seemingly endless and they are increasing at an accelerating rate. The position is made even more complex when national authorities suddenly decree, for one reason or another, that chemicals which have been in worldwide use for 20 or 30 years are no longer acceptable. Notwithstanding the need for and acceptability of such chemicals in other countries, such prohibitions will inevitably lead to trade difficulties. There are many insecticides and fumigants which fit this category at the present time and it is anticipated that the position will become increasingly difficult.

The presence of chemical residues in food and agricultural commodities has resulted in many 'unofficial' trade restrictions. When the importing country has established very low legal limits for such residues, it is possible to reject or refuse imports on the grounds that the rejection is legally justified. The defence that the legal residue limits are designed to protect the health of the consumers is hard to challenge. Many countries have attempted to seek protection for their local agricultural interests by designing legislation refusing importation of food commodities containing even insignificant quantities of residues. Such moves have been attempted in countries with heavily subsidised agriculture where attempts to invoke maximum residue limits have been proposed in an effort to achieve protection for an uneconomic local agriculture.

Overly strict phytosanitary requirements (freedom from pest and disease) of importing countries, when imposed simultaneously with unrealistic demands for freedom from residues, can effectively prevent the importation of many food commodities. This system of double standards is well recognised but almost impossible to overcome.

Concern over the development of such trade barriers and the need to have assurance on matters concerning public health, prompted the Food and Agriculture Organization and the World Health Organization of the United Nations to sponsor meetings of member governments and provide a forum for discussion and agreement on international standards for residues in food commodities. Since the initiation in 1965 of the Joint FAO/WHO Meeting of Experts on Pesticide Residues and, in 1966, of the Codex Committee on Pesticide Residues, slow but effective progress has been made towards international agreement on the levels of residues which might be accepted in raw agricultural commodities moving in national and international trade. An ability to meet these standards is not only advantageous to exporters of agricultural products but also essential to secure a place in the international grain market.

It is important to realise that any country with special pest-control problems involving the use of pesticides can have its needs considered and dealt with by the Codex Committee on Pesticide Residues. All that is needed is an official submission to the Codex Committee on Pesticide Residues or to FAO for consideration by the Joint FAO/WHO Meeting of Experts on Pesticide Residues. The agricultural practices and residue data will be assessed and an appropriate recommendation will be make for consideration by governments. This then serves as a basis for reaching international agreement.

Safety of Livestock

Many of the insecticides under consideration for application to stored grain have already been evaluated and developed for direct application to cattle, sheep, pigs and poultry for the control of external parasites and flies. Several of them have been extensively used for dipping cattle for the control of ticks where the treatments have to be repeated regularly at short intervals. There is therefore a reasonable amount of information available about the topical and systemic toxicity to livestock.

Virtually all these insecticides have been studied to determine their fate following ingestion by livestock. In these studies, the excretion and metabolism have been examined. Whilst some of the compounds are known to give rise to residues in animal tissues and foods of animal origin when fed experimentally at relatively high concentrations, there appears to be no measurable amount of residue accumulated when they are fed at concentrations likely to be encountered in animal feeds derived from treated grain.

Since most of the insecticides used to protect stored grain do not penetrate to any extent into the individual grains, most of the deposit remains on the hulls of oats and rice which are discarded along with their insecticide content. In the case of wheat and hulled rice the residue is removed along with the bran to an extent ranging from 73% in the case of pirimiphos-methyl to 92% in the case of fenitrothion. The effect of feeding bran and pollard from treated grains should be carefully considered.

Following reports of an isolated case of alleged reduction of egg laying in a poultry flock where silo dust had been fed to poultry for many months, the author made a comprehensive review of the scientific literature on the toxicity of malathon and dichlorvos to avian species. This review also considered the question of potentiation of the toxicity of dichlorvos by malathion (Snelson 1980). The information available, though conflicting, indicated that poultry could withstand relatively high intake of both insecticides for a considerable period. However, there was a dose-related effect on feed intake which could manifest itself in reduced egg production. A selection of the literature is provided for information.

Golz and Shaffner (1955) fed 95% technical malathion to chickens at a concentration of 5000 ppm in the rations (approximately 450 mg/kg/day). This level produced definite signs of toxicity, such as retardation of growth, slower feather development, soft droppings, leg weakness, and paralysis.

Studies by Gaafar and Turk (1957) suggested that the apparent LD/50 reported by Golz and Shaffner (1955) was too high. They reported that young chickens can withstand more malathion by oral administration than can older birds, the LD/50 for 3-week-old chicks ranging from 200–400 mg/kg and, for yearling fowl, 150–220 mg/kg. This trend towards reduced tolerance in the older chickens is in marked contrast to data reported for rats.

The American Cyanamid Company reported an oral LD/50 of malathion to chickens of 850mg/kg. Technical malathion (95%) was fed to day-old chicks for 2 weeks at a level of 10 ppm in their rations. For the following 10 weeks they were divided into groups of ten and fed 100, 1000, and 5000 ppm in their diets. The groups on 100 and 1000 ppm behaved normally and showed a similar growth rate and food consumption to the controls. Four animals died in the 5000 ppm group, and signs of intoxication and growth retardation were observed. At necropsy, no pathological lesions were found. Plasma and brain cholinesterase activities were significantly lower in the 5000 ppm group (American Cyanamid Company 1955).

Rehfeld et al. (1969), investigated the effect of various levels of dietary malathion on the performance of chicks. One-day-old chicks showed no apparent adverse effect from levels of malathion up to 1000 ppm. Levels of 2500 ppm in their rations caused a depressed growth rate, but no mortalities. A diet containing 5000 ppm malathion resulted in death of day-old chicks within 19 days. Except for weight loss, 1-day-old and 20-day-old chicks were able to tolerate diets of 0.5% malathion for up to 1 week. Chicks gained weight at the same rate as the controls after they were placed on normal diets again.

In a 2-year study, 21 female chickens were fed 250 ppm and 21 females and 6 males 2500 ppm malathion in their rations. The 250 ppm group did not differ significantly from the controls. At the 2500 ppm level a decrease in plasma cholinesterase activity was found between the 195th and 465th day of the experiment. The test hens came into production later and laid slightly fewer eggs, but the hatchability was not influenced. The offspring showed no deformities. At necropsy no gross or microscopical lesions were found (American Cyanamid Company 1960).

Malathion was administered to laying hens orally via capsule and in the feed. Daily intake of 250 or 500 ppm did not result in egg or tissue residues (Marion et al. 1968).

Sauter and Steele (1972) reported that 1 and 10 ppm malathion in rations significantly reduced hatchability of white leghorn eggs, though the shell thickness was not significantly reduced.

Page and Bush (1978) reported feeding trials conducted at the University of Georgia, where birds were fed diets spiked with graded levels of malathion (2.5, 5, 10, 20 ppm). The results are reported to indicate that:

(1) feed levels up to 20 ppm malathion do not significantly effect egg production;
(2) feed levels as low as 5 ppm malathion tend to reduce hatchability and fertility of broiler hatching eggs;
(3) feed levels as low as 2.5 ppm malathion significantly reduce hatchability of leghorn hatching eggs;
(4) malathion depressed hatchability of leghorn eggs more severely than broiler hatching eggs.

Details of these studies have not been sighted by the author. The information presented here has been obtained from reports on the work in two poultry trade magazines.

The Kettering Laboratory (1964) reported the LD/50 of dichlorvos in adult leghorn hens to be 22.8 ± 1.6 mg/kg. Multiple daily doses of 2.5 mg dichlorvos per kg in capsules were non-toxic to fowls over a three-week period.

Pym et al. (1976) reported a study of the effect of dichlorvos as a contaminant in feed on the performance of laying hens. Four groups of birds were administered a conventional layer diet containing either 0, 12, 24, or 48 ppm of dichlorvos for a period of 4 weeks, followed by a further period of 2 weeks during which the layer diet without dichlorvos was administered. Food consumption, egg production, and egg quality were monitored. It was concluded that a level of 24 ppm dichlorvos or above in the laying diet depressed feed consumption and egg production and appeared to increase the incidence and severity of blood spot inclusions in the eggs.

When the combined action of two active ingredients is greater than the sum of the effects of each alone it is generally said that one potentiates the other. The term potentiate is generally used to mean activate or to increase the activity above normal.

The Kettering Laboratory studied the immediate toxicity of dichlorvos alone and in various combinations with other organophosphorus insecticides (Kettering Laboratory 1963). It was found that dichlorvos does not exhibit significant potentiation with organophosphorus insecticides except those materials which have already been shown to potentiate any other OPs. Dichlorvos is intermediate in the list of 22 insecticides studied for potentiation. Malathion heads the list.

Pym and Armstrong (1977) carried out an extensive experiment to determine the effect of a number of grain protectant insecticides on egg production. They conclude that dichlorvos interacts with malathon to cause a depressing effect on egg production greater than the estimated additive effect.

Pym et al. (1984) carried out three experiments to study laying performance in hens given graded levels of malathion, dichlorvos, and pirimiphos-methyl either separately or combined in the feed over a four-week test period. Results conclusively demonstrated interaction between dichlorvos and malathion, as measured by depressed food consumption and egg production. Combining the three insecticides at levels which when given separately had no effect severely depressed food consumption and egg production. Plasma acetylcholinesterase (AChE) levels were reduced by 70% with dichlorvos at 30 μg/g, by 30% with malathion at 100 μg/g, and by 90% with pirimiphos-methyl at 50 μg/g. There was no indication of potentiation between insecticides as measured by plasma AChE inhibition, and effects upon food consumption and egg production appeared unrelated to plasma AChE activity. The relationship between food consumption and egg production was similar in groups receiving dichlorvos/malathion mixtures and in those receiving graded levels of untreated food, suggesting that the insecticide's effect upon egg production was mediated via a reduced food intake.

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Regulatory Requirements for Pesticide Use

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Abstract

In keeping with long-standing practice, all pesticides, including insecticides for use in grain storage, must be approved and are regulated by government authorities under legislation established in most, but not yet all, countries. The method of effecting such regulation is described. It involves a system of registration, whereby the particular formulation, label, and package are authorised to be sold to designated end users for specific purposes. The decision to grant registration is based on the evaluation of extensive scientific data on the chemical, physical, biological, toxicological, and environmental properties of the pesticide active ingredient and formulation, which are usually provided by the basic manufacturer in compliance with a protocol of requirements. These requirements have been harmonised worldwide through the efforts of the United Nations organisations FAO and WHO. Scientific data which can be generated in laboratories are acceptable worldwide, provided they have been developed by good laboratory practices. Data which depend on local climatic, environmental, or biological conditions, and which involve field experiment, must be reproduced in the region where the pesticide is to be used. Reference is made to the action taken to harmonise the production and presentation of such data and how this aids the development of sound grain storage systems.

ONE of the prerequisites of a pesticide is that it should be toxic to the target organism when applied in a convenient manner at a predetermined rate. Since few pesticides possess a high degree of specificity, most present at least a potential hazard to non-target organisms including man. It has been accepted that the availability and use of pesticides should be controlled in the public interest.

The goal in regulating pesticides is to provide society with adequate protection from adverse effects while not denying it access to benefits.

The principal method of establishing the manner in which a pesticide may be marketed and used is through the registration requirements. The term 'registration' used in this context should not be confused with the registration of, for example, a motor vehicle, a trade mark, or a dog. In these cases, the procedure simply involves the recording in a register of a few salient details that establish ownership, evidence of which is then provided by a document for which the registrant pays a designated fee. Such a procedure entails the minimum of time, expense, or documentation. In the case of pesticides, registration implies the acceptance by statutory authority of extensive, documented proof submitted in support of all claims of efficacy and safety made for the proposed product. Registration implies a number of different controls among which evaluation is the most important. For a pesticide to be adequately assessed for registration purposes, extensive scientific information must be developed by the manufacturer on all aspects of the properties and performance of the product.

Evaluation of pesticides involves the mature judgment of experienced professionals using a multi-disciplinary approach, and, as in other fields of human endeavour, some degree of risk must be considered acceptable to society. The alternative would be needless prohibition of important benefits.

There are potential problems with pesticide usage but the purpose of the large amount of research going into the generation of data for registration is to tackle the issues before they become problems. Registration enables authorities to exercise control over use levels, claims, labelling, packaging, and advertising, and thus to ensure that the interests of end-users are well protected. The registration legislation provides a system under which the public's interest and the manufacturer's rights are protected.

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Most nations are committed by law, policy, and traditions to assure their constituents that their food supply is adequate, safe, clean, and wholesome. In order to give effect to such laws and policies, it is necessary to develop criteria and protocols that are effective, workable, and enforceable. It should be the objective to achieve these goals with minimum dislocation of production or trade, but under no circumstances should adverse affects on people or the environment be countenanced to serve economic goals. While pesticides are intended to effectively control organisms that destroy or endanger man's food, health, or environment, like virtually every chemical they may have physiological effects on other organisms living in the environment, including man himself. Whether the effects occur or not is simply a question of the dosage and of proper use.

How best to reduce the hazards of pesticides to man and animals is a problem that has occupied many individuals and organisations the world over. In electing to control the introduction of pesticides through some type of registration scheme, national authorities have been mindful of the needs of the many interrelated and interdependent segments of the community.

Responsibility

There are four levels of responsibility associated with the registration of pesticides.

Manufacturer

The prime responsibility rests with the manufacturer who must first be satisfied that the product fulfils the many requirements demanded by the public and the government authorities charged to watch the public interest. The manufacturer must ensure that there is adequate scientific evidence to support all claims for efficacy and safety. It is not generally recognised that registration authorities do not usually ask more difficult or different questions to those demanded by corporate management of those charged with research and development responsibilities for new pesticides.

The manufacturer must be satisfied that he has generated sufficient scientific information to effectively and positively answer questions about a pesticide's effectiveness, efficiency, reliability, safety to users, bystanders, consumers, livestock, and wildlife, and acceptability in the environment.

Implicit in these questions are many issues and aspects which the manufacturer must consider and on which appropriate scientific data must be forthcoming. If and when all this information is available, the manufacturer may approach regulatory authorities in confident expectation that they will judge the data adequate and acceptable.

Government

In most countries, it is recognised that we have entered a period characterised both by a fuller understanding of the risks and advantages of pesticides and a desire to provide adequate controls, either voluntary or mandatory, to ensure that the use of pesticides does not affect public health, the environment, or trade.

Public policy must be aimed at protecting the public and the environment from excessive exposure to harmful substances while also preserving and increasing the great variety and utility of those products that have contributed so much to the improvement of our food supply, protection of our health, the increase in trade, and the standard of life.

Governments must establish legislation to regulate the manufacture, sale, and use of pesticides. Such legislation must be based on regulations that establish a permissible safe use pattern for each chemical. This use pattern must be described on the labelling for each product and the labels need government approval. In addition, safe legal limits must be established for residues in food and feed.

Some countries exercise control over both safety in use and efficacy, while others control one or the other. In some countries, the protection of the operator stops with the label directions, whereas in others the law imposes responsibility on employers in respect of their employees. Many countries make use of the idea of an experimental permit, temporary clearance, or licensing to allow new pesticides to be field-tested, and some registration authorities undertake a critical laboratory and field examination of new products.

In summary, the responsibility of government as regards use of pesticides is to: protect the unwary from the unscrupulous; prevent unsubstantiated claims; ensure adequate directions for use; highlight precautions and limitations in use; protect the uninitiated from their own ignorance; safeguard reputable manufacturers from spurious claims by disgruntled users; and engender public confidence in the registration system.

Pesticides legislation requires manufacturers and distributors of products classified as pesticides to obtain registration of their products and product labels before offering them for sale. The registration requirements are most exacting. They provide protection for the general public from fraud or misrepresentation but, in addition, are designed to ensure that the registration labels contain adequate directions for safe, effective, and proper use in the interests of all concerned.

Vendors

Those engaged in the distribution and sale of pesticide products carry a heavy responsibility to ensure that they do not offer for sale products which are not registered and that they do not promote uses which are not recommended on approved labels. Users rely heavily upon their suppliers for guidance in the safe and effective use of pesticides and it is recognised that such sales outlets provide the major source of information reaching users. Because of this, the role of supplier carries with it both privilege and responsibility.

Users

Users must recognise a responsibility to themselves, their families, their neighbours, the community, the environment, and those who might ultimately consume the produce grown with the aid of pesticides.

The directions on registered labels have been developed at great cost in time, money, and scientific manpower, have been evaluated by experienced scientists, and have been approved by government authorities. The claims and directions are made in the knowledge that if they are followed the result will be entirely satisfactory and there will be no untoward hazard. Unless users accept this responsibility, the efforts of manufacturers and government will have been to no avail.

National Requirements for Insecticides to be Used in Grain Storage

Only those insecticides that have been specifically approved should be used on and around grain. The choice of insecticides that may be used is limited by the very strict requirements that must be enforced to ensure absolute safety for consumers of these important basic food commodities. To qualify for selection as a possible candidate material for use on or around grain, the insecticide must fulfil the following 10 requirements (FAO 1982a):

1. It must have a wide spectrum of high insecticidal activity;
2. It must present no hazard to consumers of grain and grain products;
3. It must be acceptable to health authorities;
4. It must be acceptable to the international grain trade;
5. Legal limits must be established for the resulting residues under the laws of the country where the grain is stored;
6. It must not affect the quality, flavour, smell, or handling of grain;
7. It must be capable of being used without undue hazard to operators;
8. It must be effective at economic rates of use;
9. It must not be flammable, explosive, or corrosive; and
10. Its method of use must be compatible with established grain handling procedures.

The requirements for insecticides used on seed are similar but, under circumstances where there is no possibility of seed being used as food or feed grain, materials of higher mammalian toxicity can be used. Additional requirements are:

1. No detrimental effect on germination of seed and seedling growth; and
2. Compatibility with fungicides used for pre-emergent and seedling diseases.

Efficacy

Because of the wide variety of stored products pests that can occur in a particular type of grain, given region or country, detailed information is required concerning the effectiveness against each important species of stored product pest. This can include information concerning the biological activity against several life stages and, where appropriate, information concerning the susceptibility of species which have already been selected for resistance to other pesticides.

Such data are generally developed under controlled laboratory conditions using cultures of stored product pests the history of which is known and which are exposed to a range of concentrations of the insecticide applied to a substrate upon which the insects will feed, reproduce, and live successfully. In many instances this may be whole raw grain.

These studies are generally designed to determine the lowest concentration of insecticide required to kill adult insects and the concentration that will prevent reproduction and development of imagoes. It is essential that the studies should be carried out under known and controlled conditions of temperature and humidity. These conditions should preferably coincide with those found in stored grain in the region.

Since the insecticide is intended to protect grain from infestation rather than to destroy existing heavy infestations, it is usual to design some of the experiments to measure the susceptibility of treated grain to infestation by the most important species encountered in the region. Samples of grain which have been treated uniformly and accurately with insecticide at a graded range of concentrations and which have been held under controlled conditions of storage for varying periods should be challenged with known numbers of insects. The mortality rate should be determined after an exposure period (generally 3 and 26 days) and the number of progeny should be determined after a period sufficient to allow for their development.

Such data should be used to decide the optimum rate of application of insecticide that would be most effective in providing the degree of protection required. It is generally necessary to carry out pilot studies in which small bulks of grain (100–200 kg) are treated with the insecticide at a predetermined rate prior to storage under conditions typical of those encountered in the region. Samples of this bulk grain should be taken at regular intervals for bioassay with selected stored-product insects. The object of such studies is to determine the length and degree of protection provided by the insecticidal treatment and to establish a reliable indication of the minimum effective concentration of insecticide that should be applied to grain.

It is absolutely vital that the rate of application should be no higher than the concentration that will confer an adequate degree of protection for a reasonable period when the commodity is stored under conditions which minimise insect attack. Insecticides are to be regarded as a supplement to good storage practices, not a substitute for them.

Because of the many pitfalls inherent in scaling up from small scale laboratory conditions to commercial scale grain storage and handling, it is generally necessary to take the results of laboratory and pilot scale studies and verify them in typical commercial practice. Such practical trials should be supervised by scientists and technical personnel who should be responsible for monitoring treatment, and collecting data on temperature, humidity, rate of treatment, etc. Samples of treated grain should be collected for chemical analysis and bioassay immediately after treatment and at intervals during storage.

Such a regime of experimentation and investigation should lead to the development of practical directions for use of the insecticide. So that the information can be evaluated by relevant authorities, it is essential that all details of experiments and their results should be systematically recorded and reported.

Recognition that efficacy studies conducted in the field in accordance with internationally accepted guidelines can produce data supportive of the results of similar field studies carried out under different climatic, meteorological, and agricultural conditions in some other part of the world has greatly reduced the cost of generating adequate data on efficacy but it does not do away with the need for adequate field trials in the region. Efficacy studies should be designed to determine the optimum method and rate of use.

The amount of grain protectant required depends largely on the insect species present, the temperature and moisture content of the stored commodity, the type of storage, and the duration of protection required. For example, moths can usually be controlled in bulk grain storage by treatment of the space above the grain and by application of a suitable protectant to the grain surface, rather than by admixture with the grain.

Other examples of optimal use include:

(1) selection of the insecticide most effective against the species likely to occur;

(2) selection of rates providing adequate protection under local storage conditions for the anticipated period of storage, but which give rise to minimum residues at the time the grain is taken for processing;

(3) reduced rates of application when grain is cool, being cooled, or aerated;

(4) careful supervision of application and a program of worker training to ensure that the application is as uniform and complete as possible, thus avoiding pockets of grain containing either too little or too much insecticide.

Fate

Comprehensive information concerning the fate of the insecticidal deposit on the grain is essential for the proper understanding of the biological activity under prolonged storage as well as the level and nature of residues in the treated commodity when it is removed from storage and passes into trade channels.

For these reasons, it is essential that the pilot studies and supervised field trials should be monitored by chemical analysis of samples of the stored commodity. The frequency of sampling should be sufficient to enable the rate of degradation to be determined with a fair degree of accuracy. It is possible to predict the fate of the insecticidal deposit from a knowledge of the storage temperature and relative humidity of the interstitial space within the grain (Desmarchelier 1978).

The climatic conditions surrounding stored grain, especially bulk grain, are much more constant than those to which field crops are exposed. For example, temperature and moisture content of stored grain are relatively stable and stored grain is sheltered from wind, rain, and light. Under such conditions, it is logical to expect that the rate of disappearance of the insecticide deposit would be predictable. Desmarchelier (1978) showed that the loss of fenitrothion from postharvest application to wheat, oats, rice in husk, and sorghum followed a second-order rate process, with rate of loss being proportional, at a fixed temperature, to the amount of fenitrothion and the activity of water. The water activity was obtained from the partial pressure of water vapour in the interstitial spaces in equilibrium with the moisture absorbed on the grain. The effect of temperature was in the form of an Arrhenius equation.

A chart relating half-life to temperatures and relative humidity was presented in a form suitable for field use (Fig. 1), and a mechanism was proposed for loss of fenitrothion. The proposed mechanism is that an absorbed molecule of fenitrothion is desorbed by replacement by a water molecule. The desorbed molecule is more likely to be degraded than an absorbed molecule because it has a greater chance of collision with enzymes, metal ions, and other active molecules.

The general model developed for fenitrothion has been extended to other insecticides, including bioresmethrin, phenothrin, and carbaryl (Desmarchelier 1980a,b), pyrethrum (Desmarchelier et al. 1981), pirimiphos-methyl, chlorpyrifos-methyl, and methacriphos (Desmarchelier et al. 1980b), and several photostable pyrethroids (Desmarchelier and Bengston 1979).

There is good agreement between predictions by the models and results obtained by careful monitoring of extensive field use involving tens of thousands of tonnes of various grains

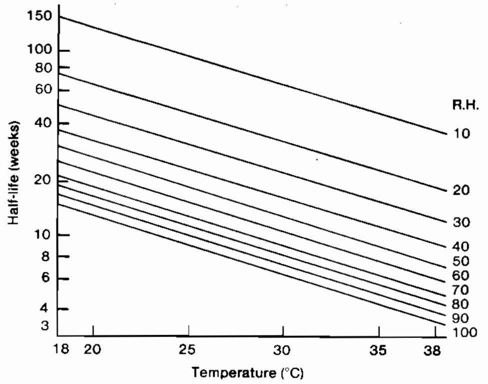

Fig. 1. Half-life of fenitrothion on grain at different relative humidities versus temperature.

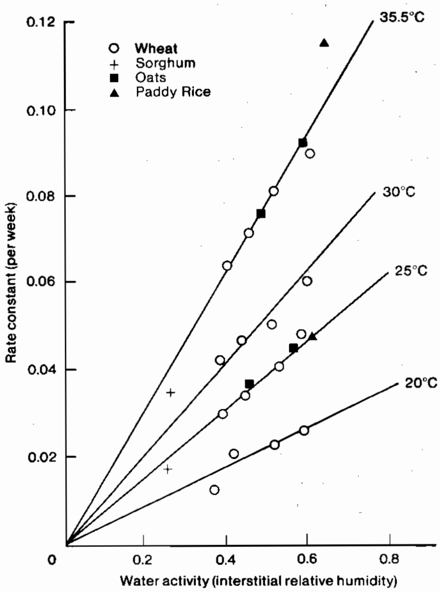

Fig. 2. Variation of breakdown rate of fenitrothion on whole grains as a function of water activity and temperature.

Table 1. Important features of insecticides currently used or under development as grain protectants.

Insecticide	In use since	Under development	Rate of application (mg/kg)	Synergist used[a]	Half-life at 30°C and 50% R. H. (weeks)	Temperature coefficient (K/°C)
Bioresmethrin	1975	−	1	+	38	0.031
Bromophos	1968	−	10	−	/	/
Carbaryl	1979	−	5	−	21	0.031
Chlorpyrifos-methyl	1978	−	5–10	−	19	0.040
Deltamethrin	—	+	1	+ −	>50	/
Dichlorvos	1966	−	4–10	−	2	/
Etrimphos	—	+	10–15	−	/	/
Fenitrothion	1977	−	6–12	−	14	0.036
Fenvalerate	—	+	2	+ −	>50	/
Malathion	1960	−	8–20	−	12	0.050
Methacriphos	—	+	5–15	−	8	0.055
Permethrin	—	+	2	+ −	>50	/
Phenothrin	—	+	2	+ −	40	0.029
Pirimiphos-methyl	1969	−	4– 8	+ −	70	Small
Pyrethrins	1935	−	2– 3	+ +	55	0.022

[a] + = yes; − = no; + − = yes and no; + + = definitely; / = no information yet available.

(Desmarchelier et al. 1980a, 1985 in preparation).

The studies by Desmarchelier (1978) and Desmarchelier and Bengston (1979) enable a direct comparison to be made of the 'reference half-lives' of different insecticides, i.e. the time required for an insecticide to degrade to half its original concentration at a fixed temperature (30°C) and relative humidity within the stored commodity (reference point — 50% R.H.). The half-lives of most of the insecticides under consideration are given in Table 1.

Moisture content of stored products, arbitrarily defined in terms of the weight loss on heating under specified conditions, is not linearly related to water activity for a particular grain and differs substantially between different commodities of the same water activity. Moisture content is, however, easy to measure and compilations are available (Hall 1963; Gough and Bateman 1977) to convert it into water activity in equilibrium with the grain under test (Banks and Desmarchelier 1978). According to these workers, if water activity is used as a measure of water present, the breakdown rate of various insecticides is found to be independent of grain type (see Fig. 2) and is a first-order reaction with respect to water activity.

Residues

Residues in food are not a novelty of the 20th century and their occurrence is not necessarily associated with the use of pesticides. Food legislation in most countries has evolved as a result of the need to protect consumers from the risks of adulteration and contamination. Limits for chemical contaminants in food appeared in food legislation in the United Kingdom and the United States in the early 1900s. Pure Food Acts and Food and Drug Acts were introduced in Australia well back in history. The proliferation of standards (tolerances) for residues in food commenced in 1952 when, as a result of public hearings, limits were fixed for DDT and other pesticide residues in many raw agricultural commodities and foods in the United States.

The science and practice of evaluating residues and establishing legal limits has spread beyond national boundaries and has become part of the Food Program of the United Nations conducted by the Food and Agriculture Organization and the World Health Organization working in close collaboration to protect public health and to facilitate trade in foodstuffs.

There have been a few instances where people have been injured by gross misuse of pesticides. The most notable examples were where HCB and methyl-mercury treated seed was used directly for human food and where people have been injured as a result of pesticides leaking into food transported or stored in close proximity. There are, however, no known instances of injury to consumers resulting from the consumption of food containing residues derived from the proper use of chemicals. The modern attitude is, however, that food should be as free as possible of man-made contaminants.

No maximum residue limits have been provided to cover accidental contamination or the misuse of pesticides. Neither is it anticipated that these residues will be accorded legitimate status.

The deliberate application of insecticides or fumigants for the destruction of insects in stored grain or for protection against insect attack presents quite different problems when it comes to consideration of residues.

Residues resulting from use of pesticides during the growth of the crop occur only occasionally and then only at relatively low levels so that the intake of residues in the diet from this source is relatively insignificant. When chemicals are deliberately added to stored grain the chances are that all or most of the grain will be treated and that the residues will be at a relatively high level. The intake in the diet could, theoretically, therefore be highly significant. Toxicologists and health authorities require greater assurance and more extensive evidence of safety before authorising the deliberate addition of toxic substances to food.

These authorities are conservative and unless the scientific data which are available are conclusive and leave no room for doubt, no recommendation for use or for a maximum residue limit will be made. The number and variety of insecticides which have been cleared for application to stored grain and for which maximum residue limits have been established is strictly limited.

The ability of a pesticide to persist for a certain length of time can be desirable and has been recognised as important in some situations for successful control of pests. Thus, a knowledge of residues of a pesticide, or arising from the use of a pesticide, is useful in establishing its efficacy. However, the assessment of the human hazards arising from very small quantities of a pesticide in food and the environment has become an important part of the overall risk/benefit evaluation and is essential before a pesticide can be introduced.

One of the basic requirements of such assessments is the availability of reliable data on pesticide residues in food, feed, and the environment so that a realistic estimate can be made of the human exposure. The increasing demands of national registration and health authorities include residue data on treated crops and commodities and additionally in water, soil, air, and wildlife. These authorities will only reach conclusions and make decisions if they are satisfied that the data are reliable.

However, variations in methods and techniques used in obtaining these data, including the selection, preparation, and analysis of samples, and the design of subsequent trials, have made it difficult to compare results and decide if they are valid. These variations have also contributed to differences in the regulations adopted in different countries.

These difficulties are most apparent when considering the conclusions reached by national authorities during the registration of pesticides and the use of residues data to set and enforce legal maximum residue limits for pesticides in food and feed. These limits have become important in the movement of food and feed commodities in international trade. The harmonisation of the methods used in the production of residue data and a more uniform approach to evaluating the data are urgently needed.

Guidance on the many aspects of producing and evaluating residue data is desirable. It will be of particular value to those countries still in the process of initiating procedures for the official control of pesticides. The need for guidance has been recognised by a number of national and international organisations and committees and several are already making contributions.

Before registration, data have to be developed to allow a reasonable judgment to be made of the residues left in a commodity when the product has been applied according to the recommendation for use. Such data are essentially predictive and enable a registration authority to estimate the maximum residue level which might be expected. This estimate is normally based on data from supervised trials and may be used as a guide to what level may be expected when the pesticide is used. Subsequently, after considering the potential toxicity of such a residue to man and using appropriate safety factors, legal maximum residue limits may be established.

After a pesticide has been registered and used, it is desirable for a competent authority to be able to confirm that the estimate of expected residues made at the time of registration is a valid one. If doubts arise about the validity of the estimate, surveillance and monitoring studies may have to be carried out to ascertain if any revision of the estimated maximum residue level is required.

Enforcement programs of maximum residue limits also produce information relevant to the need to reconsider maximum residue limits.

The estimation of a maximum residue level is based mainly on a knowledge of the residues which occur following the use of a pesticide in accordance with good agricultural practice normally obtained by the analysis of samples from supervised trials. This may be supplemented by selective surveys of commodities where there is detailed information available on the use of the pesticide.

Data obtained from trials and studies are limited by practical considerations and the estimation of a maximum residue level must be part *assessment* and part *prediction.* It is obviously impossible to carry out sufficient trials to cover all the various conditions under which a pesticide may be used. Therefore, although well-planned trials demonstrate a range of residues, emphasis should be directed towards the identification of conditions and factors which lead to the highest residue levels following recommended use patterns.

Well-planned trials take all factors into account so that the residue data represent the widest range of treatment conditions possible. Although the number of variables can be reduced in a supervised trial, it is rarely possible to isolate the influence of an individual parameter and subsequently use the information accurately in predictions.

Insecticides are available in a number of different types of formulation, i.e. liquid, emulsifiable concentrate, suspension, wettable powder, and dust. They may be applied as sprays or dusts by methods ranging from relatively simple techniques, such as those used for maize in cribs or stacked commodities in sacks, to automated systems, such as those used in large central storages. In none of these will the application be completely uniform, and representative sampling presents considerable difficulties, particularly from bulk transports and bulk storages. The difficulty is increased by segregation, which inevitably occurs when the commodity is moved, turned, or transported. The presence or absence of grain dust and dockage influences the level of residues found in non-representative samples and numerous studies have drawn attention to the need for care in taking samples and interpreting the results of analysis (Snelson 1971, 1974).

For these reasons it has been considered necessary to establish maximum residue limits for grain protectant insecticides somewhat above the maximum rate needed in good storage practice to allow for variations that cannot be avoided in sampling and analysis. Usually a factor of about two is regarded as appropriate to cover the contingencies mentioned in the preceding paragraph. Nevertheless, those responsible for the application of insecticides must take extreme care

Table 2. Percentage reduction of residues brought about by various steps in processing raw grain for human consumption.

Insecticide	Wheat to wholemeal	Wheat to white flour	Wheat to wholemeal bread	Wheat to white bread	Rice in husk to husked rice	Rice in husk to polished rice	Rice in husk to cooked rice	Barley to malt	Barley to wort
Bioresmethrin	0	35	100	100	85	93	97	90	99
Bromophos	0	76	72	90	/	/	/	/	/
Carbaryl	57	98	75	99	93	98	99	97	100
Chlorpyrifos-methyl	(67)[a]	(94)[a]	(83)[a]	98	/	/	/	95	99+
Deltamethrin	0	80	30	80	/	/	/	/	/
Dichlorvos	50	80	95	100	90	96	100	/	/
Etrimphos	0	70	80	95	/	/	/	/	/
Fenitrothion	40	92	80	99	92	97	99	80	99+
Fenvalerate	0	88	30	90	/	/	/	/	/
Malathion	20	75	80	95	90	97	98	98	99+
Methacriphos	50	87	100	100	90	97	99	93	99+
Permethrin	0	88	68	94	/	/	/	/	/
Phenothrin	0	82	46	87	90	97	98	83	99+
Pirimiphos-methyl	0	73	53	88	85	93	97	100	100
Pyrethrins	/	/	100[b]	100[b]	/	/	/	/	/

/ No information available. [a]To be checked. [b]Assumed to be destroyed by cooking but no information available.

to keep the variation within such limits.

The cleaning of grain before milling removes dust and dockage containing disproportionately high concentrations of insecticide and the blending that occurs during milling and processing make it unnecessary to provide a significant margin to cover variations in the residue levels due to sampling difficulties in milled products.

After application, the pesticide, depending on its chemical constitution and the nature of the commodity, may move from the surface of the individual grain to internal tissues. The extent of penetration can range from complete retention of the residue on the surface to near equilibrium throughout the whole grain. The processing of grain usually results in the concentration of the insecticide in the hull, husk, or bran, making it important to consider the uses to which such fractions might be put. Table 2 records information gathered from numerous studies designed to determine the effect of milling, processing, and cooking on insecticide residues in a variety of stored grains. The data have been expressed in terms of the percentage reduction in residues in converting various treated commodities to processed grain fractions or prepared food. Although much useful data have been published more are needed to reflect the fate of various insecticide residues after milling, processing, and cooking under various conditions typical of different regions of the world.

Toxicological Requirements

The assessment of safety basically depends upon toxicological studies, most of which are conducted on laboratory animals. The World Health Organization has published a review of the principles and methods of evaluating the toxicity of chemicals (WHO 1978) and this supplies details which could help the investigator to select the most suitable technique for a specific study. It must be noted that the toxicological issues relevant to biologically active chemicals used as pesticides may differ considerably from those for other chemicals.

Acute toxic hazards to operators, by-standers, and those exposed during transport or storage are determined by the short-term toxicological properties of the formulated produce and may not reflect the results of tests done on the active consituent alone. A comprehensive review of toxicological investigations appropriate for pesticides has been published by the Council of Europe (1981, 1984). WHO, through its International Program on Chemical Safety (IPCS), convened a Scientific Working Group during 1983 to establish the principles and methodology for evaluating environmental epidemiology (WHO 1983). In order to promote mutual acceptance of toxicological test data, the Organisation for Economic Co-operation and Development (OECD) has issued guidelines for individual test parameters (OECD 1981a).

The aim of guidelines for toxicity testing is to produce a framework for each toxicity test which is sufficiently well-defined to enable it to be carried out in a similar manner in different countries and to produce results that will be fully acceptable to various regulatory bodies. The growing demands for testing and evaluating the toxicity of chemical substances will place an increasing pressure on personnel and laboratory resources. A harmonised approach, promoting the scientific aspects of toxicity testing and ensuring a wide acceptability of test data for regulatory purposes, will avoid wasteful duplication or repetition and contribute to the efficient use of laboratory facilities and skilled personnel.

The objective of all safety testing is to ensure attainment of the desired benefits of use without incurring needless risks. There must of course be some balance between the benefit and the cost of assessment, just as there needs to be a balance between the benefit and acceptable risk. Thus, to rigidly subject all pesticides to the same routine of study would be gravely off the mark and self-defeating. The more general questions should be asked first and particular issues broached sequentially as the need for more detail is demonstrated.

Our understanding of the effects of chemicals is increasing very rapidly. Hence it would be unwise to establish a rigid evaluation scheme at this time. Any testing procedure should be flexible enough to permit updating as scientific understanding advances and as new procedures become available.

To demand too much testing would prevent the development of some socially and technologically beneficial chemicals; to demand too little would permit the development of certain products whose net impact on society could be harmful.

No test procedure provides an exact measure of all the potential effects that need to be identified. Toxicological tests on laboratory animals must be extrapolated to predict potential effects on man at much lower doses, and are therefore subject to considerable uncertainty. Even after a pesticide has been released into the environment in quantity, only a limited number of its effects, on possibly non-representative species, can be measured. All tests are thus models and, as predictive tools, are subject to error.

It is unrealistic to expect that any system of pre-market evaluation will ensure absolute safety. With our present incomplete knowledge, we cannot expect to predict all the potential hazards of each new chemical. Even with a reasonably elaborate evaluation scheme, potential hazards associated with some chemicals could well go unrecognised. A more reasonable goal is to minimise the hazard within the limitations imposed by our knowledge and resources, with periodic review.

Labelling

The best insecticides will be found wanting if used incorrectly and the presentation of the product to its users must therefore be as clear and concise as possible. A great deal of time and effort is put into labelling, both by the manufacturer and the registration authority. Agreement on the claims and the directions for use are the final stage in the granting of registration. The aim is to ensure that the registered label of each product carries sufficient, well-authenticated information to allow its proper use.

It is well recognised that failure to understand and follow the directions on labels is one of the main causes of disappointment, misadventure, and injury following the handling and use of pesticides.

The topic of pesticide labelling is currently being discussed in several national and international arenas in an endeavour to find effective ways of passing information to illiterate and semiliterate users.

Several national authorities have issued guidelines on the labelling of pesticides. A similar guideline suitable for international use is currently being developed by FAO. This will be available later this year (FAO 1985a).

Many factors influence the amount, nature, and distribution of the residue. The most important of these factors are the chemical, its formulation, the rate of application, method of application, time of treatment, the number of treatments, use of adjuvants, and the interval between the last application and the release of the commodity into trade channels. In order to reduce the incidence and level of residues of chemicals occurring in raw agricultural commodities (and hence in foodstuffs), it is essential to adopt good agricultural practices in the use of chemicals. The concept of good agricultural practice in the use of chemicals in the realm of residues embraces all interrelated and essential factors and functions which ensure that the desired effect will be achieved without leaving behind more than the minimum of residues necessary for effective performance. Good agricultural practice in the use of chemicals is therefore the officially approved usage of a chemical which is essential for the control of pests under all practical conditions, bearing in mind all the difficulties and hazards involved. It is absolutely vital that the concept of good agricultural practice in the use of pesticides should be appreciated and applied so as to control the pest but to leave the minimum amount of residue that is practicable.

The directions on labels of registered products are designed to produce the required effect without giving rise to residues in excess of legal limits. The legal limits for residues in raw agricultural commodities are based on residue trials, and users of pesticides may rest assured that their produce will not contain residues in excess of approved limits if they follow the directions on the registered label.

In the case of specific chemicals offered for sale to the general public, all the above factors except the pesticide and its formulation are under the direct control of the user. Directions for use are designed to guide users to apply the product correctly and in a manner which ensures not only that the desired effect will be obtained but also that any residues which occur will be within legally acceptable limits. Too little stress is placed on the value and importance of label directions. The message which should be brought before users of pesticides regularly and repeatedly is 'READ THE LABEL — FOLLOW THE LABEL'.

Surveillance

While it is very important to have legislation and to try to educate people in proper procedures, it is none the less essential that there should be continuous monitoring to ensure that everything is as it should be.

Most industrially developed countries have introduced some form of monitoring of food for residues. Some such systems are highly sophisticated and continuous; others depend on regular or ad hoc surveys of critical food commodities. Whichever system is considered appropriate for the particular country it should be capable of determining whether the bulk of food produced, imported, consumed, or exported conforms to acceptable standards so far as residues are concerned.

In the event that a result is found to be above the permitted level or in conflict with national or international limits, action should be taken to investigate the cause and to modify practices accordingly. Grain handling authorities should initiate quality control analysis to check the effectiveness of operator training and supervision. In this way they can maintain the effectiveness and efficiency of their pest control practices whilst gauging compliance with government standards and trade requirements.

Residue levels at harvest do not, except in the case of immediate consumption, indicate in any way the amount of pesticide which may be consumed. Residues of most pesticides continue to degrade, and information on the further disappearance on storage and transport enables an estimate to be made of the residue level in the commodity when it is normally offered for sale. These levels are usually appreciably lower than the maximum residue limit.

It is also recognised that surveys of residues in raw commodities do not provide a measure of the amount of pesticide residues ingested by consumers since much or most of the residue is lost during the preparation, processing, and cooking prior to consumption. In order to accurately gauge the intake of pesticide residues by consumers, total diet studies, otherwise known as market basket surveys, are conducted. In these surveys, a typical diet for a young adult consuming more than the average amount of food is chosen and appropriate quantities of food are purchased in retail shops. The surveys are generally repeated four times throughout the year to represent food available in the four separate seasons. The food is then cooked (where appropriate) or otherwise prepared for eating, and samples of the ready-to-eat food are forwarded for analysis. The results reflect the intake of residues by consumers and may be compared with the Acceptable Daily Intake (ADI) to determine the relative hazard posed by the residues.

Governments, representing the interests of the public as consumers, have attempted to minimise any hazard from pesticide residues in one of two basic ways.

(1) By controlling the use of pesticides, legally or by advice, so that good agricultrual practice is carefully followed. Such control, with cooperation of users, should ensure that residues in food do not exceed the acceptable maximim residue levels estimated from data obtained in supervised trials;

(2) By the establishment and enforcement of legal maximum residue limits.

When the legal limit is based on the maximum residue level and has been arrived at from the consideration of reliable data then a residue determined during enforcement to be greater than the maximum residue limit can be regarded as a clear indication that (a) good agricultural practice has not been followed, (b) there has been a deliberate misuse, or (c) there has been some accidental contamination of the food.

A residue greater than the maximum residue limit does not in itself imply a health risk although an enforcing authority could take appropriate action on the basis of a 'substandard' food produced as a result of one of the three indications above. A legal limit does not have any real effect unless it is enforceable and a clearly 'substandard' food ought to be rejected for trade or consumption.

The chance of a food produced by good agricultural practice being rejected in this way is very small since the recommended sampling method is aimed at determining the *average* pesticide residue content of a lot of goods. This average would then be compared with the *maximum* residue limit and there should be an ample safety margin for the producer against a false rejection.

The real risk to a commodity lot lies in the situation where a country has based its legal maximum residue limits on either a small data set or on average data from supervised trials or both. This will result in a falsely low legal maximum residue limit which can be exceeded by many samples, especially if the samples are drawn from commodities not covered by the supervised trials.

Some food control activities are necessary, both for the direct protection of the consumer and in relation to the acceptability of commodities in trade. However, both commodity monitoring and dietary studies should be undertaken only after a careful study of the real need for such activities. These of course may be justifiable on the basis of administrative 'reassurance' of the consumer but it is difficult to justify massive monitoring programs for pesticides in food on the basis of current scientific evidence.

The scientific arguments for initiating or continuing monitoring programs are weak but there is a political and administrative need to continually reassure consumers that their food is not contaminated. The decision on how much reassurance can be afforded will vary from country to country but where analytical resources are at a premium, a very close examination should be made of the real benefits of monitoring. The position of minimal scientific return from routine monitoring has probably been reached.

The development of complex, new, and sensitive electronic equipment has revolutionised analytical chemistry and has been largely responsible for the current insight into the question of residues. It has brought about a new era of analytical methodology much of which no longer depends upon chemical reaction but rather on the measurement of physical and electronic responses to a series of carefully standardised physical stimuli. The responses of purified extracts made from the sample are compared with those given by standard samples of known composition and quality, and the concentration is determined by comparing the magnitude of the separate responses.

Over the past 10 years, methods for the detection and determination of minute traces of pesticide residues have become highly sophisticated, specific, and sensitive. It is now possible to measure very small amounts of many substances. The determination of 0.01 mg/kg lindane is considered quite straightforward and commonplace. Determination of 0.0001 mg/kg of lindane (1 g of lindane in 10 000 t of grain) is possible.

Methods of residue analyses have been worked out in official and industrial laboratories and these methods have been examinied by such international bodies as the Food and Agricultural Organization, the Association of Official Agricultural Chemists, and the International Union of Pure and Applied Chemistry. There is, as yet, no international agreement on methods of residue analysis, largely because residue analysis methodology is constantly changing, becoming more sensitive, more accurate, and more reproducible. The Codex Committee on Pesticide Residues, however, has recently issued a list of 'Recommended Methods' for determining a wide range of residues in many food commodities (FAO 1983a) and a Code of Good Analytical Practices (Bates 1982).

Modern methods and equipment have made it possible to carry out complex analyses on as little as a few grams of sample containing very small traces of complex substances. The speed with which these determinations can now be executed is such that it has been possible to carry out a substantial surveillance of food moving in commerce, including food moving in international trade. As a result, there are extensive data on the level of residues in many commodities and it has become possible for administering authorities to take regulatory action as a result of their examination of a significant sample of the foods moving in commerce.

Generally, as little as 10–25 grams of grain is required to carry out a determination of the various residues which may be present. Enormous problems are encountered, however, in obtaining a truly representative sample from a bulk of grain. Infinite care and effort are required to be sure that the sample drawn from any bulk is truly representative of the whole.

Maximum Residue Limits and Means of Establishment

In order to limit the contamination of food with chemical residues, it has been customary to fix administrative action levels to gauge whether chemicals have been used in accordance with registered directions and good agricultural practices. Governments of many countries have established limits which they refer to as 'tolerances'. This was an unfortunate choice of terms because it conjures in the minds of most people the idea of biochemical or toxicological tolerances, that is, a safe limit beyond which danger would ensue. However, the term means legal limit — literally the amount which is tolerated within the law. For these reasons, the world 'tolerance' is gradually being abandoned and preference is shown for the phrase 'maximum residue limit' (MRL).

Fundamentally, the MRL reflects the maximum residue that could result when the chemical is used according to approved directions and the crop is harvested, the grain stored, or the cereal product processed as the case may be. Residues greater than the MRL are tantamount to evidence that the chemical has been misused or 'good agricultural practice' has not been followed.

MRLs are established on the results of extensive supervised trials designed to determine the nature and level of residue resulting from the approved use of the chemical. These trials are conducted in a number of different regions or situations in order to determine the maximum concentration of residue likely to occur in or on the food. In addition to experiments carried out at the normal rate of application, it is usual to also conduct parallel experiments at double the approved rate and to sample the produce at varying intervals thereafter up to and beyond the normal date of harvest, storage, shipment, processing, etc.

Such trials are the responsibility of the manufacturer of the chemical and normally the trials are conducted in a manner simulating the most extreme conditions likely to be encountered in commercial practice. Such studies are generally supplemented by additional studies to show the effect of storage, processing, preparation, and cooking on the level and nature of residues reaching consumers. Further studies are carried out to determine the effect of plants and animals on the chemical and its conversion into metabolites. If the metabolites in plants and domestic animals are not the same as and similar in magnitude to those formed in laboratory animals used for toxicological studies, additional toxicological studies will be carried out on the metabolites themselves.

In order to gauge the safety of such residues to consumers, extensive long-term feeding studies on laboratory animals must be made. Such studies usually involve two distinct species for periods approaching their life-span, during which time a complete veterinary record is kept of each animal in the trial, and a complete histopathological study is carried out on all important organs of all animals which die, as well as those which are sacrificed at the end of the trials. In addition, studies of reproduction teratology, mutagenesis, carcinogenesis and other features appropriate to the chemical in question must be carried out and all data submitted to the authority.

From these studies, the level of intake which causes no discernible effect on the most susceptible species is ascertained and this is used to calculate the level of intake which could be considered safe for humans if consumed daily for a whole lifetime. A large safety factor (usually 100) is incorporated as an additional safeguard. This Acceptable Daily Intake (ADI) is used to gauge the acceptability of the MRL needed to cover residues arising from use in 'good agricultural practice'. Some agricultural commodities will require higher limits than others. Some chemicals likewise require limits higher than others. The legal limit is, however, not an indication of the relative risk (or hazard) associated with a particular chemical.

On the basis of the evaluation of the data, a MRL is established. There is thus a large margin of safety built into the legal limit fixed for the residue in the specific raw agricultural commodity. The knowledge that only some of the food contains the residue, that only some of this fraction contains residues at levels approaching the limit, and that much or all of the residue is removed in preparation or processing for eating gives further reassurance for the safety of the consumer. The numerical value of all such residue limits is generally rather small.

International Harmonisation

As indicated previously, limits known as 'tolerances' are established in many countries including in the United States by the Environmental Protection Agency, and in Canada by the Food and Drug Directorate. Each authority examines similar though not necessarily identical data and applies generally similar criteria in reaching its decisions. Although there may be minor differences in the numerical values and in the foods in which the residues may occur, basically both philosophy and practice in all countries are similar. Some variation in numerical value is sometimes necessitated by variations in the use pattern from one country to another, and efforts are being made to reach international agreement on residue limits to reduce the effect of such variations on international trade.

The basis for such international agreement is provided under the Food Programme of the United Nations by the recommendations of the Food and Agriculture Organization Panel of Experts on Pesticide Residues and the World Health Committee of Experts on Pesticide Residues. Working in joint session (known as the joint FAO/WHO Meeting of Experts on Pesticide Residues), these bodies examine all available scientific information on the properties, use, and residues of selected pesticides and evaluate their effects on laboratory animals and man. On the basis of this evaluation, recommendations on ADI, MRLs, methods of analysis, metabolism, fate, and effect of residues are published for the information and guidance of governments. The recommendations become the basis for agreement between member governments of the Codex Committee on Pesticide Residues which meets each year.

The complexity of the pesticide residue problem and its international implications were recognised by the Food and Agriculture Organization of the United Nations as early as 1959, when the FAO Panel of Experts on the Use of Pesticides in Agriculture made the recommendation that FAO, jointly with the World Health Organization, should study:

(a) the hazard to consumers arising from pesticides residues in and on food and feedstuffs;
(b) the establishment of principles governing the setting of pesticide maximum residue limits;
(c) the feasibility of preparing an international code for the toxicological and residue data required in achieving the safe use of a pesticide.

As a result of this recommendation, a joint meeting between the FAO Panel of Experts on the Use of Pesticides in Agriculture and the WHO Expert Committee on Pesticide Residues was held in 1961. The purpose of the meeting was to consider the establishment of MRLs for pesticide residues in food, from the aspect of consumer safety. The first regular Working Session of the FAO and WHO expert groups took place in 1963 and since 1965 meetings have been held on an annual basis. These regular sessions have since become familiar as the Joint Meeting on Pesticide Residues (JMPR).

Joint FAO/WHO Meeting of Experts on Pesticide Residues

The JMPR consists of experts in their individual capacity (i.e. not representing governments), invited by the Directors-General of FAO/WHO. Their task is to establish the ADI values for individual pesticides on the basis of existing toxicological evidence, to recommend MRLs for pesticides residues in food, and to recommend acceptable methods for chemical analysis to be used by food inspection authorities for regulatory purposes.

WHO assembles a group of experts with special competence in matters related to toxicology of pesticides, while FAO experts are chosen for their knowledge and experience in the use, fate, and analysis of pesticides.

Firstly, the WHO part of the JMPR is responsible for proposals with respect to ADI for each individual pesticide under consideration. The ADI of a chemical is defined as 'the daily intake, which during an entire lifetime, appears to be without appreciable risk on the basis of all the known facts at the time'. It is expressed in milligrams of the chemical per kilogram of body weight. It is therefore a purely toxicological concept.

Secondly, the FAO part of the JMPR is responsible for recommending maximum residue limits for each pesticide under consideration and on each food commodity or group of food commodities on which the pesticide is being used. These recommendations take into account the worldwide use pattern. A MRL is defined as 'the maximum concentration of a pesticide residue resulting from the use of a pesticide according to good agricultural practice directly or indirectly for the production and/or protection of the commodity for which the limit is recommended'. The MRL should be legally recognised. It is expressed in milligrams of the residue per kilogram of the commodity.

Thirdly, the FAO part of the JMPR makes recommendations for methods of chemical analysis, suitable for regulatory actions by those responsible for enforcement of MRLs.

Fouth, the joint session of both FAO and WHO experts critically examine the compatability of recommended MRLs with ADI figures.

MRLs are based on, among other things, good agricultural practice. The concept of good agricultural practice in the use of pesticides is defined as 'the officially recommended or authorised usage of pesticides under practical conditions at any stage of production, storage, transport, distribution and processing of food and other agricultural commodities, bearing in mind the variations in requirements within and between regions and taking into account the maximum quantities necessary to achieve adequate control, the pesticides being applied in such a manner as to leave residues that are the smallest amounts practicable and that are toxicologically acceptable'. The definition implies that a maximum residue limit should be based on two main considerations. On the one hand, the limit should be low enough that the total amount of residues reaching the consumer does not exceed the ADI; on the other hand the limits should be high enough to give an adequate degree of pest control.

The JMPR depends on information and background data on toxicological, agricultural, and chemical aspects provided by industry and member countries so that it can properly evaluate the pesticide under consideration.

The Codex Committee on Pesticide Residues

Parallel with the establishment of the JMPR another development took place — the establishment of the Codex Alimentarius Commission. Based on initiatives taken by the Government of Austria in the early 1960s the Codex Alimentarius Commission was established as part of the Joint FAO/WHO Food Standards Programme and an initial meeting was held in Rome in 1963. The Codex Alimentarius Commission is charged with the establishment of food standards and it comprises a great number of committees dealing with standards for individual food groups and for more general subjects related to food.

In order to make the Codex machinery operative, member countries were asked to take responsibility for the organisation and accommodation of regular sessions. The Netherlands was asked to take the responsibility for the two Codex Committees on general subjects namely, the Codex Committee on Food Additives and the Codex Committee on Pesticide Residues (CCPR). The Codex Committees consist of delegates from member countries in their capacity as government representatives, but sessions are also attended by observers from other international organisations and from the agrochemical industry.

The prime objective of the CCPR is to reach agreement on internationally acceptable maximum limits for pesticide residues in food commodities moving in international trade.

From the beginning of the work of the CCPR, it was stipulated that a close collaboration with the JMPR should be the basis on which a worldwide program of harmonisation of pesticide residue limits should be developed.

On completion of its evaluation the JMPR publishes a report and monographs setting out its evaluation of each pesticide and these are submitted to the CCPR for formal consideration at the government level. In dealing with these proposals, the CCPR follows the procedure laid down in the Procedural Manual of the Codex Alimentarius Commission. In theory, 11 steps are involved, but in practice some of these steps are combined. Although the procedure is long, it has the advantage that member countries are given ample opportunity to comment on the proposals between and during the CCPR sessions, and this opportunity is given at several stages of the procedure. After each CCPR session, progress is formally reported and submitted to the Codex Alimentarius Commission for approval. Thus, countries not present at the CCPR session but attending the meeting of the Codex Alimentarius Commission (comprising 117 member countries) also have an opportunity to comment. Proposals for maximum residue limits which have reached Step 9 of the procedure are published and are formally submitted to governments for acceptance.

Acceptance of Codex International Maximum Limits for Pesticides Residues

The legal implications of the acceptance procedure pertaining to international food standards, including the obligation to incorporate in national legislation any such standards when accepted, for a long time hampered progress in the field of MRLs for pesticides. Acceptance with minor or specified deviations, as provided for in the Codex Procedural Manual, was not applicable to an MRL, as this involved a single figure. It became increasingly clear that pesticide residues presented a special problem which required adjustment in the acceptance procedure. It was also recognised that the requirements for MRLs were greatly dependent on regional, climatic, and/or pest control conditions, and that it was hardly possible to cover all requirements in one single figure applicable worldwide, particularly when this was coupled with an obligation to adopt this figure in the legislation of individual countries. It was a fundamental step forward when the CCPR was able to agree on a modified acceptance procedure which provides, among other things, for limited acceptance. This implies that a country would not hinder the importation of food complying with the Codex MRL, and that it would not impose a

Codex MRL which would be more stringent than it applied domestically. This new procedure has enabled member countries to accept CCPR proposals more readily.

The CCPR has recently initiated a review of legal problems inhibiting the acceptance of Codex MRLs as a further step in the harmonisation procedure.

Factors Inhibiting Acceptance

During the years that I have served as a delegate at the Codex Committee on Pesticide Residues, I have noticed the steady evolution of an organisation that serves not only as a forum for the exchange of views between governments but as a valuable piece of machinery for decision making. The democratic processes that are followed are slow and somewhat cumbersome but they do provide reassurance that the MRL, when adopted, is politically acceptable and scientifically sound.

Many people, including myself, have been somewhat frustrated by the slowness with which the process has evolved and the apparent reluctance of many food importing (industrialised) countries to adopt the Codex MRLs into their legislation. Let us look at some of the reasons which have delayed or slowed down the adoption of international limits for pesticide residues. These include:

(1) Failure by many people and national authorities to recognise the need to use chemicals to protect valuable food, ensure the availability of staple commodities as a buffer against famine, maintain economy, and meet the food demands of an increasing population.
(2) Lack of knowledge about the limitations of available non-chemical measures to control pests.
(3) Lack of understanding of the needs and agricultural practices of trading partners.
(4) Lack of sympathy for those who live under tropical and semitropical conditions.
(5) Belief that man-made chemicals are somehow different to chemicals that occur in nature.
(6) Tradition that foods, particularly staples, should be 'pure' and that nothing should be deliberately added to food.
(7) A political attitude opposed to the concept of residues.
(8) The development of the 'natural food' cult and the attendant rackets in 'health foods'.
(9) Political pressure by merchants, domestic producers, and other self-interest groups to create misgivings in order to produce non-tariff barriers to trade.
(10) The sensation-seeking news media.
(11) Fear of the unknown. What cannot be seen could well be dangerous!
(12) Inability to understand the significance of toxicology studies on laboratory animals, the dose-related effect, and the concept of no-toxic-effect level.
(13) Failure to understand and accept the concept of ADI.
(14) Mathematical calculations of intake of residues based on the assumption that every lot of each commodity contains residues and that residues always occur at the level of the MRL.
(15) Laws that lay down rigid procedures for establishing MRLs in national legislation.
(16) Existing MRLs that are lower than those being recommended for international acceptance.
(17) Legislative procedures that make amendments difficult.

What has science done to break down these barriers to the acceptance of residues of chemicals used for protecting world food supplies? I believe that science has produced adequate data to convince informed scientists of the safety and acceptability of these chemicals. Whether it has done sufficient to convince the sceptics and the non-scientific sector remains open to question.

Most of the delegations that attend the annual session of the Codex Committee on Pesticide Residues come from food-importing countries, so they naturally take the consumers' point of view. In its simplest form, this point of view is that they would prefer to have no residues in food. Unfortunately, many delegations are not familiar with the problems facing agriculturalists generally and food producers in the semi-tropics and tropics in particular. It is therefore understandable why they often appear unsympathetic to the needs of countries producing and exporting from other regions. However, in the process of exchanging comments at the CCPR a better understanding has developed and in recent years there has been noticeable softening of attitudes towards the presence of residues.

Unfortunately, some of the officials in developing countries, who do not have access to comprehensive technical information and advice, are seriously disturbed by the alarmist publicity in the news media about the alleged dangers of chemicals, particularly pesticides. Since they take their responsibilities seriously they are reluctant to accept the use of insecticides lest there should be adverse effects upon consumers, particularly in countries where staple foods, such as raw grain, are consumed after a minimum of preparation and cooking.

We must therefore accept that the process of achieving an extensive set of international MRLs will be slow, the more so because the resources available in FAO and WHO to provide the requisite amount of technical information and educational material are sorely limited. Even these are being whittled down by inflation and the escalating costs of the increasingly complex information which is being generated.

Harmonisation of Registration Requirements

The idea of achieving a high level of harmony between the requirements of different countries was often discussed privately but remained little more than a dream until 1975 when at the FAO Ad Hoc Government Consultation on Pesticides in Agriculture and Public Health it was proposed that the Director-General of FAO convene a consultation between government and industry to discuss the possibility of harmonising registration requirements for pesticides (FAO 1975). Among the many resolutions made at the consultation, this received the highest priority and FAO convened a further consultation in October 1977. This consultation was attended by representatives from almost 50 governments, many international agencies, and chemical industry. The level of agreement achieved and the spirit of cooperation, which was so evident, surprised everyone.

The Report of the 1977 Consultation (FAO 1977a), of which 7500 copies were distributed, is a blueprint for the guidance of government and industry alike. Whilst drawing attention to all of these aspects and requirements, which could be harmonised, or even standardised, it drew attention to those issues where national, international, and collaborative effort was required in order to develop standards, guidelines, test procedures, codes of practice, and other information which could serve as a basis for harmonised requirements. Many governments, agencies, organisations, and local committees responded to the challenge and most of the missing information was developed, coordinated, and published in the next few years.

In order to consolidate the achievements of the 1977 Consultation, to draw attention to the subsequent developments, and to seek a commitment from governments and industry, FAO convened a second Consultation on International Harmonization of Pesticide Registration Requirements in Rome in October 1982. This was attended by over 60 governments, 9 international organisations, and chemical industry under the aegis of the International Group of National Associations of Agrochemical Manufacturers (GIFAP). The initiative and level of agreement, once again, astounded even the most enthusiastic supporters. The report on the consultation (FAO 1983b) is proof of what can be achieved when people of goodwill forget their political, economic, and cultural differences and agree to work together in the interests of international understanding.

The objective of the consultation was to agree upon test procedures, practices, and presentation, which would adequately delineate the properties, effect, and fate of biologically active chemicals in a manner which would adequately demonstrate the suitability, efficacy, and safety of each compound under conditions of use representative of the practices that would be followed by farmers and other users. The consultation accepted the concept that scientific data, which have been generated under standardised laboratory conditions by competent people using good test methods and well-defined procedures of 'good laboratory practice', should be transportable and acceptable anywhere in the world (OECD 1981b).

Recognition that efficacy studies conducted in the field in accordance with internationally accepted guidelines can produce data supportive of the results of similar field studies carried out under different climatic, meteorological, and agricultural conditions in some other part of the world has greatly reduced the cost of generating adequate data on efficacy.

Methodology of Residue Trials

Variations in methodologies in conducting trials to determine residues (including the selection, preparation, and analysis of samples) have created difficulties in evaluating the significance of residues on commodities during their production, storage, preparation for market, and processing. These variations have also made it difficult to compare information from different sources and have contributed to differences in the MRLs adopted in different countries.

In response to an invitation from the Ad Hoc Government Consultation in 1977 (FAO 1977b), the Codex Committee on Pesticide Residues (CCPR), through its Working Groups, has developed 'Guildelines on Residue Trials Methodology' and these have been published (Department of Primary Industry 1981; FAO 1981). Proposals to harmonise procedures for reporting laboratory results and for developing data for foods of animal origin are also being considered by CCPR.

Further guidance on methods of sampling, the portion of the agricultural commodity to be analysed, recommended methods of analysis, and on good analytical practice in residue analysis has also been prepared by CCPR (FAO 1979, 1982b, 1983a, 1984) and this has also been published by the International Union of Pure and Applied Chemistry (IUPAC) (Bates 1982).

Code of Conduct in the Distribution and Use of Pesticides

The action by FAO to develop, in conjunction with a number of United Nations agencies and other organisations, an International Code of Conduct on the Distribution and Use of Pesticides, has occurred against a background of many other events, some going back 25 years, all designed to benefit the international community and to serve to increase international confidence in the availability, regulation, marketing, and use of pesticides for the improvement of agriculture, public health, and personal comfort.

The Director-General of FAO, in addressing a meeting in 1981, suggested that such a code could help to overcome a number of difficulties associated with pesticides. The FAO Panel of Experts on Pesticide Specifications, Registration Requirements and Application Standards, at its meeting in 1982, agreed that the control of export and import of pesticides, and thereby their safe use, might be best dealt with through the adoption of a code of conduct and to that end prepared a working paper for the Second Government Consultation on the International Harmonization of Pesticide Registration Requirements convened by FAO and held in Rome in October 1982. It was recommended by the meeting that the Director-General, in consultation with appropriate UN and other international organisations, draft such a code. Because of its wide interests and responsibilities in the use of pesticides in agriculture, FAO has given high priority to its preparation.

A number of organisations and countries have expressed concern about the propriety of supplying pesticides to countries which do not have infrastructures to register pesticides or to ensure that these materials are used safely and effectively. There has also been concern over the possibility that residues of pesticides, not needed or not permitted to be used in some countries, are present in imported agricultural commodities produced in countries where such restrictions do not apply. While recognising that it is impossible to eliminate such incidents because of diverging pest control needs, it is essential that every effort should be made to apply pesticides only in accordance with good and recognised practices. It is therefore important for industrially developed countries to recognise the pest control needs of developing countries, particularly those situated in the tropics.

In the absence of an effective pesticide registration process and infrastructure for controlling the availability of pesticides, countries importing pesticides must depend heavily on the pesticide industry to promote the safe and proper distribution and use of pesticides.

The export to developing countries of pesticides which have been banned in one or more other countries or whose use has been severely restricted in some industrialised countries has been a subject of discussions on whether the exporting country can assume responsibility for the marketing and use of such products in the importing country. In this respect it is essential to note that when pesticides are banned it is generally for toxicological, environmental, or political reasons. Valid and adequate toxicological reasons justifying banning a product are of concern, though not necessarily of equal importance, to most countries. Consequently, such products should not be exported or imported without careful consideration of the toxicological implications for those likely to be exposed.

While a code of conduct may not solve all the problems, it should go a long way towards defining and clarifying the responsibilities of the various parties involved in the development, distribution, and use of pesticides, and should be of value in countries which do not yet have control procedures.

The aim of the code is to establish standards of conduct for all those engaged in the regulation, production, distribution, and use of pesticides of all types and for all purposes, in order to ensure that adverse effects on people and the environment are restricted to the maximum extent possible and that pesticides are used properly and effectively for the improvement of agricultural production and human, animal, and plant health.

The Code which was approved by the FAO Committee on Agriculture in March 1985 (FAO 1985b) and by the FAO Council in June 1985 has been recommended for adoption by all member governments, non-government organisations, and chemical industry. It is accompanied by a series of comprehensive guidelines on regulation and registration, evaluation of efficacy, labelling, packaging, disposal of containers and unwanted pesticides, and control of hazards. It is anticipated that the code and guidelines will go a long way towards promoting safe, efficient, and effective use of pesticides.

Conclusion

The regulatory requirements for pesticides used in grain storage systems have become strict and demanding but it is accepted that they are not inconsistent with the responsibilities of manufacturers, governments, vendors, and users. These requirements have been embodied in legislation in most countries and international efforts to harmonise the legislation and requirements have been outstandingly successful.

Whilst it is essential that information on effectiveness should be generated, or at least confirmed, under conditions typical of those encountered in practice in each country or region, recognition that scientific data generated by field trials carried out by qualified scientists in accordance with accepted guidelines should be accepted in support of applications for registration irrespective of where such studies were conducted, has reduced the cost and extent of such testing.

Procedures for evaluating the toxicological implications of such uses of pesticides have been accepted by national and international authorities as have the procedures for determining MRLs in raw agricultural commodities and food. Guidance on such matters is available from meetings of experts convened by FAO and WHO which organisations also provide the forum for discussion and adoption of such limits into national legislation. This serves to provide assurance for the safety of consumers and to facilitate trade in essential foodstuffs.

There is a need to encourage and support these efforts in order that the full value of pesticides in contributing to the improvement in grain storage practices and in reducing loss and damage of valuable food stocks can be realised with minimum delay.

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Industry Perspectives in Pest Control in the Humid Tropics

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Abstract

Although stored products insects cause postharvest losses of rice and maize estimated at 5 - 10% of annual production in the Philippines, a look at the flow of grain in the trade from farm level through the different stages shows that few steps are taken to prevent these losses. Only a limited number of grain processors and the National Food Authority, a government agency, institute any kind of measure to control insect infestation in stored grain. Storage, grain trading, and pest control practices in the Philippines are outlined, and recommendations are made for research and development work at farm and warehouse level aimed at reducing storage losses. It is pointed out that the yellow maize which is often imported to make up for shortages in feed grains could be replaced by domestic production if losses were reduced.

THE Philippines produced 7.3 million t of rice (Tanchanco 1984) and 3.1 million t of maize, and imported 520 643 t of maize and 797 243 long tons of wheat (Mangaoang and Perez 1984) in 1983 to meet the country's grain requirements.

It was expected that some of this grain would be lost during storage due to a number of causes, foremost among which would be losses due to insect infestation. Definite percentages of losses of stored grain have not been established but have been estimated at between 5 and 10% (Morallo-Rejesus 1981c).

Morallo-Rejesus (1981b) stated that infestation is almost always present at the beginning of storage but that it does not become evident for 2 months. Although an insect population will increase by 10–100 times each generation in about five weeks, the increase becomes evident only after two or three generations.

Forty-two species of insects have been reported to be associated with stored grain in the Philippines and of these, eight are considered to be destructive to grain. The destructive species are (Morallo-Rejesus 1981c): *Sitophilus zeamais, Sitophilas oryzae, Rhyzopertha dominica, Tribolium castaneum, Tribolium confusum, Oryzaephilus surinamensis, Plodia interpuntella,* and *Corcyra cephalonica.*

Storage Practices

It has been reported that farm households or rural storage account for 60% of the total stored grains (Anon. 1974a) in the Philippines. Grain stored on farms is either kept in containers such as bamboo 'sawali' cribs, baskets, wooden bins, clay jars, and jute bags, or simply dumped in bulk in a corner of the house (Labadan 1969). This manner of storing grain exposes it to insect attack.

For larger volumes, the grain is stored in gunny sacks in a miller's, wholesaler's, or government warehouse. Most of these warehouses have a wooden or iron frame and concrete floors. The walls are either of corrugated galvanised iron sheets, or hollow, concrete blocks. A concrete drying pavement is usually built next to the building (Anon. 1974a; Gonzalez 1978).

Even in these improved warehouses, the grain is subject to insect attack because the gunny or jute bags are easily invaded by stored products insects.

Wheat and maize imported into the country are stored in concrete silos.

The Grain Trade

Farmers with small farm holdings usually dispose of their entire grain production immediately after harvest. Owners of larger farms make two or more sales during the year. The grain is sold to local wholesalers, agents of central warehouses or rice millers, or the National Food Authority

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(NFA), a government agency created to stabilise prices of grains in the market.

The wholesalers and millers seldom stock more than a few weeks supply of milled grain (Anon. 1974b). The length of storage ranges from 15 to 90 days (Gonzalez 1978).

Retailers do not make use of warehouse storage. They stock from 20 to 30 cavans (1 cavan = 50 kg) of rice in their market stalls (Anon. 1974b).

The government warehouses, by the nature of their mandatory functions, keep grains in storage for longer periods. Gonzalez (1978) reported this to be from 3 months to 2 years. This extended period of storage exposes the grain to greatest damage due to insect infestation.

Most of the yellow maize produced and imported goes into the warehouses and silos of feed manufacturers. In 1983, 613 000 t were produced (data provided by Mrs Guia Minguez of the National Food and Agriculture Council, Ministry of Agriculture, Philippines) and 520 643 t imported (Mangaoang and Perez 1984). Yellow maize makes up 50% of livestock feed. The feed millers keep in stock several months supply. While in storage, the maize is very susceptible to infestation by weevils. In such storages, it is not uncommon to stand between bags of corn and hear the activity of weevils among the grain.

Pest Control Practices

Grain stored in rural areas, although exposed to insect infestation, does not receive any kind of protective treatment. This is because of the farmer's lack of understanding of the insect problem, the unavailability of the necessary pesticide, or the high cost of pesticides appropriate for storage pest control.

Because they dispose of their stocks within a few days, rice millers do not undertake measures to control insect infestation other than cleaning their premises. The few wholesalers who keep large inventories of grain rely on licensed commercial pest control operators for the control of pests in their warehouses (Gonzalez 1978). However, most of this pest control work is directed to the control of rodents, since these are seen as a serious problem in warehouses.

The feed millers, because they have to keep their stock of yellow maize for some time, are the ones most affected by losses due to insects, particularly infestations of weevils. In this group are the grain handlers who attempt to control the insect infestation, either on their own or by securing the services of commercial pest control operators to fumigate their grain and apply residual sprays to protect the stock from further infestation.

The warehouses of feed millers usually contain feed ingredients such as bran, meat meal, fish meal, as well as maize. These will also be infested by insects, so the entire warehouse is fumigated.

The warehouse is made as airtight as possible. All holes, including gaps made by the corrugated roofing material, are plugged with old newspaper soaked in glue made from maize starch. They are covered with masking tape. The windows and doors are closed and sealed with masking tape.

Phosphine (Phostoxin or Detia) is the more common fumigant used because of its ease of application. The entire warehouse is kept under fumigation for 96 hours after which it is ventilated. About 1.5–2 g of hydrogen phosphide is used per cubic metre of space. The walls and floors and the outer layers of the bag stacks are sprayed with a thick layer of permethrin (Coopex) wettable powder. The dilution of permethrin used is 25 g permethrin per 5 l of water. This protects the commodities from reinfestation for some time. Other pest control operators use 2.5% malathion as their spray material to protect the stored materials.

Imported maize that is stored in silos is treated with malathion as it is being conveyed to the silos. A low-pressure sprayer is mounted alongside the conveyor with its nozzle set just above the belt such that the spray pattern covers the entire width of the grain stream.

Wheat that is brought into the silos from barges receives similar treatment.

Pest control measures are undertaken in government warehouses although this is not regular practice because of certain constraints (Gonzalez 1978). The stocks of bagged grain are given a surface treatment with a residual insecticide in the form of a spray. Fogging of the warehouse using a fogging machine is also practiced but fumigation is seldom carried out (Gonzalez 1978). Without initial fumigation, spraying or fogging cannot stop insect infestations developing within the bagged grain.

Recommendations

1. In as much as definite percentages of losses of stored grain have not yet been established, it is suggested that an appropriate agency conduct a

continuous study to determine the losses due to insect infestation along the route that the grain passes from farm to end user, so that emphasis on control measures can be directed toward those areas where losses are greatest.

2. Farmers store their grain in a wide variety of containers that are vulnerable to insect attack and which do not lend themselves to fumigation of any kind. It is suggested that grain containers that would hold from 5 to 25 cavans of grain be designed such that they exclude insects and can be easily fumigated. Chemical suppliers could then be asked to package fumigants in amounts appropriate to small-scale fumigation by farmers.

3. An information campaign should be conducted among warehouse owners and managers on how the insect pests of grain can be recognised, how they can cause losses, and how to protect the grain from the ravages of insects (Caliboso 1977). Then arrangements should be made with commercial pest control operators so that when the warehouse owners or managers need their services, they would be capable of providing assistance.

4. Personnel in charge of government warehouses should be given lectures and seminars on proper warehouse procedures and pest control. As pest control is not regularly practised in some warehouses because of lack of chemicals, equipment, or pest control officers (Gonzalez 1978), the materials and personnel needed for pest control work should be made available where and when they are needed.

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Developing Country Perspectives and Use of Pesticides

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Abstract

The increase in pesticides use in developing countries has brought with it an increasing awareness of their potential for good and harm. Consequently, these countries have adopted or enacted regulations with varying degrees of complexity and levels of enforcement. In general, pesticide registration is required, but the ways and means to effect registration vary. There is a need to standardise pesticide regulations in developing countries, especially as regards registration, use, and residues. The impact of regulations on pesticide use for tropical grain storage systems is discussed, including aspects of health. Some expectations as a consequence of regulations are expressed, with a view to rectifying deficiencies in the system of pesticide use.

PESTICIDES are of especial importance in developing country agriculture because these countries have a food-deficit economy. In other words, from the production standpoint, it is the area of the world which can least afford the losses due to pests. In the case of rice in the tropics, for example, the 35% preharvest losses that Cramer (1967) estimated when combined with the 20% postharvest losses (Pimentel and Pimentel 1978) translate to about 8.4 million t of unmilled rice for the Philippines in 1978 (Sanchez 1983). This should be compared with actual production of 6.89 million t. Of course, the enormity of such losses is not felt by consumers because they are not involved in production, but however one looks at these figures they are staggering and the Philippine economy would have received a boost if these losses were 'saved.'

With the widespread use of pesticides in developing countries and the attendant publicity that these compounds receive, public concern for the safety of both direct and indirect users has increased. Unfortunately, just as in the developed countries, the gains that accrue from pesticide usage are easy to understand and accept but the risks in their use, both to man and the environment, are not so well understood. It it not surprising that the public, if only to show its sympathy for the production sector as well as concern for its own well-being from pesticide residues in food, is demanding more and more knowledge about these compounds.

What is unfortunate about the situation is the insatiable nature of these demands, to the extent that there seems to be a quest for absolute safety out of an imperfect technology developed and used by imperfect minds and systems. The public, being inadequately prepared to evaluate the risk-benefit equation with pesticides, normally delegates this responsibility to regulatory agencies. The irony of the situation is, however, that it is also unwilling to place complete trust and confidence on these agencies. Of course, from a philosophical standpoint it may not be wise to have complete trust, and any regulatory agency has to live with this burden. Such a mistrust, however, may lead at times to demands that border on the unreasonable.

Those matters aside, the question that we should address here is whether, in a tropical, developing country setting, there is safety in pesticide use. Our concern involves the following issues:

(1) adequacy of the research and development process for pesticides from the standpoint of safety;

(2) adequacy of the evaluation process by regulatory agencies as embodied in the pesticide registration system;

(3) adequacy of safety procedures during use so that the health of the direct user and of the consumer of pesticide-treated products is assured;

(4) adequacy of management practices to ensure an environment safe from the adverse effects of pesticides.

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If we can be assured that the safety components built into the use of pesticides are adequate from all points of view, then we can use them with confidence. However, where there are gaps then it behoves us to fill these so that no sector suffers from the potential for adverse effects that pesticides undeniably possess.

The Pesticide Research and Development Process

Before a pesticide is introduced onto the market, it undergoes a lengthy and extensive research and development (R & D) process directed towards establishing (a) adequate biological efficacy, (b) adequate safety in use, and (c) commercial feasibility. Commercial feasibility is entirely the province of the individual pesticide companies and should not concern us much, except perhaps to accept that a company will not commercialise a product for certain uses if doing so would not be profitable. Some products have fallen short of commercial expectations but we, the consumers, generally dismiss such failures as a hazard of the free-enterprise economy.

Biological efficacy and safety are our twin concerns in the R & D process. To give an overview of how data on these are obtained, let us take an overview of the process.

The R & D process starts with the synthesis of a compound. This is largely a hit-or-miss process because there are still serious limitations in our ability to predict biological efficacy from molecular structure. The direction of synthesis is based on best judgment and some guesswork from the voluminous literature on what types of structures will have biological efficacy.

A synthesised material is then tested against a range of standard pest organisms, for example, cutworms, aphids, house flies, a stored grain pest, weeds, fungi, and nematodes. If a compound is found to have pesticidal properties, it is now subject to tests with more organisms. Initial toxicological tests are performed. If the compound lacks biological efficacy, it is immediately discarded.

Assuming that the compound passes these initial biological efficacy and toxicological tests, it is now subject to more rigorous tests to pinpoint its effectiveness against specific pests and to identify safe practices for its use. The database continues to grow, but if at any time the compound fails, it is discarded. If the product passes all these in-house requirements, it will also undergo commercial feasibility studies.

The whole process has several stopping points and any product is evaluated many times before it passes a final judgment. The R & D process may therefore also be viewed as a rigorous evaluation system, which a compound must pass before it is commercialised. More specifically, the R & D process generates four main types of data, namely, (1) specifications, (2) biological efficacy, (3) toxicology, and (4) residues and fate in the environment. The specifics for each category as proposed by the Groupment International des Associations Nationales de Fabricants de Pesticides (GIFAP, an international organisation of pesticide manufacturers) and which were adopted by the Fertilizer and Pesticides Authority of the Philippines (Magallona 1980) are given in the Appendix.

Provision of data on specifications is a form of assurance that the user will receive materials which conform to what is declared or considered acceptable by regulatory authorities. The acceptability of a product is defined in terms of active ingredient content and absence of deleterious impurities in the manufactured and formulated products.

In the case of biological efficacy, the concern is demonstration that the product will be useful as it is prepared for the user. Thus, the concern is not only potency of the active ingredient but its formulation to give a usable product.

Toxicological data are the ones that pertain primarily to human safety and because of their importance they are evaluated meticulously by regulatory authorities. Humans cannot be used as experimental subjects so several types of animals are used in accordance with their biochemical and physiological similarity to man for a particular test. Thus, monkeys are used for eye irritation tests because they have tear glands similar to those of humans, while rabbits are used in most other tests. The data gathered with these experimental animals are then extrapolated to man on the assumption that 'man is as sensitive as the most sensitive test species.'

Data on residues and fate in the environment are generally considered as a group because they both require analysis. The rationale for this requirement is that if we cannot get rid of all residues, then the next best thing is to limit their levels to the minimum which may be considered safe. This requires a demonstration of the degradation rates, pathways of loss, and related parameters in foodstuffs as a result of direct or indirect application.

All these data requirements are enlarged as the pesticide progresses through the R & D process. Thus, for biological efficacy, one starts in the laboratory, then moves from pot experiments in greenhouses to small plot tests, to bigger plot tests, to company experimental farms, and finally to public experiment stations. In toxicology, there is progression from acute oral LD50/LC50 to small animals, to dermal toxicity, to sub-chronic feeding tests (6-weeks duration), to long-term feeding studies, and then to special tests on matters such as carcinogenicity. For residues, one starts with development of analytical methods and progresses to analysis of residues (as parent compounds of metabolites) in crops and substrates of interest.

To illustrate the magnitude of the R & D work done, it is estimated that, in 1977, on the average $14 million was spent by the pesticide industry to come up with each marketable product; as much as $20 million was spent for some products. Furthermore, it is estimated that about 12 000 compounds go through the R & D process to produce one successful product. In 1973, it was also estimated that it takes about 7 years from synthesis to actual marketing of a pesticide.

The data generated in this whole exercise are submitted to regulatory authorities for evaluation within the registration system.

Regulations in Some Developing Countries

In accordance with each government's desire to provide a safe and wholesome environment and food for its people, and recognising the interest in pesticides, many developing countries have opted for pesticide regulations. Some of these are patterned after mother countries while others are quite distinctive. The coverage of these regulations, while possibly extensive on paper, in reality depends on the capability of each country.

As can be seen in Table 1, all countries in the ASEAN region have pesticide regulations, as have Bangladesh, India, Sri Lanka, the Republic of China, and the Republic of Korea. The approaches are essentially the same: registration, label requirements, and use patterns/recommendations. The Philippines, however, has gone a step further in that it has established a pesticide safety program centred around (1) training of physicians and paramedics in the management of pesticide poisoning, (2) training of agricultural technicians and agrochemical dealers, and (3) dissemination of information of safe use of pesticides. This approach is in consonance with the Philippine Government's policy on public information.

Table 1. Pesticide regulations applicable in some ASEAN and other countries.

Country	Regulation	Date
Bangladesh	Agricultural Pesticides Act	1980
India	Indian Insecticides Act	1968
Indonesia	Government Decree No. 7	17 March 1973
Malaysia	Pesticide Act	1974
Philippines	Presidential Decree 1144	30 May 1977
Republic of China	1) Rules of Pesticide Control	July 1959
	2) Pesticide Control Act	1972
Republic of Korea	1) Pesticide Management Act	28 August 1957
	2) Amendment	22 May 1969
	3) Revision	17 February 1976
Sri Lanka	Control of Pesticides Act No. 33	1980
Thailand	1) Poisonous Article Act	1967
	2) Poisonous Article Act	1973

As regards the requirements of registration and labelling, information on efficacy and safety are generally sought from applicants. This is essentially the same information as provided by multinational companies to regulatory authorities in the developed countries, with the exception of a few compounds which do not have markets in the developed countries. Furthermore, one country may have requirements similar to those of a neighbouring country. There is thus the potential for regulatory harmonisation. Such harmonisation could be developed in regional groupings such as ASEAN. It has the benefit not only of reducing development and registration costs to agrochemical companies — costs which are passed on to the farmers — but also allows for the maximum usage of limited technical expertise in these countries. Although harmonisation has a long way to go, the initial steps have already been taken.

Pesticide regulations have many constraints, so that while they may be good 'on paper,' their implementation leaves much to be desired. For some countries, such deficiencies were introduced as early as the framing of the regulations, because there is a tendency for us to incorporate into our regulations features found in those of developed countries. Furthermore, we have neglected to incorporate regulatory approaches which, though radical in concept, may be better suited to our national temperaments.

Even when the regulations are properly framed, we may be faced with an inadequate pool of technical expertise. This problem is further aggravated by our personalised society wherein the personal relationship is more important than professional competence. Personalities are quite difficult to set aside in the developing country setting. For example, while pesticide companies and environmental groups exchange court suits with regulatory authorities in developed countries, such groups, the pesticide companies especially, would think more than twice before doing this in our countries. Here, they run the very real risk of being blacklisted, with all the implications that that would bring. The same is true with our limited technical expertise.

The resources that could be made available for regulation present another problem. A developing country usually cannot see its way clear towards devoting sizable budgetary chunks for the 'directly non-productive, checkpoint type activity' that is pesticide regulation. So, a regulatory institution tries to make do with what it can get. And yet, the irony of the whole situation is that we expect it to be almost omnipresent, so that it is on top of all problem situations in the country. Thus, not only do we expect it to enact laws but also to catch all violators. However, have we ever tried to compare its budget and size with our generally huge police agencies which, notwithstanding all that they are doing, are unable to check all criminal activities?

Laymen, especially those with 'bones to pick' or issues to advocate, also generally tend to blow up episodes involving pesticides out of all proportion, partly to earn some publicity for themselves or their programs. For example, in the Philippines sometime in 1975–76, pesticides were accused as causing massive fish kills in Laguna de Bay fishpens. Everybody wanted to get into the act, making 'educated guesses' on how much pesticide we have in this body of water, proclaiming that the government should virtually stop use of pesticides. All the emotionalism died down when it was pointed out that the fishpens were overstocked and this could be the main cause of fish deaths. Has anyone made a correlation between pesticide levels and fish kills, analysed lake muds, waters, fishes, tributaries, etc. for pesticides? Was anyone willing to finance studies on the dynamics of pesticide transport and degradation? The answer is no, but for some time, pesticides suffered the brunt of adverse publicity.

Another incident which illustrates our unbalanced concept of pesticides was when a proponent of non-pesticide use argued in 1981 that our Fertilizer and Pesticide Authority was remiss in its job of ensuring farmer safety. It was claimed that (1) pesticides not recommended (by FPA and our Masagana-99 Program) were being used against rice pests in one village, and (2) that leaky sprayers were in use. The inconsistency in the arguments is evident. While in (1) it was acknowledged that the pesticides being used were not recommended, the regulatory agency was still blamed for their unauthorised use. In (2), the problem was that there were no regulations covering leaky sprayers. The FPA is still so involved in pesticide regulation that it cannot deal with all aspects of pesticide use. In 1981, leaky sprayers were not even on the regulatory agenda.

Perhaps another glaring weakness of pesticide regulation in developing countries is the lack of appreciation of the need for local research to support regulatory activities. While in developed countries, the research link is very good and, in fact, regulatory agencies frequently give research grants, such is not the case in developing countries. Whatever research has to be done, the agencies want to do it themselves, probably rationalising that supporting outside research will strengthen agencies other than themselves. However, they are ill-prepared for this and this may entail the need to expand themselves to such a point that their work becomes too thinly spread. Also, they may be open to the suspicion of doing the research to support preconceived results. This approach sacrifices common goals to the altar of self-glorification.

Conclusions

What does all this mean in terms of our concern for a safe, clean, and wholesome food supply and environment?

The creation of pesticide regulatory agencies in many developing countries augurs well for these expectations, especially if they can adopt realistic and effective pesticide management approaches which can overcome developing country limitations. For their part, lay people should understand that even in developed countries, regulatory agencies have shortcomings notwithstanding their adequate resources. Our regulatory agencies are relatively new, and function under a heavy disadvantage. If we are bent on making them succeed for the common good, they need all our assistance.

On the other hand, there is no question that the basic idea of fulfilling a mandate, rather than fulfilling unrelated expectations in the existing political structure, should be pursued singlemindedly. We have to mobilise our existing technical expertise regardless of personal conflicts. We have to join forces not only with other line agencies for mutual strengthening but also with research agencies in the fulfillment of goals which are relevant to a developing country setting.

For our own safety and for the generations to come we should always be vigilant not just with pesticides but with the host of other chemicals and technologies we are using. However, let our vigilance be based on enlightenment and the interests of our people as a whole. With pesticides, let us first and foremost accept that we cannot simply leave everything to a regulatory agency but should consider ourselves part of the total pesticide management effort of a country.

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APPENDIX 1

Information required for registration of proprietary pesticides in the Philippines.

A. SPECIFICATIONS

1. **Active Ingredient**
    a. Chemical name (Use IUPAC nomenclature)
    b. Formula (empirical and structural) and molecular weight
    c. Other names (ISO name and synonyms, code numbers, etc.)
    d. Manufacturer of the technical product and method of synthesis
    e. Composition of the technical product
    f. Stability under different conditions: in water, in organic solvents, etc.
    g. Melting point, boiling point, vapor pressure, density
    h. Solubility
2. **Formulated Product**
    a. Name and address of applicant
    b. Name of manufacturer of the product
    c. Proprietary name of the product or proposed name
    d. Type of pest control product (herbicide, fungicide, insecticide, rodenticide, etc.)
    e. Physical state and nature of the formulation (emulsion, solution, granule, bait)
    f. Detailed information on composition of the product (active ingredient, main impurities, solvents, etc.)
    g. Stability of the formulated product
    h. Suspensibility and emulsifying characteristics
    i. Known compatibilities and incompatibilities of the formulated product with other products or active ingredients
    j. Flash point or other indications of flammability or spontaneous ignition
    k. Methods of destruction and disposal
    l. Compatibility with proposed packaging materials

B. BIOLOGICAL EFFICACY

1. **Intended Uses and Methods of Application**
    a. Mode of action (effects on pests)
    b. Types of pests controlled and/or types of crops, materials or premises to be protected, be it agricultural or non-agricultural use
    c. Application rate
    d. Number and time of application (season or stage of growth)
    e. Method of application (high volume, ULV, fumigation, etc.)
    f. Phytotoxicity, necessary waiting time to avoid phytotoxic effect
2. **Biological Efficacy**
    a. Laboratory experiments
    b. Experiments under practical conditions, including tests with reference product
    c. Development of resistance
    d. Local tests (at least two seasons)
    e. Recommendation on pests controlled
3. **Disposal of Surplus Pesticides and Pesticide Containers**
    a. Disposal of unwanted pesticides
    b. Disposal of containers
4. **Specimen Labels** (Attach)

C. TOXICOLOGY

1. **Toxicology Data**
    a. Acute toxicity
        a.1. Oral (mg/kg)
        a.2. Percutaneous or dermal (mg/kg)
        a.3. Inhalation (mg/1)
        a.4. Other routes (intraperitoneal, etc.)
        a.5. Skin and eye irritancy

- b. Short-term toxicity
    - b.1. Oral
    - b.2. Other routes
    - b.3. Allergic sensitisation
- c. Supplementary toxicological studies
    - c.1. Toxic effects of metabolites or impurities
    - c.2. Metabolic studies
    - c.3. Long-term toxicity
    - c.4. Carcinogenicity
    - c.5. Neurotoxicity
    - c.6. Reproduction studies
    - c.7. Teratogenicity
    - c.8. Mutagenicity
    - c.9. Potentiation

2. Observations on Man

- a. Direct observation (e.g. clinical cases)
- b. Health records, both from industry and agriculture

3. Information on Diagnosis and Treatment

- a. Diagnosis of poisoning, specific signs of poisoning, clinical tests
- b. Treatment of poisoning
    - b.1. First-aid measures
    - b.2. Supplementary treatments

D. RESIDUES AND FATE IN THE ENVIRONMENT

1. Methods of Analysis

- a. Formulation
- b. Residues
- c. Metabolites

2. Residues Data

- a. Statement on principal residues in edible crops, food or feedstuff, including suggested metabolic routes
- b. Residues level in named edible crops, food or feedstuff
- c. Data from supervised trials, experimental feedings, etc., giving all experimental conditions and details
- d. Other data, if available (food commodities in commerce and monitoring program)
- e. Effects of industrial processing and/or cooking on residues
- f. Taint due to normal residues on or in fresh foodstuff or after processing

3. Environmental and Wildlife Hazards

- a. Soil
    - a.1. Residues in soil, methods
    - a.2. Movement and persistence in soil (disappearance curve)
    - a.3. Metabolism
    - a.4. Tests on soil organisms
- b. Water
    - b.1. Residues in water
    - b.2. Tests on water organisms
- c. Toxicity to wildlife
    - c.1. Toxicity to birds
    - c.2. Toxicity to fish
    - c.3. Toxicity to bees
- d. Information on beneficial insects other than bees
- e. Field trials and observations
- f. Other information

Some Constraints to Use of Pesticides Session Chairman's Summary

Renato Labadan*

Pest Control Practices and Problems

The papers presented by *Calverley* and *Gonzalez* highlighted the common methods of pest control in current use in specific storage situations and some general recommendations for improvement.

Calverley noted that chemicals are often applied in situations where the principles of good storage practice have been neglected, which has culminated in the belief that they are now an essential part of procedures for minimising loss rather than a supplementary component, as they were initially advocated. It is unlikely, however, that good storage practices will achieve an insect-free environment in the open ventilated storage systems in the humid tropics of Southeast Asia, due to the continuous and high reinfestation and cross-infestation pressure that exists. In addition, grain is often infested in the field before storage. Good storage practice does, however, encompass those simple precautions that help to minimise the natural presence of insects, rodents, and birds, their natural build up, and the rate at which damage and losses become economic.

These practices include:

(a) Care in the initial design of stores and in their maintenance, the lack of maintenance after construction being a common problem that is often tolerated without due cognizance of the difficulties it poses in pest control management.

(b) Attention to store hygiene and cleanliness.

(c) Implementation of inspection and quality control. This is often difficult, due to the multitude of farmers producing small quantities of grain with enormous variability in purity and moisture during the peak procurement periods. Moreover, the grain is often already infested.

(d) Stock control procedures which can minimise pest management problems by attention to stock movements and storage, and the disposal of commodities. The principles of First In-First Out (FIFO) are often neglected, and new stocks are often stacked together with stocks already infested. Stocks that are deteriorating need to be moved quickly, whatever their age.

Losses can be drastically minimised without relying on pesticides, as was evinced by an example from Sri Lanka involving the simple matching of milling to consumption patterns, and introducing a coding system to minimise length of storage. *Gonzalez* noted that rice millers in the Philippines do not carry out any active pest control other than cleaning, since stocks are disposed of very quickly. However, wholesalers who maintain large inventories rely on licensed commercial pest control operators, principally for rodent control. It was also noted that about 70% of grain remains on farm.

In ASEAN, however, the proportion remaining on farm for subsistence, later

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sale, and for seed is quite variable. It depends on farm size, on whether it is the dry or wet season harvest, and on cash flow requirements at the time of harvest.

The opportunity for preventing losses by use of chemicals is greatest in long-term storage. The use of contact insecticides for on-farm use is essential once traditional agricultural systems have been changed, but problems in obtaining good quality formulations with broad spectrum activity, stable dust preparations, package sizes suitable for small-scale use, and adequate protection over a reasonable storage duration were outlined.

Insecticides are not used for protection of farm-stored paddy in ASEAN, neither has their use been researched, but there are possibilities for a combination of protectant systems to be used, such as for controlling *R. dominica* and *S. cerealella* which are frequently encountered.

The use of fumigants on-farm is constrained by the problem of ensuring gastight conditions in many of the traditional stores and bamboo baskets that are used, and because grain is often stored within the farm dwelling itself. Specifications for a container of 0.25–1.25 t capacity suitable for fumigation should be developed, but it is likely that most storage bins on farms will remain unsuitable.

In central storage systems, most of the grain is handled in bags, except for large exporters in Thailand, importers of wheat and maize in the Philippines, and the LPN complexes in Malaysia. The main weapon in the pest control arsenal in this situation is fumigation with either phosphine or methyl bromide. Problems identified were inadequate gas retention through the use of poor quality sheets, and inadequate fumigation periods, especially when phosphine is used. Professor Gonzalez also mentioned that pest control is not regularly practiced in some government warehouses because of lack of chemicals, equipment, and pest control officers when and where they are needed. Feed millers in the Philippines often store (as well as maize) bran, meatmeal, fishmeal, and other commodities. Often these are also heavily infested, so the entire warehouse is fumigated. Attempts to seal the store are made, but it is unlikely that the methods used are effective in making a sufficiently gastight seal unless the extensive (and expensive) application of sealants is performed.

For complete in-store fumigation with phosphine where sealing is difficult and leakage rates do not exceed 40% per day, a system of multiple dosing to maintain effective concentrations has been proposed. Where it is a case of absorbing huge economic loss or enhancing the onset of resistance in leaky enclosures where fumigation will be done regardless, multiple dosing while monitoring gas concentrations during the fumigation is seen as good fumigation practice.

After fumigation with phosphine at 0.3–0.4 g/m^3, private pest control officers in the Philippines treat all structural surfaces and outer surfaces of bags with permethrin or malathion to prevent infestation. *Calverley* stated that spraying stacks after fumigation and with disregard to the resistance profile of the target species is likely to be uneconomic and a complete waste of time and resources. Contact insecticides are most economically applied as structural treatments only.

Wheat and maize imported into the Philippines and stored in transit facilities such as concrete silos are treated with malathion as they are being conveyed into the silos. It is suggested that, because of widespread resistance to malathion, other protectants would be more effective. Also, residual effectiveness would be enhanced by applying a mixture of concentrated insecticides, either by gravity feed or atomised ULV systems. The application of fumigants in these concrete silos may also lead to pockets of grain receiving sublethal doses due to poor gas retention unless some form of recirculation is carried out, a problem that is being recognised in Thailand.

Pesticide Safety and Regulation

The two papers by *Snelson* and *Magallona's* paper dealt with safety and regulatory requirements for pesticides, and the registration process for their use in grain storage systems and admixture to grain for human consumption. Safety in the use of pesticides requires common sense, good management, and supervision, and their application according to good agricultural practice, such as using registered products in specific circumstances or situations in strict accordance with the label directions. Good agricultural practice encompasses the quantities necessary to adequately control the pest under practical conditions while leaving the smallest possible amount of residue, taking into account the toxicological and environmental hazards involved.

Concern over residues in grain has often disregarded the significant losses and degradation that occur in storage, and the further losses that occur during milling, processing, and cooking. However, the degradation of residues in developing countries causes special concern where raw grain is converted into food with minimal of preparation and cooking, and has perhaps prevented the widespread introduction of grain admixture of protectants.

With regard to registration of insecticides of botanical origin, there are no legal grounds for using separate registration procedures, since in many instances they are toxicologically more potent that synthesised chemicals. Adequate information on their efficacy, safety, and fate must therefore be generated.

Gaston outlined for participants the activities of the Regional Network for Production, Marketing and Control of Pesticides in Asia and the Pacific (RENPAF), which has also absorbed the Agricultural Requisites Scheme for Asia and the Pacific (ARSAP)/Agro Pesticides Programme of ESCAP since 1983 (see Gaston's paper). It is seen that the activities of regional networks such as this can promulgate the availability of stable formulations of pesticides and packaging in suitable sizes for specific situations, thereby increasing their efficacy and effective life.

Harmonisation of Registration Requirements for Pesticides in the Region

Invited Comments

Cecilia P. Gaston*

In 1982, UNDP funded a project which established the Regional Network for Production, Marketing and Control of Pesticides in Asia and the Pacific (RENPAF). The project was under UNIDO execution in collaboration with FAO and ESCAP (now also WHO), and nine countries participated: Thailand, Indonesia, Korea, India, Pakistan, Philippines, Sri Lanka, Bangladesh, and Afghanistan.

The key activity considered of highest priority for regional cooperation was that of harmonisation of registration requirements. The network engaged a consultant to review the status of registration among the member countries and recommend measures to be taken to harmonise registration requirements in the region. A consultation was held in October 1983 for the countries in the region and a scheme for harmonisation of registration requirements (the FAO/WHO Model Scheme for Registration) was accepted. The countries (which included Malaysia and Japan) agreed in principle to adopt as far as practicable the guidelines and procedures recommended by FAO and WHO in registration.

It was noted that, although differences in registration schemes among the countries exist, there are major similarities that could facilitate attainment of objectives of harmonising registration.

In a few countries, however, the main deterrent to immediately adopting the FAO scheme was their basic legislation. For example, in some countries regulation begins only after a product has been officially gazetted as a poison. Under their legislation, therefore, not all pesticides need to be regulated. Some forms of legislation require the use of the skull and crossbones sign on *all* pesticides. The registrant therefore has no recourse but to abide by his country's law even if his agency agrees to implement the WHO classification by hazards. It is noteworthy, however, that these countries have started to work on amending their legislation as a step towards regional and eventually international harmonisation, and in particular to require: (a) all pesticides to be registered before they can be sold, without a need to gazette them before the registration process can be undertaken; and (b) the use of WHO classification of pesticides by hazard for labelling of pesticides.

The countries agreed that the label should be considered a vital part of registration and that colour coding be harmonised and based on hazards rather than method of use.

Several related activities were carried out, all geared towards harmonising registration and regulatory requirements within the region:

(1) Workshop on Residue Analysis, which trained delegates on laboratory techniques of residue analysis using agreed methods.

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(2) Experts Meeting in Quality Control of Pesticides, which agreed to adopt, to the greatest extent possible, the FAO specifications for agricultural pesticide products and WHO specifications for pesticide products used for public health, and the CIPAC methods of analysis. Countries have participated in collaborative studies conducted for pesticides used in the region.

(3) Workshop on Toxicology, which noted the need to train evaluators of toxicity data and explained the different studies used to support toxicological data submissions. It also adopted the WHO Classification of Pesticides by Hazards for labelling purposes and proposed that draft guidelines on labelling (based on FAO recomendations) be prepared for dissemination to member countries.

In summary, the groundwork for harmonisation of pesticide registration requirements has been started by the Regional Network and although it might be a long process, substantial progress is evident. Thailand and India are starting to work on amendments to their legislation; Pakistan has started to implement recommendations proposed by the Network; the Philippines is revising the Guidelines based on agreements; Sri Lanka has implemented a registration scheme. A second consultation is being organised for late 1985 or early 1986 to look into adoption of common protocols for bioefficacy trials. It is hoped that, as with toxicological data, efficacy data can become transportable if protocols are agreed upon for crops grown under similar climatic conditions.

Background Studies on Residual Pesticides

Background Studies on the Metabolism of Residual Pesticides in Stored Grain

D. G. Rowlands*

Abstract

In order to facilitate complete assessment of losses of residues and of bound metabolites, studies on the metabolic fate of contact insecticides in stored grain preferably use radiolabelled compounds. They also seek to determine the translocation within the grain in relation to the metabolism taking place and are, of necessity, carried out on a small (laboratory) scale. The problems inherent in such studies are reviewed, with particular reference to: vapour-phase losses, effects of the (glass) container used, volatility of metabolites produced, and the recovery of bound metabolites. Also discussed is the extent to which experiments on single grains or with small amounts of grain (i.e. grams) can reflect real practice at pilot (kilograms) or bulk (tonnes) scales.

HARVESTED cereal grains are stored against future use as a foodstuff or marketable commodity by most cultures and economies throughout the world. The conditions under which they are stored vary according to the climate, the life-styles of the communities, and the prevalent marketing practices. Cleanliness and awareness of the causes of pest infestation are more important in preventing spoilage and loss than are sophisticated or modern premises. Heavy reliance is still placed on chemical control of pests: by fumigation or by admixture with contact insecticides.

There is only a small armoury of compounds that are considered safe enough to admix with stored cereals, and because of resistance and other factors there has been a movement away from short residual-life compounds like malathion to those like etrimfos which can persist for months even under tropical conditions (Fig. 1). Furthermore, where there are mixed populations and species of pests present, recourse to mixtures is often necessary; notably where, for example, a pyrethroid may have to be combined with organophosphate(s) to control *Rhyzopertha dominica* in the presence of *Sitophilus oryzae* (Bengston et al. 1983).

Before these pesticides are 'cleared' for such purposes and recommended by national and international agencies, there are many data required: toxicity studies; long-term feeding trials; efficacy; persistence of residues and where they are located, as well as metabolic studies to determine the fate of the compound both in the treated commodity and in the animals (including humans) that may consume the raw or processed foodstuff after storage.

This paper will discuss the sort of laboratory work that is undertaken to determine the metabolic fate of pesticides applied to stored grains, and the relevance that such studies have to the practical situation.

The Scale of the Experiment

In attempting to determine the metabolic fate of a residual insecticide in stored grain we necessarily make use of small-scale laboratory experiments that we hope will model the field situation. Ideally we want to use a radio-labelled insecticide so that we can account — perhaps ultimately by combustion — for all the dose that is applied, and in particular for any residue (parent compound or metabolite) that may not be recovered by conventional solvent blending, maceration, or homogenisation. This immediately restricts the scale on which we can operate: radiotracers are both expensive and potentially hazardous, and the treating and handling large bulks is not possible.

We also want to know the location within the grain of the pesticide residue, and relate this to the

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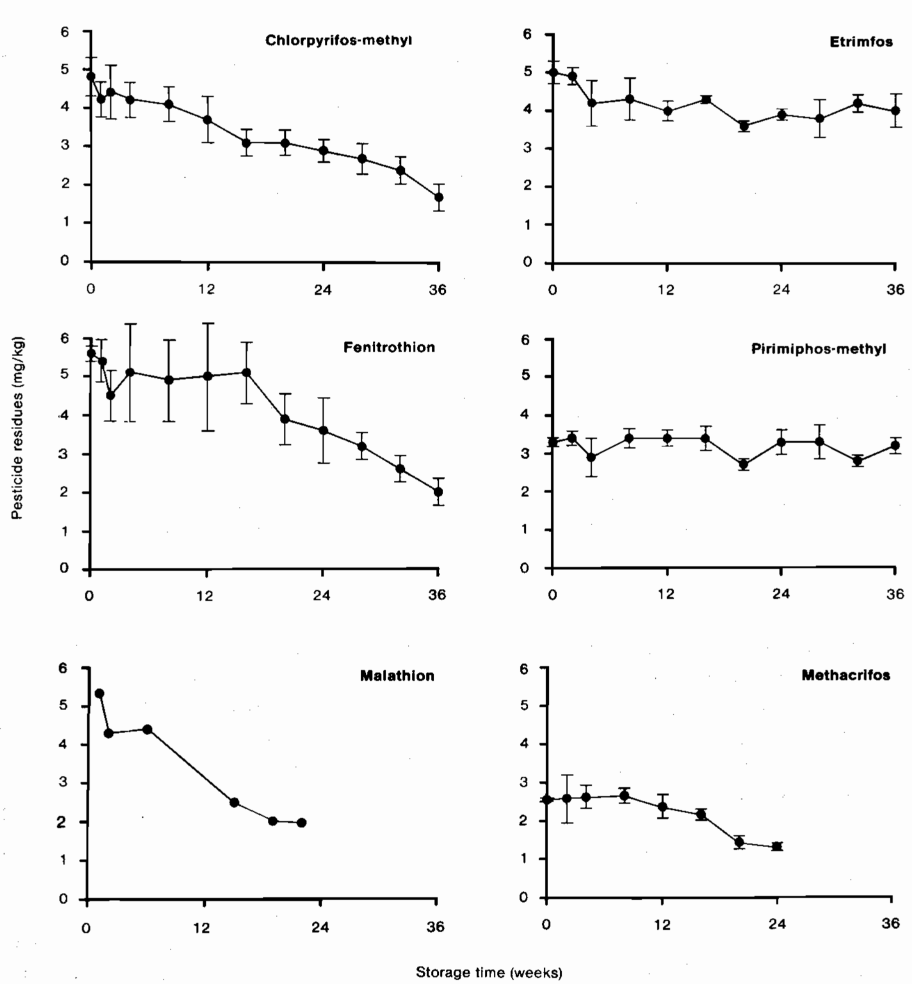

Fig. 1. Apparent loss of insecticides from 25-t bulks of wheat (14–16% moisture content) at ambient temperatures, range 24°–25°C (from Wilkin 1985).

overall residue at a given time. It may be, for example, that of the total residue 1 mg/kg parent compound remaining in a sample taken four months after a treatment at 4 mg/kg, some 70% will be found in the outer layers of the grain (bran or perhaps the husk) and the remainder in the starchy endosperm, or the germ. Such findings might have important toxicological implications for the way in which the raw cereal is processed or consumed. They may also help us to decide where degradation is taking place — in the aleurone layer perhaps, or in the germ/embryo.

We can obtain such data as these by experimental milling of kilogram batches taken from bulks in store, or we can assay the commercial milled fractions at the end of storage when the bulk cereal is being processed. Recent work by my colleagues Wilkin and Fishwick (1981 and unpublished data) has shown that laboratory scale experimental millings of kilogram amounts using a Buhler mill do not necessarily represent large-scale practice (Table 1).

However, for metabolic experiments with radiotracers, the total amount of cereal treated may indeed be as much as a kilogram, but the samples and replicates used will be in gram amounts. This presents a further problem because the milling of *small* samples (perhaps 1–20 g) into recognisable fractions: bran/husk/seedcoat, flour/starchy endosperm, and germ is neither easy nor

Table 1. Comparison of laboratory, pilot, and full-scale treatments and milling of grain treated with chlorpyrifos-methyl.

	Laboratory (20° C)+		Pilot (kilos)	Commercial (tonnes)
	Indiv. grains	Small bulk	Buhler mill*	Hammer mill*
Intended dose (mg/kg)	4.5	4.5	4.5	4.5
Actual dose achieved (mg/kg)	3.8	3.8	6.1	5.7
Time of milling	6 weeks	6 months	4 weeks	5 months
Residue at milling (mg/kg)	3.6	3.3	4.3	2.3
Concentration (mg/kg) in:—				
white flour	0.6	0.8	1.1	1.1
offals bran	10.2	10.0	14.0	7.6
offals germ	1.3	1.7	1.0	13.0

*Wilkin and Fishwick (unpublished data).

reproducible. The ingenious milling procedure, partly mechanical partly manual dissection, developed for 5 g samples by Takimoto et al. (1978) seems to have overcome the problem of replication, but is too prolonged (⩾15 hours) for studies on initial uptake to be meaningful. The manual dissection of a few individual grains does, with practice, give clearly-defined and reproducible fractions that correspond quite closely with the milled products of commerce. Even so, a single 10 g sample would involve dissecting about 200 individual grains; a daunting task! Where examination of the milled fractions is desirable in radiotracer studies it may therefore be necessary to work with a few individual grains as representative of the bulk.

The distribution of pesticides and metabolites within individual grains changes very little after 7–14 days in laboratory studies (Rowlands 1975) and on the tonne-scale appears to be stable after a month or so (Thomas and Fishwick, personal communication; Table 2), unless dosing has deliberately been designed to exploit the 'uneven dose strategy' (Minett and Williams 1976). Therefore, the usual degradation rate/metabolism study which is not concerned with a detailed study of initial breakdown, but which requires sampling at monthly intervals during 6–9 months storage, can satisfactorily be carried out in the laboratory with radiolabelled pesticide using 10–20 g samples withdrawn from a total bulk treatment of 1 kilogram. Anderegg and Madisen (1983b) have shown that differences in uniformity of application do not affect the subsequent metabolism of malathion in stored wheat.

Initial Losses and Apparent Rapid Decay

An aspect of metabolic studies that often dictates working with individual grains is that a most interesting part of any such experiment lies in the first few hours and days directly after treatment. Residue analyses after 1–2 days sometimes show a considerable loss of the dose actually achieved. Is it lost by volatilisation from the surface? Is it taken up rapidly by the grain and degraded as it passes through the seedcoat or husk and so into the aleurone layer (Fig. 2)?

If the grain is freshly harvested and still warm and humid under tropical conditions, and forced aeration is used to assist drying, this could cause

Table 2. Distribution (mg/kg) of pirimiphos-methyl and chlorpyrifos-methyl in milling fractions from 25-tonne bulks after 0, 1, 3 and 6 months storage.

	Pirimiphos-methyl				Chlorpyrifos-methyl			
Fraction	0	1	3	6	0	1	3	6
Whole wheat grain	4.2	3.3	3.0	2.9	5.7	3.8	3.0	2.6
1st reduction*	0.17	0.17	0.16	0.17	0.11	0.13	0.13	0.09
Fine offal*	1.4	3.7	4.1	3.1	1.0	3.3	3.3	2.3
Bran*	3.0	3.7	3.4	2.8	1.6	3.3	2.9	2.3

*Expressed as $\frac{\text{level of pesticide in milling fraction (mg/kg)}}{\text{level of pesticide in whole grain (mg/kg)}}$

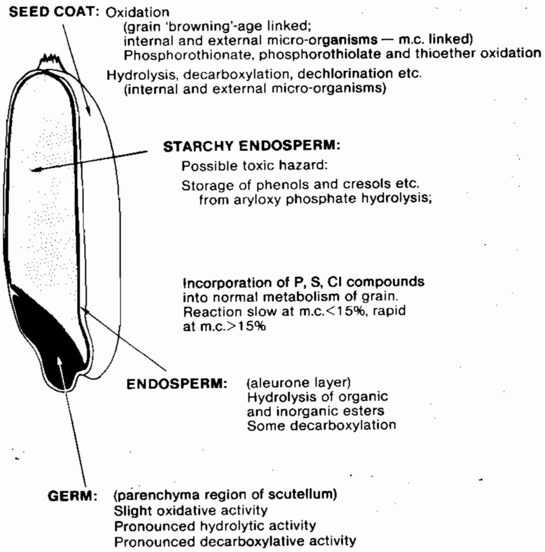

Fig. 2. Locations of possible insecticide metabolism within the cereal grain.

some loss of volatiles. On penetration, the insecticide may be subjected to breakdown catalysed by ripening processes still active in the seedcoat or by similar enzymes in the microflora on the surface of, or just under, the outer husk. Some evidence of the role of microflora in wheat and maize on malathion degradation has been obtained by Anderegg and Madisen (1983a).

Banks and Desmarchelier (1978) have made some shrewd and salutory observations on the lack of a scientific approach to such studies (my own included) and I would commend their paper to all workers in this field. In discussing the 'apparent rapid decay' found in laboratory studies, they say that it is not duplicated in large-scale applications. This seems to be true of the more stable compounds coming into use, and it has to be accepted that there are major obstacles to the determination of rapid initial degradation, such as sampling errors, variation in replication, and in analytical techniques. Where the analytical results can vary by 10–15%, the reliance that can be placed on an apparent loss of 1 mg/kg from a 9 mg/kg original dose is doubtful. Nevertheless, despite these and sampling problems it is possible to point to examples of rapid initial loss on the practical scale, though unfortunately few workers have ever attempted to account for such losses.

As an example from our own work, I have chosen conditions as 'tropical' as possible: storage temperatures 26–30°C and fairly high moisture content (18%). An intended application of 10 mg/kg bromophos as an emulsion to 28 tonnes of wheat stored at 26–30°C gave an actual dose (time 0) of 9.3 mg/kg (+12% — average of three replicates). The moisture content of the wheat was 18%. Within a day, the residue of intact bromophos was down to 8.4, and within 3 days to 7.6 mg/kg. These 'losses' are almost within the 12% experimental error (ignoring the problem of sampling such large bulks adequately), but with the 7-day figure of 6.8 mg/kg we have an unequivocal loss, especially as the apparent amount — some 2.5 mg/kg (range 1.5–3.6 mg/kg) — was accounted for by the presence of 2.1 mg/kg of desmethyl bromophos. Laboratory studies on the 1 kilogram scale and on individual grains at a lower temperature (20°C) showed a similar pattern (Table 3).

Table 3. Bromophos application to wheat (10 mg/kg) and residues at 1 and 7 days.

	Size of bulk		
	28 tonnes	1 kilo	Individual grains
Temperature	26–30°C	20°C	20°C
Moisture	18%	18%	18%
Dose achieved (mg/kg*)	9.3	9.5	10.0
Residue at 1 day*	8.4	8.1	7.5
Residue at 7 days*	6.8	5.5	5.0
Amount desmethyl bromophos (7 days)	2.1	2.8	3.1

*Standard error ± 12%

Data from Green et al. (1970); Rowlands (1966 and unpublished).

In order to relate such initial breakdown to processes in the grain, it is essential to know where the residues are located, and to relate this accurately to the time after treatment. However, there remains the limitation that it is not possible to dissect many grains in the space of a few hours, so that once again such 'immediate' translocation and metabolism studies with radiolabelled pesticides need to be carried out on replicate individual grains.

In general — and with the exception of chlorpyrifos-methyl (to be discussed below) — we have found that where they are necessary, individual grain studies can model the practical scale quite satisfactorily.

Vapour and Volatility

Vapour-phase activity of contact insecticides is an important aspect of storage pest control, and perhaps more so under tropical than temperate conditions. Studies on air movement and how pesticide vapour distributes through the intergranular spaces of a cereal bulk have been made by Storey (1972) for malathion and by Desmarchelier et al. (1977) for dichlorvos and malathion. The latter group demonstrated an increase in the biological efficacy of dichlorvos under forced airflow conditions and made an interesting quantitative assessment of the phenomenon. In addition, Desmarchelier (1978) has considered the mathematics of availability to insects of vapour from aged deposits of dichlorvos, chlorpyrifos-methyl, and pirimiphos-methyl on wheat. In view of the high intrinsic toxicity of such vapour to insects, more studies along these lines would be valuable.

To offset the enhanced toxicity perhaps, one would expect that vapour losses (volatility) might contribute significantly to the difference between the intended dose and that actually achieved in practical situations; also to the initial apparent loss of this achieved dose, particularly from the surface.

Practical situations involving the use of forced aeration might therefore be expected to play a role in vapour losses of contact insecticides. Surprisingly, a comparison of unaerated 20 t bulks of wheat treated under United Kingdom conditions at 4 mg/kg with chlorpyrifos-methyl, and similarly treated bulks that were aerated upwards at 10 m^3/t/hour showed no difference in either biological effectiveness, as determined on samples removed from the bulks, or pesticide residues during 16 weeks storage (Thomas 1985). Grain temperatures followed ambient throughout, in the range 5–24°C.

Vapour losses must be considered of importance in laboratory studies on translocation and metabolism: particularly those on individual grains. Where the container is sealed the problem may not be so much one of loss, but rather of transfer of the pesticide or metabolite from the treated grain to the catalytic or sorptive walls of the vessel.

Recent studies with chlorpyrifos-methyl by my colleague Paul Adams have highlighted these problems and I will deal with them in some detail. Our previous work on translocation and metabolism using small bulks of grain or individual grains treated with malathion, dichlorvos, bromophos, pirimiphos-methyl, fenitrothion, and other contact insecticides (Rowlands 1975) had lulled us into a false sense of security. We had been able to account for virtually all the pesticide (and metabolites) as radiolabelled by the usual techniques and had concluded that — except for loss of dichlorvos from open vessels — losses due to volatility of the pesticide and sorption by the glassware used were minimal. (An exception was the sorption by glassware of ^{32}P label from pirimiphos-methyl. No similar problem was found with the ^{14}C-labelled compound, which is curious.)

Detailed studies using solitary grains treated with either ^{14}C or non-labelled pirimiphos-methyl showed no rapid loss of the insecticide from either sealed (Rowlands 1981) or unsealed containers (O'Donnell and Rowlands 1981; Table 4).

Table 4. Loss of pirimiphos-methyl from solitary individual grains.

No. of days after treatment	Residues of pirimiphos-methyl (mg/kg) Open tubes[a]	Sealed tubes[b]
0	7.4 (±0.3)	3.9 (±0.4)
1	7.7 (±0.3)	3.7 (±0.3)
7	6.7 (±0.5)	3.6 (±0.4)
14	5.3 (±0.4)	3.4 (±0.3)

[a] Data from O'Donnell and Rowlands (1981). Assay by GLC.

[b] Data from Rowlands (1981). Assay by ^{14}C-counting and TLC.

The Behaviour and Fate of Chlorpyrifos-methyl on Single Wheat Grains

Working on the basis of comparison with an inert substance (filter paper), Adams (1985) showed that individual grains treated topically at 4.5 mg/kg with ^{14}C-chlorpyrifos-methyl lost 80–90% of the dose from unsealed containers within 7 days; no radioactive materials were recovered from the walls of the glass vessels.

He also showed that in a sealed container, chlorpyrifos-methyl was transferred from both grain and paper to the inner surface of the vial and that quite rapid degradation to 3,5,6-trichloropyridinol occurred there. He was further able to suggest that the glass was the major catalyst responsible for the breakdown. Moreover, the volatiles present in the atmosphere and on the glass surface could be reabsorbed by the individual grain. Anderegg and Madisen (1983b) suggest a similar reabsorption of ^{14}C volatiles from malathion degradation in a small experimental bulk.

Since the pyridinol is also the major (*and volatile*) metabolite produced by the grain, the catalytic role of the glass complicated any assessment of true metabolism. A PTFE container did not catalyse any such breakdown of the volatile insecticide, but on the other hand intact chlorpyrifos-methyl was rather more difficult to recover initially from that material. However, it is clear that a glass container will not do for work on solitary individual grains treated with chlorpyrifos-methyl. Adams found, however, that loss of this insecticide and/or the pyridinol to the glass, and subsequent breakdown to more of the pyridinol on that surface could be prevented by surrounding the individually treated grain with other (100) grains similarly treated with non-^{14}C-labelled material. This had the further advantage of being a better model for a bulk of grain. Most interestingly, although the same *concentration* of insecticide was maintained in the particular grain studied over the 7-day period, most of the ^{14}C label was recovered from grains surrounding the single marked grain. Transfer/exchange had occurred between the single grain and those surrounding it, despite all the grains having been dosed at the same level. Thus, in order to work on this basis with a single grain for dissection and assay of ^{14}C products, all the grains in the container would need to be treated with ^{14}C-chlorpyrifos-methyl. This has the advantage that any grain could be selected for individual assay from the centre of the hundred or so, and replicates taken from the same equilibrated 'bulk.'

So far, chlorpyrifos-methyl would seem to have been a special case. The problem of the rapid loss of this insecticide from individual grains in open containers first arose when attempting an oviposition and development study with the grain weevil (*Sitophilus granarius* L.) in direct comparison with an earlier study on pirimiphos-methyl treated grains (O'Donnell and Rowlands 1981). Although pirimiphos-methyl is appreciably volatile (Desmarchelier 1978) and has a higher vapour pressure than chlorpyrifos-methyl, we found no undue loss of this insecticide from open vials, or from sealed vials (Rowlands 1981). The levels of pirimiphos-methyl applied to the individual grains were different (twofold) in the two experiments but in both cases 91–92% of the original dose was recovered 7 days after treatment (Table 4.)

However, there could be problems in working with dichlorvos-treated solitary grains in open containers. We have no data comparing 'normally' treated single grains in open and sealed vials, but solitary grains which had previously been saturated with non-labelled dichlorvos before application of a ^{14}C-labelled dose, lost 80–90% of the radioactivity within 7 days, from an open vial, compared with only 7% loss from a sealed one (Rowlands 1970). From a treatment of solitary grains with ^{14}C-dichlorvos stored in sealed containers, 98% of the applied radioactivity was recovered after 7 days storage. However, breakdown had occurred and only one-tenth of this activity was intact dichlorvos; any catalytic effects of the glass vessel in this rapid degradation were not investigated. Since, however, this rapid breakdown was matched in 10 g 'bulk' samples stored under identical conditions, any effect of the glass can probably be discounted.

Adams' study has shown that future work necessitating experiments with single grains will sensibly adopt the basis of small bulks rather than solitary grains, and non-glass containers where acceptable recoveries are feasible. These precautions should minimise any errors or discrepancies in translocation and metabolism studies, such as have been demonstrated can occur with chlorpyrifos-methyl.

Comparison of Breakdown of Chlorpyrifos-methyl in Stored Wheat under Laboratory and 'Field' Conditions

Recently, my colleagues Matthews and Adams took the opportunity of a 25-t bulk of wheat being treated at 4.5 mg/kg with chlorpyrifos-methyl by other colleagues Thomas and Wilkin, to compare directly the breakdown of the insecticide on this scale with that in 1 kg of the same wheat stored under laboratory conditions. The aim was to determine how far the laboratory study, which used ^{14}C-labelled insecticide, could reflect the practical scale treatment.

The wheat (cultivar Bounty) used for both experiments was of 14.4% initial moisture content. Storage conditions in the laboratory were at 15°C and 60% RH, as close as possible to those in the barn containing the large bulk, where temperatures in the grain ranged from 24°C to 5°C during the 5 months of storage. Samples were taken from the concurrent experiments at monthly intervals and were extracted and analysed using the same procedures. Additionally, the samples from the ^{14}C (laboratory) treatment were combusted in a tissue oxidiser and the evolved CO_2 was counted to determine the unextracted radioactivity remaining within the grain that had not been extracted by the solvents used. These samples were also compared with replicates combusted directly without prior solvent extraction.

The tonne-scale experiment was terminated after 5 months, but the laboratory study continued for a further 9 months. All samples were examined for the presence of metabolites.

The apparent rate of degradation of chlorpyrifos-methyl proved similar in both barn and laboratory experiments (Fig. 3) with some 70% of the applied dose on insecticide still recoverable after 5 months storage. Of the apparent loss, very little could be detected as discrete metabolic products. Traces of the 3,5,6-trichloro-2-pyridinol were detected after 3 months, and 0.12 mg/kg of this compound were detected from the 'field' samples at the 5 month termination, compared with 0.14 mg/kg in the laboratory. From the radiotracer experiment additional traces were obtained initially of a more polar ^{14}C-labelled product which has not so far been identified. After 9 months of storage, laboratory samples were found to contain 2.9% and 3.5% of the total activity applied, as the pyrimidinol and the more polar compound respectively.

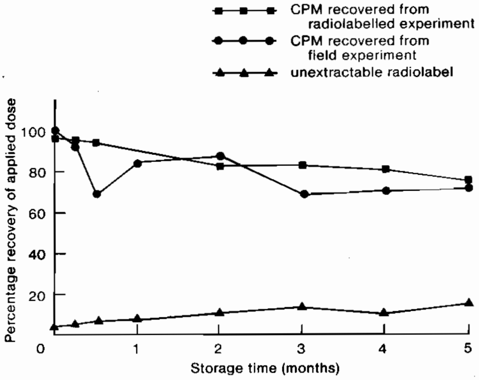

Fig. 3. Comparison of loss of chlorpyrifos-methyl on laboratory and tonne scales.

Unextractable or 'bound' radioactivity remaining in the grain tissues gradually increased throughout the storage period (15% at 5 months) and at the termination point (14 months) accounted for 29.4% of the total applied activity.

Our studies on the nature of this unextractable or 'bound' material are continuing but clearly the portion of chlorpyrifos-methyl or metabolites that is unextractable by conventional solvent blending must result from a significant process continuously taking place during storage. The levels of the free metabolites are insignificant and intact chlorpyrifos-methyl accounts for the rest of the applied dose which was recovered.

Attempts to analyse the 'bound' residues further, using chemical solubilisation procedures, have yielded little more information, and enzymic methods are currently being employed. Initial results from a bioassay of extracted grain (i.e. containing 'bound' residues only) against susceptible flour beetles suggest that these residues may have a delaying effect on the development of the insect, but no immediate toxicity. Similar phenomena were found with 'bound' malathion residues by Anderegg and Madisen (1983b).

In general terms, this comparative study shows similarities between laboratory and tonne-scales in terms of extractable residues of intact pesticide remaining during the storage period, and similarly trivial amounts of free metabolites.

These studies and those mentioned earlier (Tables 1 and 2), justify the use of small-scale laboratory studies as models for the large-scale practical situation.

Recent Studies on Metabolism of Insecticides by Stored Grains (1978–84)

Except for pyrethroids this section will deal only with papers that have attempted identification of the metabolic products.

Pyrethroids

I am not aware of any studies to date that have identified the metabolic pathways involved. Desmarchelier et al. (1979) showed that an average of 89% of pyrethrins I in an applied dose of pyrethrins-piperonyl butoxide were still present in wheat and oats 3 weeks after treatment and that 77% of this 89% were still present after 30 weeks storage at an average of 29°C and equilibrium relative humidity of 50%. This demonstrated that breakdown/loss of pyrethrins I was considerably slower than some earlier work had suggested.

Noble et al. (1982) calculated half-lives for the apparent loss of permethrin, phenothrin, fenvalerate, and deltamethrin from wheat stored in the laboratory at 25°C and 35°C and observed that permethrin and phenothrin which are mixtures of *cis* and *trans* isomers lost the *trans* isomers more readily; also that deltamethrin was apparently lost more rapidly than permethrin. The loss of efficacy of deltamethrin against grain weevils during storage was assessed by Hargreaves et al. (1982). They suggested that reduced efficacy might be attributable to the location of residues in the grain making them unavailable to the developing insects until adults were emerging.

Organophosphates

The bulk of the metabolic studies has been concerned with organophosphorus compounds currently in use, though I am not aware of any present studies that have attempted to elucidate the metabolic fates of methacrifos or etrimfos. The latter seems to be extremely stable on stored grain (see Fig. 1). Akram et al. (1978) determined a low level of etrimfos metabolism by bean and corn plants to free pyrimidinols and to the P=O analogue.

Dealing first with the major group in use today — organophosphates with pyrimidinyl leaving groups — Leahey and Curl (1982) studied the fate of ^{14}C-pirimiphos-methyl during 6 months storage at 20°C on wheat grains and on both paddy and brown (dehusked) rice, a very useful comparison. They found that the breakdown was qualitatively and quantitatively similar on both wheat and rice, the main pathway being to the free 2-diethylamino-6-methyl-pyrimidin-4-ol (2–23%) and to a more polar compound — probably a conjugate — that yielded the same pyrimidinol on acid hydrolysis (1.10%). They also identified trace elements of the N-monoethyl parent compound and the corresponding pyrimidinol, the bis-N-dealkylated pyrimidinol, and an unknown metabolite. Radioactivity not extractable by solvents, as determined by combustion, accounted for 3–7% of the applied activity after 3 months storage and for 2–13% after 6 months. However, there was virtually no 'bound' material in the dehusked rice (only 1–2% after 6 months) and this was matched by the almost negligible breakdown of pirimiphos-methyl in dehusked rice: only 5% loss after 6 months storage as against 25% in paddy and wheat where the seedcoats were present. This work seems to confirm the importance of the seedcoat/husk in the degradative processes.

Rowlands (1981) had shown somewhat more breakdown and loss of ^{14}C-pirimiphos-methyl on wheat (about 40% loss after 6 months at temperatures and moisture similar to the highest used by Leahey and Curl (op. cit.), compared with the 25% they found), but the major product detected was also the free 2-diethylamino-6-methyl-pyrimidin-4-ol with lesser amounts of the free N-dealkyl pyrimidinol. Some 15% of the applied radioactivity was not recoverable by solvent extraction but was released by sequential enzyme digestion (amylase, lipase, protease, and cellulase). Neither of these recent studies nor earlier work (reviewed by Rowlands 1975), investigated the nature of the bound material beyond digestion experiments to recover it.

I have seen no published information on the metabolic fate of chlorpyrifos-methyl in stored grain, other than general statements about hydrolysis to non-toxic products in the Dow Company's technical leaflets on Reldan, but have already mentioned recent work by my colleagues Adams and Matthews. As indicated above, they identified the free pyrimidinol and an unidentified more-polar compound as the only detectable metabolites from ^{14}C-chlorpyrifos-methyl during 14 months storage. A large amount (about 30% of the total radioactivity applied) of radio-labelled material that was not extractable by conventional solvent blending or acid digestion remains to be identified.

It may be worth noting that Kansouh (1975) studied diazinon metabolism in wheat during 3 months storage after treatment. He found rapid loss of the parent compound (probably due to volatilisation) and traces of the free pyrimidinol, the only metabolite detected, after 1 and 3 months.

Moving on to consider the older organophosphorus compounds still in use, Takimoto et al. (1978) made an extensive and valuable study of the metabolism of ^{14}C-fenitrothion and ^{14}C-melathion on unpolished rice grain (i.e. husk not present). They showed that some 60% of the radioactive residues were located in the seedcoat and could be removed by milling. The penetration of fenitrothion and its subsequent metabolism were studied in considerable detail, major products detected being at first, desmethyl fenitrothion, and later 3-methyl-4-nitrophenol; a similar pattern to that established for other aryloxphosphorothionates such as bromophos, iodfenphos, and fenchlorphos (Rowlands 1971). They also detected small amounts of the S-methyl isomer of fenitrothion and its desmethyl derivative, fenitroxon and the corresponding desmethyl derivative, 3-hydroxymethyl-4-nitrophenol and corresponding nitro-benzenes. Of the 5% of total radioactivity not extracted from aged samples after 12 months storage, they recovered a little more than half by digesting with amylase, and this digested fraction contained 0.1%, 1.5%, 0.3%, and 0.6% of the applied radioactivity as fenitrothion, 3-methyl-4-nitrophenol, fenitroxon, and desmethyl fenitrothion, respectively; a painstaking and thorough piece of work.

In their concurrent study of malathion metabolism in rice grains, the same workers found, most interestingly, that a major metabolic product was desmethyl malathion. This had not been reported previously in studies of malathion degradation by grains. The carboxyester-hydrolysis products (malathion mono- and di-acids) usually reported were found to be relatively minor metabolites. After 12 months of storage, a major portion (47%) of the applied radioactivity was not extractable by solvents. One-third to one-half of this 'bound' portion was released by amylase digestion, but no recognisable metabolites of malathion could be identified. This is indeed interesting. Various other researchers (Rowlands 1975; Anderegg and Madisen 1983b) have determined the 'bound' portion from aged cereal grains (though at shorter time intervals after treatment) to be of the order 10% of the original dose. Attempts at bioassay of such bound fractions with insects have not so far shown any direct toxicity (Rowlands 1970; Anderegg and Madisen 1983b).

In a series of recent papers, Anderegg and Madisen (1983a, b, c) and Anderegg (1984) investigated the breakdown of ^{14}C-malathion in maize and (chiefly) in wheat, taking into account several different factors and storage practices, such as the presence of fungi (1983a), a quantity of dockage, i.e. chaff, dust, etc. (1983c), and also deliberately uneven dosing (1983b).

They demonstrated that storage fungi could be partially responsible for the accelerated degradation of malathion in stored grains at high temperatures and moisture levels. This may be an important factor to consider under tropical conditions. Wheat and maize inoculated with *Aspergillus glaucus* contained significantly less intact malathion than sterilised controls (in which the activity of grain enzymes per se was unimpaired), although the sterilised grains nonetheless metabolised malathion quite extensively. The major products found were the monocarboxylic acid and two unidentified compounds. Recoveries of radiocarbon were low from inoculated samples and this may have been due to loss of volatiles or $^{14}CO_2$.

They were able to show (1983b) that there was no significant difference in either the extent of the nature of malathion degradation in wheat when the same total dose was applied to either 5% only or to 100% of the grains in the experimental bulk. Most interestingly, they made provision for trapping of volatiles, recording greater amounts of volatile radiocarbon after 6 months than after 1 month or 12 months storage. They suggested that some of the volatiles may have been resorbed by the grain (as was the case in Adams' experiment with chlorpyrifos-methyl). No $^{14}CO_2$ was recovered at 1, 6, or 12 months after treatment. They also attempted to bioassay wheat containing 'bound' residues remaining after solvent extraction, and although the mortality of flour beetles used as test insects was not affected by the presence of unextractable residues, beetles developed more slowly in wheat containing bound residues.

A third paper (1983c) suggested that in wheat containing dockage, the total quantity of ^{14}C-malathion recovered from the dockage fraction increased significantly both as the ratio of dockage to whole grain increased and with increasing storage time. The large quantity of ^{14}C activity not recovered from the dockage by solvent extraction may indicate that more rapid degradation takes place than in the whole grain. Recovery of ^{14}C volatiles decreased with increase in the proportion of dockage present. Malathion monoacid and an unknown compound were the major degradation products formed, the unknown predominating in the dockage fractions; no $^{14}CO_2$ was recovered from any of the experiments.

Other Compounds

Little use is made of organochlorine pesticides in grain storage practice today and there have been no recent metabolic studies in storage situations.

Few carbamates have proven useful for storage pest control in the past, and the one that has — carbaryl — has been largely displaced by the synthetic pyrethroids for controlling *Rhyzopertha.*

A carbamate insect juvenile hormone analogue — fenoxycarb, ethyl [(p-phenoxy)ethyl] carbamate — shows considerable potential, however. It is fully effective against *Sitophilus* spp. (which develop within the kernel and have proven difficult to control with other hormone analogues) and there was no loss of biological activity in wheat at 5 ppm even after storage at 25°C and 70% RH for 12 months (Edwards and Short 1984). Residue and metabolic studies on this compound will be of considerable interest.

Conclusion

This paper has examined a number of aspects of laboratory studies on the uptake, translocation, and metabolism of contact insecticides in stored cereals, and how they may be relevant to the 'real' situation of storage practice. In concluding, it is worth re-emphasising four topics on which more detailed study is required:

(1) the vapour-phase action, distribution, and losses of contact insecticides and their metabolites;

(2) the nature of the residues that are not extractable by conventional solvent blending from aged cereal grains, some months after initial treatment;

(3) comparative studies between cereal types and varieties; and

(4) comparative studies between laboratory and tonne-scale treatments.

Acknowledgments

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Behaviour of Pesticide Residues on Stored Grain

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Abstract

The distribution and breakdown of grain protectants are processes that conform to laws of physical chemistry which provide models of general applicability. At an operational level, these models enable existing usage to be optimised: for example, application rates can be tailored to storage conditions. They also facilitate research into the ideal protectant — one which protects but leaves no residues. This paper describes three approaches to the ideal that follow from chemical behaviour: the kinetic, the chromatographic, and the partitioning. High thermal dependence of stability is sought in the kinetic approach, so that a chemical will be stable during storage but destroyed by cooking. Methacrifos, whose half-life is halved for every 5°C rise in temperature, approaches this ideal. In the chromatographic approach, the removal, and often the introduction, of a chemical is controlled by air movement. Examples range from phosphine, where natural air flows must be minimised, to dichlorvos, which requires high flows of forced air. In the partitioning approach, protectants are applied in carriers which retain most of the chemical, thereby enabling physical removal of the protectant with the carrier. Fenitrothion, applied in 'dusts' such as Steecoben or Steecomull, exemplifies this approach. These dusts give longer protection than conventional spray treatments, and more than 90% of residues are removed during cleaning.

POSSIBILITIES for use of chemicals on stored grain have two basic constraints: inherent restraints on the behaviour of chemicals, as described in well established laws and restraints from the system such as those imposed by the structure of grain kernels.

If these restraints are taken as the only restraints for research, the possibilities for steady improvements and for breakthroughs in the use of chemicals become apparent, and I will illustrate this point with examples.

Apart from restraints on the possibility of chemical use, there are economic and social restraints on the feasibility of use. While this aspect of feasibility is not the subject of this talk, I note that possibilities become more feasible when practical benefits are demonstrated.

One type of restraint that I refuse to consider is that imposed on chemical behaviour by general statements, often found in the literature, which are not derived from well-established theory. My attitude is entirely justified on the *a priori* grounds of not accepting limitations without proof. It is also justified *a posteriori* from a perusal of statements such as 'there are no alternative fumigants to existing ones' or 'wheat is a chromatography column,' which are made, and repeated, without spelling out the very limited range of conditions within which they are true.

I will concentrate on three areas of chemical theory, namely thermal effects on degradation, (equilibrium) partition coefficients, and non-equilibrium partitioning. These processes, if not their names, are well-known to all of you. They are used in many aspects of life, from preparing food to cleaning paint brushes, and they are already utilised in stored products. I wish to show how these familiar processes, if considered only from the basic considerations of chemical laws and the grain system, can be exploited to give chemical usage that approximates the ideal in stored products, the ideal being indefinite protection for as long as the grain remains in storage and no residues in food.

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Thermal Effects

I have shown (Desmarchelier 1978a; Desmarchelier and Bengston 1979; Desmarchelier et al. 1980a) that protectants degrade on stored grain in a predictable manner that is governed only by storage temperature and grain equilibrium relative humidity (RH). I refer you to those papers to see how application rates can be calculated from quantitative models. I wish to extend these models to losses during cooking, with the aid of two concepts. These are the half-life, $t_{1/2}$, or time for any value to degrade by 50%, and the temperature lability, or rise in temperature that halves the half-life. This temperature lability differs between protectants; for example, it is 5°C for methacrifos and 8°C for fenitrothion (this is an approximation only, and for extrapolation over a wide temperature range one should plot log $t_{1/2}$ against reciprocal Kelvins, as I have done to collate the data in Table 1) (Desmarchelier and Bengston 1979).

Grain protectants decay according to the form of the Arrhenius equation, as do many chemicals. What separates stored grain from other chemical systems is not this kinetic model, but the range of temperatures of interest to stored products. This is the range 10–40°C during storage, and 100–230°C during cooking and baking.

Integrating these basic stored product data with the standard chemical theory, it is a straightforward exercise to demonstrate that chemical lability is the desired property to render a protectant stable during storage but degradable during processing. I have illustrated this in Table 1 for three chemicals. Two of these, A and B, have different thermal labilities of 5 and 8°C, but each has a half-life of 32 weeks at 20°C. It can be seen that A, and to a lesser extent B, become insufficiently stable as storage temperatures increase to 30–40°C. However, A is extensively degraded during cooking of rice, as the half-life at 100°C (10 min) is much less than the cooking time. Compound B, however, will not be extensively degraded, as the half-life of 200 min exceeds most cooking times. Compound A will be 'completely' degraded during baking of bread, whereas compound B will be only partly degraded (Table 1).

While the data in Table 1 are theoretical illustrations, data for compounds A and B correspond to experimental data for methacrifos and fenitrothion respectively, at least according the semi-quantitative description of the preceding paragraph (Desmarchelier and Bengston 1979; Desmarchelier et al. 1980a, b).

To date, there are quantitative models for twelve protectants (Desmarchelier and Bengston 1979), but only for low relative humidity (< 60%). These models are useful in planning application rates for protectants in use, and for planning future strategies. One such, for Australian conditions, is to use methacrifos, a chemical 'entirely' degraded during processing, but to make it stable by cooling grain with ambient air to about 20°C as soon after application as is possible.

The analysis of the kinetic data points to the possibility of chemicals like chemical C (Table 1), which is stable at 30 but not 100°C. Such theoretical evaluations may cause chemical companies to reassess some thermally labile compounds, which I believe are rarely patented because they are seen to have no place in agriculture.

There are, however, other kinetic approaches to the ideal protectant. It should be possible, for example, to use a formulation that renders labile chemicals stable at storage, but not processing, temperatures. The unstable dichlorvos (Minett and Belcher 1970) is rendered stable by impregnation in strips (Gueckel et al. 1974) or application to wheat in oil (Desmarchelier et al. 1977). However, no one has attempted to seek formulations that confer stability on labile chemicals below 40°C, but not at cooking or baking temperatures. Thermally labile formulations that

Table 1. Theoretical effects of thermal lability on half life ($t_{1/2}$).

Compound	Thermal lability[a] (°C)	Half-life 20°	30° (weeks)	40°	100° (minutes)	230°
A	5	32	8	2	10	≪1
B	8	32	14	6	200	9
C	4.5	100	20	4	10	≪1

[a] Temperature rise required to halve the half-life.

melt between 40 and 100°C would be one possibility.

In summary, the analysis of thermal lability has brought improvements in usage of existing approved protectants, pointed to a feasible way of making the emerging protectant methacrifos close to an ideal protectant, and illustrated the untapped research idea of thermally labile formulations.

Equilibrium Partitioning

A partition coefficient is the ratio, at equilibrium, of the concentration of one chemical (e.g. paint) in one phase (e.g. turps) to that in another phase (e.g. a paint brush).

Partition coefficients can be used to describe the distribution of a protectant in grain into what become milling fractions. In one experiment, methacrifos was applied to wheat starch, which was mixed, at intervals after application, with wheat bran. Treated bran was also mixed with starch. In each experiment the ratio of residue levels in bran to starch approached the same (equilibrium) value of 24. Partition coefficients for the systems are given in Table 2.

Table 2. Ratio of methacrifos in bran to starch 1 and 7 days after mixing these commodities one of which contained aged insecticidal deposits.

Treated commodity	Age of deposit (days)	Ratios of residues, bran to starch, after admixture for 1 day	7 days
Bran	1/24	24	24
	1	26	24
	7	27	25
Starch	1/24	23	24
	1	21	24
	7	19	23

The ratio of distribution of methacrifos in fractions such as bran and starch is of the same order as that found in milling studies, namely wheat bran > gluten flour > starch and rice bran > hulls >flour. Such partitioning results in distributions that may be favourable, if the end product is white rice, for example, or unfavourable, if it is unprocessed bran, for example.

A further partitioning process is that between water and water insoluble grain residues, which are mainly protein. Although partition coefficients have not been determined, very little of the several protectants investigated is found in the aqueous phase, namely starch, from wheat flour, or wort from malt.

Partition coefficients are therefore an excellent method of reducing residues during some processes including the milling of paddy to polished rice and the extraction of wort for brewing.

The partition coefficients determined on grain fractions have values very much lower than values in excess of 100 000 observed in many chemical systems. This leads to the question 'what would happen if materials with high partition coefficient for protectants, relative to grain, were introduced into a grain mass?' This has been achieved in my laboratory by mixing wheat with fenitrothion in certain dusts, such as Steecomul or Steecoben, with partition coefficients of more than 90 000. Over a 62-week period, there was little net migration of fenitrothion from the dusts into the wheat. In parallel experiments, however, fenitrothion applied as a spray to wheat migrated into the dust.

One result of this partitioning was that removal of dusts with high partition coefficients also removed the impregnated fenitrothion. A further result was that fenitrothion, applied in such dusts, was much more effective against the test insect *Tribolium castaneum* (Herbst) than it was when applied as a spray or in dusts with low partition coefficients, such as talc or pyrophyllite. The time for 28-day mortality to decay to 99.9% was calculated (Desmarchelier 1978b) as 2 weeks from 4 mg/kg fenitrothion applied as a spray, but in excess of 66 weeks for 4 mg/kg fenitrothion applied in dusts with partition coefficients in excess of 50 000 (Halloysite, Steecomull, Steecoben, bentonite, Nuclo H).

This system of admixture of protectants in pesticide-retaining dusts combined existing milling and cleaning technology, which removes dusts, and a straightforward chemical theory of partitioning. Complete optimisation of the system requires studies on the effect of different carriers, of amounts of carriers, of particle size, of protectant, and of partitioning from carriers into insects. The potential of such systems is enormous when it is appreciated that an insect comes into more contact with adhering carriers than with grain, and the concentration in such carriers can remain at least 90 000 times those in the grain, the vast majority of which is locked in the aleurone layer, out of contact with insects.

While the theoretical benefits have not been fully exploited, I have demonstrated several systems where fenitrothion, applied at 4 mg/kg, gives more than 66 weeks protection against *T. castaneum* and leaves residues in clean wheat, before milling, of less than 0.2 mg/kg. This is a significant step towards the ideal protectant.

Non-Equilibrium Partitioning

As I pointed out in the previous section, it takes time, and sometimes a considerable amount of time, to attain equilibrium. Indeed, rapid equilibrium partitioning, which is the ideal in gas-liquid chromatography (glc) (Ponec et al. 1974; Giddings 1967) is difficult to obtain.

Are there any circumstances when it would be to our advantage to delay equilibrium in partitioning? Such delays would be of advantage if we wished to move a chemical, whether liquid, solid, or vapour, through a grain mass, with forced air flow, and avoid equilibrium processes of sorption.

I will first demonstrate that this can be readily achieved, and then develop the theory. Air at 68% RH was blown at different speeds through wheat in a column (height 8 cm, diameter 3 cm) in equilibrium with 58% RH and the eluate RH was measured. This ranged from 58% at low air speeds of 100 ml/min, to 68% at high air speeds of 1400 ml/min, although the grain equilibrium RH remained below 59% throughout the experiment. Thus, the equilibrium process of sorption was completely prevented, within experimental error, by high airflow rates. The implications of this simple experiment are first, that movement of chemicals in the vapour phase and their sorption are not limited by equilibrium processes, and second, that wheat need not be a chromatography column, in the sense understood by chromatographers of rapid equilibrium partitioning (Ponec et al. 1974).

I would like to develop briefly and non-mathematically the theory of non-equilibrium partitioning. This theory has been studied in adsorption studies and glc, but mainly from the view of preventing, not promoting it. The theory, however, is based on typical studies on vapour-solid interactions, such as the Langmuir adsorption process. There are many variations in derivation of such theories, and even more diversity in terminology, but the theories can be described in terms of average movement times. These are: the time to move from air to surface (ta) and back again (ts), and the time to move from the surface into a strongly sorbed site (ti) or back again (tf). These times generate corresponding — but not necessarily equilibrium — values of concentrations in air (Ca), on the surface (Cs), and in sorbed sites (Css).

Non-equilibrium partitioning will assist the movement of low volatility chemicals through grains if it either increases ta or reduces the ratio ts/tss. Processes such as eddy currents, that prevent vapour from contacting solids, increase ta (Ponec et al. 1974). Because rate of vapour loss from a surface is proportional to surface area, and not amount (Gueckel et al. 1973; Spencer et al. 1973), 'overloading' a system by causing more than one surface layer increases ts. This will also increase the ratio Cs/Css, which controls sorption. That is, the longer a molecule occupies a surface site, the greater the chance of it moving into grain. Gilby (1983) noted that commercial concentrations of halogenated fumigants, including methyl bromide, 'overloaded' a column of wheat connected to a glc.

The ratio Cs/Css can, however, be reduced to a process well known to increase rate of surface volatisation, namely airflow (Gueckel et al. 1973; Spencer et al. 1973).

Non-equilibrium partitioning from high airflows will have two effects not found in glc. First, it will increase the proportion of applied chemical in the vapour phase (principally because of reducing sorption but also through increasing ta). Second, the time for a defined concentration to be reached at a defined distance from the inlet will not be linearly related to flow rate, as in (isothermal) ideal glc, but will be less than expected from a linear relationship.

Each of these effects has been demonstrated for dichlorvos (Desmarchelier et al. 1977). Indeed, the time to reach a certain concentration decreased exponentially with flow rate, over the range 18–150 L/s m^2. Non-ideal partitioning explains why lethal concentrations of dichlorvos vapour were achieved 4 m from the inlet in a large storage, at relatively low flow rates.

One area where non-equilibrium partitioning could become important is in moving relatively non-volatile selective toxicants, such as dichlorvos, through grain. It could, however, be especially important for physical toxicants according to the theory that median lethal doses are inversely proportional to the volatility, as determined from the saturated vapour pressure.

Ferguson and Pirie (1948) have demonstrated such effects for a range of chemicals, including simple hydrocarbons, against *Sitophilus granarius*. The median lethal doses of physical toxicants such as n-decane or 2-xylene are lower, in fact, than those for liquid fumigants such as ethylene dichloride, methyl chloroform, or carbon disulphide. Recent work on camphor as a highly effective fumigant (Abivardi and Benz 1984) indicates another physical toxicant possibly suitable for non-equilibrium partitioning, but the list of candidates is indefinitely large.

There are some aspects of non-equilibrium partitioning which require comment. First, airflow rates could enhance the toxicity of vapours to insects, as Galley (1967) has demonstrated for nicotine and dichlorvos. Second, the initially high toxicities of freshly applied grain protectants have been explained as due to non-equilibrium vapour and surface concentrations, (Desmarchelier 1978b) and may be regarded as examples of non-equilibrium partitioning. Third, all uses of methyl bromide as a fumigant illustrate non-equilibrium partitioning, as the equilibrium concentration of this labile chemical is effectively zero.

Although my analysis of non-equilibrium partitioning is not entirely novel, it does illustrate that the potential of this method has not been sufficiently studied, much less exploited. The crux of this analysis is that stored products are in many aspects essentially the opposite of adsorption and glc, though understandable in terms of the same theories. In stored products, we can vary the inlet chemical, whereas one has to adsorb or analyse a particular chemical in the other disciplines. On the other hand, chromatographers and 'adsorbers' can vary the solid phase, whereas we cannot. Above all, our aim is to prevent equilibrium, and this is the opposite of the aim in adsorption or glc.

I will conclude this section with some comments on slow-release formulations. These can be regarded as non-equilibrium partitioning, because the ratio of chemical in the vapour to the solid phase is not that attained at equilibrium, but that governed by the rate of release. Such slow release formulations could be applied to grain in a variety of ways, including layers or admixture, and volatile or unstable chemicals could be made persistent.

Integrated Control

The types of manipulation used to alter chemical behaviour, such as cooling, drying, partitioning chemicals into microgranules and using airflows, also affect insects in a variety of ways. Some or all of these manipulations affect the reproductive biology of insects. They also affect insect behaviour, such as movement, and they affect the toxicology of insects to a given dose of insecticide.

Integrated control aims at utilising the combined effects, chemical, reproductive, behavioural, and toxicological, of a manipulation, such as cooling, on an insect population. Some examples of integrated control are outlined in this seminar. They include Dr Bengston's work on the effect of moisture and my comments on hygiene. Integrated effects of cooling have been discussed theoretically (Desmarchelier et al. 1979) and some results in an extensive program have been published (Longstaff and Desmarchelier 1983).

I would like to make some comments on how the chemical effects of partitioning microgranules and high airflows could be enhanced by studies on behaviour and toxicology. To be effective, partitioning microgranules must not only partition an insecticide from the wheat but partition it into the insect. David and Gardiner (1950) reported that insects pick up appropriately-sized microgranules from grain or surfaces, and use mouth parts to preen themselves. There is obviously scope for enormous improvements in studying these processes.

Integrated control is already well established in stored products, but there is room for enormous improvement in both the research side, of providing data, and on the practical side, of implementing existing knowledge. Sometimes serendipity can play a part in integrated control, that is one can realise that the peculiar circumstances happen to be appropriate for a given program. For example, the ability to cool grain with ambient air to about 20°C soon after receival is a 'happy accident' of climates which have a few cool hours in a 24-hour period, but is ideal for methacrifos in two ways. First, it renders methacrifos stable during storage and second, it prevents development of the Coleoptera species most tolerant to methacrifos, namely *Rhyzopertha dominica* .

Integration of non equilibrium partitioning with on-floor drying could be another example of serendipity because on-floor drying already incorporates desirable features such as high airflow rates, relatively shallow grain depths and, generally, relatively high temperatures. That is, processes designed to move one chemical, water, through and out of bulk grain can also be used for other chemicals.

Conclusion

I have combined two basic parameters, namely established chemical theories and basic properties of storage systems, and derived three approaches to ideal protectants, each of which has been demonstrated to be effective, at least in laboratory studies. None of these approaches is entirely new, and indeed one would hardly expect to derive something entirely new from basic chemical theories that are taught in high schools. Despite this, the quantitative measurement of thermal effects, or partition coefficients of dusts in grain, or non-equilibrium partitioning are new to this paper or to cited articles over the last few years.

I believe the 'novel' aspect of these approaches, and the most important point here, is the use of established theory to exploit the potential of chemical usage, with the concomitant refusal to accept inadequately justified statements that attempt to limit the behaviour of chemicals. Such a 'philosophical' approach has been recently well advocated by Gieren (1985) in an article entitled 'Analytical Thinking for Chemists — Necessity or Luxury?'.

If this approach is more widely adopted we will move much more quickly toward the goal of ideal chemicals, and very possibly by processes other than those I have outlined.

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Biological Efficacy of Residual Pesticides in Stored Grain at High Humidities and Moisture Contents

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Abstract

The effects of extrinsic factors, particularly moisture, on the biological efficacy of residual pesticides, are reviewed. As far as possible, effects on chemical decay of the applied deposits are distinguished from effects on efficacy of the residue. Effects on efficacy are grouped as reflecting availability of residues for pick-up by insects, differences in pick-up for reasons other than availability, and insect responsiveness after pick-up. Insect responsiveness is little affected by humidity. Its relationship with temperature, described by temperature coefficients, varies with the insecticide.

With admixture treatments, efficacy is, within limits, little affected by distribution of the insecticide in the grain mass. Efficacy is reduced on smaller grains because of their greater surface to volume ratio and perhaps because insect movement is restricted. Availability of actual residues declines during storage, and is reduced irreversibly at high moisture contents. Residues on fabrics also lose their efficacy over time, particularly on sorptive surfaces. The effect is lessened if insecticides are applied in wettable powder form. The availability of sorbed residues on hydrophilic substrates may be reversibly increased at higher humidities. Pick-up of insecticide is enhanced at higher temperatures because of increased availability and insect activity, but whether this is reflected in insect mortality depends on the temperature coefficient of the insecticide.

The relevance of basic studies to practical usage of residual pesticides is discussed, as are possible topics for future research.

RESIDUAL pesticides are those compounds which leave a residue that is able to affect pests for a significant period after application. Thus, they are distinguished from fumigants, which have a very short residual life unless special sealing of the enclosure is undertaken. Residual pesticides for pest control in grain storage are applied to surfaces: to the grain directly, i.e. by admixture, to bag surfaces if grain is stored in bag stacks, or to the fabric of the store.

The terminology to be used in this review must be defined at the outset:

- a stated concentration of a residual pesticide may refer to the nominal rate at the time of application, the *applied residue*, or to the concentration as measured by chemical assay, the *actual residue*;
- the ability of an applied residue to affect pests will be referred to as *biological activity*. Biological activity is measured by biological assay, usually by confining test animals in the treated grain or on the treated surface for a particular length of time (= exposure period) and then assessing their response;
- the ability of an applied residue to maintain biological activity over time will be referred to as *biological persistence*. Biological persistence is measured by a series of biological assays at different times after the pesticide is applied;
- the biological activity of actual residues will be referred to as *biological efficacy*. Therefore, biological persistence will depend on, first, changes in the actual residue present, and second, changes in biological efficacy.

The aim of this review is to determine what factors influence biological efficacy of residual pesticides, and insecticides in particular, and how they operate. Intrinsic factors — the relative toxicity of different insecticides or the relative susceptibility of different insect species or strains — will not be discussed. Rather, I wish to assess the importance of extrinsic factors. Particular

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attention will be given to the effect of moisture level, as this is a major difference between grain storage conditions in the humid tropics and in more temperate areas.

The insecticidal action of residues can be considered as having two components: first, response of insects to given doses of insecticide; and second, pick-up of insecticide from the treated substrate. The second of these is dependent on the nature of the substrate to which the insecticide is applied. Therefore, I will discuss biological efficacy under several headings: (i) insect responsiveness, with particular reference to the effects of humidity and temperature; (ii) the efficacy of insecticides admixed with grain; and (iii) the efficacy of insecticides applied to surfaces, i.e. bag and storage fabric treatments.

Insect Responsiveness — Effects of Humidity and Temperature During the Post-Treatment Period

Measurement of the effect of either humidity or temperature on insect responsiveness requires that test insects initially receive a standard dose of insecticide. This criterion is not fulfilled by studies in which insects are allowed to 'dose themselves' under different conditions, such as when they are continuously exposed to treated surfaces at different humidities or temperatures (= continuous dosing). Responsiveness can be measured by exposing insects to insecticide deposits, but only if they are exposed under a single condition of humidity and temperature and then transferred to the different experimental conditions. However, this procedure has the disadvantage that the exposure time may occupy a significant proportion of the time required for reaction to the insecticide, so insects may react before they reach the experimental regimes. Therefore, topical application is the best procedure for applying a standard dose of insecticide 'instantaneously.'

Experiments in which humidity was varied during the post-treatment period only have produced conflicting results. Pradhan (1949) found that toxicity of DDT to *Tribolium castaneum* increased with higher relative humidity in the range 0–84% RH. Hadaway and Barlow (1957), however, found that relative humidity in the range 20–95% RH had no effect on the toxicity of several chemicals, including DDT, to mosquitoes and houseflies, and a similar lack of effect of post-treatment humidity was found by Crauford-Benson (1938) and Elmosa and King (1964). Several other papers have suggested increased toxicity of some chemicals at lower relative humidity (e.g. Harries et al. 1945; Sales 1979; Reichenbach and Collins 1984), but the effects seem to have been slight; e.g., the increase in toxicity of propoxur to German cockroaches reported by Reichenbach and Collins was only ×1.6 times at 20% RH compared with 100% RH.

The procedures for measuring effects of post-treatment humidity include sources of error. It is sometimes difficult to establish different humidity regimes quickly after dosing, because the chambers in which such experiments are usually performed, e.g. desiccators, may take a significant time to return to the desired humidity after opening. Also, the method of applying a known topical dose is not foolproof, as a considerable proportion of the applied dose can be lost from the insect before it is absorbed through the cuticle; e.g. Matthews (1980) found that 30–40% of a topical dose of malathion dissolved in cyclo-hexanone was lost from *Rhyzopertha dominica* onto a filter paper substrate within 3 hours of application. This proportion might well vary depending upon post-treatment

Table 1. Effect of post-treatment relative humidity on the response of *Tribolium castaneum* to fenitrothion applied topically in cyclohexanone, when held after treatment by three different procedures (response assessed as knock-down 5 days after treatment) (Source: Samson and Keating, unpublished data).

Effect of relative humidity	Post-treatment holding conditions		
	In conditioned grain in desiccators	Without grain in desiccators	Without grain in conditioned airstream, then CE room
Relative potency 90% vs 35% RH[a]	0.50	1.19	1.11
95% confidence interval	0.35–0.66	0.96–1.48	0.90–1.38

a. Relative humidity

humidity (or temperature).

We have done some experiments to measure the effect of humidity on the response of *Tribolium castaneum* to fenitrothion applied topically in cyclohexanone (Table 1). Three different post-treatment holding procedures were tried: (i) treated insects were placed in maize conditioned to 9 or 20% moisture content (MC) in desiccators containing appropriate salt solutions to give either low or high relative humidity, (ii) treated insects were placed into the desiccators without grain but with a paper foothold, and (iii) treated insects were placed into holding jars conditioned to appropriate relative humidities by forced ventilation, and later transferred to appropriate relative humidities in controlled environment rooms.

Toxicity was reduced at the higher humidity when treated insects were held in grain. However, a residue of fenitrothion was found in the grain after the insects were removed, suggesting some of the applied dose had rubbed off. Lack of effect of humidity using method (ii), placement of treated insects in desiccators, could have been due to delay in achieving the required relative humidities each time the desiccators were opened. No such proviso could be applied to method (iii), however, as the treated insects were exposed to the desired relative humidities immediately after treatment, but again there was no effect of humidity. We suspect that the apparent effect of humidity on the toxicity of fenitrothion to insects held in grain was due to greater loss of insecticide from insects held in the moister grain, although it should be noted that a residue of fenitrothion was also found in jars in which treated insects were held without grain in method (iii).

Thus, we were not able to produce unequivocal evidence of an effect of humidity on insect responsiveness. A probable explanation for the conflicting results of studies cited earlier is that the effect of humidity on toxicity is slight, and the investigatory procedures used contain considerable experimental error. With reference to the effect of moisture or humidity on biological efficacy as discussed in later sections, I would agree with the conclusion of Hadaway and Barlow (1957), that 'atmospheric humidity may affect the insecticide and its availability rather than (the insects)'.

Temperature during the post-treatment period appears to have a greater effect on insect response than does humidity. No attempt will be made to review the extensive literature concerning effects of temperature on insecticidal action, although it should be noted that many studies, by using a continuous dosing procedure at different temperatures, confound the effects of temperature on pick-up and response. There is unlikely to be a simple relationship between post-treatment temperature and insect responsiveness, as there are several component processes leading up to toxic action: penetration of insecticide through the cuticle, metabolism (toxification or detoxification), storage or excretion, penetration to the target site of toxic action, attack upon the target, and consequent insect mortality or recovery (O'Brien 1967). Each of these may have its own relationship to temperature (Busvine 1971), and the relative importance of each in determining the overall temperature-toxicity relationship may depend on the insecticide, the species of insect, and even the resistance status of particular strains of a given species (see, e.g. deVries and Georghiou, 1979; Scott and Georghiou 1984). Also, the apparent relationship between temperature and toxicity may vary depending on the time when insect response is assessed: whether at an arbitrary time after dosing or after end-point mortalities are reached (Das and McIntosh 1961).

With the above points in mind, the following generalisations can be made. Organophosphorus insecticides seem to have a positive temperature coefficient during the post-treatment period, i.e. toxicity is greater when insects are held at higher temperatures after dosing (see, e.g. Rai et al. 1956; Hadaway and Barlow 1957; Norment and Chambers 1970). DDT, pyrethrins, and the synthetic pyrethroids usually have negative temperature coefficients (see, e.g. Hadaway and Barlow 1957; Harris and Kinoshita 1977; Harris et al.1978; de Vries and Georghiou 1979; Sparks et al. 1983; Scott and Georghiou 1984). Inconsistent effects of temperature on toxicity have been observed for lindane (e.g. Hadaway and Barlow 1957; Busvine 1971; de Vries and Georghiou 1979) and carbamates such as carbaryl and propoxur (Busvine 1971; Harris and Kinoshita 1977; Reichenbach and Collins 1984).

Biological Efficacy of Admixture Treatments

The Meaning of Biological Efficacy of Admixed Insecticides

Residual pesticides admixed with grain to protect against insect infestations are frequently called 'grain protectants.' Admixed residues become part of the stored grain environment, and pest infestations can develop only if all the steps involved in reproduction — adult mating, oviposition, immature development, adult emergence, and survival to reproductive age — are able to proceed successfully in this contaminated environment. Therefore, the biological efficacy of protectants should be assessed as their ability to prevent the production of subsequent generations, usually F_1 and F_2 progeny (see, e.g. Champ et al. 1969).

However, many basic studies concerning factors influencing biological efficacy use a biological assay that measures mortality of the original test insects only. It is conceivable that conclusions reached from results of such an assay might not apply if effects on reproduction were considered. This is discussed further in the section on changes in biological efficacy during storage.

Biological Efficacy of Fresh Residues At a Single Moisture Content and Temperature

Immediately a grain protectant is applied, the initial deposit will presumably be present on the outside of individual grains. This insecticide can either be physically picked up by free-living insects moving through the grain mass, or it can be absorbed by insects as a vapour. The relative importance of these two components in killing insects will depend on the volatility of the insecticide and its vapour toxicity. The synthetic pyrethroid insecticides and many of the organophosphorus insecticides have low volatility and act as contact poisons. However, several of the organophosphates such as methacriphos and particularly dichlorvos have a fumigant action (Desmarchelier et al. 1977; Wegecsanyi and Rosenbaum 1984).

Deposits of admixed insecticides are frequently distributed very unevenly between individual grains (Tyler et al. 1969; Hargreaves et al. 1982). Tyler et al. (1969) measured the distribution of malathion amongst individual wheat grains following treatment on a conveyor at the rate of 1 litre of emulsion per tonne of grain, to give a nominal overall concentration of 10 mg/kg. The resulting concentration of malathion immediately after treatment ranged from <0.1 to 424 mg/kg in the 524 grains sampled. The effect of uneven distribution of insecticide on biological activity was investigated by Minett and Williams (1971). Grains of wheat treated uniformly with different concentrations of technical grade malathion in ethanol were mixed with untreated grains in different ratios to give the same overall concentration of insecticide, and activity was then bioassayed. Results of one such bioassay are given in Table 2. A non-uniform distribution of residues did not reduce biological activity provided at least 1–2% of grains were treated (see also Tyler et al. 1969).

Random movement of insects through the grain presumably results in the pick-up of contact insecticides being independent of insecticide distribution within certain limits, i.e. as the proportion of grain treated decreases in Table 2, the number of grains likely to be encountered by an insect during a given period decreases, but the amount of insecticide picked up at each encounter increases. The limits within which insecticide distribution can vary without disadvantaging efficacy may depend on the mobility of the target insects, and so depend on the test species, its stage of development, and on other factors affecting behaviour such as temperature and population density (J.M. Desmarchelier, personal communication). In the case of insecticides with a significant vapour action, the concentration of vapour in the intergranular spaces will probably be little affected by the distribution of insecticide deposits, and in addition such insecticides may rapidly redistribute within the grain mass (Rowlands and Bramhall 1977).

The biological activity of initial deposits of contact insecticides varies depending on the grain

Table 2. Effect of the distribution of malathion in wheat on the biological activity of an overall concentration of 10 mg/kg against *Sitophilus oryzae* (Source: Minett and Williams 1971).

Length of exposure period (D)	% Insects affected when following % of grain treated						
	0(Control)	0.1	0.2	1	2	10	100
1	0.0	13.9	52.0	88.3	93.2	99.0	99.5
7	0.3	61.0	100.0	100.0	100.0	100.0	100.0

Table 3. Relative potencies of three insecticides on sorghum compared with wheat, measured by exposure of test insects to the treated grain for 3 days at 25°C, 70% RH (Source: Bengston et al. 1983).

Insecticide	Test species	Relative potency (95% confidence interval)
Bioresmethrin	*Rhyzopertha dominica*	0.27(0.25–0.30)
Carbaryl	*R. dominica*	0.54(0.42–0.69)
Fenitrothion	*Sitophilus oryzae*	0.45(0.39–0.50)

species to which they are applied. For example, Bengston et al. (1983) reported lower potency of three grain protectants on sorghum compared with wheat (see Table 3) and Weaving (1975) reported much lower potency of five insecticides on sorghum compared with maize (see also Kadoum and La Hue 1974). These effects are probably due in part to differences in the surface area to weight ratio of grains of different species. Godavari Bai et al. (1964) applied malathion to particles of wheat, rice, and sorghum ground to different sizes, and to steel ball bearings of different diameters, and found that mortality of test insects declined as particle size decreased. The smaller particles had a greater ratio of surface area to weight, and so on such particles an insecticide deposit of a given concentration per unit of substrate weight actually represented a lower concentration per unit of substrate area. Therefore, insects would be expected to pick up less insecticide as they moved between smaller particles. Weaving (1975) added two interesting observations. His test insects (*Sitophilus zeamais*) appeared to move less freely through sorghum than through maize because of the closer packing of the individual grains, and if grains of sorghum and maize treated with fenitrothion were bioassayed in single layers rather than in bulk, the difference in biological activity on the two grains was reduced. He interpreted this as meaning that, on sorghum, the actual concentration per unit of surface of a given rate of insecticide was lower than on maize, because of the greater surface area to volume ratio of the former grain, but in addition, insects moved a lesser distance through sorghum during a given exposure time and so picked up insecticide at a reduced rate. However, Weaving admitted that his results concerning insect movement through grain were only preliminary, and required confirmation.

In the case of residual pesticides having significant fumigant action, it will be concenration of vapour in the intergranular spaces rather than concentration of deposit on the grain surface that will determine biological activity. The effect of grain species on the activity of such insecticides is not known.

Changes in Biological Efficacy During Storage

Early work on the use of organophosphorus compounds as grain protectants showed that biological activity declined with time (Lindgren et al. 1954; Strong and Sbur 1960). This was attributed to a combination of two factors: (i) chemical decay of the insecticide deposit, and (ii) a decrease in availability of the remaining deposit to insects (Kane and Green 1968; Champ et al. 1969). However, the relative contributions of these two factors towards the decline in biological activity could not be determined. The first measurement of changes in availability over time was reported by Desmarchelier (1978), who correlated results of biological and chemical assays to describe changes in the biological activity of actual residues, i.e. biological efficacy, over time.

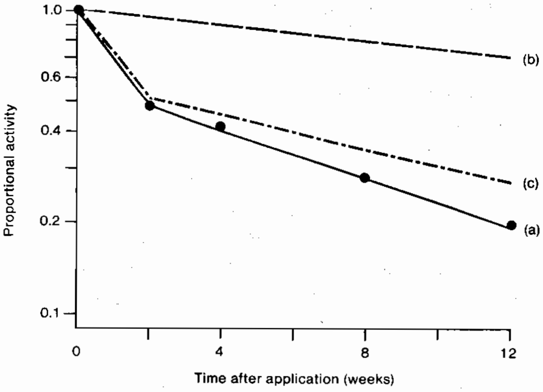

Fig. 1. Biological and chemical persistence of chlorpyrifos-methyl on wheat of 11% MC at 25°C, expressed as activity on each occasion relative to that at time 0 (activity = 1.0): (a) biological activity of applied residue, by bioassay with *Tribolium castaneum*; (b) chemical activity of applied residue, i.e. actual residue as a proportion of applied residue; (c) biological activity of actual residue = biological efficacy (from Desmarchelier 1978).

Desmarchelier's results for chlorpyrifos-methyl on wheat of 11% MC are given in Fig. 1. Biological activity on each of five bioassay occasions, determined as an LC_{50} value, is expressed in Figure

1 as potency relative to that immediately after application, i.e. LC_{50} (t = 0)/LC_{50} (t = 0, 2, 4, 8, 12). Biological activity of the applied residue declined abruptly during the first two weeks after application, and thereafter declined in a linear fashion on the logarithmic scale. Chemical decay of the applied residue was kinetically first order with respect to the residue remaining, and so plotted as a straight line on the logarithmic scale. The difference between these two lines on the logarithmic scale is the biological activity of the actual residue. Clearly, the major part of the decline in biological activity of the applied residue over time was due to reduced biological activity of the actual deposit, not chemical decay. This process, whereby an aged deposit is less biologically active than a fresh deposit of the same concentration, has been called 'biological inactivation' (Hargreaves et al. 1982).

Desmarchelier (1978) stated that his results conformed with data of Rowlands (1967, 1971) concerning the speed with which insecticides penetrate grain kernels. This suggests that biological inactivation results from movement of the insecticide from the exposed grain surface. The rapid decrease of insecticidal activity of chlorpyrifos-methyl during the first two weeks after application was attributed to initial rapid loss of the external residues from the grain surface, presumably before equilibrium was reached with the internal residues, as suggested by Champ et al. (1969).

Results of a study performed by Hargreaves et al. (1982) on the availability of deposits of a synthetic pyrethroid, deltamethrin, on wheat of 12% MC are plotted in Fig. 2, using the same methods as in Fig. 1. These authors were not able to measure any loss of the deltamethrin residue during the 15 month storage period, and on this basis the decline in potency in Fig. 2 is wholly attributable to inactivation. There was an initial rapid loss of activity followed by a gradual decline, qualitatively similar to that measured for chlorpyrifos-methyl but much less marked. If some decay of the residue is assumed during storage — Noble et al. (1982) determined a half-life for deltamethrin of 29 months under the same conditions — then inactivation would be even less significant.

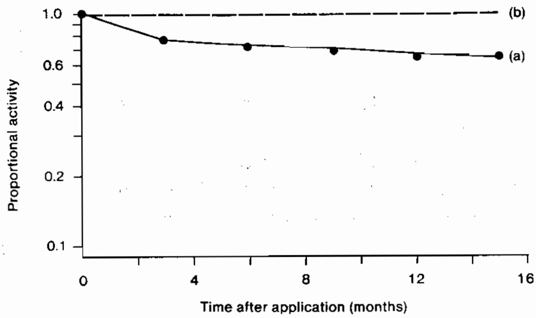

Fig. 2. Biological and chemical persistence of deltamethrin on wheat of 12% MC at 25°C, using the notation of Figure 1. Test insect was *Sitophilus oryzae* (from Hargreaves et al. 1982).

It should be noted, however, that data collected in our laboratory indicate that not all the synthetic pyrethroids remain as available to insects as does deltamethrin. There seems to be variation in the amount of inactivation within both the organophosphorus and pyrethroid groups of protectants.

At present, wheat is the only grain species for which there are published measurements of inactivation. It would be of some interest to know whether there are differences between grain species, including non-cereals, and also between different stages of processing of a single grain species, e.g. unhusked paddy rice, husked unpolished rice (brown), and polished white rice.

Also, the idea of inactivation refers here to loss of biological efficacy against free-living adult stages. It is conceivable that as insecticide residues move from the grain surface they may concentrate in other tissues such as the germ or endosperm, where they could be active against other developmental stages. Thus, decreased activity against adults could be compensated by increased activity against immatures. However, such an effect has not been demonstrated.

Biological Efficacy at Different Grain Moisture Contents

At high grain moisture contents, the biological persistence of certain organophosphorus residues may be reduced (Watters 1959; Strong and Sbur 1960; King et al. 1962). For example, the biological persistence of residues of malathion at 10 mg/kg on wheat of different moisture contents is given in Table 4, from the data of Strong and Sbur. They suggested that a moisture content of 14% was the critical level for the persistence of biologically effective malathion residues on wheat.

Chemical breakdown of malathion is accelerated

Table 4. The effect of moisture content on the persistence of biological activity of residues of malathion applied at 10 mg/kg to wheat and stored at 16°C, measured by biological assay with *Sitophilus oryzae* at different times after treatment (2 week exposure at 27°C) (Source: Strong and Sbur 1960)

Time after application (months)	% Mortality at following % moisture contents					
	10	12	14	16	18	20
1	100	100	100	100	100	100
3	100	100	100	100	89	0
6	100	100	100	98	11	0
9	100	94	83	48	1	0

at higher moisture contents (see e.g. Kadoum and La Hue 1979; Watters and Mensah 1979), but can this alone account for reduced biological persistence, or does moisture content also influence the efficacy of the residue that remains? This question can be answered by conducting parallel biological and chemical assays of grain treated and stored at different moisture contents, as was done in studies of biological inactivation at a single moisture content, or by measuring biological activity at different moisture contents shortly after protectants are applied, before the deposits have time to decay significantly. The latter comparison cannot be made using the data of Strong and Sbur (1960), as the single dose of malathion they applied was sufficient to kill all the test insects during the first month of storage regardless of moisture content (Table 4).

Champ et al. (1969) measured the relative potencies of malathion, fenitrothion, and diazinon on wheat at 11, 12, and 13% MC by confining adult *Sitophilus oryzae* in the grain for 24 hours the day after treatment. All the insecticides were slightly less potent at high moisture contents, but only for fenitrothion was the difference statistically significant. However, these moisture contents all represent quite dry grain — assays were done at 14% MC or above.

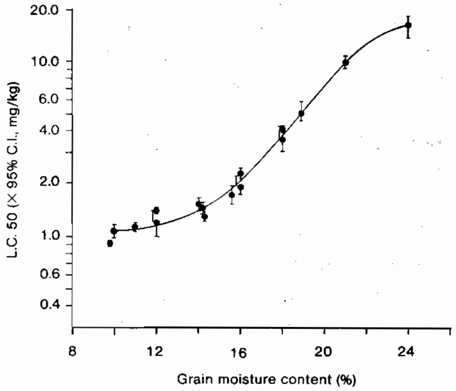

Fig. 3. Effect of the moisture content of maize on the biological activity of fenitrothion against *Tribolium castaneum* at 25°C (3 day exposure starting 1 day after treatment) (Samson, Parker, and Keating, unpublished data).

We determined the effect of a greater range of moisture contents on the biological activity of fresh residues of fenitrothion emulsifiable concentrate (EC) on maize. The results are plotted as LC$_{50}$ values in Fig. 3. Activity decreased with increasing moisture content, particularly above 14% MC with perhaps a lessening of effect above 20% MC The effect was considerable: fenitrothion was about 15 times more potent at 10% MC than at 24% MC

The decrease in biological activity at high moisture contents could have been due to: (i) reduced availability of insecticide; (ii) reduced pick-up of insecticide for reasons other than reduced availability, e.g. because of a change in insect behaviour; or (iii) reduced responsiveness of the insects. The last of these was discounted in the section on Insect Responsiveness earlier. We believe that (i) reduced availability is the primary cause; in particular, we have found that drying does not restore the potency of fenitrothion applied to moist grain, and of the three possible explanations above, only (i) is likely to be irreversible.

We attempted to measure chemically the availability of residues, by applying fenitrothion (EC) at 10 mg/kg to maize of 10–32% MC and then measuring the 'available' and 'unavailable' fractions 4 days later. The 'available' fraction was extracted by soaking the grain in methanol for 60 sec. Although Rowlands (1967) discourages the use of such a procedure for measuring penetration of chemicals into grain, the residue that is readily extractable should be correlated with biological activity: residues that cannot be extracted in 60 sec are unlikely to be available to insects. The

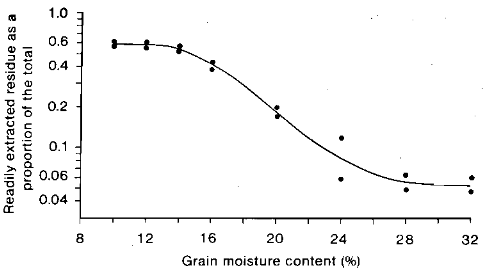

Fig. 4. Effect of the moisture content of maize on the proportion of the total recovered residue of fenitrothion that was extracted by initially soaking grain in methanol for 60 seconds. Maize was treated at 10 mg/kg and stored for 4 days at 25°C, and there were duplicate grain treatments at each moisture content. (Samson, Parker, and Keating, unpublished data).

'unavailable' residue was then extracted in methanol for 36 hours, and residues were measured by gas-liquid chromatography using a phosphorus-specific detector (Desmarchelier et al. 1977). The resulting curve in Fig. 4 is qualitatively a mirror image of Fig. 3; between 14% and 24% MC, the proportion of the total residue that was readily extracted decreased rapidly, corresponding to the declining biological activity of fenitrothion above 14% MC. The total residue was little affected by moisture content ($\bar{x}$ = 8.1 and 6.0 mg/kg at 10% and 32% MC, respectively).

Therefore, it seems that at high moisture contents of maize a considerable proportion of an applied deposit of fenitrothion becomes unavailable at the grain surface within a short time after application. Rapid loss of initial efficacy on dry grain was discussed earlier as inactivation and attributed to penetration of the deposit into the kernel. Variations in efficacy at different moisture contents may therefore reflect different initial rates of penetration (see e.g. Rowlands 1971), with perhaps the eventual establishment of different equilibria between external and internal residues.

Further work needs to be done on the effect of moisture content on the biological efficacy of fenitrothion on different grains, as discussed for inactivation in the previous section. It seems that treatment of maize with fenitrothion at 14% MC, an acceptable moisture content for storage in the humid tropics, is borderline for effective control. Fenitrothion is quite effective at 14% MC but there is little margin for error with respect to grain moisture. By reference to Figs 3 and 4, it can be seen that a small rise in moisture content above the nominated value will be much more serious if the nominal moisture content is 14% MC rather than 10–12% MC.

The potencies of fresh residues of three organophosphorus compounds (EC formulations) on maize at moderate and high moisture contents (14 and 18% MC) are compared in Table 5. The LC_{50} values for fenitrothion were 1.65 and 4.61 mg/kg at 14 and 18% MC, respectively, which is consistent with the data in Fig. 3. The other two compounds, and particularly chlorpyrifos-methyl, were less affected by grain moisture. Further work is needed to determine whether this difference between compounds is maintained during longer storage of the treated grain. Also, we plan to investigate the effect of grain moisture on a greater number of candidate protectants, including the synthetic pyrethroids. In the meantime, Table 5 gives hope that it may be possible to select protectants that are suited to the humid tropics.

Biological Efficacy at Different Temperatures

The biological persistence of grain protectants may be reduced at high storage temperatures. For example, the biological persistence of malathion at 10 mg/kg on wheat at a single moisture content, 10% MC, and seven storage temperatures is given in Table 6, from the data of Strong and Sbur (1960). Because all treatments were bioassayed at a common temperature (27°C) the results show the effect of temperature on availability of malathion deposits only. Possible further effects of temperature at the time of bioassay are discussed later.

Chemical breakdown of malathion is accelerated at high temperatures (see e.g. Watters and Mensah

Table 5. Effect of the moisture content of maize on the biological activities of three organophosphorus insecticides against *Tribolium castaneum* at 25°C (3 day exposure starting 1 day after treatment) (Source: Samson, Parker, and Keating, unpublished data)

	Fenitrothion	Pirimiphos-methyl	Chlorpyrifos-methyl
Relative potency 18% vs 14% MC (95% Confidence interval)	0.35 (0.31–0.40)	0.59 (0.53–0.66)	0.75 (0.66–0.84)

Table 6. The effect of storage temperature on the persistence of biological activity of residues of malathion applied at 10 mg/kg to wheat at 10% MC, measured by biological assay with *Sitophilus oryzae* at different times after treatment (2 week exposure at 27°C) (Source Strong and Sbur 1960).

Time after application (months)	% Mortality when grain stored at following temperatures (°C)						
	16	21	27	32	38	43	49
0.5	100	100	100	100	100	100	78
1	100	100	100	100	71	40	4
3	100	96	57	43	8	2	0
6	100	94	41	20	3	0	0
9	81	54	2	3	0	0	0

1979). However, as with the effect of moisture content on biological persistence, the question is whether this accelerated breakdown can alone account for reduced biological persistence, or whether the process referred to earlier as biological inactivation might proceed faster at high temperatures? This does not seem to have been investigated.

Assuming treated grain is stored at a single temperature, such that residues are equally available at the grain surface, the temperature during the biological assay may also influence biological activity. First, pick-up of insecticide is likely to be reduced at both low and very high temperatures because of reduced insect activity. Second, chemicals which have a fumigant action may be more active at higher temperatures because of their increased vapour pressure. And third, temperature may affect toxicity of the insecticides after pick-up (see earlier section of this paper). A combination of these factors might be reflected in the results of Champ et al. (1969), who measured the biological activity of freshly applied deposits of malathion, diazinon, and fenitrothion by biological assay with *Sitophilus oryzae* at 25 and 30°C. Being organophosphorus compounds, all would be expected to have positive temperature coefficients of toxicity after pick-up. Deposits of the three compounds were about 1.5 times more potent at 30°C than 25°C.

Doses of grain protectants required to prevent breeding of pest populations at different temperatures would reflect a summation of the possible effects discussed above. Longstaff and Desmarchelier (1983) used life-table analysis to study the rates of population growth of *Sitophilus oryzae* in wheat treated with two very stable grain protectants, pirimiphos-methyl and deltamethrin, and stored at three different temperatures. During the four weeks after treatment of grain, the lowest rates of population increase were achieved at 21°C using deltamethrin, and at 32°C using pirimiphos-methyl. The difference in optimal temperature for each insecticide reflects in part the opposite directions of the temperature coefficients of the two compounds, one a synthetic pyrethroid and the other an organophosphate.

Biological Efficacy of Fabric Treatments

The Meaning of Biological Efficacy of Fabric Treatments

Residual pesticides are applied to bag fabrics or to store fabrics to leave a 'chemical barrier' against insect infestations. The biological efficacy of such treatments should therefore refer to their ability to prevent the passage of insects into the stored grain.

Obtaining a realistic measurement of biological efficacy of fabric treatments can be quite difficult. Their efficacy will depend on the length of time insects are in contact with the treated surface, which will be affected by such factors as insect behaviour and, in the case of bag treatments, type of weave and insect size. Small insects that readily penetrate bags, such as *Oryzaephilus* spp., can be difficult to exclude with a chemical barrier (Kane and Green 1968). Some parts of the fabric will inevitably be missed during treatment (see e.g. McFarlane 1961), leaving refuges in which insects can survive without coming into contact with the insecticide (Pinniger 1974).

In addition, insecticides can be translocated into stored grain from both treated bags (see e.g. Green et al. 1959, 1960; McFarlane and Harris 1964; Webley and Kilminster 1981) and treated store fabrics (see e.g. Watters and Grussendorf 1969; Mensah et al. 1979; White and Abramson 1984). The resulting residues in the grain are biologically active, and will contribute to the chemical barrier afforded by the fabric treatment. They may even imitate an admixture treatment if the ratio of contaminated to uncontaminated grain is sufficiently high, as occurs when insecticides are applied to 'mini-bags' with a high surface area to volume ratio (Green et al. 1959, 1960).

The most realistic biological assay of the efficacy of fabric treatments would seem to be one which measures penetration of the chemical barrier and consequent insect breeding in the grain. A convenient but artificial assay of the persistence of insecticides on the surface, and one often used in comparative studies of different insecticides and formulations, is to confine insects on the treated surface and measure their response after one or more exposure periods. The following discussion of factors affecting biological efficacy of fabric treatments will use results of the latter type of assay, but it should be noted that the determination of efficacy in practice is considerably more complex.

General Behaviour of Residues on Surfaces and Biological Efficacy

Miller and Gold (1983) measured the availability of chlorpyrifos to cockroaches confined on painted-wood surfaces at different times after application of the insecticide. Rate of uptake of chlorpyrifos, which is an indicator of availability, declined rapidly immediately after treatment but the curve gradually flattened out (Fig. 5). Biological activity was assessed as LT_{50} values. The LT_{50} increased rapidly during the first 90 days after treatment, reflecting the declining rate of uptake of the insecticide. No measure of biological activity was obtained for longer storage times, as the LT_{50} then exceeded the longest exposure time (24 hours).

Unfortunately, Miller and Gold did not measure the actual residues present on the treated surface, so we cannot say whether the declining availability of chlorpyrifos in Fig. 5 is due to loss of the chemical residue or to loss of activity of the actual residue. However, the extremely rapid loss of initial activity suggests that some inactivation occurs. Inactivation of residues on certain surfaces has been attributed to sorption of insecticide by the substrate, making it less available for pick-up by insects (Barlow and Hadaway 1968).

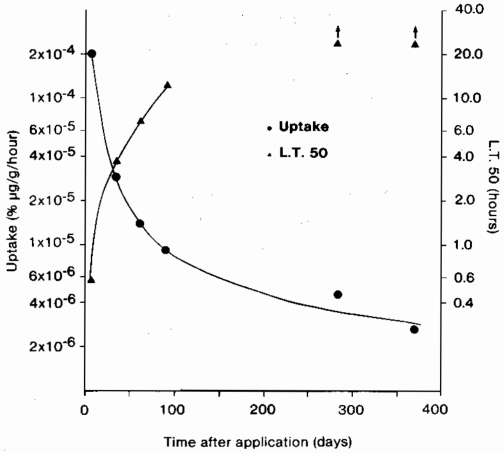

Fig. 5. Availability of chlorpyrifos to cockroaches at different times after application of Dursban (EC) to latex-painted pine boards. Availability is measured as uptake (µg of chlorpyrifos sorbed per gram of mean cockroach body weight per hour of exposure time divided by the total µg applied per surface) and as toxicity (LT_{50}) (from Miller and Gold 1983).

A higher relative humidity increases the toxicity of residues of many chemicals applied to cellulosic materials such as wood (Ebeling and Wagner 1965; Barlow and Hadaway 1968) and filter paper (Kalkat et al. 1961; Barson 1983), and to other sorptive hydrophilic substrates such as soil (Barlow and Hadaway 1958; Harris 1964). For example, the biological activities at two

Table 7. Effect of humidity on the biological activity of two formulations of fenitrothion on filter papers, measured by biological assay with *Tribolium castaneum* (5 hours exposure 1 day after treatment). Treated papers were placed in the relevant humidities 1 hour before bioassay (Source: Samson and Keating, unpublished data).

Insecticide formulation	LC_{50} (95% confidence interval (mg AI[a]/paper) 40% RH	90% RH	Relative potency 90% vs 40% RH (95% confidence interval)
Emulsion in water	21.88	0.104	209.7
	(21.21–22.54)	(0.099–0.109)	(199.0–220.7)
Solution in acetone	1.991	0.120	16.6
	(NA)	(0.114–0.126)	(14.7–19.0)

a. Active ingredient

humidities of deposits left by two different formulations of fenitrothion on cellulose filter papers are given in Table 7. The effect of humidity on activity was considerable, particularly in the case of the emulsion.

Associated phenomena at higher humidities include greater pick-up of insecticide by insects confined on the surface (Gerolt 1963), higher mortality of insects suspended above the surface, i.e. greater fumigant action (Kalkat et al. 1961; Ebeling and Wagner 1965), and more rapid evaporation of insecticide (Kalkat et al. 1961; Lyon and Davidson 1965). The effects have been observed not only on sorptive substrates, but also on substrates which are quite non-sorptive such as glass (Gerolt 1963; Lyon and Davidson 1965). There is some evidence that they might not occur with hydrophobic substrates such as oil-painted wood (Ebeling and Wagner 1965).

The effect of humidity on toxicity has been interpreted by Barlow and Hadaway (1968) to be a consequence of sorption of insecticide by the substrate, described above as inactivation. Water increases the activity of the sorbed insecticide in some way, perhaps by competitively displacing insecticide molecules from active sites on the substrate. The different magnitude of the effect of humidity on biological activity of two different formulations of fenitrothion suggested by the results given in Table 7 is presumably caused by physical differences in the resulting deposits: the deposit left by the aqueous emulsion was more strongly sorbed at the lower humidity, as evidenced by a larger LC_{50} value, whereas at high humidity there was little difference in biological activity of the two formulations. The magnitude of the effects of humidity also depends on the concentration of a deposit and on its age. If an insecticide is applied to a surface at a high dose, insecticidal activity may depend initially on a superficial deposit which is not sorbed by the substrate, and in this situation humidity may have little effect (Barlow and Hadaway 1968). Although substrates such as glass would not usually be considered sorptive, sorption phenomena might still operate provided that the amount of insecticide is reduced in proportion to the effective area available for sorption.

Thus, the effect of humidity or moisture on the biological efficacy of many surface residues is in the opposite direction to its effect on the biological efficacy (cf. earlier section of this paper) of protectants admixed with grain. Also, the effect is reversible with sorbed surface residues, i.e. activity can be alternately increased and decreased by transfer between high and low humidities (Barlow and Hadaway 1968), but this is not so with residues on grain. The mechanisms of inactivation on the two types of substrates — one non-living and one living — are presumably quite different.

Ways that temperature might influence biological efficacy of residues were discussed earlier. Briefly, these involved changes in: (i) insecticide availability, in particular, insecticides may desorb at high temperatures; (ii) vapour pressure; (iii) insect activity; and (iv) insect responsiveness. Effects (i) to (iii) favour increased efficacy of surface deposits at higher temperatures (within reasonable limits). Therefore, the direction of the overall effect of temperature on efficacy will depend on (iv), described earlier in terms of temperature coefficients. Deposits of organophosphorus insecticides with positive temperature coefficients are more effective at higher temperatures (Norment and Chambers 1970; Tyler and Binns 1982; Barson 1983). For example, Table 8, from Tyler and Binns (1982), gives the response of *Tribolium castaneum* to different rates of two organophosphates on filter papers at three different temperatures. About 50 times the concen-

Table 8. Effect of temperature on the response of *Tribolium castaneum* to two organophosphorus insecticides on filter papers (24 hours exposure) (Source: Tyler and Binns 1982).

Insecticide	Temperature (°C)	% Knockdown at following deposit rates (mg/m^2)					
		10	50	100	500	1000	1500
Pirimiphos-methyl	25	40	100				
	17.5	0	100				
	10			0	95	100	
Fenitrothion	25	32	100				
	17.5	0	100				
	10			0	17	82	100

tration of both compounds was required at 10°C to give the same response as at 25°C. The difference was much less striking between 17.5 and 25°C, presumably because temperature changes in this range have less effect on insect activity. With pyrethroids, their negative temperature coefficient will oppose the other effects of temperature, and the outcome may depend on the temperature range being considered. If temperatures are so low that insects are almost immobile, efficacy must be greatly reduced, but once temperatures exceed a threshold for insect activity the negative temperature coefficient may assume greater importance. Thus, biological efficacy of surface deposits of pyrethroids may sometimes be greatest at intermediate temperatures, e.g. Watters et al. (1983) found that deposits of cypermethrin and fenvalerate on plywood were more effective at 25°C than at 20 or 30°C against *Tribolium castaneum*.

Finally, factors such as high humidity or temperature that increase the availability of surface deposits to insects will probably increase their availability to other forms of loss from the substrate such as volatilisation, depending upon the type of insecticide. Therefore, factors that increase biological efficacy in the short term may increase rate of depletion of the deposit in the long term. The persistence of biological activity will depend on a combination of these two processes.

Biological Efficacy of Residual Pesticides on Fabrics Used in Grain Storage

The biological activity of residual insecticides applied to bag fabrics decreases with time after application (see e.g. McFarlane 1961). The influence of fabric type, and insecticide type and formulation on biological persistence of bag treatments has been described in a series of papers co-authored by Webley (Webley and Kilminster 1980, 1981; Webley 1981). For example, Table 9 compares the persistence of permethrin and two formulations of malathion on jute and polypropylene bags. Biological activity of all the insecticide treatments was lost more rapidly on jute than on polypropylene. On jute, the wettable powder formulation of malathion maintained biological activity longer than did the emulsifiable concentrate.

Residues remaining in the fabrics after 12 weeks are also given in Table 9. Chemical persistence of malathion was much greater on jute than on polypropylene — the reverse of biological persistence. Deposits of permethrin persisted well on both fabrics.

The results indicate that insecticides are strongly inactivated on jute, perhaps because of sorption onto the fibres. Inactivation of malathion is somewhat reduced if the insecticide is formulated as a wettable powder rather than an emulsion, presumably because the resulting deposit is more superficial to the surface (see also Kantack and Laudani 1957 and Parkin 1966). Sorption of malathion by jute not only inactivates the residue biologically, but also prevents loss of the deposit from the fabric. This is much less relevant to permethrin, which has a lower vapour pressure and is less liable to be translocated from the surface. On polypropylene, a similar but much less significant process of inactivation might also occur

Table 9. The persistence of deposits of an organophosphorus and a synthetic pyrethroid insecticide on different fabrics, as measured by biological assay (exposure of *Sitophilus zeamais* for 3 hours) and chemical assay (Source: Webley and Kilminster 1980).

Chemical and fabric	Formulation	% Mortality at following weeks after treatment 0	1	4	9	12	Chemical deposit at 12 weeks (mg/m²)
Malathion (g/m²)							
Polypropylene	WP[a]	100	100	50	40	20	11
	EC[b]	100	100	100	10	0	33
Jute	WP	100	100	10	0	0	356
	EC	100	0	0	0	0	378
Permethrin (0.1 g/m²)							
Polypropylene	WP	100	100	100	100	100	31
Jute	WP	100	100	0	0	0	54

[a] Wettable powder

[b] Emulsifiable concentrate

during storage, but this cannot be assessed from the data in Table 9.

Store fabrics usually consist of concrete, wood, or galvanised iron. Table 10 gives results for the biological persistence of fenitrothion (EC) on the three surfaces (from Williams et al. 1983).

Table 10. The persistence of biological activity of deposits of fenitrothion (1 g/m^2) on different store fabrics, measured by biological assay with *Sitophilus oryzae* (24 hours exposure) (Source: Williams et al. 1982).

	% Mortality at following weeks after treatment				
Substrate	1	8	16	24	32
Galvanised iron	100	93	100	91	69
Wood	90	98	90	45	10
Concrete	56	38	1	0	0

Fenitrothion lost biological activity very rapidly on concrete, as do many other chemicals (Parkin 1966; Lemon 1967; Watters and Grussendorf 1969). Loss of activity is attributable in part to the rapid breakdown on concrete of insecticides, particularly malathion, as a result of the alkaline conditions. In addition, it is likely that actual residues will have low biological efficacy, because concrete has a large real surface area due to its rough surface, and is very porous (Parkin 1966).

Fenitrothion maintained biological activity slightly longer on galvanised iron than on wood (Table 10). Williams et al. (1983) obtained a similar result with the other insecticides they tested — pirimiphos-methyl, azamethiphos, and carbaryl. Slightly greater biological persistence of deposits on galvanised iron in comparison with wood was measured for malathion and bromophos by Watters (1976), and for malathion and fenitrothion by White et al. (1983). Watters and Grussendorf (1969), however, found that lindane and methoxychlor were more toxic and retained their toxicity longer on wood than on galvanised iron.

Differences in results between studies may reflect differences in the substrates, e.g. with respect to age, texture and porosity, sorptive activity, and pH. The basic substrates may also be treated with a coating of paint or whitewash. Therefore, it is difficult to generalise about the biological activity of residues on store fabrics. Comparison of biological efficacy of actual residues is impossible, as actual residues are rarely measured because of technical difficulties (see e.g. Williams et al. 1983).

Conclusions

The biological efficacy of residual insecticides is probably better understood for grain admixture than for fabric treatments. In part, this may reflect the greater ease with which admixture treatments can be simulated realistically on a small scale.

Basic understanding of the biological action of admixed insecticides may considerably improve their efficiency in practice. Insect control by means of mixing insecticide with grain represents a very 'finely tuned' system. A balance must be struck between minimum effective concentrations for insect control on the one hand, and maximum residue limits on the other. This balance is achievable because many of the factors influencing efficacy of the insecticides can be controlled: the substrate to be treated, viz. the grain, is very uniform; a sufficiently uniform distribution of insecticide in the grain mass is readily achieved; desired concentrations of insecticide can be applied accurately; and both temperature and moisture content are controllable to some extent. In this circumstance, it is quite feasible that insecticides or dose rates can be varied, on the basis of results of basic research, to be appropriate for different storage conditions.

By contrast, insect control by means of fabric treatments, and particularly bag treatments, represents a very coarsely tuned system. Control of application rate is not so critical. Uniform treatment is difficult to achieve and there are usually many untreated refuges for insects. The largest refuge of all is the mass of untreated grain. Efficiency of bag treatments is limited by practical difficulties of application and by inherent inefficiencies of the technique rather than by understanding of the biological efficacy of residues.

Therefore, I believe that at present the potential benefits of basic research are greater in the field of admixture. Suggested topics are listed below:

(1) understanding of the mechanism causing biological inactivation of insecticides, and how it might be prevented;
(2) effect of temperature on insecticide availability;
(3) comparative efficacy of insecticides on different grains, both immediately after application and during storage;

(4) comparative effect of grain moisture on the biological activity of different insecticides and formulations; and

(5) comparative effect of the moisture content of different grains.

A quantitative study of inactivation of residues on bag surfaces, by conducting parallel biological and chemical assays, would fill a gap in our basic knowledge of fabric treatments. In particular, results of such a study might show whether the conventional wisdom of frequent applications of moderate rates of insecticide to bag stacks during storage is the best strategy, or whether a single very heavy application during stack construction might not be preferable. Designing a suitable assay could be the greatest difficulty.

Acknowledgment

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Background Studies on Residual Pesticides Session Chairman's Summary

Belen Morallo-Rejesus*

THE first paper in this session was presented by *C.E. Dyte* on behalf of *Rowlands* and dealt with background studies on the behaviour of residual pesticides in stored grain.

The main points were:

1. In making small-scale laboratory experiments to predict the possible fate of insecticides applied to grain there are numerous pitfalls introduced by (a) major differences in the performance of laboratory mills when compared with commercial mills, (b) difficulties in dissecting grain kernels into components which are representative of fractions produced in commercial mills, (c) losses encountered in the first hours/days following application suggest occurrence of volatilisation or degradation or both, (d) sampling errors, variation in replication and in analytical techniques, (e) in small scale (micro) studies, glass vials can catalyse decomposition that does not occur in bulk, (f) transfer/exchange of insecticides occurs when treated grains are in close contact with untreated, and (g) effects of volatility produce major errors in small scale experiments.

2. Work with some insecticides applied to high moisture grain at tropical temperatures (26–30°C) clearly shows degradation within 7 days. This may be higher and faster in fractures due to presence of microflora and the continued ripening process.

3. The volatility of insecticides under tropical storage could be very important in measuring toxicity to insects whilst promoting losses.

4. It has been shown that chlorpyrifos-methyl gives rise to a residue that is not extractable by conventional solvents. This can represent up to 30% of the original deposit. Such information can be revealed only by laboratory studies.

5. It is suggested that reduced efficacy of pyrethroids after a lengthy storage period might be attributed to location of residue away from the surface where insects move.

6. Information on degradation of organophosphorus compounds on grain is reviewed. (a) It shows that the seedcoat is an important element in the process, (b) bound residues of pirimiphos-methyl, chlorpyrifos-methyl, fenitrothion, and malathion occur, (c) desmethylmalathion has been identified for the first time. The desmethyl derivative is the major metabolite of bromophos and methacrifos and a minor derivative of fenitrothion.

Relevance of Current Research

Knowledge of the metabolism of insecticides on grain is important in determining and studying residues in grain, milling fractions, and prepared food. It does not have a critical bearing on the practical application of insecticides but many of the laboratory techniques described are, however, relevant to laboratory studies on residues.

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Research Areas Requiring Attention

1. Vapour-phase distribution, losses, and action of contact insecticides.

2. The nature of unextractable residues, or at least their biological potency after prolonged contact.

3. The confirmation of laboratory studies under large-scale conditions in the region.

4. Comparative studies between cereal types and varieties.

Desmarchelier's paper on the behaviour of pesticide residues explained in a simple manner using analogies that were easily understood by everyone, that the application of basic chemical/physical principles and controllable factors in grain storage would enable us to develop insect control methods that (a) were cheaper than alternatives, (b) produced long-term protection, and (c) resulted in destruction of all residues prior to consumption.

Examples were:

1. The half-life of methacrifos doubles for each 5°C that the temperature is lowered. We can profit from this knowledge by cooling to $<20°C$ for storage. We know too that subsequent cooking of rice or baking bread causes rapid and complete destruction of all the residue.

2. Use of knowledge of partition coefficients to develop dusts that (a) are highly concentrated, (b) don't give up their insecticide to the grain, (c) are readily contacted by insects, (d) have long persistence and high kill, and (e) are easily removed in cleaning and processing.

3. The high biological activity of enzymes in sprouting barley results in the complete degradation of insecticide residues on stored barley so that none is carried over into the malt or wort.

4. Use of non-equilibrium partitioning to circulate low concentrations of volatile liquids through grain at a high rate/velocity. Such techniques can greatly increase the potency to insects whilst reducing the uptake by the grain.

5. Use of microgranules that are easily contacted by insects, that adhere to their bodies, and are cleaned off by insect mouthparts resulting in high toxicity. The granules are easily removed from the grain, resulting in low residues.

Relevance to Current Research

Several of these proposals appear most relevant to current research if they could (a) increase the potency of insecticides available, (b) reduce the residue in the milled/cooked cereal, (c) make it possible to remove insecticide by simple cleaning, (d) reduce the cost, and (e) combine with processes being developed for drying grain for tropical storage.

Research Areas Requiring Attention

Each of the proposals should be subjected to a feasibility study to determine what further experimental work is required to adapt them for use in humid tropics.

Samson's paper reviewed the effect of moisture and temperature on the efficacy of residual insecticide deposits.

The effects examined included those relating to (a) insecticide distribution, including evenness, (b) type of grain, (c) interval after application, (d) moisture content of grain, and (e) temperature, on activity of the insect and the insecticide and how these interact to regulate biological efficacy.

The subject was divided into the availability of residues for pick-up by insects, differences in pick-up for other reasons, and insect responsiveness.

The main points were:

1. Insect responsiveness is not affected by humidity but residues are irreversibly reduced by available moisture. Temperature affects insect responsiveness.

2. Availability of insecticide deposit is little affected by uniformity of application, though the size of the grains appears to regulate the movement of insects and the surface area to volume ratio.

3. Penetration of deposit into the grain kernel adversely affects availability to insects and could explain the apparent decrease in biological efficacy with time.

4. Potency of insecticides is affected by temperature. Generally, OP compounds are more effective (toxic) at high temperatures (positive temperature coefficients) whilst pyrethroids become more toxic at low temperatures (negative temperature coefficients).

Relevance to Current Research

Many of the issues discussed are very relevant to current research under humid tropical conditions as they obviously determine the optimum treatment/ management conditions that should be applied to minimise the adverse effects of high temperature and high humidity.

Research Areas Requiring Attention

1. Study of mechanisms causing biological inactivation of insecticide deposits on grain and how it might be overcome.

2. Study of the effect of temperature on availability of insecticide.

3. Comparative efficacy of deposits on different grains, both immediately after application and during storage.

4. Comparative effect of grain moisture on the biological activity of different insecticides and their formulations.

5. Comparative effect of the moisture content of different grains taking into consideration the effect of relative humidity and temperature on residual life of insecticides.

Background Studies on Fumigants

Sorption and Desorption of Fumigants on Grains: Mathematical Descriptions

H.J. Banks*

Abstract

For a technology as old and well established as fumigation, it is remarkable that no explicit general description has yet been developed to describe the interaction between grain and the fumigant. The interaction can be viewed at three levels: sorption–desorption behaviour for individual grains ('grain level'), transport of fumigant around a grain mass ('commodity level') and loss of fumigant to the atmosphere ('storage level'). A sound description of behaviour at the grain level is a fundamental requirement for modelling at higher levels.

Fumigants are sorbed on grain either by physical forces (e.g. carbon tetrachloride) or a combination of physical and chemical forces (e.g. carbon dioxide). Sometimes this is accompanied by an irreversible reaction on grain constituents (e.g. phosphine and methyl bromide). Sorption of some fumigants has been successfully described in terms of solutions to the diffusion equation, considering a grain as a sphere, but terms for reaction have not been included in this model. Models describing sorption in terms of quantity of different constituents (e.g. fat, protein) show promise, and progress has been made in quantifying reaction of fumigants with grain in terms of chemical kinetics.

The basic descriptions of sorption–desorption of fumigants as found in the literature are reviewed. They appear to provide a satisfactory conceptual framework, but there are few studies on the values of the controlling parameters, such as are required for modelling fumigants behaviour in a grain mass. A compilation of those values deducible from published work is given.

ONE of the main objects of research into fumigation must surely be to elucidate and quantify the underlying principles of the process. Intelligent application of a detailed knowledge of these processes should then ensure that fumigations can be carried out efficiently, with minimum risk to health and taking into account residue formation, detrimental effect on the treated commodity, and fumigant usage.

For a complete physical description of the fumigation of a commodity, it is necessary to understand the mass transfer processes occurring at three levels of organisation: the interaction of fumigant with an individual particle of commodity (the 'particle' level), distribution of gases within the commodity bulk and associated free spaces such as headspaces and gaps between pallets (the 'commodity' level), and loss of gas to the atmosphere outside the enclosure under treatment (the 'storage' level). There has been progress recently towards modelling of behaviour of gases at the commodity and storage levels (Banks and Annis 1984; Nguyen, these proceedings) so that the general conceptual framework describing the movement of fumigants in a storage is now known. However, a complete model for a fumigation can only be produced by integrating the descriptions of behaviour of gases at the commodity and storage levels with information about that at the particle level. The rate with which a fumigant is sorbed and desorbed on a commodity will influence the rate at which it disperses through a bulk. The magnitude and speed of sorption and desorption on the commodity will determine the quantity of fumigant in the free space of a storage under treatment which in turn will affect the insecticidal effect of the fumigation and the rate of loss from the store by natural or forced ventilation.

The literature relating to the sorption of fumigants on stored products is large and diverse. However, most published studies relate to a specific commodity and fumigant. Data are usually presented in crude form without analysis

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to make them comparable directly with other studies and without attempts to generalise the findings so that they are applicable in circumstances other than those studied directly. It is regrettable that this should be so since most of the necessary theoretical framework, based on simple physicochemical principles described in basic texts such as Glasstone and Lewis (1960), was tested in the 1940s and demonstrated to be applicable. If it had been used as a guide to the parameters that should have been measured, it may well now have been possible to describe fumigant–commodity interaction adequately for modelling purposes.

Since 1950 the advances in the conceptual and quantitative understanding of sorption of fumigants on grain have been slight, although in many of the more recent studies a small change in emphasis in the experimental design and reporting would have given data that could have contributed substantially. The few recent studies that have attempted to make mathematical generalisations have developed the required theoretical framework anew and ignored both the published studies of the 1940s and often the newer work as well. It is to be hoped that such a situation will not continue.

This review aims to provide a critical summary of the mathematical descriptions of fumigant–commodity interaction at the particle level and to recast where possible the published data on sorption-desorption phenomena into a standardised form that may be used as input into models of fumigations. The review is restricted largely to data for whole cereal grains and covers both fumigants still in use and, in part, those superseded or no longer permitted. Data from fumigants no longer in use can provide information relevant to the three remaining fumigants commonly used for stored grain; methyl bromide, phosphine, and carbon dioxide.

The treatment of fumigant sorption-desorption in this paper is divided into two independent sections, the first dealing with the quantity of fumigant taken up or lost and the second with the rate at which these processes occur. The notation used here is summarised in Table 1.

Quantity of Fumigant Sorbed

General Influences on Sorption

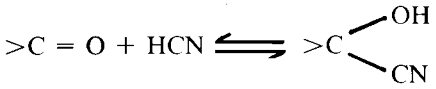
Several authors (Sinclair and Lindgren 1958; Berck 1964; Dhaliwal 1975) have listed the various influences on a fumigation acting at the 'particle' level. They can be summarised thus: (1) Attributes of the commodity: the material itself, temperature, water activity, proportion of constituents (protein,

Table 1. Notation.

A	frequency factor
D	diffusion coefficient
E_a	energy of activation
E_s	heat of sorption
F	flux
R	gas constant
V_g	gas volume (i.e. excluding volume of grain)
V_{tot}	total enclosed volume
a	Freundlich isotherm coefficient
c_{app}	applied concentration (calculated on V_{tot})
c_g	concentration of fumigant in gas phase
$c_{g,e}$	equilibrium concentration in gas phase
$c_{g,o}$	initial concentration
c_r	concentration of residue (reaction products)
c_s	concentration of fumigant in sorbed phase
$c_{s,e}$	equilibrium concentration in sorbed phase
$c_{s,1}$	concentration of 'firmly bound' fumigant
$c_{s,2}$	concentration of 'loosely bound' fumigant
c_{sat}	saturated vapour concentration
f	filling ratio (bulk volume of grain/total volume)
k	loss rate constant
k'	loss rate constant, uncorrected for filling ratio
k_1	loss rate constant for 'firmly bound' fumigant
k_2	loss rate constant for 'loosely bound' fumigant
m	mass of grain
n	summation
n	Freundlich isotherm index
n_1	moles of solvent
n_2	moles of solute
r	radius
t	time
x	distance
ρ_{bulk}	bulk density
ρ_{true}	true density of individual grains
α, β	empirical coefficients

fat, ash, etc), state of subdivision, load factor, ? previous history. (2) Attributes of the fumigant and its application: type and structure of the fumigant, concentration, time of exposure, rate of air movement.

Many of these influences can be quantified in terms of simple chemical kinetic theory. This can be used to describe the two types of sorption: reversible and irreversible sorption. The latter, often referred to as 'chemisorption' (e.g. Berck 1968; Sosedov 1959), is assumed to involve the reaction of the fumigant on the commodity and the breaking and formation of chemical bonds, while the former, known as 'physisorption,' is usually assumed to involve the binding of fumigant to the substrate by weak physical forces. However, it should be noted that there are a number of reversible chemical reactions that can be involved in fumigant–commodity interaction, so the distinction of chemi- and physi-sorption on the basis of reversibility may not always be correct. For instance, the reaction of hydrogen cyanide (HCN) with carbonyl groups can be reversible. Turtle (1941) suggests that HCN reacts with the carbonyl in fructose in dried fruit thus:



$$>C = O + HCN \rightleftharpoons >C\begin{matrix}OH \\ CN\end{matrix}$$

Even in a system undergoing what is regarded as purely physical sorption, e.g. ethylene dichloride $[(CH_2)_2Cl_2]$ on grain, there appear to be two more or less distinct states of sorption. These have been classed as 'loosely bound' and 'firmly bound' fumigant (e.g. Lubatti 1944a; El Rafie 1954; Bielorai and Alumot 1975). The ratio of these states for a particular fumigant may vary with conditions, particularly time of exposure. When a fumigant is aired from a commodity there is initially a rapid loss which then slows. The initial loss is said to be of the loosely bound material while the firmly bound material is lost more slowly and, in the cases such as that of whole grains, may even require grinding, solvent extraction, or heating for complete and rapid release (Lubatti 1944a; Lubatti and Harrison 1944). It will be shown below that this distinction may be, at least in part, artificial and merely a reflection of how far fumigant has to travel to escape from within particles of the commodity; the fumigant close to the surface of the particles being lost quickly and thus regarded as 'loosely bound' and that in the interior being lost more slowly and thus 'firmly bound'. The nature of the physical retentive processes acting on fumigants have not been fully elucidated but phenomena such as surface adsorption (Sato and Suwanai 1974), capillary condensation (Winteringham 1944), true solution (Pepper et al.1947) and permeability barriers (Lubatti 1945) have been invoked.

Sorption Isotherms

Despite uncertainties as to the mechanism of the process, sorption of fumigants has been well described (e.g. Winteringham 1944; Winteringham and Harrison 1946) by the semi-empirical Freundlich isotherm:

$$c_s = a\, c_g^{1/n} \qquad (1)$$

where c_s is the concentration of the sorbed fumigant from a free fumigant concentration of c_g, and a and n are empirical parameters. The value of n is normally close to unity. The deviation from unity is characteristic of the type of sorption occurring, with $n < 1$ signifying a multi-molecular adsorption layer and $n > 1$ a uni-molecular layer (Winteringham and Harrison 1946). Table 1 gives values of n for various systems. The Freundlich isotherm strictly applies to systems in equilibrium but it has been applied to non-equilibrium situations in which sorption is incomplete or the fumigant continues to react. Under such circumstances the value of a varies with time (Table 2). The value of n for whole grains has been found to be close to 1.0 in all cases except for carbon tetrachloride (CCl_4) and carbon dioxide (CO_2). For CCl_4 on wheat, $n = 0.63$ for data of Pepper et al. (1947) and 0.42 for data of Park and Kyle (1975) (a cannot be determined from the data of these two groups of authors). Mitsuda et al. (1973) give a value equivalent to about 0.67 for n for carbon dioxide (CO_2) sorption on brown rice. The data from which this is derived lie on a distinct curve when transformed logarithmically (points should lie on a straight line to conform with the Freundlich isotherm). However, it appears that these authors did not take variation of pressure into account when calculating the quantity of CO_2 sorbed and the information given is insufficient to determine a correction for this. New data are required on CO_2 sorption to show if n in fact differs significantly from 1.0.

The reason for the deviations from 1.0 for n for CCl_4 are unclear. However, the values for CCl_4

Table 2. Freundlich isotherm values (a = coefficient; n = isotherm index) for whole cereals with various fumigants.

Fumigant	Commodity	Temp. (°C)	Moisture content	Exposure period (hours)	a[a]	n	Data source
Carbon disulphide CS_2	Wheat	25	13	?24	1.9	1.0	El Rafie (1954)
Ethylene dichloride $(CH_2)_2Cl_2$	Wheat	20	14	24	11.6	0.96	Winteringham (1944)
		20	14	48	13.3	0.96	Winteringham (1944)
		20	14	168	17.1	0.96	Winteringham (1944)
Ethylene oxide $(CH_2)_2O$	Wheat	22	7.5	48	0.67	0.90	Pfeilsticker and Rasmussen (1968)
Hydrogen cyanide HCN	Wheat	20	13.2	24	31.0	1.00	Lubatti (1944b)
		20	13.2	96	53.7	1.01	Lubatti (1944b)
		20	13.2	168	63.4	1.01	Lubatti (1944b)
Methyl bromide CH_3Br	Wheat	5	13.8	48	2.53	1.08	Mori annd Oda (1961)
		20	10	48	2.36	1.11	Winteringham and Harrison (1946)
		20	13.1	48	2.00	0.99	Lubatti and Harrison (1944)
		20	14	48	2.84	1.11	Winteringham and Harrison (1946)
		20	13.1	96	3.41	1.03	Lubatti and Harrison (1944)
		20	13.1	168	4.31	1.02	Lubatti and Harrison (1944)
		28	13.8	48	1.30	0.90	Mori and Oda (1961)
		28	13.8	48	0.33[b]	0.81	Mori and Oda (1961)
	Milled Rice	28	14.9	48	3.69	1.12	Mori and Oda (1961)
		28	14.9	48	0.49[b]	0.87	Mori and Oda (1961)
Phosphine PH_3	Wheat	20	?	336	0.049	0.89	Noack et al. (1983)
	Wheat	25	11	48	0.040	1.0	Sato and Suwanai (1974)

[a] In units appropriate to a full container (mass in 1L gas phase/mass in grain filling 1L total volume). To correct to units of mass in 1L gas phase to mass in 1L solid grain multiply by ρ_{true}/ρ_{bulk}. To convert to units of mass in 1L gas phase to mass in 1 kg grain multiply by ρ_{bulk}.

[b] Free methyl bromide. Other values for total sorbed methyl bromide.

were obtained for partial pressures approaching saturation and may have been influenced by factors not occurring with the other fumigants investigated (e.g. capillary condensation). In the only other instance where concentrations approaching saturation were used, Winteringham (1944) found some decrease in the value of n at high concentration of $(CH_2)_2Cl_2$ on wheat. This was ascribed to the effect of capillary condensation. It is notable that the sorption isotherms for all the fumigants except CCl_4 and CO_2 were obtained from observations taken considerably before sorption equilibrium was attained [sorption equilibrium for non-reactive fumigants may take more than 10 days to achieve (Lubatti 1945)]. There is thus some confusion between the rate at which the process is occurring and the eventual value of sorption at equilibrium. This may also have influenced the value of n.

Winteringham (1944) demonstrated how the data obtained from laboratory measurements fitted to the Freundlich isotherm could be used to estimate the concentration-time curve expected in a bag of wheat under fumigation with $(CH_2)_2Cl_2$. The equilibrium sorbed quantity of fumigant, c_s, is related to the expected free space concentration, c_g, in the system with an initial dosage of $c_{g,o}$ (calculated in terms of the free space) with m kg of wheat per litre with a true density, ρ_{true}, in a total volume, V_{tot}, by

$$c_s = a c_g^{1/n} = \frac{c_{g,o} - c_g}{m} (V_{tot} \rho_{true} - m) \qquad (2)$$

(adapted to conform with units used here). Mori and Oda (1961) used an essentially similar approach and implicity assumed $n = 1$. In terms of the parameters used here, they described the residual space concentration c_g after a time, t, by:

$$c_g = \frac{c_{app} V_{tot}}{V_{tot} + m \left(\frac{\alpha}{\rho_{bulk}} - \frac{1}{\rho_{true}} \right)} \qquad (3)$$

where a is the appropriate Freundlich isotherm coefficient, c_{app} is the concentration applied calculated on the basis of the total volume V_{tot} and ρ_{bulk} is the bulk density. Pfeilsticker and Rassmussen (1968) also assumed $n = 1$ and gave an equation intended to predict the loss of ethylene oxide $[(CH_2)_2O]$ from wheat by both aeration and reaction. Unfortunately, they used information from El Kishen (1950) incorrectly and their expression requires modification to rectify this fault.

Clearly, more data are required on sorption isotherms since they are fundamental to the quantification of sorption on grains, relating the quantity of fumigant sorbed to the free space concentration, as attempted in equations (2) and (3). Data for grains other than wheat are notably scarce.

Influence of Grain Composition on Quantity Sorbed

There have been few studies that have attempted to relate the quantity of fumigant taken up with some measurable property of the grain. However, such an approach seems worthy of further research since, if successful, it could result in a generalised model of sorption where the quantity sorbed could be predicted independently of grain type.

Pepper et al. (1947), studying the sorption of CCl_4 on wheat, found that it was possible to explain the sorption in terms of the solvent power of the lipid fraction of the grain. The sorption followed Raoult's Law, so that

$$\frac{c_{g,e}}{c_{sat}} = \frac{n_2}{n_1 + n_2} \qquad (4)$$

where $c_{g,e}$ is the concentration of a vapour at equilibrium, c_{sat} is the saturated vapour pressure, n_1 is the number of moles of involatile solvent present,and n_2 is the number of moles of vapour absorbed. They found a value for n_1 of 0.022 moles kg for wheat of 8% moisture content (m.c.). This value did not vary appreciably with temperature (20–35°C) or concentration of CCl_4 ($c_{g,e}/c_{sat}$ varied from 0.15 – 0.64) and also applied at 35°C, 16% m.c. On the basis of a molecular weight of the solvent of 850, a reasonable value for triglycerides, Pepper et al. (1947) calculated that the solvent was equivalent to 1.9% by weight of the wheat, a value close to that of the fat content. They also showed that the sorption of CCl_4 on wheat at equilibrium (i.e., after about 3 weeks) was given by

$$c_{app} = c_g \left(1 - \frac{f \rho_{bulk}}{\rho_{true}} + \frac{f \rho_{bulk} n_1}{c_{sat} - c_{g,e}} \right) \qquad (5)$$

where f is the filling ratio of the container.

Pfeilsticker and Rasmussen (1968) studying interaction of $(CH_2)_2O$ with wheat, used a similar conceptual system, dividing the grain into two regions, a water 'space' and a xylol-available 'space,' presumably analogous to the lipid 'space' treated above. They state that the proportion, a, of $(CH_2)_2O$ in the gas phase to that in the wheat was approximately independent of moisture content when the concentration in the wheat was expressed as concentration in the water phase of the grain (a = 0.031 and 0.019 for 7.5 and 12.7% m.c. at ~22°C respectively).

Mori and Oda (1961) investigated the sorption of methyl bromide (CH_3Br) by water and attempted to relate this data to uptake of CH_3Br by dry commodities. Mitsuda et al. (1973) unsuccessfully attempted to correlate sorption of CO_2 with water or fat content of grains.

Despite the low rate of success in relating sorption to quantity of particular constituents present, it is apparent that such an approach may yet be effective for both reversibly and irreversibly sorbed gases. Thus, the bromide residue in milling fractions from wheat treated with CH_3Br is related to the protein and fat content of the grain (protein and fat content are themselves correlated, so the effect of each cannot be distinguished). However, in both sets of data available (Fig. 1 and 2) there are occasional substantial and unexplained deviations from the trend. The CH_3Br sorbed by different ground commodities appears to be correlated with their protein content (Fig. 3). Since most of the CH_3Br sorbed reacts to give bromide ion, the bromide residue is presumably also correlated with protein content. Berck (1968) suggested that irreversible sorption of phosphine (PH_3) may be correlated with protein and ash content and Mitsuda et al. (1975) demonstrated substantial reversible uptake of CO_2 by proteins. It would be a useful advance to have substantiation of such relationships for whole cereal grains in terms of sorption isotherms relating to fumigant taken up to constituents of the treated material.

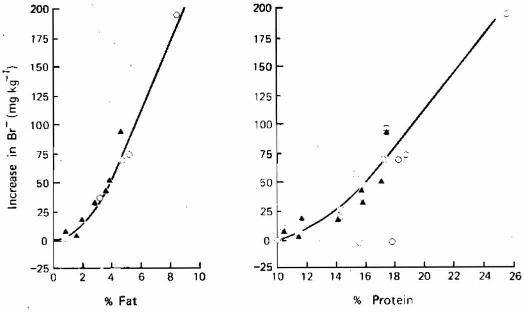


Fig. 1. Increase in bromide ion in various milling fractions derived from whole grain (▲, □ hard red winter wheat, ○ hard red spring wheat) fumigated with methyl bromide (data of Gibich and Pedersen 1963).

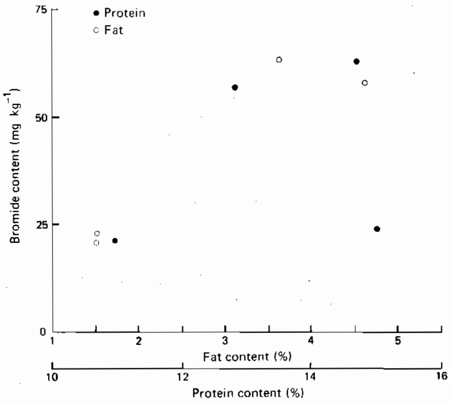


Fig. 2. Increase in bromide ion in various milling fractions from whole wheat fumigated with methyl bromide (data of Lindgren et al. 1962).

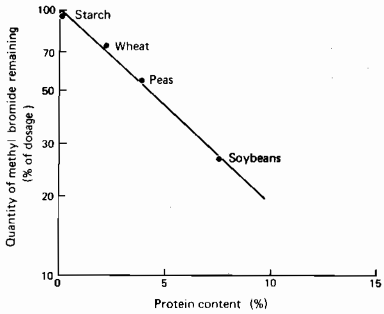


Fig. 3. Correlation of methyl bromide reaction rate with protein content for some ground commodities (data of Lewis and Eccleston, 1946).

Influence of Water Activity on Sorption

Where it is investigated, the influence of the water activity in grain under fumigation usually appears as a minor item in a larger study. There are no published mathematical models to describe its influence but specific details of the effect (observations at more than two values) have been given for CO_2 on paddy and brown rice (Mitsuda et al. 1973) and for PH_3 (Meuser 1972), several halogenated fumigants (Berck and Solomon 1962), CH_3Br (Lubatti and Smith 1948) $(CH_2)_2O$ (Lubatti 1944a), HCN (Lubatti 1944b), and carbon disulphide (CS_2) (El Rafie 1954) on wheat.

Generally, the effects of change in water activity on sorption are small (but see below) with sorption somewhat increased for reactive materials such as CH_3Br, PH_3, and $(CH_2)_2O$ and physical sorption slightly reduced. The combined effect of these two factors usually leads to an observed increase in sorption with moisture content (e.g. as found by Lubatti 1945). However, the sorption of CO_2 on brown rice and paddy changes by +38 and −38%, respectively, as the moisture content increases from about 9 to 16% (Mitsuda et al. 1973). Systematic studies are needed to quantify the role of water activity on sorption-desorption.

Influence of Temperature on the Quantity Sorbed

For a reversible process, such as physisorption, the temperature dependence of the concentration in equilibrium with the grain is given by the Clausius-Clapeyron equation:

$$\frac{d(\ln c_{g,e})}{d(1/T)} = -\frac{E_s}{R} \qquad (6)$$

This equation has been used to determine E_s, the heat of sorption, for CCl_4, CH_3Br, and $(CH_2)_2Cl_2$ on ground wheat. The heat of sorption of CH_3Br was found (Winteringham and Harrison 1946) to be concentration dependent and to be 60 000 and 44 000 kJ/kg-mol for absorbed concentrations of 0.3 and 1.0% w/w, respectively. The sorption of $(CH_2)_2Cl_2$ was also concentration dependent (Winteringham 1944), being 23 000 and 31 000 kJ/kg-mol at 10 and 200 g/m^3 respectively. Pepper et al. (1947) obtained a value of 35 000 kJ/kg-mol with CCl_4. With CH_3Br, heat of sorption was greater than the heat of condensation, with CCl_4 they were similar and with $(CH_2)_2Cl_2$ the heat of sorption was significantly less.

There have been no values published for E_s for whole grains. The data of Mitsuda et al. (1973) for sorption of CO_2 on polished rice and brown rice, fitted to equation (6), give heats of sorption of 16 000 and 18 000 kJ/kg-mol, respectively. (Their data for paddy give a poor regression: no value for E_s was calculated.) The heat of sorption was greater than the heat of condensation. Sato and Suwanai (1974) give data for variation with temperature of sorption of PH_3 on millet and polished rice but E_s values cannot be estimated as equilibrium had not been attained.

The quantity of fumigant retained at equilibrium by physical sorption can be expected to decrease with temperature, while the speed of reaction with grain constituents will increase, leading to higher residues with increasing temperature. This typical situation was noted by Lubatti (1944b) for HCN and may also be seen in the data of Mori and Oda (1961) with CH_3Br.

A survey of heat of sorption for various fumigants on whole grains is needed, in order to provide quantitative data for the prediction of the equilibrium quantity of fumigant sorbed for various temperatures. The latter is an important measure as it defines both the maximum uptake of fumigant and is essential for predicting the rates of uptake.

Rate of Sorption of Fumigants

Sorption of Unreactive Fumigants

Residual fumigant is typically lost rapidly from treated grain as soon as it is aired and then more slowly later. There may be detectable quantities of unchanged fumigant desorbing several weeks after the end of a fumigation, even with a volatile material such as PH_3 (Dumas 1980). Similarly, with sorption there is an initial rapid phase followed by a slower one. Sorption equilibrium may not be attained even with unreactive fumigants for more than 10 days at 20°C. When transformed semilogarithmically, data from either sorption from a constant concentration or desorption of fumigants into a freely aired space apparently give a linear trend after the initial stages. With reactive fumigants, the linear phase has been taken to reflect the rate of reaction of the fumigant with the grain (e.g. Scudamore and Heuser 1970). However, a similar trend is obtained even with fumigants that react little in comparison with the total sorbed or desorbed (Fig. 4, see also Bielorai and Alumot 1975) and thus it appears that this explanation is inadequate. Data for unreactive fumigants, including the initial phase, are well described by equations based on Fick's law of diffusion,

$$F = -D\frac{\partial c}{\partial x} \qquad (7)$$

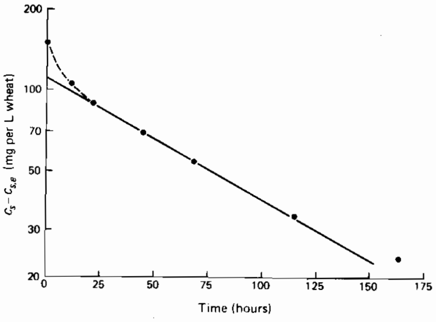


Fig. 4. Sorption of hydrogen cyanide by wheat from a constant concentration. Data of Lubatti and Smith (1948) cast in semilogarithmic form.

where F is the rate of transfer of the substance diffusing per unit area, D is the diffusion coefficient, and c is the concentration of the substance at the position x where diffusion is occurring.

Many authors have stated that uptake of fumigants into whole grains will be diffusion controlled. Three groups of workers, first Lubatti and Smith (1948), and later, without reference to earlier work by others, Park and Kyle (1975), Chang and Kyle (1979), and Noack et al. (1984a, b), have noted that, if this is so, then sorption should approximately follow

$$\frac{c_s}{c_{g,e}} = 1 - \frac{6}{\pi^2} \sum_{1}^{\infty} \frac{1}{n^2} e^{-\frac{D\pi^2 n^2 t}{r^2}} \qquad (8)$$

for a constant fumigant concentration in the free space. This equation, derived from Fick's law, describes the uptake of material by a spherical homogeneous particle of radius r, initially free of sorbed material, or loss from a particle, initially at an even concentration of sorbate, into air at zero

Table 3. Values of the group, D/r^2, for various fumigants and commodities.

Gas	Commodity	Sorption(S) or desorption(D)	Temp. (°C)	Moisture content (%)	D/r^2 (per hour)	Correlation coefficient (adjusted)	Number of observations	Data source
CCl_4	maize	D	10	?	2.94×10^{-3}	0.983	8	Scudamore and Heuser (1973)
CCl_4	maize	D	25	?	$6.65–7.72 \times 10^{-3}$	0.980–0.990	8	Scudamore and Heuser (1973)
CCl_4	wheat	D	10	?	$5.05–11.9 \times 10^{-3}$	0.948–0.968	8	Scudamore and Heuser (1973)
CCl_4	wheat	S	24	11–12	$3.44–3.97 \times 10^{-4}$	—	—	Park and Kyle (1975)
CCl_4	wheat	D	25	?	1.45×10^{-2}	0.998	8	Scudamore and Heuser (1973)
CCl_4	wheat	S	30	12.3	7.72×10^{-4}	—	—	Chang and Kyle (1979)
CCl_4	wheat	D	30	12.3	2.24×10^{-4}	—	—	Chang and Kyle (1979)
CCl_4	wheat	S	30	11–12	5.82×10^{-4}	—	—	Park and Kyle (1975)
CCl_4	wheat	S	36	11–12	8.20×10^{-4}	—	—	Park and Kyle (1975)
CCl_4	pearled wheat	D	30	12.3	7.14×10^{-4}	—	—	Chang and Kyle (1979)
CCl_4	pearled wheat	S	30	12.3	8.56×10^{-4}	—	—	Chang and Kyle (1979)
CO_2	brown rice	D	25	?	1.37×10^{-2}	0.992	9	Mitsuda et al. (1973)
CO_2	polished rice	D	25	?	9.61×10^{-3}	0.990	9	Mitsuda et al. (1973)
CO_2	peanuts	D	25	?	1.92×10^{-2}	0.969	9	Mitsuda et al. (1973)
$(CH_2)_2Br_2$	wheat	D	10	9	1.10×10^{-2}	0.924	8	Sinclair et al. (1962)
$(CH_2)_2Br_2$	wheat	D	32	9	8.57×10^{-3}	0.912	10	Sinclair et al. (1962)
HCN	wheat	S	20	13	8.39×10^{-4}	0.9995	7	Lubatti and Smith (1948)
CH_3Br	wheat	D	5	13	6.91×10^{-3}	0.976	6	Scudamore and Heuser (1970)
PH_3	wheat	D	20	14.6	$4.68–7.91 \times 10^{-4}$	0.929–0.967	5–6	Noack et al. (1983)
PH_3	milled rice	S	25	11	2.64×10^{-2}	0.834	6	Sato and Suwanai (1974)

? = moisture content not specified.

concentration of the material. Strictly, it does not apply where there is irreversible reaction of the sorbate within the particle and it is inappropriate under conditions of changing free space concentration as occurs in most well-filled, closed systems under fumigation. Table 3 summarises the data available on sorption or desorption of fumigants fitted either to equation (8) or to the equivalent expression,

$$\frac{c_s}{c_{g,e}} = \frac{6}{\pi^2} \sum_{1}^{\infty} \frac{1}{n^2} e^{-\frac{D\pi^2 n^2 t}{r^2}} \qquad (9)$$

where the data are in the form relating loss of concentration of sorbate with time (Chang and Kyle 1979).

It can be seen that for large values of t, when the first term in the summation becomes dominant, equation (9) simplifies to

$$c_s = c_{s,e}\, \alpha\, e^{-\beta t} \qquad (10)$$

where α and β are constants. Thus, as observed by Bielorai and Alumot (1975), Jagielski et al. (1978), and Lubatti and Smith (1948), the residue of unreactive fumigants is approximately an exponential function of time, after an initial, more rapid decay. Bielorai and Alumot (1975) found that the airing of various halogenated hydrocarbon fumigants from grains and pulses could be described well by

$$c_s = c_{s,1}\, e^{-k_1 t} + c_{s,2}\, e^{-k_2 t} \qquad (11)$$

where $c_{s,1}$ and $c_{s,2}$ are taken to be the initial concentration of 'firmly bound' and 'loosely bound' fumigant and k_1 and k_2 the respective loss rate constants. In effect, this equation is equivalent to equation (9) with only two terms of the summation considered.

Table 3 summarises values of the group, D/r^2, obtained either by fitting equation (8) or (9), as appropriate, to published data or directly from published values of D and r. It can be seen from equations (8) and (9) that it is not necessary to estimate D and r individually in order to be able to predict sorption-desorption behaviour for a particular grain, since these parameters occur together. There are as yet insufficient data available to show whether the value of D is specific to a particular grain and fumigant or whether a general theory independent of grain type is appropriate.

Since almost all desorption data available relates to grain which has not achieved sorption equilibrium, data for CO_2 being a notable exception, it is to be expected that equation (9) will not be followed exactly. Generally, the fitted curve for desorption gives a low estimate of the residue present at the start of airing and shows some systematic deviation from the data in the middle of the desorption period (Fig. 5). These deviations are probably an artefact of the curve-fitting procedure as it attempts to accommodate the higher-than-expected initial desorption by compromising on goodness-of-fit in other parts of the data.

Data obtained for sorption from a constant concentration (Fig. 6) or for desorption from grain

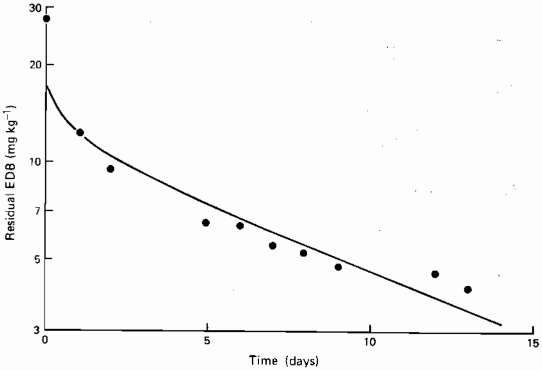


Fig. 5. Desorption of ethylene dibromide by wheat with time, fitted to equation (9). Data of Sinclair et al. (1962).

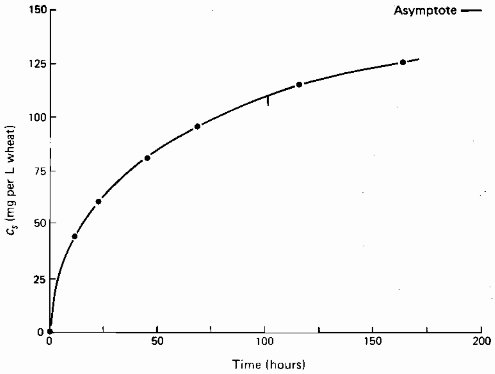


Fig. 6. Data of Lubatti and Smith (1948) for sorption of hydrogen cyanide by wheat from a constant concentration (15 g/m³), fitted to equation (8).

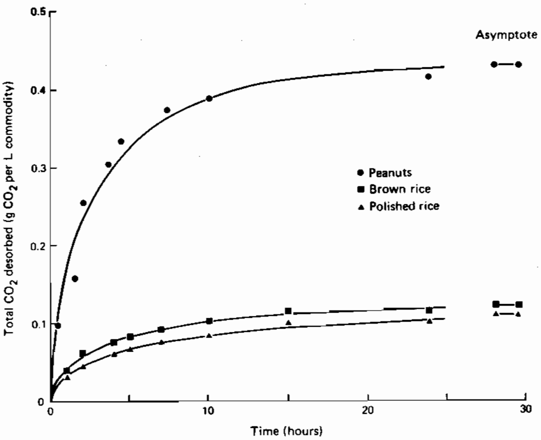


Fig. 7. Data of Mitsuda et al. (1973) for desorption of CO_2 from various commodities, fitted to equation (9).

that has achieved sorption equilibrium (Fig. 7) are well described by equations (8) and (9) (see also Chang and Kyle 1979) and there can be little doubt that these equations reflect the basic process occurring in sorption-desorption of fumigant on grains.

Sorption of Reactive Fumigants

Appropriate mathematical descriptions of diffusion-controlled sorption or desorption of fumigants with concurrent reaction are not yet available, so empirical equations will have to suffice at present for the description of these systems.

Winteringham and Harrison (1946) produced an empirical model for the sorption of CH_3Br by wheat from a constant concentration followed by decomposition of the sorbed material assuming no loss. While the circumstances which the model describes are unlikely to occur in practice, the theoretical framework introduced is valuable. In particular, they note that at any instant the rate of reaction is proportional to the concentration of physically sorbed gas. Assuming no loss by desorption from the grain, the concentration of CH_3Br in the grain would follow:

$$\ln (c_{s,o} - c_r) = \ln c_{s,o} - kt \tag{12}$$

where k is the rate constant for the decomposition treated as a first-order irreversible reaction, $c_{s,o}$ is the concentration of sorbed gas at $t = 0$, and c_r is the quantity of residue formed. Several workers have used this equation to describe the rate of reaction of CH_3Br with grains. Unfortunately, the observed value of k, the slope of the semilogarithmic curve describing the decrease in free CH_3Br with time, is not truly a measure of the reaction rate. Desorption also gives a linear trend with time under semilogarithmic transformation at large values of t and thus the observed slope is a combination of the rate of reaction with some function of the diffusion constant. In practice there is usually little difference between grain freely aired and that where loss of CH_3Br is prevented (Table 4), suggesting that the observed value of k is approximately that for reaction alone.

Assuming irreversible first order kinetics of decomposition after physical sorption equilibrium has been attained, the rate of loss of CH_3Br from the free space of a closed system can be shown to follow:

$$\ln c_g = \ln c_{g,o} - k't \tag{13}$$

where k' is related to the first order rate constant for the decay by

$$k' = fk. \tag{14}$$

where f is the filling ratio. The data of Soma et al. (1978) illustrate the constancy of k calculated from

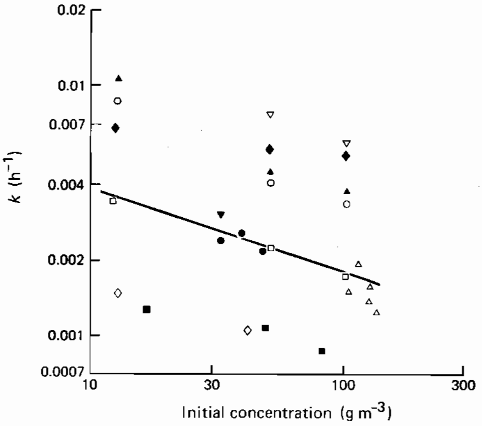


Fig. 8. Values of the apparent reaction rate constant for methyl bromide on grain showing range observed and variation with initial concentration (line fitted to data of Soma et al. (1978), ●, and Zakladnoi and Myl'nikova (1977), □, for wheat of 20°C, 12% m.c.). Other data: Berck 1961 (9°C, 15.8%, ◇); Lubatti and Harrison 1944 (20°C 13.2%, △); Soma et al. 1978 (5°C, 11.87%, ■); Whitney 1963 (26°C, 12–13%, ▼); Zakladnoi and Myl'nikova 1977 (10°C, 15%, ○; 20°C, 15%, ▲; 20°C, 17%, ◆; 30°C, 15%, ▽).

Table 4. Apparent rate constants for methyl bromide loss from cereals either exposed in thin layers or sealed in glass jars (from Scudamore and Heuser 1970).

Commodity	Temperature (°C)	Moisture content (%)	Loss rate constant (per hour) Sealed	Loss rate constant (per hour) Freely aired
Paddy rice	25	12.4	0.046	0.127
Sorghum	25	13.3	0.033	0.038
Wheat	25	11.4	0.088	0.088
	5	13.0	0.017	0.025
Yellow maize	25	14.3	0.042	0.046
	5	12.4	0.017	0.021

Table 5. Rate constants for sorption of methyl bromide. Derived from data of Soma et al. (1978).

Commodity	Moisture content (% w.b.)	Filling ratio f	Apparent rate constants (per hour) Observed k'	Apparent rate constants (per hour) Corrected k
Soybeans	11.6	0.136	0.0066	0.0485
		0.407	0.0172	0.0423
		0.678	0.0399	0.0588
Wheat	11.8	0.125	0.0030	0.0240
		0.375	0.0095	0.0253
		0.625	0.0148	0.0237
Yellow maize	13.0	0.133	0.0054	0.0408
		0.400	0.0150	0.0376
		0.660	0.0201	0.0304

k' for various filling ratios (Table 5). Again, the observed value of k' will in practice be a combination of effects of reaction and diffusion. It will be noted that equation (14) is the mathematical explanation of the observed increase in rate of sorption with increase in 'load factor.' A number of papers (e.g. Sinclair and Lindgren 1958; Soma et al. 1978) have investigated the effect of load factor, apparently without realising that it is very simply explicable.

Values for the apparent rate of decomposition of CH_3Br and PH_3 on grain, corrected to refer to a completely filled system, $f = 1.0$, are given in Fig. 8 and Table 6, respectively. These values are useful as an indication of the rate at which fumigant will be taken up after the so-called 'rapid initial phase' of sorption and also as a guide to what total residue will remain after a given time. A full description must await development of a model based on a combination of the kinetics of reaction and diffusion and measurement of isotherms to determine the magnitude of sorption.

Table 6. Apparent rate constants for phosphine reaction on wheat.

Temperature (°C)	Moisture content (% w.b.)	Apparent rate constant[a] (per hour)	Data source
20	11.6	0.0033	El-Lakwah (1978)
24	15	0.0064	Berck (1968)
35	15	0.0186	Berck (1968)

[a] For a full container.

Influence of Temperature on the Rate of Sorption and Desorption

The temperature dependence of the rate of a chemical process is given by the Arrhenius equation

$$k = A\,e^{-\frac{E_a}{RT}} \qquad (15)$$

where E_a is the energy of activation of the process and k is its rate constant or the diffusion coefficient, and A is a constant known as the frequency factor. A similar equation describes the temperature dependence of the diffusion constant, D.

The data of Soma et al. (1978) for sorption of CH_3Br on wheat (11.8% m.c.) gives the trend shown in Fig. 9, corresponding to an activation energy of 40 000 kJ/kg-mol. Data of Zakladnoi and Myl'nikova (1977) show a similar result. The activation energy for sorption of $(CH_2)_2O$ on wheat at 13% is 64 000 kJ/kg-mol (derived from Lubatti 1944a). Park and Kyle (1975) found an activation energy of 50 000 kJ/kg-mol for the diffusion coefficient of CCl_4 with wheat.

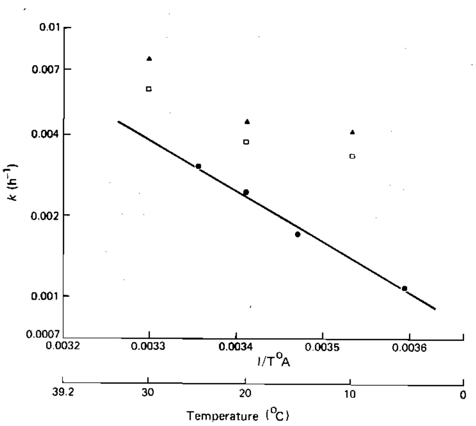


Fig. 9. Change of apparent rate constant with temperature for wheat of 11.8% with 49.0 g/m^3 initial dosage of methyl bromide (●, data of Soma et al. 1978) and of 15% with 50.8 and 101.6 g/m^3 (▲, □, respectively, data of Zakladnoi and Myl'nikova 1977).

The influence of temperature on the rate of desorption of fumigants has been investigated by several groups of workers but as yet there is no definitive work on the subject. The research has been confounded by difficulties in determination of residues of the halogenated hydrocarbon fumigants on grain. The extractability of these materials varies with the fumigation history and temperature of the grain (Dumas and Bond 1979) and this effect may invalidate much early work on this subject. Dumas and Bond (1979), working with ethylene dibromide [$(CH_2)_2Br_2$] and Bielorai and Alumot (1975) working with $(CH_2)_2Br_2$, CCl_4, chloroform ($CHCl_3$), and trichlorethylene (CCl_2CHCl) found that grain fumigated briefly (48 hours or less) lost fumigant more rapidly at lower temperatures than at higher ones. In contrast, Jagielski et al. (1978) using CCl_4 and $(CH_2)_2Br_2$ on various grains with exposures of 72 hours or 7 days confirmed the results of Scudamore and Heuser (1973) and found the rate of loss of residue to increase with increasing temperature. A simple diffusion-controlled phenomenon may be expected to have such a positive temperature coefficient. The observations of Dumas and Bond (1979) and Bielorai and Alumot (1975) are thus apparently not consistent with a simple diffusion theory for fumigant uptake and loss. However, their data relate to non-equilibrium distribution of fumigant in the grain, fumigant presumably restricted largely to the outer layers of the grain, and the observations may be simply explained when the influence of such a situation is modelled using the mathematics associated with diffusion.

Influence of Concentration on Rate of Sorption

In the simplest case, the diffusion coefficient and thus the rate of physical sorption is independent of concentration of the gas being sorbed. This has been found to be so for sorption of CCl_4 by whole wheat (Park and Kyle 1975), but not for PH_3 sorption on hazelnuts (Noack et al. 1984b). In the latter case, the apparent variation with concentration may be a consequence of the combination of diffusion with reaction.

With reactive fumigants, if the Freundlich isotherm index n = 1.0, then the sorbed concentration is proportional to the free concentration of gas. For an irreversible pseudo-first order reaction the value of the rate constant should then also be directly related to the free concentration under these conditions. For CH_3Br, the only fumigant for which adequate data are available, this appears not to be so. The apparent rate constant varies ($r^2 = 0.96$) with the initial concentration according to the empirical equation (see Fig. 8):

$$k = 0.08\ (c_{g,o})^{-0.33} \qquad (16)$$

for data of Soma et al. (1978) and Zakladnoi and Myl'nikova (1977) for wheat at 20°C and 12% m.c.

Variation of Diffusion Coefficient with State of Subdivision

There are statements in the literature that the permeability of the seed coat may control the rate of sorption-desorption. For instance, Lubatti (1945) states 'seed coats . . . appear to be the main factor controlling sorption.' Usually, the belief that the seed coat is rate-limiting is based on the observation that ground products take up or release fumigant much faster than whole grains. However, it makes no allowance for the change in particle size, one of the controlling parameters in diffusion-controlled sorption (see *r* in equation (8)) and there may, in fact, be no true effect attributable to the seed coat.

There are few useful data available on this problem. However, Winteringham (1944), in an elegant experiment, showed that while $(CH_2)_2Cl_2$ was sorbed slowly by whole wheat, wheat carefully cut in half with a sharp scalpel sorbed at a higher rate. The rate was higher still for milled products (ratio of quantity sorbed after 24 hours at 20°C of halved and ground wheat to whole wheat, 1.8 and 5.1 respectively). Even scraping the seed coat with abrasives may cause an increase in rate of sorption (Lubatti 1945). Chang and Kyle (1979) found no appreciable difference in diffusion coefficient for sorption of CCl_4 on whole or pearled wheat (Table 3) but, unexpectedly, found desorption to vary with state of the grain: the diffusion coefficient estimated from desorption of pearled wheat was similar to that of sound grain, but the coefficient for desorption from sound grain was about a third of the value (i.e. desorption was slower).

Sato and Suwanai (1974) found that the quantity of PH_3 taken up under fixed exposure conditions could be related to the surface area of the grain and was independent of the grain type. They consequently inferred that PH_3 sorption is controlled by surface adsorption. However, their data on sorption of PH_3 on milled rice and brokens of various sizes are consistent with the variation in quantity sorbed expected for a change in *r* and fixed value of *D* (Fig. 10) and thus do not conclusively show that surface adsorption is involved.

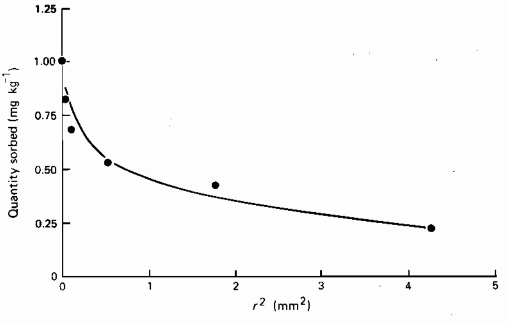


Fig. 10. Variation of quantity of PH_3 sorbed from 0.37% v/v phosphine after 48 hours by various sizes of particles of milled rice, fitted to equation (9). Data of Sato and Suwanai (1974).

Closely controlled experiments, taking into account such factors as change in particle size and surface adsorption, are needed to investigate the variation of *D* with state of subdivision and seed coat damage of various grains and to show what contributions diffusion, surface adsorption, and reaction make to the sorption dynamics of fumigants in grains.

Summary

It is clear that the quantitative data on the rate and magnitude of sorption-desorption on grains are fragmentary and there is need for much further work in order to provide a full and consistent picture of the process. However, despite this, the conceptual bases on which to plan suitable experiments are clear: the uptake of non-reacting fumigants can be described in terms of diffusion-controlled physical sorption (equations (8) and (9)), the possible magnitude of the physical sorption is quantified by isotherms such as equation (1), and its variation in magnitude with temperature by equation (7) and in rate by equation (15). Where sorption is accompanied by irreversible chemical reaction, the rate of reaction is given by equation (13) and its temperature dependence by equation (15). The combination of the diffusion equation and chemical reaction to give a solution for sorption-desorption of reactive fumigants is mathematically complicated, but is currently being attempted. A solution in terms of the diffusion coefficient and reaction rate constant, and application of the diffusion equation to non-equilibrium conditions may provide an explanation for the variation of the various parameters with concentration and time of exposure.

Any studies on sorption should include studies on the changes in the controlling parameters with water activity if the data are to be of general utility.

Most sorption studies on whole grains have used wheat as a substrate and have investigated the behaviour of halogenated fumigants. The range needs broadening. Studies with rice and with PH_3 are notably lacking. Comparative studies using grains of different sizes and proportion of constituents may show whether the value of the diffusion coefficient for a particular fumigant under fixed conditions is general or particular for a particular species or variety of seed. Such studies should also show whether the equilibrium quantity of sorbate is predictable from the constituent analysis of the grain.

With a knowledge of the values of the controlling parameters and how they affect sorption-desorption as set out in this paper it should be possible to predict the rate of gain or loss of gas from grains under fumigation, subject to a particular free space concentration and taking into account the immediate previous exposure history. This may well require numerical solution of the diffusion equation, a quite straightforward procedure given the readily available computer programs, as there may be no simple analytical solutions for the particular conditions. Incorporation of this submodel into the descriptions of distribution of fumigants by convection, forced distribution, and diffusion within enclosures, and descriptions of gas loss from structures should lead to a valid model of a fumigation, predicting the gas concentration at any point in the enclosure and its variation with time.

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Movement of Fumigants in Bulk Grain

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Abstract

Fumigation and controlled atmosphere techniques of insect control in stored grain are receiving widespread interest as alternatives to grain protectants. In many cases, the practice of fumigation relies on convection currents to carry and distribute the gas throughout the sealed grain store. A basic understanding of fumigant movement by natural convection is therefore essential in grain storage technology. A transient mathematical model that has been developed to simulate the flow patterns and temperature distribution in grain stores is described. The main variables that can be studied using this computer model are: type, shape, and orientation of storage structure; physical and thermal properties of grain; initial temperature of grain; and ambient temperature. These studies reveal the most basic features of the temperature field and fumigant flow patterns established in the grain store. They also enable the selection of the most suitable locations for the introduction of the fumigant.

In Australia and elsewhere, many of the insect control measures in current use for stored grain are rapidly becoming unacceptable, either through development of insect resistance, or because of the need to restrict pesticide residues on grain. Fumigation and controlled atmosphere techniques have so far received most attention as alternative methods of grain disinfestation. The concept is simple: gases are added to alter the atmosphere to which insects are exposed within an enclosure. The gases may be either specific poisons, such as methyl bromide or phosphine, or particular atmospheric constituents, such as CO_2 or nitrogen, which at abnormally high concentrations are toxic or will not support insect life. The treatment must be maintained for long enough and the enclosure should be gastight. The enclosure may be either a permanent structure, such as a grain store, or a temporary system, such as a fumigation tent or a plastic-covered bunker.

In the last thirty to forty years, there have been many theoretical and experimental studies of the transport processes in saturated porous media (see Cheng 1978). These studies have shed considerable light on the nature of natural convection in porous media over a broad range of different fields and applications, including industrial drying and catalysis, geothermal systems, and nuclear engineering. A few papers (e.g. Chan and Banerjee 1981; Bejan and Poulikakos 1982) have been published on transient heat transfer in packed beds or in irregularly shaped structures. There have been even fewer fundamental studies on how natural convection in stored grain affects the transient character of the gas flow pattern, the movement of fumigants, and the temperature distribution (see Yaciuk et al. 1975).

The physical factors affecting fumigant movement and moisture migration by natural convection can be studied empirically by taking measurements in grain stores. These experimental studies can be complemented by the more rapid and less expensive method of simulation. By using a mathematical model, various factors can be studied separately or in selected combinations while others are kept constant. The model used to simulate such physical phenomena must be based on the analysis of heat, mass, and momentum changes in the grain store (Nguyen 1985). The rates at which these simultaneous changes occur depend mainly on the initial conditions of the grain, on boundary conditions such as ambient temperature fluctuations, and on the type and shape of the storage structure.

The main objective of this paper is to present the results of a transient analysis of fumigant movement in grain storages of different shape and with various boundary conditions applying. Starting with a set of basic differential equations describing the laws governing heat and momentum transfer in hygroscopic porous media, generalised equations were developed and verified with experimental results (Nguyen and Close 1985) for use in simulation studies.

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Simulation Methods

Consider a grain bed of permeability κ and porosity ε which is subject to a temperature difference ΔT and pressure P. The moving gas has thermal expansion coefficient β, heat capacity $(\rho C_p)_f$, and dynamic viscosity μ.

The appropriate generalisation of Darcy's law, when the transient term is included, can be written as follows:

$$\frac{\rho_f}{\varepsilon}\frac{\delta \underset{\sim}{V}}{\delta t} = -\,\text{grad}\,P + \rho_f \underset{\sim}{g} - \frac{\mu}{\kappa}\underset{\sim}{V} \qquad (1)$$

Introducing Boussinesq's approximation, and a vorticity ζ defined by $\zeta = \delta v/\delta x - \delta u/\delta y$, where u and v are the x and y components, respectively, of $\underset{\sim}{V}$, equation (1) becomes

$$\frac{\rho_f}{\varepsilon}\frac{\delta \zeta}{\delta t} - \beta g \rho_f \frac{\delta T}{\delta x} - \frac{\mu}{\kappa}\zeta \qquad (2)$$

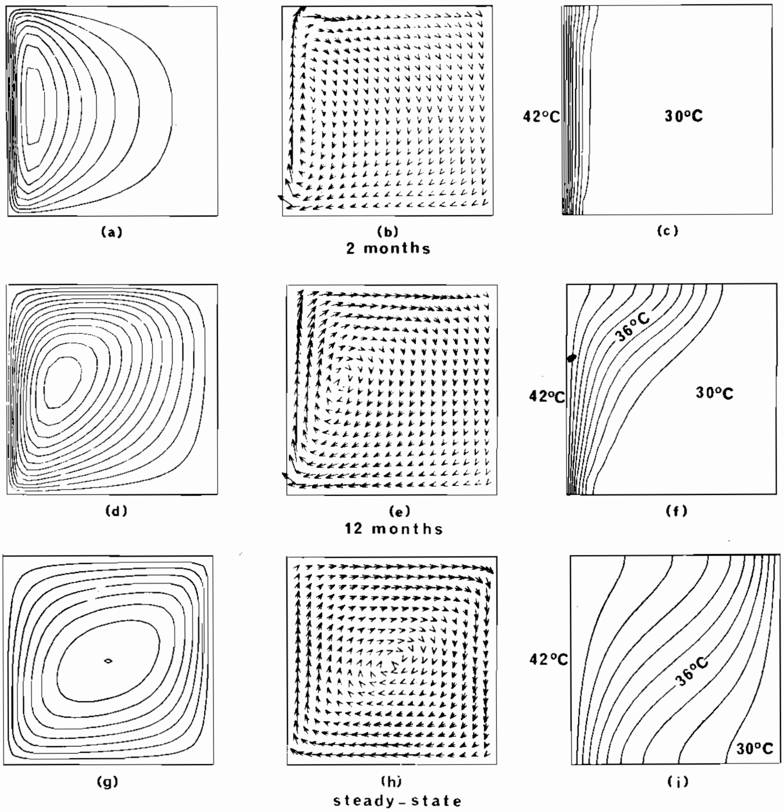
From the equations of Combarnous and Bories (1975), energy balances taken for both phases yield:

$$\varepsilon(\rho C_p)_f \frac{\delta T_f}{\delta t} = -(\rho C_p)_f\, u \frac{\delta T_f}{\delta x} - (\rho C_p)_f\, v \frac{\delta T_f}{\delta y} + k_f^*\left(\frac{\delta^2 T_f}{\delta x^2} + \frac{\delta^2 T_f}{\delta y^2}\right) + A_{uv}\, h_c (T_s - T_f) \qquad (3)$$

$$(1 - \varepsilon)(\rho C_p)_s \frac{\delta T_s}{\delta t} = k_s^*\left(\frac{\delta^2 T_s}{\delta x^2} + \frac{\delta^2 T_s}{\delta y^2}\right) + A_{uv}\, h_c (T_f - T_s) \qquad (4)$$

where k_f^* and k_s^* are the effective thermal conductivities of the gas and the grain, respectively.

Equations (2) to (4) expressed in a non-dimensional form (for more details, see Nguyen and Close 1985), together with the Poisson



(a) (b) (c)
2 months

(d) (e) (f)
12 months

(g) (h) (i)
steady-state

Fig. 1 Circulation patterns and temperature distributions in a grain store heated from the side: (a), (d), (g), streamlines; (b), (e), (h), vector plots; and (c), (f), (i), isotherms.

equation, were converted to discrete form by replacing the spatial derivatives with second-order central difference approximations and the time derivatives with forward difference approximations.

The resulting finite difference equations were then solved by the Alternating Direction Implicit (ADI) scheme. A combined Fourier Analysis — Fast Fourier Transform (FA-FFT) direct method was used to solve the Poisson equation whenever appropriate.

Results and Discussion

Results were obtained for rectangular, horizontal, and bunker storages. The grain was assumed to have an initial, uniform temperature of 30°C. Most of the results are transient, but some are at steady state, i.e. a particular pattern of circulation and temperature distribution has established itself.

In Fig. 1, typical results are shown for the case of a 10 m x 10 m grain store with one vertical side heated regularly by the sun's radiation for a period of 10 hours/day. In these and later diagrams, the results are plotted at the end of the heating periods. As can be seen in Figures 1(a) and (d) the convection currents are still developing after 12 months of storage and are confined to the region near the hot wall. At this stage, the flow is still parallel to the hot wall along most of its extent. The core region of the flow moves slowly towards the centre of the enclosure and eventually establishes itself as shown in Fig. 1(g). The development of the convective motion is slowed down considerably by the discontinuous heating imposed on the boundary.

The velocity of the flow is represented by the lengths of the arrows in Fig. 1(b), (e), and (h). The

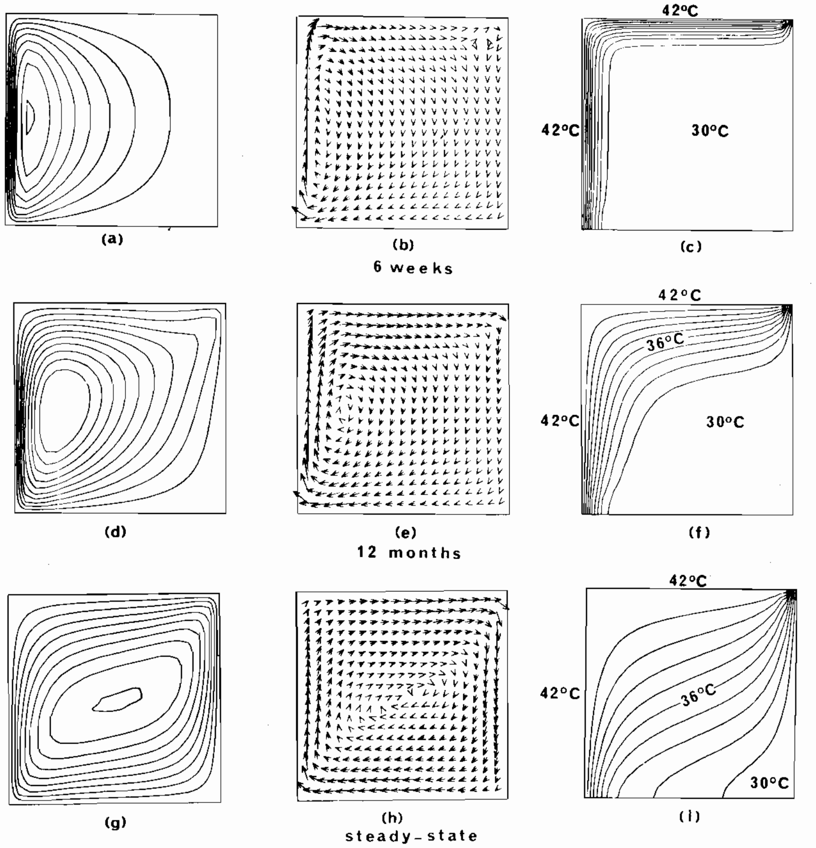


Fig. 2 Circulation patterns and temperature distributions in a grain store heated from the side and top. (a), (d), (g), streamlines; (b), (e), (h), vector plots; and (c), (f), (i), isotherms.

flow at early stages is strongest near the hot wall and diminishes away from it, whereas at steady state the flow is quite uniform along all sides of the enclosure. Fumigation of grain stores under similar conditions will effectively be enhanced by natural convection within the first year of storage if the fumigant is introduced along the hot wall. Conduction plays an important role in establishing the temperature distribution in the grain bulk until the flow is more established. The isotherms [Fig. 1(c), (f), and (i)] are then distorted by the convection currents resulting in a warmer region of grain near the top left corner.

Fig. 2 shows the results for a grain store running east-west. The left wall and the roof are heated by sunshine during daytime and are assumed to be at ambient temperature for the rest of the day. In the early stages, the flow pattern is similar to the previous case, in that the flow region is confined to the hot wall and progressively moves away to the centre. However, the gas velocity along the roof is slightly higher and the flow is no longer symmetrical about the centre. Again the distribution of a fumigant would be enhanced if it were introduced near the hot wall.

For a well-sealed, horizontal shed running in a north-south direction with sunshine on both sides of the roof and plastic covers on the grain surface, the gas circulation pattern and the temperature distribution caused by natural convection are shown in Fig. 3. Warm air rises along each side of the roof and gives up heat to the grain in the region below the ridge, resulting in two small convection cells which rotate in opposite directions. The cells do not increase markedly in size and tend to remain close to the roof. The gas velocity is strongest just below the roof surface and is parallel to it. A fumigant would therefore be best introduced at the midpoints of both sides of the roof. The influence of natural convection on the grain temperature distribution in this case is not noticeable.

In Fig. 4, the long axis of the storage shed runs east-west. The core flow is driven primarily by the horizontal temperature gradient generated by one hot wall*. The change in the orientation of the storage produces a considerable change in flow structure, as indicated by comparing Figs. 3 and 4. The single cell driven by the buoyancy-induced forces in the thermal boundary layer region now extends to most of the grain bulk. As expected, the region of largest vertical velocity is confined close to the vertical wall and the major portion of the temperature drop occurs across the core. The distribution of fumigant in these east-west storages would be more effective and more rapid than in the ones running north-south. The fumigants are carried by convection currents throughout

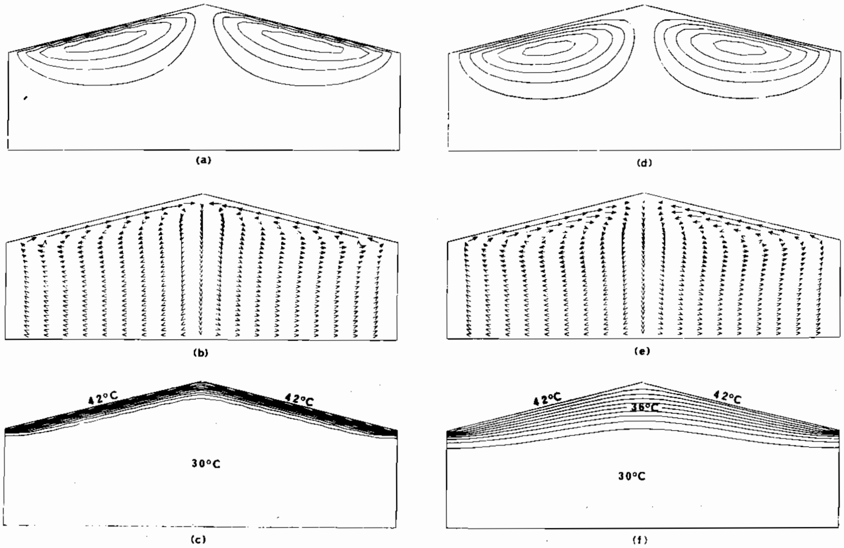


Fig. 3 Circulation patterns and temperature distributions in a north-south orientated horizontal grain store after 6 weeks and 12 months of storage. (a), (d), streamlines; (b), (e), vector plots; and (c), (f), isotherms.

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* The northern wall in the Southern Hemisphere and vice versa.

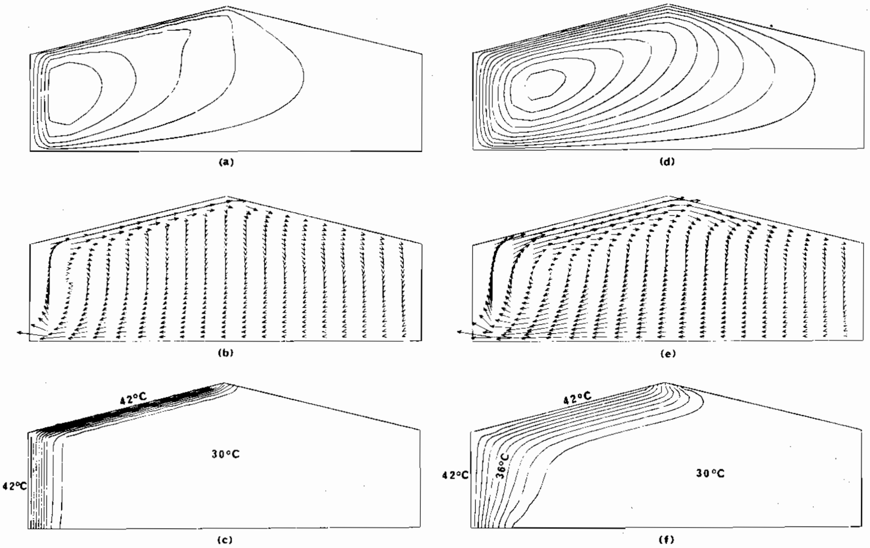

Fig. 4 Circulation patterns and temperature distributions in an east-west orientated horizontal grain store after 6 weeks and 12 months of storage. (a), (d), streamlines; (b), (e), vector plots; and (c), (f), isotherms.

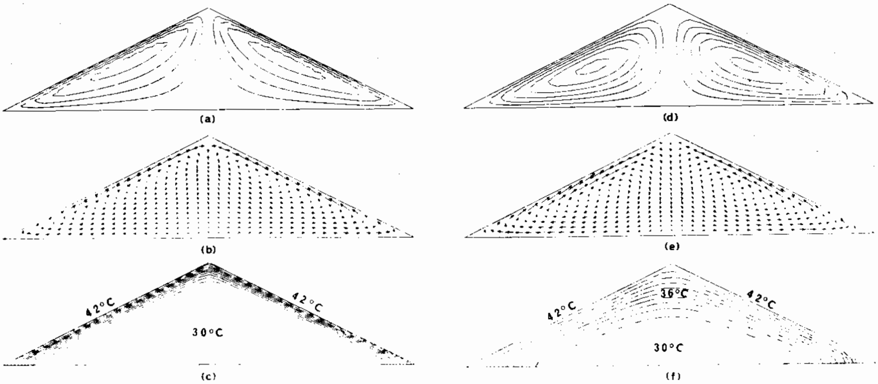

Fig. 5 Circulation patterns and temperature distributions in a north-south orientated bunker storage after 6 weeks and 12 months of storage. (a), (d), streamlines: (b), (e), vertical plots; and (c), (f), isotherms.

most of the grain bulk with greater speed.

Similar circulation patterns develop in bunker storages, as shown in Fig. 5. The temperature gradients that exist along the whole length of both sides of the roof produce two counter-rotating convection cells. The cells occupy the whole storage and the gas velocity is generally even throughout the grain bulk. Bunkers therefore appear to be the best type of grain storage for fumigation purposes.

Fig. 6 is a plot of gas velocity as a function of vertical distance along the hot wall for the case of a single-cell structure. It is obvious that as the circulation develops the maximum gas velocity increases and shifts its position. Generally, for these types of storages, fumigants should be introduced at a point somewhere in the middle one-third of the hot vertical wall.

Summary and Recommendations

This paper presents the results of a numerical

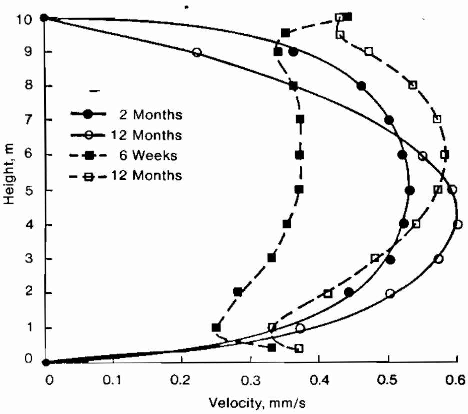

Fig. 6 Gas velocity along the vertical hot wall of a grain store. Solid lines: rectangular enclosures, heated left wall. Broken lines: horizontal storage, heated left wall and roof.

study of the movement of fumigants and the temperature field in grain stores. The fundamental objective was to document the basic features of gas circulation patterns and temperature distributions in various grain storage structures. The engineering objective was to determine the effect of natural convection on the movement of fumigants, to assist in laying down guidelines for the most effective fumigation procedures.

The study was carried out on three storage structures subjected to 10 hours of sunshine each day. It is shown that the grain store contains a single convection cell driven by the development of horizontal temperature gradients and two identical cells, which rotate in opposite directions, by non-horizontal temperature gradients. It is also shown that the circulation pattern is greatly influenced by the temperature fluctuation. The gas velocity reaches its peak midway along the hot wall, and the grain in the top left region is always warmer than the rest of the bulk.

Based on these observations, fumigation of grain stores would be enhanced by natural convection if the fumigant were applied correctly. Fumigant should be introduced along the hot wall for a single-cell structure and under both roofs for a double-cell structure. The north–south bunker configuration was found to be the most affected by natural convection and therefore the most effective for fumigation purposes.

This was an idealised study of the phenomenon of buoyancy-driven circulation in grain stores. Further research could usefully proceed along the following lines:

(1) The incorporation into the model of the effect of concentration gradients on the movement of fumigants;

(2) Consideration of sorption and desorption of fumigants, as well as moisture migration;

(3) Computation based on more realistic thermal boundary conditions, especially diurnal temperature fluctuations, and more accurate initial conditions of grain.

Acknowledgment

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Nomenclature

A_{uv}	surface area of spheres per unit volume of bed	units/m
c_p	specific heat of fluid	J/kg/K
g	gravitational acceleration	m/sec/sec
h_c	fluid-to-particle heat transfer coefficient	W/m^2/K
k_f^*	effective conductivity of gas	W/m/K
k_s^*	effective conductivity of grain	W/m/K
P	pressure	Pa
T_f	temperature of gas	K
T_s	temperature of grain	K
u	velocity in x direction	m/sec
v	velocity in y direction	m/sec

V	seepage velocity	m/sec
x, y	coordinates	m
β	coefficient of volumetric expansion	K^{-1} units/K
ΔT	temperature difference between isothermal surfaces	K
ε	void fraction of grain bed	—
κ	permeability of grain bed	m^2
ρ_f	density of gas	kg/m^3
μ	viscosity of gas	$N/sec/m^2$
ζ	vorticity	units/sec

Action and Inaction of Fumigants

N.R. Price*

Abstract

Although the mode of action of contact insecticides has been much studied and written about, there are few reports of studies on the mode of action of fumigants on insect pests. Because of the recent development of resistance to fumigant gases, and the urgent need to investigate this phenomenon, it has become important to understand some of their characteristic effects. A review of the available information concerning the physiological and biochemical effects of some of the common fumigants is presented, along with more recent studies on the action of, and resistance to, phosphine in stored-product insects.

IN any consideration of their biochemical action, the fumigants are usually dismissed broadly as respiratory inhibitors, anaesthetics, or narcotics. Because of the physical properties required of a fumigant they are simple molecules, but they can exert a complex range of effects on the biochemistry of the target organism. With the recent concern over the adverse toxicological properties of some fumigants, together with the development of resistance to fumigants in insects, it is becoming more important to understand something of the toxic action of these compounds. The effective use of existing fumigants and the development of new fumigants and fumigant mixtures now has a high priority. Knowledge about their toxicological actions can help to devise safe and effective control strategies and to forecast and perhaps circumvent the development of resistance.

The development of resistance to an insecticidal compound may be due to the selection of a number of biochemical and physiological factors. Firstly, insects may acquire a behavioural trait which causes them to avoid the toxin; in the case of fumigants this may be manifested as a movement away from high concentrations of the gas. Entry of the fumigant into the insect may be impaired in resistant strains, and this will be dealt with in detail later.

Once inside the insects, a number of biochemical mechanisms may render the fumigant less toxic. The biochemical site of action of the fumigant may be less sensitive, in the same way that some insects resistant to the anticholinesterase insecticides have an altered acetylcholinesterase (Devonshire and Moores 1984). Also, the fumigant may be detoxified by a range of enzymes, or may simply be expelled from the body by excretion or by diffusion back through the respiratory tract.

This paper will consider what is known about the way in which fumigants act and the possible mechanisms of resistance to fumigant gases.

Carbon Tetrachloride, Ethylene Dichloride and Ethylene Dibromide

These compounds are the most common liquid fumigants. Ethylene dichloride (EDC) and ethylene dibromide (EDB) are not true ethylenes. They are correctly 1, 2 dichloroethane and 1, 2 dibromoethane. Carbon tetrachloride (CTC) has been widely used as a fumigant on stored grain but because of its generally low toxicity to insects has often been mixed with more potent fumigants such as EDC and EDB. Much of the work on the toxic action of CTC concerns long-term hepatotoxicity in mammals; studies which may lead to restrictions on its use as a fumigant. In recent years, the toxicity of CTC has been attributed to the formation of the reactive CCl_3 radical. Mixed function oxidases normally associated with the detoxication process cleave the CCl_3-Cl bond to release the radical, resulting in peroxidation of membrane lipids and catastrophic biochemical lesions. The toxic action of CTC in insects may be similar. Patton and Sarkaria (1958)

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observed gross pathological damage to cockroach malpighian tubules and fat body which was reminiscent of mammalian liver damage caused by CTC. Insects poisoned with CTC show a number of physiological symptoms. In the early stages, respiration was stimulated in *Tribolium castaneum* (Bang and Telford 1966), but in common with observations on cockroaches (Bhatia 1976), the overall effect on oxygen consumption was inhibitory. Bhatia also reported desiccation of the insects due to the effect of CTC in opening the spiracles, and it may be that water loss from the insect plays an important part in the toxic action of this fumigant.

Despite the chemical similarity of EDC and EDB their effects on insects appear to be different. EDC rapidly induces narcosis (Winteringham and Barnes 1955), whereas no such effect was noted in the early stages of EDB poisoning. EDC and EDB are also the subjects of considerable study of chronic mammalian toxicity but how these findings relate to the toxicity to insects is unknown. Earlier studies have shown that a number of insect enzyme systems are affected by EDC or EDB. Both EDC and EDB have been found to inhibit house fly succinate dehydrogenase (Pant 1958), an enzyme important in cellular energy production (Fig. 1), though neither compound produced a reduction in overall ATP levels. The observed reduction in total glycolysis produced by EDB was attributed to a blocking of the SH groups in phospho-glyceraldehyde dehydrogenase (Fig. 1). Inhibition of this same triosephosphate dehydrogenase was noted by Morikawa (1964), who also reported that the enzyme inhibition was paralleled by the onset of poisoning symptoms. In contrast, EDC was found to have a slight stimulatory action on glycolysis (Pant 1958). Both EDC and EDB have been reported to block SH groups but the evidence is often contradictory. Lewis (1948) was unable to detect any such effect due to EDB in larvae of *Calliphora erythrocephala* although EDB has been found to interact with SH groups 'in vitro', notably in papain (Lewis 1948) and glutahione (Hirade and Ninomiya 1950). The protective action of cysteine, methionine and other sulphydryl compounds action of EDC suggests that this compound may indeed block SH groups 'in vivo' (Heppel et al. 1947).

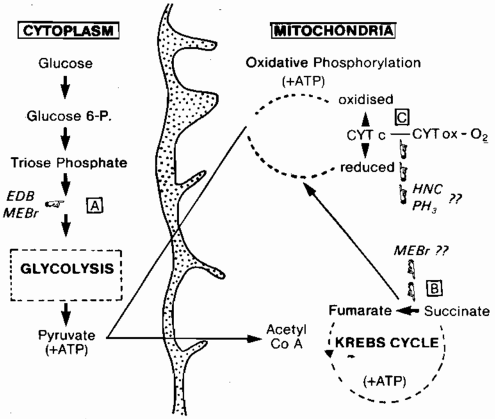

Fig. 1. Energy generation in the cell. Some effects of fumigants on glycolysis, the Krebs cycle and oxidative phosphorylation. Enzymes: A, triose phosphate dehydrogenase: B, succinate dehydrogenase: C, cytochrome-c oxidase. EDB = ethylene dibromide; MEBr = methyl bromide; HCN = hydrogen cyanide; PH_3 = phosphine; ATP = adenosine triphosphate.

Resistance to the liquid fumigants has been slow in developing and at present appears to occur only at low levels. Some resistance to CTC has been detected in U.K. populations of *Oryzaephilus surinamensis* though this was only in the order of a two-fold resistance at the LD_{50}. Experiments with radiolabelled CTC failed to show any conclusive differences in uptake or metabolism of fumigant between susceptible and resistant strains (Price, unpublished data). When selection pressure was removed the resistance quickly regressed.

Bond (1973) reported a field strain of *Tribolium castaneum* with twofold resistance to EDB which he was able to increase to threefold by selection. Ellis (1972a), using a strain of *Sitophilus granarius* with a 1.9 fold resistance to EDB, found that resistance was not due to differences in respiratory rate but in part due to weight differences between strains. In addition, using radiolabelled EDB he was able to show that resistant insects had a lower rate of uptake of toxicant and a faster rate of detoxication (Ellis 1972b).

Methyl Bromide

The mode of action of methyl bromide (CH_3Br) is uncertain although a number of studies have been made of the interaction of this gas with insect biochemical systems. The physiological response of insects to methyl bromide varies but is usually described as 'irritant.' No anaesthetic action was detected in a number of insect species (Bond 1956). Generally, short periods of hyperactivity, often accompanied by uncoordinated, spasmodic movements are followed by paralysis and death. It was concluded that respiratory inhibition was not a primary feature of the action of methyl bromide (Bond 1965).

An early hypothesis for the biochemical action of methyl bromide was that toxicity was due to the release of inorganic bromide, but this view has not been substantiated. Lewis (1948) demonstrated that methylation of vital SH groups by methyl bromide led to impaired functioning of some SH-containing enzymes, including succinate dehydrogenase, an enzyme important for the generation of ATP (Fig. 1). Loveday and Winteringham (1951) were able to show that methylation of SH groups by methyl bromide did indeed occur in insects, and there was evidence that the reaction was irreversible in vivo. Accordingly it was proposed that methylation of proteins was the toxic mechanism of methyl bromide (Winteringham and Barnes 1955).

The primary biochemical lesion resulting from the methylation of SH groups by methyl bromide has been the subject of some discussion. Classic SH inhibitors like iodoacetate exert their effect by disrupting glycolysis and causing an irreversible depletion of ATP by way of inhibition of triosephosphate dehydrogenase. Observations on the poisoning of insects has failed to confirm that methyl bromide produces a similar effect. However, Bond (1956) suggested that the inhibitory effect of methyl bromide on the oxidative enzyme succinate dehydrogenase (Fig. 1) may stimulate glycolysis in the early stages of poisoning, whereas in the later stages both glycolysis and oxidative ATP production may be reduced. From the number of enzymes known to be dependent on SH groups for activity, it is likely that methyl bromide causes various detrimental biochemical effects, though an irreversible inhibition of both aerobic and anaerobic ATP production would certainly be lethal.

Resistance to methyl bromide has developed in stored product insects in recent years. In a global survey, Champ and Dyte (1976) found that 5% of insect samples surveyed showed some resistance to this compound, and levels as high as ×12 were recorded. Using ^{14}C-methyl bromide, Bond and Upitis (1976) found that uptake of fumigant was similar in susceptible and methyl bromide-resistant strains of *Sitophilus granarius,* and that the amounts of radiocarbon in the bodies of the insects at various times were much the same. It was later postulated that resistance in these insects was due to the chemical conjugation of methyl bromide with the tripeptide, glutathione (Starratt and Bond 1981). Although they did not detect any increase in the conjugating enzyme glutathione-S-transferase in the resistant insects, these authors did find almost double the titre of glutathione itself. In addition, S-methyl glutathione sulphoxide was produced as a metabolite by the resistant insects but not by susceptibles.

Hydrogen Cyanide

Hydrogen cyanide (HCN) has been used to control insects in stored grain and seeds and may be generated in practice by the action of moisture on sodium or calcium cyanide, by dispensing of gaseous HCN from a cylinder, or by release of HCN absorbed onto an inert material. HCN was first used extensively in the late 1800s against scale insects on citrus trees in California. Cyanide has become known as a classic metabolic inhibitor and thus much is known about its cellular toxicology. Many enzymes are inhibited by cyanide, including most haem-containing enzymes, and other enzymes with metal prosthetic groups (Dixon and Webb 1958). However, since 1929 the enzyme cytochrome-c oxidase has been proposed as the major toxic site of cyanide (Keilin 1929). Cytochrome-c oxidase is the vital terminal electron acceptor in the oxidative production of ATP in the mitochondrion (Fig. 1). In other words, this enzyme is at the very heart of the biochemical processes of respiration. If cytochrome oxidase is blocked then no utilisation of oxygen can occur in the tissues. Thus, the interaction of cyanide with this enzyme could explain the high toxicity of HCN to insects and mammals. However, the effect of HCN on insects is not quite so straightforward.

Many species of insects can tolerate long periods without oxygen and yet succumb to the effects of HCN. Indeed, administration of oxygen to insects sublethally poisoned with HCN is detrimental to their survival (Bond 1963a). Absorbtion of cyanide by insects may continue long after total respiratory inhibition has occurred (Bond 1961a), whereas death may occur in some species without 100% inhibition of respiratory enzymes.

So in insects there does not appear to be a good correlation between cytochrome-c oxidase inhibition and the toxicity of HCN. In *Sitophilus granarius* there appeared to be a closer relationship between inhibition of the enzyme catalase, and HCN toxicity (Bond 1963b). Catalase is another haem-containing enzyme whose cellular role is unclear but it facilitates the reduction of hydrogen peroxide to water. Some researchers believe that this enzyme is vital for the removal of toxic peroxides whch would otherwise poison the cell (Masters and Holmes 1979). Thus, exposure of HCN-poisoned insects to pure oxygen is likely to produce more free radicals and peroxides than exposure to air or nitrogen. If catalase were implicated in HCN action, then one would expect to see a higher kill of insects exposed to oxygen, and this is what Bond (1963b) observed.

The accumulation of a number of respiratory metabolites (Bond 1965) together with the various fates of the cyanide ion within the insect body (Bond 1961b) indicated that the action of HCN in insects is not simply a matter of respiratory inhibition.

Since HCN is one of the oldest fumigants, it is perhaps not surprising to find that resistance to the gas in insects has been around for a long time. In the early 1900s, California scale insects were found to be resistant to HCN. An early hypothesis to explain resistance was protective stupefaction; an idea which still survives. Resistant insects were belived to be 'narcotised' at low doses. In narcosis, they would survive without oxygen, thus reducing the amount of HCN they absorbed, and also being immune to its respiratory-blocking properties. Quayle (1942) found that resistant insects became narcotised after 2 min exposure to HCN compared with 20 min for susceptibles.

Hardman and Craig (1941) found that resistant insects closed their spiracles for longer periods than susceptibles and thus absorbed less HCN. Indeed, there is a body of evidence to suggest that lowered uptake of HCN may account for insect resistance, but there are few data on whether this is due to a lowering of respiratory rate, as anticipated, or to some other phenomenon. The significance of this is discussed in the section on phosphine resistance.

The enzyme rhodanese is widely distributed in nature and serves to detoxify cyanide by way of conversion to thiocyanate using a variety of sulphur donors. One might expect that induction of this enzyme in insects might account for HCN resistance. Only low levels of this enzyme have ever been detected in insects and Bond (1961b) failed to detect either rhodanese activity or thiocyanate products in the granary weevil. Another possible resistance mechanism discussed in the introduction to this review is that of altered biochemical target. Yust and Sheldon (1952) found that the respiratory rate of resistant scale insects did not differ from that of susceptibles, but that respiration of resistant insects was not sensitive to HCN. Such insects could not tolerate anoxia and it was postulated that they possessed an alternative oxidase to cytochrome-c oxidase, which operated ineffectively at low oxygen tensions and thus made the insects sensitive to anoxia. Unfortunately, uptake of HCN was not measured and thus some form of gas exclusion cannot be ruled out. More recently, Hall et al. (1971) reported that mitochondria isolated from millipedes which are tolerant of HCN have a cyanide insensitive oxidative biochemistry. This work adds further weight to the idea of an alternative respiratory biochemistry as a possible resistance mechanism to HCN.

Phosphine

Hydrogen phosphide (phosphine, PH_3) has become, in recent years, a popular fumigant for the disinfestation of stored grain. It is generated by the action of atmospheric moisture on a metal phosphide, usually aluminium or magnesium. The active ingredient is usually formulated with inert ingredients in the form of tablets, pellets, sachets, or other suitable forms. Phosphine has a number of toxicological properties in common with HCN. Its symptoms of poisoning in insects are that of a respiratory inhibitor (Nakakita et al. 1974; Price 1980a). The presence of oxygen is necessary for the full insecticidal potential of phosphine (Bond et al. 1969) and exposure of sub-lethally poisoned insects to oxygen enhances the toxicity of this fumigant (Bond 1963b). In the light of some of the similarities of phosphine and HCN, it is perhaps not surprising that studies on its mode of action have centred on cytochrome-c oxidase. Phosphine, however, exhibits a few peculiarities in its toxicology. The toxicity of most fumigants to insects conforms to Haber's rule of concentration-time (CT) products. That is, a given insect mortality may be achieved with a fixed CT product (gas concentration × exposure time), no matter how this is achieved (e.g. 1 mg/l for 10 hours or 5 mg/l for 2 hours). At high concentrations of phosphine this relationship breaks down and exposure time becomes the critical factor. These high phosphine concentrations can induce a narcotic response in some insects, and this may offer a measure of protection (Winks 1985).

That phosphine is indeed a respiratory inhibitor in vitro has been demonstrated in a number of studies using isolated mitochondria (Chefurka et al. 1976; Nakakita et al. 1971; Price 1980a). These studies showed that phosphine is a potent inhibitor of oxidative phosphorylation and that this effect is due to the inhibition of cytochrome-c oxidase (Kashi and Chefurka 1976). Indeed, cytochrome-c oxidase in solution is sensitive to inhibition by phosphine (Nakakita 1976; Price 1980b). However, Price (1980b) and Price and Dance (1983) were unable to detect significant lowering of cytochrome oxidase activity in *Rhyzopertha dominica, Oryzaephilus surinamensis,* or *Cryptolestes ferrugineus* which had been poisoned with phosphine. The same authors, and Price et al. (1982), showed that phosphine fumigation of insects reduces their catalase activity. This is similar to the effects of HCN (Bond 1963b), although unlike HCN little direct inhibitory effect of phosphine on catalase in vitro could be detected (Price and Dance 1983) (Table 1). Despite this, it was suggested that the ability of phosphine to inhibit catalase in vivo might contribute to the toxic action of phosphine. (Price et al. 1982). However, very recent experiments have indicated that *R. dominica* with artificially lowered catalase levels do not differ from normal insects in their sensitivity towards phosphine (Price unpublished data). The reducing properties of phosphine have also led to suggestions of non-specific toxic actions such as the disruption of disulphide bonds in vital enzymes. Clearly, a further characteristic shared by phosphine and cyanide is that the modes of action may not be so straightforward as originally proposed.

Resistance to phosphine has developed rapidly in recent years. In a global survey carried out in 1972–73, 9.7% of stored product insects tested from 82 countries showed resistance to phosphine (Champ and Dyte 1976). The maximum level of resistance found was x2.5, In more recent years, a number of highly resistant strains of stored product beetles have been found surviving repeated phosphine fumigations in Bangladesh (Tyler et al. 1983; Mills 1984; Dyte and Halliday 1985). Many of these insects are sufficiently resistant for adults to survive recommended dosages, requiring up to 100 times the dose for 7 days for complete control at 25°C (Table 2).

Table 1. The effect of HCN and PH_3 on catalase and cytochrome-c oxidase. In vivo figures are percent inhibition. In vitro figures are micromolar concentration for 50% inhibition.

	In vivo		In vitro	
	HCN	PH_3	HCN	PH_3
Cytochrome oxidase	87(a)	0(b)	0.01(c)	100(d) 800(f)
Catalase	71(e)	60(b)	5(c)	1800(b)

(a) unpublished data *Rhyzopertha dominica.* CT product 8;
(b) Price and Dance (1983) *Rhyzopertha dominica.* CT product 6;
(c) Dixon and Webb (1958);
(d) Chefurka et al. (1976);
(e) Bond (1963b). *Sitophilus granarius.* CT product 8;
(f) Estimated from Price and Dance (1983).

Table 2. Dose (mg/L) and exposure times for 100% kill of susceptible and phosphine resistant stored product beetles. 25°C, 70% RH.

	20 hours	3 days	4 days	7 days
R. dominica susceptible	0.05			
R. dominica resistant	>0.5	>0.5	>0.5	0.47
O. surinamensis susceptible	0.02			
O. surinamensis resistant	>0.63	>0.54	>0.54	0.54
T. castaneum susceptible	0.04			
T. castaneum resistant	>0.65	0.16		

The ease with which resistance can be further selected in the laboratory, together with these extremely resistant field strains, has provided good material with which to study the mechanism of phosphine resistance. The ability of some insects to enter narcosis at high phosphine concentrations has been linked with the ability of insects to survive phosphine fumigations (Bond et al. 1969; Winks 1985). The essential feature of this phenomenon is that the insects reduce their respiratory metabolism and thus reduce the uptake of toxicant. Price (1980a) found that physical activity and respiratory rate of a phosphine-resistant strain of *R. dominica* were not significantly depressed by exposure to the fumigant. Despite this, resistance did not appear to be due to metabolism of phosphine but rather to a

Table 3. Uptake of ^{32}P-radiolabelled phosphine by *Oryzaephilus surinamensis, Cryptolestes ferrugineus* and *Rhyzopertha dominica.* Figures are the means of two separate experiments. Figures in brackets are the amounts of [P] excreted onto filter papers per g insect.

Sample		Weight of 20 adults (mg)	μg [P]/g insect
O. surinamensis	S	11	37.80 (1.2)
	R	9	6.71 (1.31)
C. ferrugineus	S	7	27.75 (1.17)
	R	8	7.75 (2.49)
R. dominica	S	33	54.30 (0.4)
	R	23	6.48 (0.32)

decrease in uptake of gas (Price 1980b) (Table 3). Insects appeared to be absorbing less phosphine because of their high respiratory rate rather than in spite of it. Indeed, by subtracting the amount of phosphine passively absorbed by dead insects from that taken up by living ones, Price found evidence to suggest that exclusion of the phosphine gas was an active process (Price 1985).

Over short exposures (up to 5 hours), it was found that stimulation of insect metabolism by increasing the temperature actually enhanced the exclusion of gas from the resistant insects (Fig. 3). As the exposure time is increased, the mechanism is overcome and insects finally begin to absorb toxicant. After this time, increased temperature results in higher gas uptake (Fig. 2) and enhanced toxicity, as would be expected. All phosphine-resistant stored product beetle species so far examined in the author's laboratory show this type of resistance. The use of ^{32}P-radiolabelled phosphine has helped us to explain why the time of exposure appears much more important than the concentration of phosphine in the control of resistant species. In addition, the results of uptake studies can help to predict the point in time at which exclusion will be overcome and aid in the estimation of suitable combinations of time and dose for control. The further aim of these studies is to discover the biochemical basis for this unusual resistance mechanism, with a view to establishing conditions under which resistant insects may be more easily controlled.

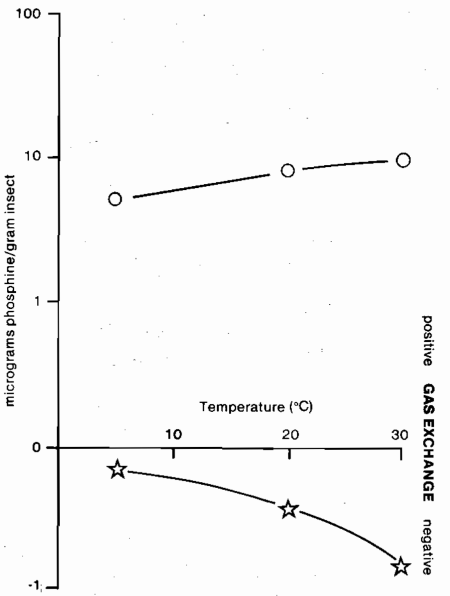

Fig. 2. The effect of temperature on the net uptake of ^{32}P-radiolabelled phosphine by susceptible (circles) and resistant (stars) *Rhyzopertha dominica.* 0.17 mg/l for 5 hours. Net uptake calculated as: (uptake of living insects — uptake of dead insects) + excreted radiolabel.

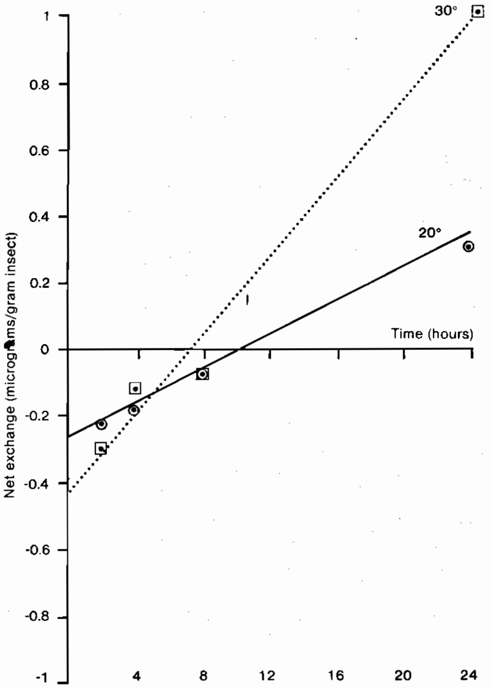

Fig. 3. The effect of exposure time on the net uptake of phosphine by resistant *Rhyzopertha dominica* at 20° and 30°C.

Conclusions

Fumigation is a 'last resort' control measure, used for disinfestation when prophylactic measures have failed. As such, all efforts must be made to ensure that fumigation succeeds. Because the physical and chemical properties required of a good fumigant are restrictive, the number of practicable fumigants is small. Concerns over environmental and toxicological hazards are beginning to restrict the choice of fumigants even more. The importance of information on the mode of action of and mechanisms of resistance to fumigants has not been appreciated in the past and, as this paper shows, knowledge on these matters is at best sketchy. Through studies on the physiology and biochemistry of resistance to fumigants, especially to methyl bromide and phosphine, we are now beginning to understand some of the characteristics of fumigant action and resistance. Much more work needs to be done.

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The Biological Efficacy of Fumigants: Time/Dose Response Phenomena

R.G. Winks*

Abstract

The biological efficacy of fumigants is discussed in terms of the relationship between concentration (C) and time (t) in the toxicity of these materials. It takes the form $C^nt = k$, where k is the dosage required for a specified level of kill and n is the toxicity index. The toxicity index varies with poison, species, developmental stage, and strain. Knowledge of the toxicity index or indices, and the range over which they apply, will help to optimise dosages. In the laboratory, an understanding of the toxicity index is essential in any meaningful comparison of strains, particularly when some measure of resistance is required. When measuring the toxicity of a fumigant in the laboratory, including comparisons of strains such as in resistance testing, it is essential that the time to respond to the dosage applied is properly considered. In a batch of insects, the time to death stabilises when all insects that have received a dose in excess of their tolerance have responded. The point at which mortality stabilises is described as the mortality end-point. This end-point varies with dosage, concentration, and the species or strain. Measurements of toxicity that are not based on end-point mortalities are of little or no value.

IN common with other poisons and drugs, if a sufficient dose of a fumigant is absorbed by an insect it will respond. However, unlike most poisons and drugs, the dose of a fumigant is absorbed from the atmosphere surrounding the insect. The dose absorbed is a function of the concentration (C) of the fumigant in the atmosphere and the time (t) during which the insect is exposed to the fumigant. Also in common with other poisons and drugs, the response to a fumigant is not instantaneous and an interval of time will elapse during which biochemical reactions are taking place that will bring about the death or other response of the insect.

Thus, time enters into the response of an insect to a fumigant in two ways: (a) the time required for an insect to absorb a dose, i.e. time as a dosage factor, and (b) the time for an insect to respond to the dose absorbed, i.e. time as a response factor. These two components of time, together with concentration, provide the basis of a comprehensive description of the biological efficacy of fumigants and many drugs, poisons, and other stimuli.

Time As a Dosage Factor

The simplest form of the relationship between concentration and time is the so-called 'Haber's Rule'. This rule states that for a specified level of kill the dosage k is a constant and is a product of the concentration and the exposure time, i.e. $Ct = k$. While this rule has been a useful practical guide with some fumigants, e.g. methyl bromide within certain limits, it does not often provide an accurate description of the toxicity of fumigants including methyl bromide. To understand the relationship between concentration and time, it is necessary to appreciate that with Haber's Rule concentration and time are equally effective, e.g. half the concentration for double the time will achieve the same result.

In the great majority of cases, the effects of concentration and time are not equal, with one of the variables having a more pronounced effect than the other. A more general expression of the relationship between concentration and time is the asymptotic curve $C^nt = k$, where n, the toxicity index, indicates the relative importance of the variables. If the value of n is less than 1, exposure time is the more effective variable of dosage; if it is greater than 1, concentration is the more effective variable. This expression generally describes the relationship between the two variables over quite a wide range of values. However, even in the simplest case there are finite limits governed on the one hand by a small finite time for the poison to reach vital sites and on the other by the ability of the organism to detoxify the poison. This realisation led early workers to include estimates of the thresholds of concentration and time in the

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models used to describe their data. Some of these models are described by Clark (1937). They may be summarised simply as:

$$(C - C_0)^n t = k$$

$$C^n(t - t_0) = k$$

$$(C - C_0)^n(t - t_0) = k$$

where C_0 is the threshold concentration and t_0 is the threshold time.

It should be noted that all of the models of this type describe the relationship for a specified level of response only, such as the LD_{99}. Moreover, log transformation of the dosage variables produces a straight line of slope $-n$. When concentration is the independent variable, the equation to this line is:

$$\log t = \log k - n \log C$$

An example of this is evident in data of Winks (1984) in which adults of *Tribolium castaneum* were exposed to a range of fixed concentrations of phosphine. Probit lines were fitted to the data for each concentration (Fig. 1) following which the dosage time for each LD_{50} and LD_{99} was plotted for each concentration (Fig. 2). In this case, log-time was linear in log-concentration over quite a wide range of concentrations, i.e., from 0.005 to 0.5 mg/L.

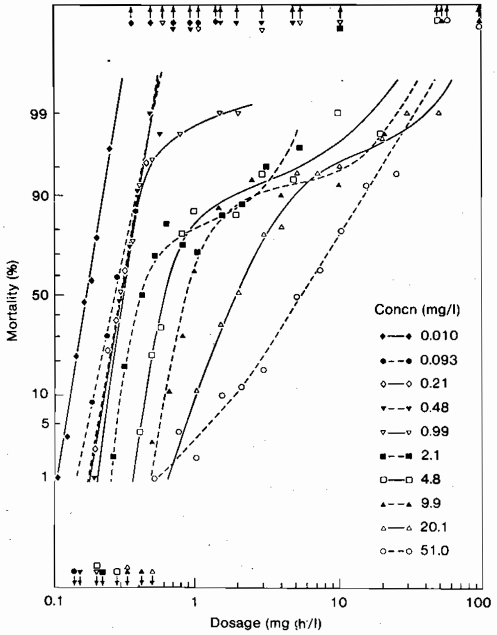

Fig. 1. Mortality response of adults of *Tribolium castaneum*, over a range of fixed concentrations of phosphine at 25°C, 70% RH (Winks 1984).

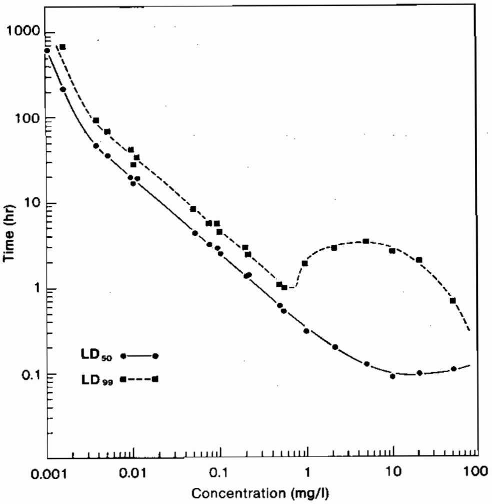

Fig. 2. The concentration x time relationship at the LD_{50} and LD_{99} level for *Tribolium castaneum* adults exposed to a range of fixed concentrations for various exposure periods (Winks 1984).

At concentrations less than 0.005 mg/L, the relationship between concentration and time changes sharply. At the LD_{50}, the value of n for concentrations from 0.004 down to 0.0011 mg/L was approximately 2. Thus, concentration became the critical dosage variable. It is suggested that, in this range of concentrations, *T. castaneum* adults were detoxifying a significant proportion of the phosphine absorbed and hence longer exposure periods were required for beetles to absorb a lethal dose.

The deviation from linearity in the *Ct* relationship at concentrations greater than 0.5 mg/L (Fig. 2) was pronounced and systematic. At these high concentrations, beetles became narcotised and their mortality response was characterised by marked curvature of probit lines and an increase in tolerance. At the LD_{99}, the increase in tolerance was x64. While this large increase in tolerance of phosphine at high concentrations may be characteristic of this fumigant, it should not be assumed that a similar deviation from linearity does not occur at high concentrations of other fumigants.

As a general rule it would seem reasonable to expect a region of linearity of slope n bounded at both ends by regions in which, at the very least, the values of n are different. At very low concentrations, the value of n would be greater than that of the middle region while at high concentrations the value of n would be less than that of the middle region, although with phosphine the relationship is frequently curved at very high concentrations. Thus, at the very low concentrations, concentration becomes the critical dosage variable while at the very high concentrations, exposure time becomes the critical dosage variable. Other examples of this type of relationship for phosphine are evident in the data of Bell (1979) for diapausing larvae of *Ephestia elutella* and in some as yet unpublished data for *Sitophilus granarius, S. oryzae, S. zeamais, Rhyzopertha dominica,* and *Tribolium confusum.*

Again using phosphine as an example, it will eventually be possible to construct a composite Ct relationship by superimposing all of the data of this type. It is evident from the data available so far that, for this fumigant, there will be a relatively narrow range of concentrations in which response is predictable from the simple model $C^n t = k$. Dosages chosen should be consistent with the concentrations within this range.

A more general approach is to use all observations of response to each of a range of exposure times for each of a range of concentrations, i.e., 'all the information in such a family of curves and not just that from a single point on each component' (Bliss 1940). Using this approach a probit plane may be fitted to the data:

$$Y = a + b_1 x_1 + b_2 x_2$$

where Y is the probit mortality and x_1 and x_2 are respectively log concentration and log time. It is implicit in such a plane that concentration and time act independently. When they do not, a third term ($b_3 x_1 x_2$) is added to describe the interaction of the dosage variables. Such interaction may be seen as a systematic change in the slope of individual regressions of, for example, probit mortality on dosage. When interaction is not significant, the expression $C^n t = k$ may be derived from the probit plane, i.e., n is equivalent to b_1/b_2 (where x_1 is log concentration) and k is equivalent to the antilog of $(Y - a)/b_2$.

As an example of this, a probit plane was fitted to the data of Fig. 1 over the range of concentrations from 0.004 to 0.5 mg/L (Winks 1984). The plane for mixed sexes was:

$$Y = 9.21 + 7.55 \log C + 8.50 \log t$$

The interaction term, b_3 (log C) (log t), was not significant. Hence, the toxicity index, n was derived as the ratio of the regression coefficients, i.e. 7.55/8.50 = 0.9.

Unfortunately, phosphine is the only fumigant for which we have data of this kind. Limited data for methyl bromide suggest that the toxicity index for this fumigant is generally greater than 1, which would favour concentration as the more important dosage variable.

The toxicity index is a specific characteristic of the species, strain, developmental stage, and the poison. Moreover, it is likely that the toxicity index will vary with environmental factors such as temperature, humidity, and the degree of satiation with food. Clearly, the variation in the toxicity index is such that any attempt to evaluate the toxicity of fumigants in the field is almost ludicrous and yet, since the primary purpose of studies on the toxicity is to use fumigants in the field more effectively, field trials would seem to be essential. However, it should be evident from the foregoing that any field trial is likely to be an almost unique event and that the results of such a trial, or trials, should be interpreted accordingly.

Time As a Response Factor

Response time may be defined simply as the time that elapses between the administration of a dosage of a drug or poison and the expression of the response to that dosage. In the simplest case, the dosage time is zero or very small, as in the case of application by injection, and the time from injection to response is entirely response time. With fumigants, time is very much a component of dosage but it is still possible and indeed essential to recognise that some response time occurs simultaneously and is quite different in character. In these circumstances the two are 'inextricably mixed' (Hewlett 1974).

Response time is significant in measurements of toxicity in the laboratory and is of particular importance because of the influence laboratory studies have on control strategies in the field. For the most part, the response time that we are concerned with is the time to death. Clearly, however, it applies to any response that is

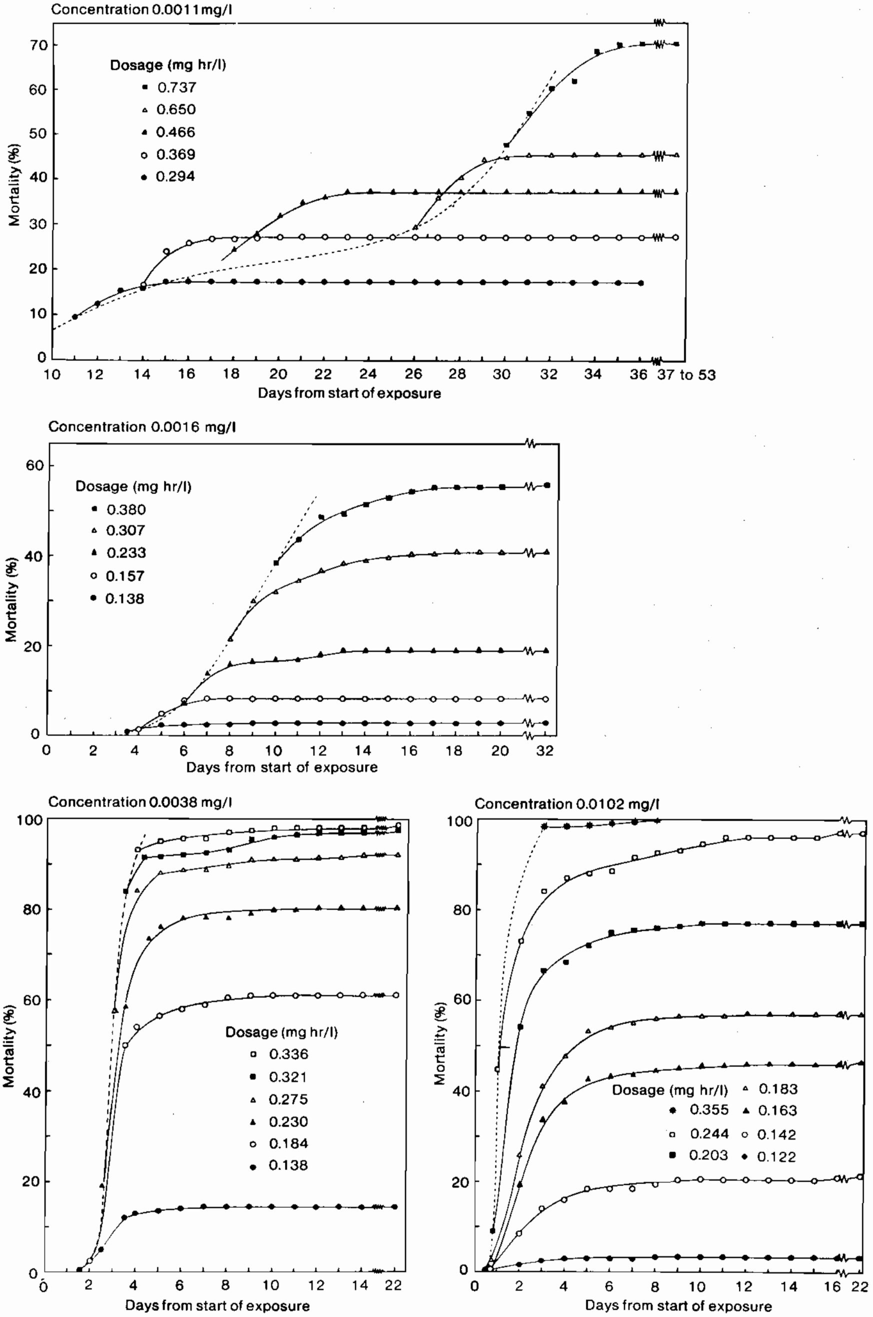

Fig. 3. Time-to-death curves for *Tribolium castaneum* adults exposed to a range of dosages at each of four fixed low concentrations of phosphine at 25°C, 70% RH (Winks 1982).

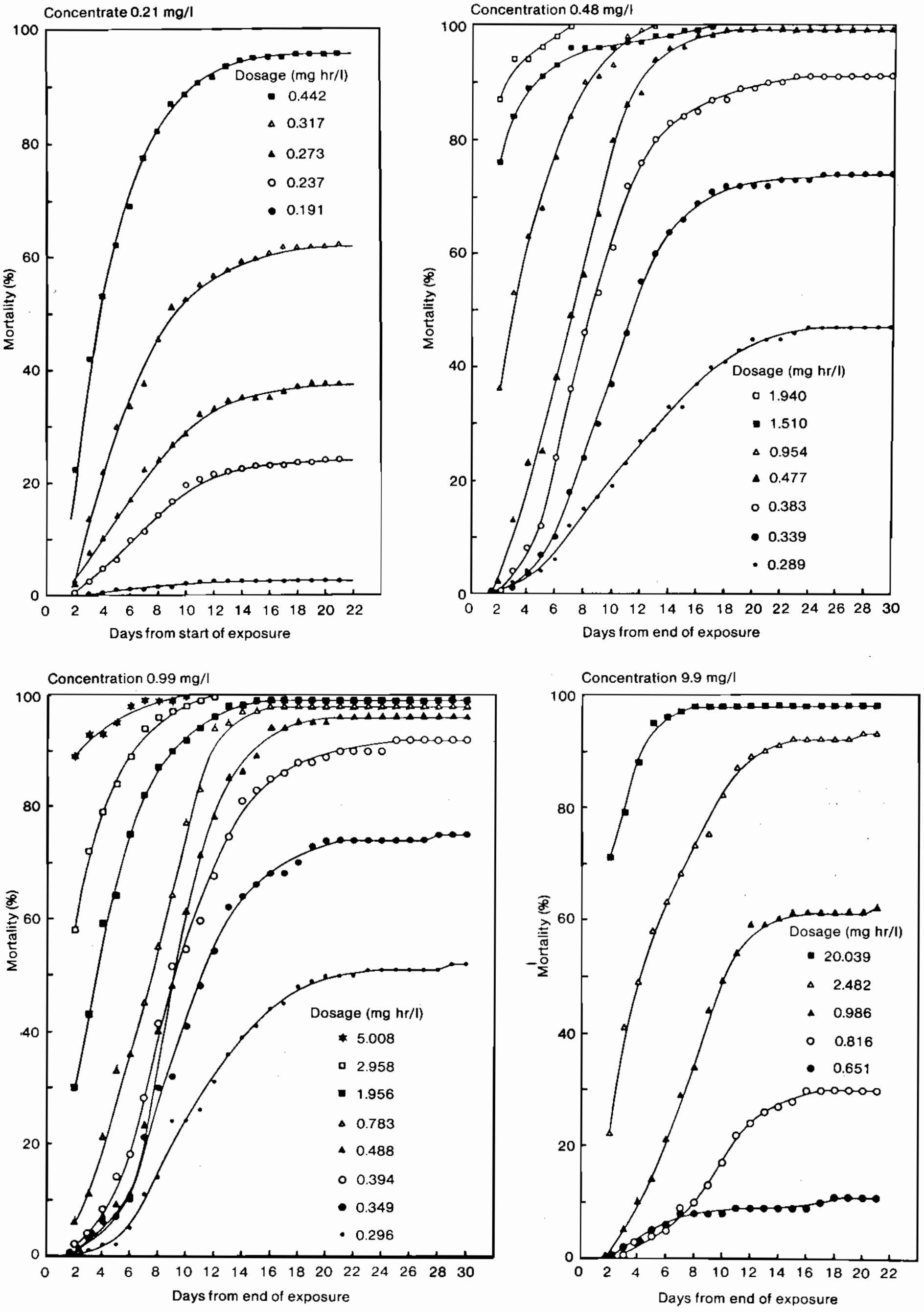

Fig. 4. Time-to-death curves for *Tribolium castaneum* adults exposed to a range of dosages at each of four, fixed, moderate to high concentrations of phosphine at 25°C, 70% RH (Winks 1982).

measured or observed following a stimulus, whether chemical or physical. Laboratory measurements of fumigant toxicity usually involve exposing insects to a range of concentrations for a fixed exposure period or to a range of exposure times at a constant or fixed concentration. The insects are removed from exposure to the fumigant and held for a period before the mortality to the particular dosage is recorded. Commonly, post-treatment holding periods in the fumigant toxicity literature have ranged between 2 and 14 days (Winks 1982).

It has long been known that different poisons exhibit different speeds of action. It was for this reason that Beard (1949) investigated the effect of different times of assessment on measurements of the toxicity of arsenic and parathion injected into the body cavity of adult milkweed bugs, *Oncopeltus fasciatus.* He found that, on the basis of observations made two days following treatment, arsenic would have been judged almost 250 times more toxic than parathion, whereas at *end-point,* when all affected individuals had either recovered or died, the difference was less than three-fold. It was apparent from Beard's studies that arbitrary post-treatment holding periods, before response assessments are made, could give rise to erroneous conclusions concerning the tolerance of test insects or the toxicity of poisons.

It is reasonable to expect that the response times of individuals given a lethal dose of poison will vary with their tolerance of the poison, i.e. the more tolerant individuals will take longer to die. Moreover, from an examination of the time-to-death curves of Winks (1982) (Fig. 3 and 4), it would seem that response time is distinctly skewed to the right, i.e. the more tolerant individuals take longer to die than would be expected from normally distributed times-to-death. It was found in this study that the acute mortality response reached an easily recognisable end-point and that the time to end-point varied with dosage (*Ct)* at fixed concentrations and with the concentration of phosphine (Winks 1982). Firstly, as the dosage was increased by increasing the exposure period, the time to end-point decreased and secondly, as the concentration was increased, the average time to end-point increased (Fig. 5).

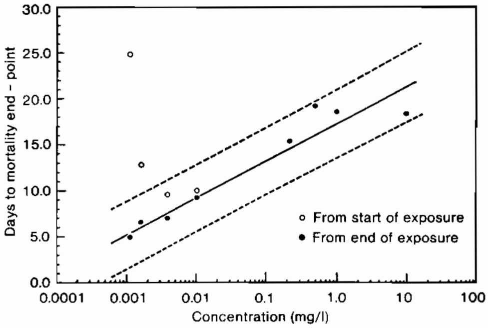

Fig. 5. The influence of concentration on mean time to mortality end-point for adults of *Tribolium castaneum* exposed to a range of fixed concentrations of phosphine at 25°C, 70% RH with 95% confidence limits of prediction of mean times to mortality end-point for individual concentrations (Winks 1982).

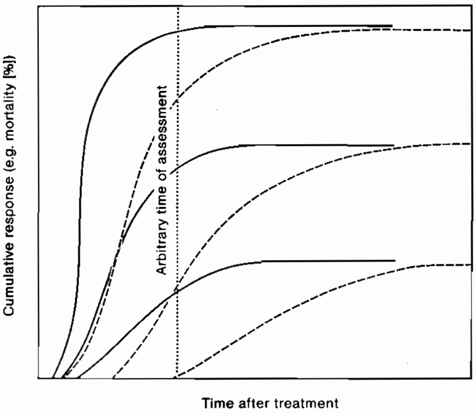

Fig. 6. Hypothetical curves for two sets of three treatments that elicit the same end-point response. The response time characteristics of the two sets are different. The two sets may represent two species, two strains of the same species, two poisons, or the same strain exposed to two different concentrations (Winks 1985).

On the basis of these arguments the curves of Fig. 6 were postulated. These sets of curves could equally represent the response times of two different species treated with three doses of the same poison, the response times of the same species treated with three doses each of two different poisons, or the response times of two strains of the same species treated with three doses of the same poison. They could also represent the response times of the same strain of the same species exposed to three dosages derived from each of two different concentrations of a poison for which time is a component of dosage, i.e. the uptake of the dose of poison is time dependent. In each case the response stabilises and the level of the end-point response to the three doses of the two sets is equal. Hence, probit mortality lines fitted to these end-points would be coincident, i.e. there would be no difference in the susceptibility of the two species, no difference in the toxicity of the two poisons, no difference between the two strains, and no difference in the efficacy of the same dosages obtained from different concentrations. However, because the times to end-point for each pair of doses are quite different, if some arbitrary time of assessment were chosen, such as that shown in Fig. 6, differences would be obtained. It could be concluded from these differences that a poison was more toxic to one species than the other, or that one poison was more toxic than the other, or that one strain was more tolerant of the poison than the other or that dosages from one concentration were more efficacious than another. In each case the conclusion would be false or at most relate to the arbitrary time.

Single, fixed, post-treatment holding periods before response is assessed are widely used in measurements of toxicity. The periods used are frequently chosen to standardise a test procedure so that different tests may be compared either for different treatments or for the tolerance of different strains or species. Often the post-treatment periods are chosen arbitrarily or because similar periods have been used in apparently similar situations. However, the use of fixed post-treatment holding periods in laboratory tests designed to measure the acute response of insects to poisons is untenable unless it is known that the time chosen is sufficient to allow all individuals, whose tolerance has been exceeded, to respond to the dose applied. It is equally untenable in all such tests with poisons, drugs, and physical stimuli applied to any organism when it is known or expected that the speed of action will vary among individuals.

The Influence of Response Time on the Measurement of Resistance

In a recent study (Winks 1985) the influence of response time on measurements of toxicity and resistance was examined in adults of *T. castaneum* treated with phosphine. To examine the impact of different concentrations of phosphine on times of assessment of mortality, three dosages that produced approximately the same end-point mortality and spanned the tolerance distribution of a susceptible strain, CTC_4, were chosen from the data for each of two concentrations of phosphine, 0.01 and 0.2 mg/L. These concentrations were from either end of the concentration range over which a linear relationship between log concentration and log time was obtained (Winks 1984). Cumulative mortality was derived from daily observations for each dosage and plotted against time (Fig. 7). Differences between the two concentrations as high as 60% were evident in the mortality levels two days from the end of exposure. They decreased to less than 5% at end-point. Even at 7 days from the end of exposure differences in mortality were as high as 20%.

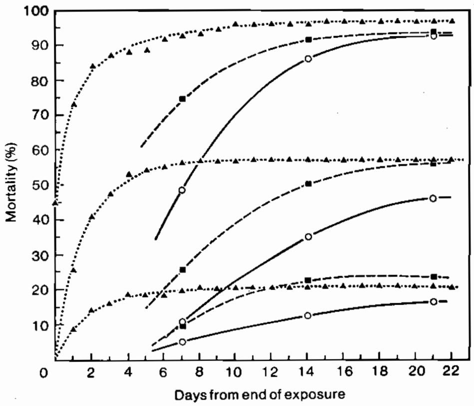

Fig. 7. Time-to-death curves for three dosages each of which produced approximately the same end-point mortalities in adults of a susceptible strain of *Tribolium castaneum* exposed to two concentrations of phosphine: ▲————, 0.01 mg/litre; ○- - - - - - - -, 0.2 mg/litre (Winks 1985).

The influence of different times of assessment on estimates of mortality was further examined by plotting cumulative, daily mortalities on a probit scale, for each of a range of log-dosages, at a phosphine concentration of 0.5 mg/L (Fig. 8). This concentration was the upper limit of the concentration range over which the relationship between log concentration and log time was linear (Fig. 2). Probit mortality lines were fitted to the data for 2, 7, and 14 days, and at end-point. The data satisfied a linear probit model at 2 days, 7 days, and at end-point. The data at 14 days showed evidence of curvature at high mortalities. In addition, there was a marked increase in the slope of the probit-mortality lines from 4.8 to 10.4 when end-point was reached. The LD_{99} was 7 times higher at 2 days than it was at end-point (Table 1). In a similar manner, probit mortality lines were fitted to data

Table 1. A comparison of the LD$_{99}$ at end-point with those obtained at earlier times following exposure of adults of a susceptible strain of *Tribolium castaneum* to a range of fixed concentrations of phosphine. At each concentration time was the variable of dosage.

Concentration (mg/litre)	Days from end of exposure	LD$_{99}$ mg h/litre	LD$_{99}$ Ratios
0.01	0	0.364	1.3
	7	0.292	1.0
	end-point	0.280	
0.2	2	1.231	2.4
	7	0.704	1.4
	14	0.532	1.0
	end-point	0.516	
0.5	2	3.416	6.9
	7	1.806	3.7
	14	0.603	1.2
	end-point	0.494	
1.0	2	12.517	23.0
	6	6.939	12.8
	7	5.821	10.7
	end-point	0.544	

* Ratios of earlier estimates to those obtained at end-point.

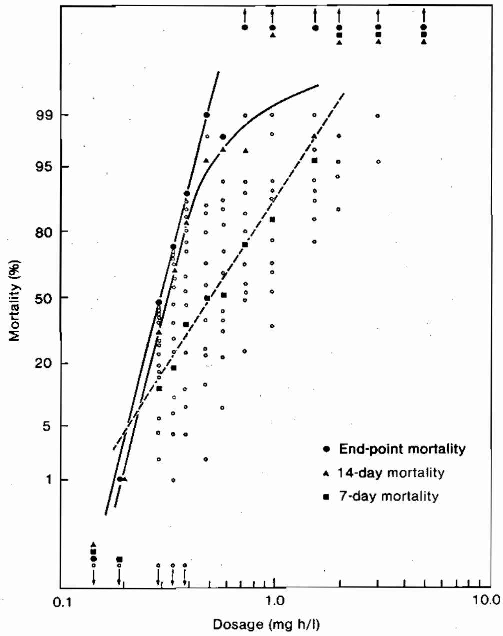

Fig. 8. Daily records (o) of probit mortality from the second day following exposure of adults of a susceptible strain of *Tribolium castaneum* to a phosphine concentration of 0.5 mg/litre for a range of dosage times. Probit mortality/log-dosage lines were fitted to the data at 7 days (■), 14 days (▲) and at end-point (●) (Winks 1985).

obtained at 0.01, 0.2 and 1.0 mg/L. While the differences in LD$_{99}$ at 0.01 mg/L were small, at 0.99 mg/L the LD$_{99}$ at two days from the end of exposure was 23 times higher than at end-point.

The speed of action of phosphine on the susceptible strain exposed to 0.01 mg/L was compared with that on the resistant strain exposed to three equitoxic dosages at higher concentrations of 0.26 and 1.0 mg/L (Fig. 9). Higher concentrations are frequently used to measure the tolerance of resistant strains, especially when an attempt is made to adhere to some concept of a standard exposure time (cf. Anon. 1975). Differences were large and were evident even beyond 14 days. Moreover, the differences were greater at the higher of the two concentrations chosen for the resistant strain.

Although the FAO method for the detection and measurement of resistance of adults of the major stored products beetles to methyl bromide and phosphine (Anon. 1975) nominates a post-treatment holding period of 14 days, the procedure recommended by Winks (1982) is preferable. This procedure requires that at least two observations of response be made and that the times from the end of exposure and between successive observations should be based on a consideration of the response time characteristics of the particular species, strain, or poison.

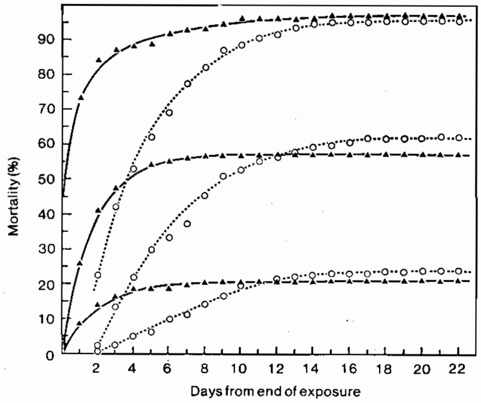

Fig. 9. Time-to-death curves for three approximately equitoxic dosages derived from different concentrations of phosphine applied to adults of a susceptible strain (CTC$_4$) and a resistant strain (CTC$_{475}$) of *Tribolium castaneum:* ▲- - - - - - -, CTC$_4$, 0.01 mg/litre; ■- - - - - - -, CTC$_{475}$, 0.26 mg/litre; O————, CTC$_{475}$, 1.0 mg/litre (Winks 1985).

Reports of fumigant resistance in the literature should be examined carefully. For example, the so-called phosphine resistance reported by Kem (1977) and Saxena and Bhatia (1980) in adults of *T. castaneum* following selection with phosphine is not resistance in the accepted sense (Dyte and Blackman 1967) but merely a demonstration of the reduction in variability of a strain that accompanies selection of this type as evidenced by the progressive increase in the slope of the probit-mortality lines for successive generations. Moreover, mortalities were determined at 24 hours (Kem 1977) and 48 hours (Saxena and Bhatia 1980). From the present study it can be seen that such periods were quite inadequate. In addition to these short, fixed, post-treatment holding periods in both studies, the concentration was progressively increased for the fixed exposure period of 24 hours and that would have exacerbated the problem.

Because of the influence that resistance measurements can have on control strategies, it is important that laboratory studies be based on sound principles. Standardised tests are only valid if they embody such principles. Since the usual objective of tests of this type is to measure the acute response, it is essential that the measurements are of the *full* acute response and not just *part* of it. Only then can meaningful comparisons be made between dosages, between different poisons, drugs, or other stimuli, and between different strains or species.

The foregoing arguments may be applied easily to the treatment of a single stage of development of a sufficient duration for all affected individuals to recover or respond, e.g. the adult. They are, however, difficult to apply in experiments in which immature stages are used. With these it is more usual and more meaningful to include disruption of normal metamorphic processes in the analysis of toxic effects and to base the assessment on survival to some later stage, preferably the adult.

Resistance to Fumigants

When resistance is detected some attempt is usually made, using standardised test procedures, to measure the magnitude of the resistance as a guide to the continued use of the particular poison (e.g. Anon 1975). For this purpose, batches of the resistant insects are exposed to a graded series of dosages and their response compared with that of a susceptible reference strain exposed to the same poison. This comparison yields a resistance factor which is the ratio of dosages required to achieve the same level of kill in both strains. Commonly, this factor is then regarded as a unique descriptor of the resistance in the strain in question. Clearly, the underlying assumption of this approach is that the factor remains constant over a wide range of the dosage variables. With fumigants, where the dosage variables are concentration and time, this would mean that the slopes of the regressions of log time on log concentration for a specified level of kill were the same for the resistant and susceptible strains. Hence, the value of n in the relationship $C^n t = k$ would be the same for both strains. Such an assumption is the converse of normal expectations. Since the value of n is a specific characteristic of the poison acting on a particular organism (see Clark 1937), it would seem more reasonable to postulate that the values of n for a resistant strain and a susceptible strain were different. Thus, the tacit assumption of parallel regressions of log time on log concentration in a single resistance factor, from either a single concentration for various times or from a limited range of concentrations for a fixed exposure period, is untenable.

The relationship between concentration and time over a wide range of concentrations was determined recently for a phosphine-resistant strain, CTC_{475}, of *T. castaneum* and compared with the relationship previously described for a susceptible strain, CTC_4 (Winks 1984). As before, the logs of the exposure time calculated from each LD_{50} and from each LD_{99} were plotted against log concentration and superimposed on the data for the susceptible strain (Fig. 10). For concentrations from 0.025 to 5 mg/L the relationship between concentration and time in the resistant strain was linear. This is the range over which the response is most predictable because the response is least variable. The relationship from 0.0095 to 0.025 mg/L appeared to be linear but deviated significantly from the relationship above 0.025 mg/L. Toxicity indices of 1.3 and 1.6 were obtained from regression equations fitted to the LD_{50} and LD_{99}, from 0.0095 to 0.025 mg/L. At concentrations above 5 mg/L, there was a substantial shift in both the LD_{50} and LD_{99} estimates.

A probit plane was fitted to the mortality data for the resistant strain over the range of concentrations from 0.025 to 5.0 mg/L:

$$Y = 1.57 + 6.32 \log C + 9.73 \log t$$

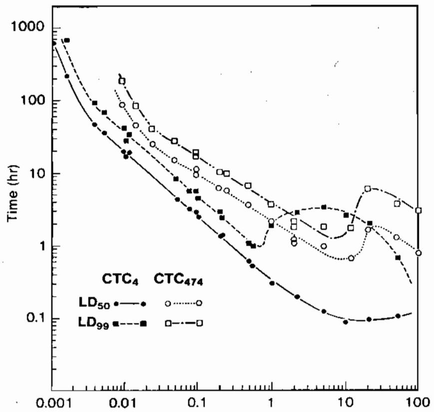

Fig. 10. The relationship between the time required for an LD_{50} and LD_{99} at each of a range of fixed concentrations of phosphine to which adults of a resistant strain, CTC_{475}, and a susceptible strain, CTC_4 (from Winks 1984), were exposed.

From the parameters of this plane, the toxicity index was calculated as 0.65.

It is clear that, in this resistant strain, the relationship between concentration and exposure time differed in two distinct ways from the relationship in a susceptible reference strain. Firstly, the thresholds of the linear range over which the response was most predictable were higher in terms of concentration and secondly, the toxicity index or slope of the regressions of log time on log concentration, was distinctly different.

The lower threshold of the linear response range in the resistant strain, 0.025 mg/L, was 5 times higher than that in the susceptible reference strain. It is likely that this lower threshold is the point at which the detoxification rate begins to exert a significant influence on the rate at which a lethal dose accumulates. If resistance were associated with an enhanced detoxification mechanism then the increase in the lower threshold would be expected.

The *narcosis threshold* (Winks 1984) in the resistant strain was approximately 5 mg/L, which was 10 times higher than that in the susceptible reference strain. This threshold is the concentration above which the narcotic effect of phosphine is correlated with an increased tolerance of this fumigant. Above this threshold beetles seem to be protected to some extent from the toxic effects of phosphine and higher dosages (longer exposures) are required to achieve the same mortality that a lower dosage would produce at concentrations below the narcosis threshold.

Perhaps the most significant difference between the resistant and the susceptible strain was the differences in the toxicity index, n. Thus a single resistance factor to describe the resistance of strain CTC_{475} is not meaningful. Resistance factors, based on a comparison of LT_{99} values calculated from the respective probit planes, increased from 2.7 at 0.025 mg/L to 5.5 at 0.5 mg/L.

It follows that, when the toxicity index is significantly different between a resistant and a susceptible strain, a single resistance factor could be misleading. This would be so irrespective of whether concentration or exposure time were the fixed dosage variables. If concentration were fixed, the resistance factor would depend on the particular concentration chosen. If the resistance of CTC_{475} were measured at from 2 to 10 mg/L it would appear to be more susceptible than the reference strain. Similarly, if it were measured at 0.01 mg/L or 0.5 mg/L it would appear to be twice as resistant as it is at 0.025 mg/L. Alternatively, if the resistance of CTC_{475} were determined from a graded series of concentrations to a fixed exposure period, such as the 20 hours recommended in the FAO test method for fumigant resistance (Anon. 1975), the slopes of the probit lines for the resistant and the reference strains would be different (6.44 and 7.12, respectively) and the resistance factor derived from a comparison of LC_{99} values would be 4.2.

Since it is unlikely that replacements with similar properties will be found for the fumigants that we have now, it is likely that, if resistance occurs in the field, efforts will be made to modify their usage so as to combat resistance. The first approach to this would seem to be to use the fumigant at the concentrations at which the resistance is lowest. Thus, when control failures occur because of resistance, a comprehensive assessment of the magnitude of the resistance should be made so that appropriate dosages may be applied. Studies based on fixed concentrations, unless comprehensive, may not even reveal a variation of resistance level with concentration let alone determine concentration thresholds. From the example quoted, if resistance were measured from probit lines fitted to data obtained from a range of exposure periods at each of three fixed concentrations such as 0.025, 1.0, and 20 mg/L the conclusion would be that the resistance was constant over that range of concentrations. This is clearly not so.

To determine the variation in resistance with changes in dosage variables and to locate the thresholds within which the response is predictable from a simple model such as $C^n t = k$, there would seem to be no alternative to the approach adopted in the present study. Measurements of resistance based on little more than one or two fixed concentrations or fixed exposure periods should be treated as a guide only to the magnitude of resistance.

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Background Studies on Fumigants Session Chairman's Summary

M. Bengston*

IN his paper on sorption and desorption of fumigants, *Banks* emphasised the value of applying established findings in physical chemistry to the study of sorption and desorption. He suggested that future research should include estimation of five basic parameters which would enable future recommendations to have a sound scientific basis.

Nguyen, in his paper on the movement of fumigants in bulk stored grain, presented an initial mathematical model to describe the flow paths and velocities of convection currents in sealed storages. The model was used to predict the influence of temperature on the movement of fumigants in a range of storage structures.

Price, speaking on the action and inaction of fumigants, reviewed our limited knowledge on the biochemical lesions caused by existing fumigants. He paid particular attention to possible mechanisms of resistance, and presented evidence that strains with a high resistance to phosphine actively exclude this gas.

Waterford presented *Winks'* paper on measuring the biological efficacy of fumigants. He elaborated the problems of measuring susceptibility to phosphine, and the limitations of toxicity comparisons involving arbitrary times of observation. His data illustrated the complexity of the interaction between fumigant concentration and the period of exposure in determining toxicity.

The discussion ranged widely over the problems of fumigation research. It emphasised the need for a rigorous scientific and numerate approach in order to understand the fundamental physical and chemical properties of fumigants, their interactions with stored commodities, and their toxicity to pests. However the urgency of practical problems necessitated the immediate application of existing knowledge. There was a shortage of fumigation sheets as well as a lack of scientific knowledge.

Codes of practice for fumigant use in the humid tropics should not only embody positive advice, but also emphasise the dangers inherent in poor practices. With phosphine, for example, the dangers of whole-store fumigations in imperfectly sealed or porous buildings, and the inadequacy of short exposure periods needed emphasis. Sub-standard fumigations were in nobody's interest, and codes of practice needed authoritative scientific backing rather than legislative authority. However, the latter is essential as regards safety considerations. For example, recommendations on appropriate desorption periods after fumigation were dependent on decisions by health authorities on acceptable residue levels. I would recommend that ACIAR be requested to convene a Working Party to draw up a suggested code of practice for fumigation in the region.

Resistance to phosphine posed important fundamental and practical problems and need further study. Strains of *Cryptolestes ferrugineus* with levels of phosphine resistance comparable to those first reported from Bangladesh had been found in England on imports from the Indian subcontinent. There is thus a need to monitor the distribution of highly phosphine resistant strains in the Asean region.

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Framework for Use of Pesticides

Principles of Integrated Use of Chemicals in Grain Storage in the Humid Tropics

M. Bengston*

Abstract

Strategies for using chemicals in stored grain pest control in the humid tropics are reviewed. As in other parts of the world, good storage practices are necessary for good pest control, and chemicals should be used only after attention has been given to the basic factors of grain hygiene, reduction in grain moisture and temperature, and minimisation of storage period, although the humid tropical environment poses obvious constraints. The use of chemicals must be integrated into the storage system. Insect populations at the start of storage are reduced by grain hygiene measures in empty storage, by segregation of stocks, by fumigation of infested containers such as bags, and by application of residual fabric treatments. Inspection systems are required to ensure infested grain is not placed in storage without disinfestation.

Insecticides are commonly applied to the surface of bag stacks and experiments are envisaged on the incorporation of insecticide into the bag fabric. The concept of combining fumigation with an insecticide barrier on the periphery of bag stacks also warrants further consideration. Bulk storage provides the opportunity for use of grain protectants with application rates adjusted for grain temperature, grain moisture, and storage interval. The interaction of high moisture levels with the efficacy of chemical treatments requires further study. Infestations which develop in storage are best fumigated, or else restricted with grain protectant, taking appropriate care in regard to maximum residue limits.

THE use of chemicals in grain storage is a supplement to good storage practices but not a substitute for them. The basic principles of grain hygiene, reduction in grain moisture, reduction in grain temperature, and minimisation of storage interval need to be applied wherever practicable to the requirements of specific storage situations. Without attention to these principles, many of the advantages of chemicals will be reduced and the use of chemicals may fail.

The warm, moist conditions in the humid tropics generally favour insect development and permit field infestation at a level much greater than in temperate regions. The warm, moist conditions also have a significant effect on the potency of many chemicals. Both factors need to be considered in integrating the use of chemicals into a storage system.

Clearly, the physical nature of the storage system also imposes demands and constraints on the use of chemicals and this is especially so in the case of the basic division into bag or bulk storage. In turn, the use of chemicals, especially fumigants, imposes demands on the physical nature of the storage.

Hygiene

All storage entomologists would agree that storages, equipment, containers, and the grain itself should be free of infestation at the commencement of storage. Such a standard is difficult to achieve and very dependent on the use of chemicals.

Following the outloading and cleaning of storages, the storage fabric is usually treated with a residual pesticide. The objectives are to reduce the initial insect population by disinfesting the surface and to provide a residual deposit which will be effective against immigrant insects from untreated areas. Dr Webley discusses the details of fabric treatment in another paper in these proceedings, but it should be noted that the pesticide, the formulation, and the application rate should be adapted to the storage fabric materials and to the storage system.

All the equipment used in grain handling should

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be cleaned and treated with insecticide or fumigated according to circumstances. It may be most convenient to spray exposed fabrics, whilst insecticide dusts may be more useful for reaching inaccessible areas.

With bag storage, fumigation of used bags is an important but often neglected means of reducing initial infestation levels.

An inspection system is necessary at intake to ensure that infested grain does not enter the storage without adequate treatment. With bagged commodities, the appropriate action usually involves segregation and subsequent fumigation of infested lots. In storages which can be made gastight, the entire structure may be fumigated soon after inloading. With bulk grain, admixture of an insecticide such as dichlorvos may be appropriate to treat the initial infestation but without providing residual protection.

Sitophilus zeamais is well known to cause field infestation in maize (Powell and Floyd 1960; Giles and Ashman 1971; Morallo-Rejesus and Eroles 1976) and varieties with husks covering the cob are more resistant to infestation. Field infestation by moth species is also common (Giles 1964). The nature and significance of such infestation warrant further research.

Fumigation

Optimal use of fumigants demands gastight enclosures. Conventional fumigation has usually been carried out using plastic sheeting with a moderate degree of gastightness. The paper by Annis and van Graver in these proceedings describes a plastic enclosure with an extremely high standard of gastightness. New storages, either concrete or metal, can be constructed to be gastight, and existing horizontal storages have been successfully sealed to a high degree of gastightness on an industrial scale in Australia (e.g. Woodcock 1984). Such systems require careful evaluation before use in the humid tropics where the problems of moisture migration are much greater.

Grain Protectants

In bulk storage systems, admixture of grain protectant insecticides by spray application during intake into storage is highly effective. Both the biological activity and the residual life of such materials are dependent on grain moisture and grain temperature. These aspects are discussed by Dr Samson and Dr Desmarchelier in other papers in these proceedings. Both topics merit further study with respect to conditions in the humid tropics and clearly have a major effect on the application rates needed.

With grain in bags, treatment by admixture with insecticide dusts may be practicable for small quantities. In some situations, admixture by spray application may be practicable as grain leaves central drying facilities, before it is rebagged.

The development of in-bin drying systems could accentuate pest problems and more data are required on the nature and frequency of pest problems in such situations. These systems would readily allow admixture of insecticides during intake and detailed data are required on the persistence and efficacy of protectants under such conditions.

Bag Treatments

Treatment of the outside of bag stacks is routinely adopted in many storages and clearly exercises a degree of control (Ashman 1964). Treatment of the tops of such stacks is often neglected because they are hard to reach. A higher degree of control is exercised by spraying bag stacks layer by layer during their construction, but the system is little used because of the practical difficulties in making such applications. Some authors have carried out research on the incorporation of insecticides into the bag fabric (Morallo-Rejesus and Eroles 1976; Webley and Kilminster 1980, 1981). This is feasible during manufacture of the bag but the economics require careful evaluation. The combination of a persistent synthetic pyrethroid with polypropylene bags looks promising (Webley and Kilminster, 1981) and research on it is continuing.

Fumigation with Stack Treatment

The concept of combining an initial fumigation of very high standard with the subsequent treatment of the outside of the bag stack with relatively high doses of a persistent synthetic pyrethroid is also attractive and is being studied further.

Space Treatments

Treatment of the airspace above bagged commodities is commonly used for control of moth species. Control of larvae inside bags or bulk is difficult, so the aim is to control adults before significant egg laying occurs. Frequent treatments are essential, generally once or twice weekly and automatic dispensing systems with daily release are ideal. Slow release strips are effective if the airspace is small and ventilation is restricted. This topic is covered in detail in one of Dr Webley's papers in these proceedings.

Treatment of Infestations

Inevitably some infestations will develop during storage. How they are treated will depend on circumstances. Retreatments by admixture may be practicable if residue levels are low. Alternatively, the infested batch may be fumigated. Fumigation of infested batches is obviously facilitated in bag storages by leaving space between stacks for appropriate access. This may not be practicable when the grain supply exceeds the storage capacity.

Protective Covers

Fumigation of bag stacks either with conventional fumigants or carbon dioxide under highly gastight sheeting which is subsequently left in place is a highly promising means of preventing reinfestation. Care needs to be taken in regard to moisture migration. The paper by Annis and van Graver in these proceedings describes current research with carbon dioxide and gastight sheeting.

Storage Interval

Pest problems increase markedly with length of storage. Whilst the average storage interval is determined by the requirements of the storage system, stock control and stock rotation in the form of a first-in-first-out policy are major factors in minimising pest infestation. Protective chemicals will not generally be successful in preventing infestation of clean grain adjacent to overstored and infested grain.

Forecasting of a storage interval for particular grain lots should be as accurate as possible so as to allow choice of optimal pest control procedures. In Australia for example, the general practice is to use one application rate of grain protectant for storage intervals up to 3 months and a higher rate for 3–9 months. Retreatment or fumigation is recommended for longer storage intervals.

The more clearly the pest control operations can be integrated into the operations of the storage system the better will be the overall result.

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Occurrence of Resistance to Pesticides in Grain Storage Pests

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Abstract

Resistances to pesticides used to protect grain and other stored foodstuffs are widespread and involve all groups of pesticides and most of the important pests. The significance of the problem is verified by the many documented cases where control failures have clearly been associated with resistance to the pesticide being used and have forced its use to be discontinued.

Listings are given of confirmed resistances to fumigants and residual insecticides, together with the areas from which they have been reported to occur. Laboratory-selected resistances are given separately from field occurrences and, wherever appropriate, data are given on other resistances and cross-resistances present in the strains of pest under examination. Resistances to residual insecticides involve 31 species and most materials in use. Resistances to fumigants have been detected in nine species representing most of the major pest species in stored grain. Methyl bromide and the liquid fumigants are involved, but the major concern is with phosphine, the most widely used material, to which high level resistances have been reported in several species.

The methods for detecting, measuring, and characterising resistance are outlined. The interpretation of dosage mortality data is discussed in terms of the recognition and confirmation of resistance. The correlation between resistance detected in one life history stage and the tolerance of the other stages is considered and the significance of cross-resistances and multiple resistances discussed. Comment is also made on aspects of the distribution of resistances by the movement of infestable commodities in trade.

THE grain industries are very susceptible to the activities of storage pests. Prevention of loss from these pests involves high levels of pest control throughout production, storage, and marketing. The problem, in large measure, is not reducing large pest populations to manageable proportions, which can be achieved easily; rather it is maintaining the grain completely free of insects. This can be a difficult and costly exercise and, in much of the world, some compromise has to be accepted on economic grounds. Thus, on a cost-benefit basis, it has been found in most circumstances that satisfactory results can be obtained only with pesticides.

This dependence on pesticides is greater in areas where storage facilities, technologies, or management are not ideal and create conditions conducive to development of serious pest infestations. Under these conditions, pesticides applied directly to the commmodity or to the storage environment provide protection against attack more effectively and flexibly than any other control system. Many stored product pests, however, have developed resistance to some of the pesticides as a result of use in the unsatisfactory circumstances outlined, and this has rendered control unreliable. Frequently, there is no economically viable, non-chemical alternative and a new pesticide must be introduced — if one is available. Thus, the industries are locked into control programs based on pesticides, and resistance remains a continuing threat to the security of the grain stocks.

A further complication is the movement of infested grain in trade. As resistant strains of pests are difficult to control completely, there will be a transfer of these strains through storage and handling systems with cross infestation occurring at all stages of movement. Similarly, there will be spread of the resistant strains back through the production chain, particularly in seed. Thus, facilities where proper caretaking of grain is practiced will also be subject to resistance problems and the problems will become general, both nationally and internationally.

Nature and Significance of Resistance

Resistance comes about by selection with a

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toxicant of the more tolerant individuals in a population of a pest. Its primary effect is to raise the tolerance of the population to levels which allow survival of individuals after treatment with doses of pesticide calculated to kill normally-susceptible populations of the species. This increase in tolerance may be offset, in some measure, by increasing doses but, in time, a portion of the population will tolerate the toxicant at concentrations in excess of economic limits determined by price structure and maximum allowable residue levels. When this occurs, control measures based on that particular material are invalidated.

The basic point is that resistance results only from selection. It follows that the rate of selection is dependent on the number of insects available for selection. Any reduction in the number available, e.g. by hygiene and good warehousekeeping, reduces variability and the probability of resistance developing. It therefore follows that control measures should achieve complete kills to prevent selection occurring. The dose applied should be sufficient to kill the most tolerant insects in any normal population and the full dose should be available to every insect. Fumigation most closely approximates this and when properly carried out gives 100% kills — hence it should be less prone to resistance development. This is one of the reasons why fumigation is recommended and should always be used following failure of residual insecticides or when infestations contain large numbers of insects.

The application of pesticides at dosages exceeding estimated minimum effective dosages may prevent the development of low-level resistances or, in certain circumstances, the expression of higher level resistances in the early stages of their development. Thus, it may be an advantage to set application rates at higher levels that make some allowance for low-level changes in tolerance. This is desirable, particularly when the species concerned characteristically shows high levels of variability in response to the material in use, or is prone to increases in tolerance from non-specific causes.

The mechanisms of resistance are by no means clear, but certain well-established features enable planning of effective countermeasures.

(i) Pesticides fall into well-defined chemical groupings and the development of resistance to one particular material may confer on the population high level resistance to related pesticides. Low level resistance to unrelated series of pesticides may also be developed concurrently.

(ii) Pests may be exposed to a number of different types of pesticide and this, together with cross-infestation by strains carrying other types of resistances that have developed elsewhere, may result in a complex of unrelated resistances being present in the same strain.

(iii) Strains in which resistance to a particular series of pesticides has developed, will develop high level resistance to unrelated pesticides with greater facility than would strains not previously exposed to pesticides.

(iv) Resistance in field populations may diminish when the pests are removed from exposure to pesticides. The rate of loss depends on the interaction between the genetic constitution of the pest, the level and nature of the resistance, and dilution by individuals of normal susceptibility from unexposed populations. In general, resistances, once expressed in populations of stored product pests, are remarkably stable. They will usually persist for long periods when resistant strains are inbred without any selection pressure. Dilution with susceptible insects may depress frequencies of resistant insects but resistance re-appears quickly when selection pressure is applied.

Where resistance has been observed, the pesticide in use should be replaced by an unrelated material. The change must recognise that further resistances may occur, and must consider the availability of reserve types of pesticides for emergencies (the latter applies more particularly where pests are vectors of human and animal diseases). A knowledge of the resistance mechanism involved is useful in the choice of possible alternative materials. When considering countermeasures to resistance, it is necessary to know at least the characteristic cross-resistance pattern for that material.

Infestations in stored grain frequently involve a complex of species with different levels of tolerance to particular pesticides. Thus, many synthetic pyrethroids may be more effective against *Rhyzopertha dominica* than against

Sitophilus oryzae and *Tribolium* spp. whilst the converse holds for some organophosphorus compounds. The choice of a suitable pesticide may involve some compromise or use of a mixture of two materials to achieve maximum efficacy.

Whether use of mixtures of pesticides delays or accelerates development of resistance to either or both materials is a contentious point and unlikely to be satisfactorily resolved. Certainly, each pest/pesticide combination would be a separate issue and expediency in achieving efficacious control should be the overriding consideration.

With residual pesticides, the first indication of resistance in the field is a progressive reduction in the time for which residual deposits remain effective. A grain protectant or other surface deposit such as a fabric treatment, when first introduced, may give a long period of protection but, subsequently, this period is reduced although residue analyses may reveal no change in the normal decay pattern of the pesticide. Early warning indications of resistance such as this often go undetected, particularly under conditions of indifferent management, and the problem is not recognised until obvious signs of resistance occur such as large-scale buildup of pest populations in treated commodities. By this time, the pesticide's operational life is finished. Regular monitoring of the tolerance status of the major pests is a valuable means of early detection of resistance and can provide unequivocal evidence of the contribution of resistance in control failures.

Breakdown of controls due to any of the factors in the list which follows does not constitute resistance.

(i) Use of inappropriate pesticide formulations or formulations that have deteriorated before use.

(ii) Use of unstable preparations, and disregard of compatibility recommendations when mixtures are used.

(iii) Incomplete coverage of material due to inadequate equipment or treatment.

(iv) Loss of pesticides at abnormally high rates because of extreme conditions of temperature, moisture, or exposure to light.

(v) Nature of the treated substrate. Residual deposits of insecticide may be sensitive to the chemical nature of the substrate, for example concrete or rusted iron may accelerate decomposition of certain active ingredients. Physical exclusion of the pest from the insecticide may occur when absorbent substrates or excessive deposition of dust renders deposits inaccessible for contact toxicity.

(vi) Variations in pest susceptibility with temperature. Dosage levels effective at normal temperatures may be inadequate during extremely hot or cold weather. With certain species, humidity can have a similar effect, although to a somewhat lesser extent but with the caveat that some materials such as fenitrothion are considerably less potent when applied to grains at high moisture contents.

(vii) Variations in pest susceptibility with commodity. The type of grain can influence responses. Thus, for example, higher doses of protectants are required for maize than for wheat. The presence of a husk also significantly increases the minimum effective dosage required for control. Paddy can be cited as an example among cereals and the effect is most pronounced with the highly sorptive shell of peanuts.

The presence of trash in grain can also contribute to reduced effectiveness of treatments because of the different characteristics of trash as a treatment substrate.

(viii) Variations in susceptibility of different life history stages. Treatments, dose rates, and exposure times must take into account differences in susceptibility between the various stages of development of pests. Where treatments have not been programmed to avoid the more tolerant stages and if doses and exposure times have not been increased commensurately, survival will occur unless exposure to the pesticide has been continued until development to more susceptible stages has occurred.

Thus, the time and type of assessment of responses is important. Complete mortality from a treatment may not occur until some time after treatment and may not find full expression in the stage of development treated. Some grain protectants, for example, at specific dose levels may cause little mortality of the stage being treated but will suppress production of progeny, and in other instances the residual effects of the pesticides will require several generations to eliminate infestations.

(ix) When pests are present in large numbers, there may be sufficient survivors to cause considerable economic damage. Reinfestation must also be taken into account.

(x) Repellency of pesticides. Treatment with certain insecticides may cause insects to move down concentration gradients of the material to refuges. Similarly, with fumigants such as phosphine used in inadequately sealed storages, insects may move out when the fumigation commences and reinfest the storage when the fumigant has dissipated. Increased activity stimulated by the low doses of pesticide received at the start of exposure may be a contributory cause.

Detection and Measurement of Resistance

General Considerations

Failure of pesticides to control pests can occur for many reasons and confirmation of the presence of pesticide resistance as a contributing factor is essential for implementation of effective countermeasures. In some circumstances breakdown of control is spectacular and unmistakable, and confirmation is simple, in effect proving the obvious, and can be achieved by comparing dosage mortality data from the strain under examination with that from known susceptible material. This, however, is not always the case and low levels of resistance or low frequencies of resistant phenotypes may escape detection or produce results from which unequivocal diagnoses are not possible.

All expressions of resistance involve some changes in tolerance to the pesticides, and, however slight, may be detected and measured provided appropriate methods are used to compare either response levels at similar doses, or doses producing similar responses. Such detection and measurement of resistance is technically simple in the laboratory where the variables affecting the response of the pest can be controlled and precisely reproduced. The inherent sensitivity of laboratory tests may be compared with tests carried out under field conditions, where it is necessary to interpret the responses in terms of ambient conditions and reproducibility is difficult. Although laboratory tests are obviously preferable, they must not detract from the significance of reports from the field that control measures that had been properly derived and carried out, and that had been effective previously, are no longer fully effective. This latter evidence is ultimately crucial and is unequivocal to the end users of control measures.

Unfortunately, laboratory evidence, as presented in the literature can often be equivocal. Every population of insects is composed of individuals which do not respond identically to a toxicant. There is a distribution of the frequencies of the different levels of tolerance which can be characterised by a mean tolerance, the LD_{50}, and a range of tolerances greater or less than this mean. In pest control, where the aim is usually to eliminate all or practically all of the pest population, it is the more tolerant individuals that are of interest. It is these more tolerant individuals, that may carry an inherent capacity for enhanced tolerance and pass this on to their progeny. By allowing these more tolerant individuals to be the only survivors from a treatment, a more tolerant strain of the pest is being selected. A critical issue in determining whether true resistance is developing, however, is whether the strain being selected has individuals with an upper tolerance limit greater than that of the more tolerant individuals of the preceding generations. If this is the case, then it can be regarded as true resistance. If, however, there is simply an increase in the frequency of the more tolerant individuals in the population without an increase in the upper tolerance limit, this is not resistance. Thus, the LD_{50} may have increased considerably but the LD_{99} has not changed and control measures properly carried out, should eliminate all the tolerant individuals. Unfortunately, laboratory workers often look at the mean responses only of a population and ignore the full range of responses, particularly those of the few but significant more tolerant individuals whose responses will determine whether complete suppression of the population is achieved. Thus, they may arrive at erroneous conclusions. Fig. 1 illustrates this using data taken from a published paper reporting selection of resistance to phosphine in *Tribolium castaneum*. Effectively all the selection has done is to concentrate the responses in the upper range of the distribution. This certainly cannot be described as resistance and highlights the necessity for resistance workers to consider the full range of responses in their studies.

If, of course, control measures are aimed at less than complete suppression of pests, for example where control programs are integrating biological control agents with use of chemicals which are required to give a specified partial kill of the pest population, then it may be a different story. However, except for some Lepidoptera, such integrated programs have no practical application in grain pest control.

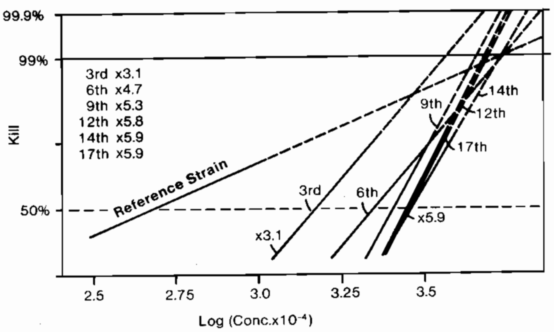

Fig. 1. Responses of a strain of *Tribolium castaneum* selected for resistance to phosphine. The solid lines represent the data as reported by the authors. The dotted lines represent extrapolation of the original lines to the 99.9% response level. It is evident that there is no significant change in the dose required for high mortalities (data from Saxena and Bhatia 1980).

Methods for Resistance Monitoring

The most satisfactory basis for monitoring for resistance is exposing samples of pests to single doses of pesticide that would be expected to kill normally susceptible pests. The 99.9% response level is used as the discriminating dosage level and survival of pests at such discriminating dosages is indicative of resistance and the need for more detailed confirmatory tests. The discriminating dosages in these primary tests are established from the dosage-mortality relationships of known susceptible strains, taking into account normal strain variability.

It is desirable, that these laboratory tests simulate field use of chemicals but this can not be done at the expense of sensitivity and reproducibility. Moreover, in the field, pesticides are often used in very different formulations and ways, and simulating these conditions and seeking common ground is difficult. Essentially, monitoring for resistance is determining changes in physiological response to pesticides and the ideal test is one in which the only variable factor is the dosage of pesticide.

The test methods used must detect resistance efficiently and allow adequate measures of the level of resistance. The tests should be rapid to allow countermeasures to be implemented quickly if resistance is detected. They must give consistent results and be such that large numbers of samples can be examined quickly. It is also desirable that the tests can be carried out by relatively inexperienced personnel after a minimum of instruction and, also, that the apparatus is simple and readily available. Another important requirement is that the method be capable of dealing with all sizes of samples including those where only one or two insects are available. In the early stages of development of resistance, only low numbers of insects may survive treatment and so attract attention for testing. It is important that these insects be tested. If a method is chosen that restricts the number of insects that can be tested, the probability of detecting low frequency phenotypes is lowered and the effectiveness of the test method is reduced. Finally, the strains under test must be preserved irrespective of the sample size and whether all available insects are used in the test. This is necessary as further tests may be required to confirm resistance, to compare it with other resistances to the same material, to check cross-tolerances, and to determine any other resistances that may be present.

The procedures to be followed in a resistance test method are:

(i) Selecting an appropriate life history stage to obtain responses representative of the tolerance status of the species concerned, taking into account the particular stages at which practical control measures may be aimed. With insects, adults usually satisfy the requirements most closely and generally provide the greatest uniformity of response.

(ii) Selecting an appropriate type of test to measure responses.

(iii) Establishing base response data from known susceptible strains.

(iv) Using discriminating doses to screen samples for resistance either on the field-collected material or their progeny, and, if the results are not considered unequivocal, carrying out supplementary discriminating tests on the progeny of the few survivors from the primary test. Susceptible reference strains are included in all tests as a check on procedures.

(v) Complete definition of resistance by comparison of graded dosage mortality responses of susceptible and resistant strains.

(vi) Determination of cross-resistance patterns.

(vii) Establishing correlations between resistance levels of different life history stages.

(viii) Correlating laboratory resistance data with responses achieved in simulated field use of the pesticides concerned.

Methods for the detection and measurement of insecticide resistance in stored product Coleoptera have been proposed from Macdonald College, Quebec, for *Tribolium confusum* and *Cryptolestes* sp. using paper which has been impregnated with insecticide (Kumar and Morrison 1963, 1964); from the Pest Infestation Laboratory, England, as a general test based on insecticide-impregnated dust mixed with grain (Parkin 1965) and as a test for *Oryzaephilus surinamensis* and malathion, based on Fluon-coated glass rings confining insects on filter paper treated with a solution of insecticide in butyl phthalate (Wilkin 1966); from Australia, for *Sitophilus oryzae* and DDT and lindane, based similarly on glass rings confining insects on insecticide-impregnated filter paper circles (Champ 1968); and similar methods have subsequently been described for *Tribolium castaneum* and lindane, malathion, carbaryl, and pyrethrins (Champ and Campbell Brown 1970a), *Sitophilus zeamais* and lindane (Dyte and Forster 1970b), and *T. castaneum* and *S. oryzae* and malathion (Rajak et al. 1973). A simple test to detect organophosphorus compound resistance by crushing insects onto filter paper impregnated with ∝-naphthyl acetate to determine differences in levels of esterase activity by colour change proved unsuccessful in *T. castaneum* (Coveney and Corban 1970).

Methods tested for the detection and measurement of insecticide resistance in Lepidoptera involved either exposing larvae of *Plodia interpunctella* to insecticide-treated foodstuff (La Hue 1969; Armstrong and Soderstrom 1975) or the topical treatment of last instar larvae of *P. interpunctella, Ephestia cautella,* and *E. kuehniella* with aliquots of diluted insecticide (Zettler et al. 1973; Attia 1977a; Ramsey and Farley 1978). Subsequently, a method was developed based on exposing adults of *P. interpunctella, E. cautella, E. elutella,* and *Sitotroga cerealella* to films of malathion deposited on the walls of the glass flasks (Anon. 1978c, 1981c; Cogan 1982).

Methods appropriate for use with mites were developed originally by Wilkin and Hope (1973) to monitor lindane resistance in mites collected during a survey of farm stored grain in England (Wilkin et al. 1975). These tests were based on admixture of lindane dust with grain and were initially concerned with *Acarus siro* and *Glycyphagus destructor.*

Standardised Test Methods

The FAO Working Party of Experts on Resistance of Pests to Pesticides at its First Meeting in Rome in 1965 outlined the principles governing the detection and measurement of insecticide resistance in arthropods and advocated, inter alia, the desirability of using standardised test methods (Anon. 1967). The principles were reiterated in a FAO Monograph on Pest Resistance to Pesticides in Agriculture (Anon. 1970b) and in the introductory paper of a series of Recommended Methods for the Detection and Measurement of Resistance of Agricultural Pests to Pesticides published in the FAO Plant Protection Bulletin (Anon. 1969). The *Tribolium* spp. were the only stored product species included in the first list of pests for which it was recommended that tests be devised (Anon. 1968).

A tentative method for monitoring resistance to malathion, lindane, carbaryl, and synergised pyrethrins in adults of *T. castaneum* appeared in October 1970 (Anon. 1970a). It was based on exposure of test insects to insecticide-impregnated filter paper and was a synthesis of tried and proven techniques that had been in extensive use in many laboratories for at least 25 years. The principles involved in, and the arguments for this test were based on applicability to a range of the smaller stored product beetles. Subsequently, as a result of collaborative work by the Pest Infestation Control Laboratory of England and the Stored Grain Research Laboratory of the Commonwealth Scientific and Industrial Research Organization, Australia, for the FAO Global Survey of Pesticide Resistance in Pests of Stored Products, the test was extended to include monitoring for resistances to the residual insecticides malathion and lindane (Anon. 1974a) and the fumigants methyl bromide and phosphine (Anon. 1975) in *T. castaneum, T. confusum, Sitophilus oryzae, S. zeamais, S. granarius, Rhyzopertha dominica, Oryzaephilus surinamensis,* and *O. mercator* as representing the more important pesticides and beetle pests of stored grain.

These tests have been modified subsequently to include further species and insecticides. These are *S. oryzae, R. dominica,* and *T. castaneum* and pirimiphos methyl, bioresmethrin, dichlorvos, and fenitrothion (Champ and Turner 1980b; Champ 1984b), *Latheticus oryzae* and malathion (Anon. 1978c), *Dermestes maculatus* and lindane and malathion (Anon. 1978c, 1981g), *Cryptolestes* *ferrugineus* and malathion (Anon. 1981m), *R. dominica, T. confusum,* and *O. surinamensis* and fenitrothion (Attia 1984), and *Callosobruchus chinensis, C. maculatus,* and *Zabrotes subfasciatus* and lindane (Tyler and Evans 1981). The fumigant tests have also been adapted for monitoring for resistance to phosphine in *Cryptolestes ferrugineus* (Mills 1983) and to the liquid fumigants, ethylene dibromide, ethylene dichloride, carbon tetrachloride, and methyl chloroform in *S. oryzae, S. granarius, R. dominica, T. confusum,* and *O. surinamensis* (Anon. 1981b).

The range of standardised tests was extended in 1980 to include larvae and adults of the lepidopterous pests of stored products using methods based on those listed above. The larval test involved topical treatment of last-instar larvae of *Plodia interpunctella* and *Ephestia cautella* with 22 chlorinated hydrocarbon, organophosphorus compound, and pyrethroid insecticides (Busvine 1980b). The adult test is based on exposure of test insects to films of insecticide coated on the inner walls of glass flasks. It is applicable to rapid detection of malathion resistance in *Plodia interpunctella, E. cautella, E. kuehniella,* and *Sitotroga cerealella* (Busvine 1980b).

Standardised tests were similarly adopted for lindane resistance in *Acarus siro* and *Glycophagus destructor* (Busvine 1980a) and have subsequently been modified to include *Acarus chaetoxysilos* and *Acarus farris* (Anon. 1981a), and then to include pirimiphos methyl and all species (Anon. 1981j).

Published tests are summarised in Tables 1 and 2.

Table 1. Test methods for detecting resistance to insecticides in pests of stored products.

	Type of test and insecticides involved (F — film, T — topical, Am — admixture) Underlining of test denotes an FAO-recommended method	References
Sitophilus oryzae	F — DDT, lindane	Champ (1968)
	F — Malathion	Rajak et al. (1973)
	F — lindane, malathion	Anon. (1974a)
	F — pirimiphos-methyl, bioresmethrin, dichlorvos, fenithrothion	Champ (1984b)
S. zeamais	F — lindane	Dyte and Forster (1970b)
	F — lindane, malathion	Anon. (1974a)
S. granarius	F — lindane, malathion	Anon. (1974a)
Rhyzopertha dominica	F — lindane, malathion	Anon. (1974a)
	F — pirimiphos-methyl, bioresmethrin, dichlorvos, fenithrothion	Champ (1984b)
	F — fenitrothion	Attia (1984)
Tribolium castaneum	F — lindane, malathion, carbaryl, pyrethrins	Champ and Campbell-Brown (1970a), Anon. (1970a)
	F — malathion	Rajak et al. (1973)
	F — lindane, malathion	Anon. (1974a)
	F — pirimphos-methyl, bioresmethrin, dichlorvos, fenitrothion	Champ (1984b)
T. confusum	F — lindane, malathion	Anon. (1974a)
	F — fenitrothion	Attia (1984)
Oryzaephilus surinamensis	F — malathion	Wilkin (1966)
	F — lindane, malathion	Anon. (1974a)
	F — fenitrothion	Attia (1984)
O. mercator	F — lindane, malathion	Anon. (1974a)
Cryptolestes ferrugineus	F — malathion	Anon. (1981m)
Latheticus oryzae	F — malathion	Anon. (1978c)
Dermestes maculatus	F — lindane	Binns and Tyler (1978)
	F — malathion	Anon. (1981g)
Callosobruchus chinensis	F — lindane	Tyler and Evans (1981)
C. maculatus	F — lindane	Tyler and Evans (1981)
Zabrotes subfasciatus	F — lindane	Tyler and Evans (1981)

Table 1. (cont.) Test methods for detecting resistance to insecticides in pests of stored products.

	Type of test and insecticides involved (F — film, T — topical, Am — admixture) Underlining of test denotes an FAO-recommended method	References
Ephestia cautella		
Larvae	T — malathion, pyrethrins	Zettler et al. (1973)
	T — DDT, endrin, dieldrin, dichlorvos, mevinphos, monocrotophos, parathion, parathion-methyl, chlorpyriphos, chlorpyriphos-methyl, naled, diazinon, pirimiphos-methyl, phoxim, fenitrothion, malathion, pyrethrins, permethrin, D-phenothrin, bioresmethrin	Attia (1976), Attia et al. (1979), Busvine (1980b)
Adults	F — malathion	Busvine (1980b), Anon. (1981c)
E. elutella		
Adults	F — malathion	Anon. (1981c)
E. kuehniella		
Adults	F — malathion	Busvine (1980b), Anon. (1981c)
Plodia interpunctella		
Larvae	Am — malathion	Armstrong and Soderstrom (1975)
	T — malathion, pyrethrins	Zettler et al. (1973)
	T — DDT, endrin, dieldrin, dichlorvos, mevinphos, monocrotophos, parathion, parathion-methyl, chlorpyriphos, chlorpyriphos-methyl, naled, diazinon, pirimiphos-methyl, phoxim, fenitrothion, malathion, pyrethrins, permethrin, D-phenothrin, bioresmethrin	Attia (1976), Attia et al. (1979), Busvine (1980b)
Adults	F — malathion	Busvine (1980b), Cogan (1982)
Sitotroga cerealella		
Adults	F — malathion	Busvine (1980b), Anon. (1981c)
Acarus siro	Am — lindane	Busvine (1980a)
	Am — pirimiphos-methyl	Anon. (1981j)
A. chaetoxysilos	Am — lindane	Anon. (1981a)
	Am — pirimiphos-methyl	Anon. (1981j)
A. farris	Am — lindane	Anon. (1981a)
	Am — pirimiphos-methyl	Anon. (1981j)
Glycyphagus destructor	Am — lindane	Busvine (1980a)
	Am — pirimiphos-methyl	Anon. (1981j)
Tyrophagus palmarum	Am — pirimiphos-methyl	Anon. (1981j)

Table 2: Test methods for detecting resistance to fumigants in pests of stored products.

	Fumigants involved (Underlining of fumigants denotes an FAO recommended method)	References
Sitophilus oryzae	Methyl bromide, phosphine	Anon. (1975)
	EDB, EDC, CTC, MC	Anon. (1981b)
S. zeamais	Methyl bromide, phosphine	Anon. (1975)
S. granarius	Methyl bromide, phosphine	Anon. (1975)
	EDB, EDC, CTC, MC	Anon. (1981b)
Rhyzopertha dominica	Methyl bromide, phosphine	Anon. (1975)
	EDB, EDC, CTC, MC	Anon. (1981b)
Tribolium castaneum	Methyl bromide, phosphine	Anon. (1975)
T. confusum	Methyl bromide, phosphine	Anon. (1975)
	EDB, EDC, CTC, MC	Anon. (1981b)
Oryzaephilus surinamensis	Methyl bromide, phosphine	Anon. (1975)
	EDB, EDC, CTC, MC	Anon. (1981b)
O. mercator	Methyl bromide, phosphine	Anon. (1975)
Cryptolestes ferrugineus	Phosphine	Mills (1983)

Occurrences of Resistance

Most of the major pest species in stored products have been reported resistant, in some degree, to most pesticides in common use. The problem has grown rapidly from 3 species in 1960, through 8 species in 1964, to 14 species in 1970, 19 species in 1979, 23 species in 1981, and involves 31 species currently. These include 18 species of Coleoptera, 7 of Lepidoptera, and 6 mites.

The range of pesticides and related compounds is very large and totals 102 pesticides and related compounds, including 18 chlorinated hydrocarbons, pyrethrins and 14 synthetic pyrethroids, 43 organophosphorus (OP) compounds, 5 carbamates, 5 juvenile hormone mimics, 1 organo-tin compound, 1 organosulfite compound, and 12 fumigants including carbon dioxide. Resistance is certainly a worldwide problem affecting and threatening, in some measure, the efficacy of all pest control programs involving pesticides. Many of the resistances are of academic interest only, while others are of considerable significance in planning pest control strategies.

The data concern only physiological resistances. Changes in behavioural patterns of pests in response to continued exposure to pesticides are largely unexplored. These changes could have particular significance in the grain industry. They may concern repellency such as reduced response time on treated surfaces or correlated, but

Table 3. Occurrence of laboratory-selected resistance to residual insecticides and related compounds in pests of stored products.

	Type of test, highest resistance level and cross resistances (F = film, T = topical, Am = admixture, S = direct spray)	References
Sitophilus oryzae		
DDT	F×40	Cichy (1971)
Pyrethrins	F×6	Cichy (1971)
Permethrin[a]	F×256. Bioresmethrin[a] ×242, cypermethrin[a] ×1183, deltamethrin[a] ×161, fenvalerate[a] ×264, phenothrin[a].	Heather and Gauldie (1982), Heather (1986)
Deltamethrin[a]	F×98. Bioresemethrin[a] ×292, cypermethrin[a] ×1100, fenvalerate[a] ×192, permethrin[a] ×392, phenothrin[a]	Heather and Gauldie (1982), Heather (1986)
Demeton methyl	F×434	Cichy (1971)
Malathion	F×49. DDT ×11, lindane ×3, dieldrin ×4, endrin ×3, isodrin ×1, endosulfan ×1, pyrethrins ×4, diazinon ×18, dichlorvos ×7, fenitrothion ×39, iodofenphos ×9, phosphamidon ×6, parathion ×33, methyl parathion ×21, disulfoton ×7, carbaryl ×5	Bansode (1974), Bansode and Bhatia (1976)
Sitophilus granarius		
DDT	Low level. Pyrethrins	Mathlein (1952)
	—	Lakocy (1970)
Pyrethrins	T×148, ×8[a]. DDT × 30, o-chloro-DDT ×55, deutero DDT ×3, Bulan ×22, Prolan × 14, fluoro DDT ×37, perthane ×76, lindane ×7, dieldrin ×2, aldrin ×3, allethrin ×28, ×14[a], bioallethrin ×39, ×9[a], bioresmethrin ×79, ×8[a], resmethrin ×207, ×8[a], tetramethrin >×10, ×8[a], carbaryl ×3, dinoseb ×6[b]	Lloyd and Parkin (1963), Lloyd (1969, 1973)
	F×17. DDT ×3.9, lindane ×4.5, bioresmethrin ×10, malathion ×3.7, pirimiphos-methyl ×2.7, propoxur ×3.8	Prickett (1980)
	F×3.5	Blackith and Gorringe (1953)
Allethrin	— ×2	Sevintuna and Musgrave (1961)
Malathion	F×10. Pirimiphos methyl ×4, chlorpyrifos methyl ×3, fenitrothion ×10, iodofenphos ×5, bromophos ×5	Anon. (1978d)
Fenthion	—	Kumar and Morrison (1967)
Propoxur	— DDT×25	Kumar and Morrison (1967)

Table 3. (cont.) Occurrence of laboratory-selected resistance to residual insecticides and related compounds in pests of stored products.

	Type of test, highest resistance level and cross resistances (F = film, T = topical, Am = admixture, S = direct spray)	References
Tribolium castaneum		
DDT	T×166	Dyte and Blackman (1967)
	Am×95. F, lindane ×1, aldrin ×1, heptachlor ×3, dieldrin ×2, endrin ×2, chlordane ×2, endosulphan ×2, toxaphene ×1, pyrethrins ×2, malathion ×3, mevinphos ×8, parathion ×9, diazinon ×9, carbaryl >×12	Bhatia and Pradhan (1968, 1970)
	F×4	Cichy (1971)
Lindane	F>×86. DDT ×1, dieldrin >×291, heptachlor >×232, endrin >×165, aldrin >×100, chlordane >×34, toxaphene >×49, endosulphan >×7, pyrethrins ×2, malathion ×1, diazinon ×1, parathion ×2, carbaryl >×12	Bhatia and Pradhan (1972)
Pyrethrins	F×8[a]	Cichy (1971)
Malathion	T×19. Pyrethrins ×13, chlorphoxim ×20, diazinon ×8, phoxim ×5	Speirs and Zettler (1969)
	F×54. DDT ×1, lindane ×1, pyrethrins ×5, diazinon ×2, dichlorvos ×1, disulfoton ×3, fenitrothion ×1, iodofenphos ×1, parathion ×2, phorate ×2, phosphamidon ×1, carbaryl ×2	Pasalu and Bhatia (1974)
	T×263. Malaoxon ×19, malathion-ethyl ×10, acethion ×2, bromophos ×1, cyanofenphos ×1, dicrotophos ×1, dimethoate ×1, fenitrothion ×1, iodofenphos ×1, mevinphos ×1, pyrethrins ×1, phenothoate ×25, phoxim ×1	Dyte and Blackman (1972)
	F×260. DDT×2, lindane ×3, pyrethrins ×1×1[a], bioresmethrin ×2, fenoxythrin ×2, bromophos ×1, bromoxon ×2, chlorpyriphos-methyl ×1, cyanophos ×1, diazinon ×1, diazoxon ×1, dichlorvos ×1, fenitrothion ×1, fenitroxon ×1, fospirate ×4, iodofenphos ×1, methacriphos ×1, pirimiphos-methyl ×1, tetrachlorvinphos ×1, carbaryl ×3	Champ and Turner (1976)
	F×254. DDT×3, lindane ×240, pyrethrins ×1×1[a], bioresmethrin ×2, fenoxythrin ×1, bromophos ×1, bromoxon ×5; chlorpyriphos-methyl ×2, cyanophos ×2, diazinon ×2, diazoxon ×2, dichlorvos ×2, fenitrothion ×1, fenitroxon ×5, fospirate ×4, iodofenphos ×3, methacriphos ×1, pirimiphos-methyl ×1, tetrachlorvinphos ×6, carbaryl ×1	Champ and Turner (1976)
Demeton methyl	F×28	Cichy (1971)
Tribolium confusum		
	DDT ×8	Maeda (1958)
Oryzaephilus surinamensis		
Malathion	F×10. Bromophos ×19, chlorthion ×2, cyanophos ×3, diazinon ×7, diacapthon ×2, fenitrothion × 11, iodofenphos ×35, phenthoate ×7, phoxim ×6, pirimiphos methyl ×8, tetrachlorvinphos ×7	Tyler and Binns (1976)
Carbaryl	Am ×120	Dyte and Wilkin (1965)
Oryzaephilus mercator		
Malathion	F×7. Lindane ×89, bromophos ×158, diazinon ×4, fenitrothion ×2, iodofenphos ×28, tetrachlorvinphos ×64	Dyte and Forster (1973)
Dermestes maculatus		
Lindane	T×26	Binns and Tyler (1978)

Table 3. (cont.) Occurrence of laboratory-selected resistance to residual insecticides and related compounds in pests of stored products.

	Type of test, highest resistance level and cross resistances (F = film, T = topical, Am = admixture, S = direct spray)	References
Ephestia cautella		
Lindane	S×38 (Am×134). DDT ×3, heptachlor ×31, endrin ×7, dieldrin ×52, thiodan ×2, malathion ×1, diazinon ×1, dichlorvos ×1, monocrotophos ×1, phosphamidon ×1, carbaryl ×1, pyrethrins ×1	Shukla and Srivastava (1982a,b)
Methyl parathion	F×7. Methyl paraoxon ×2, parathion ×1, EPN ×1, malathion ×3, fenitrothion ×3, fenthion ×2	Hashimoto and Fukami (1964)
Plodia interpunctella		
DDT	T>×42. Lindane ×1, endrin ×1, dieldrin ×1, chlordane ×1, malathion ×1, fenitrothion ×1, pyrethrins ×1	Attia (1981)
Dieldrin	T>×53. Endrin ×69, chlordane >×206, DDT ×2, lindane ×13, malathion ×1, fenitrothion ×1, pyrethrins ×1	Attia (1981)
Malathion	T>×260. DDT×3, lindane ×1, endrin ×1, dieldrin ×1, chlordane ×1, fenitrothion ×1.4, pyrethrins ×1	Attia (1981)
Tineola bisselliella		
Dieldrin	×70	Kühne and Becker (1965)
Endrin, chlordane	—	Kühne (1967)

[a] Synergised with piperonyl butoxide.

[b] This strain was also resistant to methoxychlor and iso-DDT but factors of resistance could not be measured.

Table 4. Field occurrences of resistance to residual pesticides in pests of stored products.

	Type of test, highest resistance factor and countries involved (F = film, T = topical, Am = admixture, D = dipping)	References
Sitophilus oryzae		
DDT	F×14. Australia	FAO Survey 1972–73
Lindane	Am×72. World-wide, 53/58 countries	FAO Survey 1972–73
Dieldrin	F>×100. Australia	Champ and Cribb (1965)
Pyrethrins	F×7×4[a], bioresmethrin F×7, fenoxythrin F×3. Australia	FAO Survey 1972–73
Deltamethrin	T, cypermethrin T, fenvalerate T	Anon. (1981d)
Malathion	Am×22. Colombia, Peru, UK, CAR, Mozambique, Israel, Pakistan, India, Nepal, China (Taiwan), Papua New Guinea, Australia	FAO Survey 1972–73, Anon. (1981g), Navarro et al. 1981
Chlorpyriphos-methyl	F×2.5, diazinon F×10, dichlorvos F×6, fenchlorphos F×4, fenitrothion F×6, fospirate F×3, pirimiphos methyl F×5, tetrachlorvinphos F×7. Australia, Nepal	FAO Survey 1972–73, Champ and Cribb (1965), Binns (1983)
Carbaryl	F×3. Australia	FAO Survey 1972–73
Sitophilus zeamais		
DDT	Am>×25. Brazil, Philippines	Mello (1972), Morallo-Rejesus (1972)
Lindane	Am×32. World-wide, 46/48 countries	FAO Survey 1972–73
Malathion	Am×180. Brazil, El Salvador, Guatemala, UK, China, China (Taiwan), Papua New Guinea, Australia	FAO Survey 1972–73, Wang and Ku (1982)
Bromophos	×2, diazinon ×7, tetrachlorvinphos ×3. Brazil	Mello (1972)
Phoxim	Am×90, diazinon T×5. China (Taiwan)	Wang and Ku (1982)
Bendiocarb	T×5. China (Taiwan)	Wang and Ku (1982)
Carbaryl	F×4. Philippines	Morallo-Rejesus (1972)

Table 4. (cont.) Field occurrences of resistance to residual pesticides in pests of stored products.

	Type of test, highest resistance factor and countries involved (F = film, T = topical, Am = admixture, D = dipping)	References
Sitophilus granarius		
DDT	F×5. Canada	Kumar and Morrison (1965)
Lindane	T×7. Canada, Brazil, Argentina, Chile, UK, Mediterranean, South Africa, Australia, Greece	FAO Survey 1972–73, Anon. (1978c, 1981c, j)
Dieldrin	F×2. Canada	Kumar and Morrison (1965)
Pyrethrins	Am×3.5. UK	Holborn (1957)
Bioresmethrin	F×2. Australia	FAO Survey 1972–73
Deltamethrin	T, cypermethrin T, fenvalerate T	Anon. (1981d)
Malathion	F×6. Argentina, UK, Greece, Australia	FAO Survey 1972–73, Anon. (1978c, 1981c)
Diazinon	×2, iodofenphos ×21, pirimiphos methyl ×2, tetrachlorvinphos ×2. Australia	FAO Survey 1972–73
Rhyzopertha dominica		
Lindane	F×3. World-wide, 41/51 countries	FAO Survey 1972–73
Bioresmethrin	F×1.7. Australia	Champ (1979)
Malathion	F×100. Widespread, 23/50 countries[b]	FAO Survey 1972–73
Bromophos	F×15, chlorpyriphos methyl F×33, cyanophos F>×100, diazinon F×3, dichlorvos ×26, fenitrothion ×9, fospirate ×43, iodofenphos ×16, methacrifos ×13, tetrachlorvinphos ×5. Australia	FAO Survey 1972–73, Brun and Attia (1983), Attia (1984a)
Tribolium castaneum		
DDT	T×82, F>×11. USA, Nigeria, India, Australia	Parkin and Bright (1965), Champ and Campbell-Brown (1970b), Speirs et al. (1971), Bhatia et al. (1971), Attia (1984a)
Lindane	F×240. World-wide, 75/76 countries	FAO Survey 1972–73
Cyclodienes	Aldrin T×3. Australia Dieldrin low. Nigeria	Parkin and Bright (1965), Dyte (1976)
Pyrethrins	T×34×6.3[a]. USA, UK, Australia	Holborn (1957) Vincent and Lindgren (1967), Lloyd et al. (1975)
Bioallethrin	T×16×71[a], bioresmethrin T×3.3×3.2[a], F×12, Am×4.3×6.4[a], cismethrin Am×1.3×0.6[a], cypermethrin T, deltamethrin T, fenvalerate T, kikuthrin, T×12×19[a], permethrin (1:3) T×12×11[a], phenothrin T×6×20[a], prothrin T×19×27[a], resmethrin T ×2.2×9.7[a], tetramethrin T ×338×266[a]. Australia, Malaysia	Carter et al. (1975), Lloyd et al. (1975) Lloyd and Ruczkowski (1980), Anon. (1978d, 1981d), Attia (1984a)
Malathion	Am×52. World-wide, 75/78 countries	FAO Survey 1972–73
Benoxafos	F×6, bromophos T×6, chlorpyriphos F×5, chlorpyriphos methyl F×4, cyanolate T×37, cyanophos F×3, diazinon F×11, dichlorvos F×3, dicrotophos T×11, fenitrothion Am×6, iodofenphos T×4, K37 T×3, phenthoate T×7, phoxim F×10, pirimiphos ethyl T×4, pirimiphos methyl T×6, temephos F>×9, tetrachlorvinphos F>×227, tetrachlorvinphos-ethyl T>×20. Australia, Malaysia[c]	Champ and Campbell-Brown (1970b), Dyte (1974, 1976), Carter et al. (1975)
Arprocarb	F×25, carbaryl F×13, promecarb F×3. Australia, Malawi, Senegal	Champ and Campbell-Brown (1970b), Dyte et al. (1973)

Table 4. (cont.) Field occurrences of resistance to residual pesticides in pests of stored products.

	Type of test, highest resistance factor and countries involved (F = film, T = topical, Am = admixture, D = dipping)	References
Juvenile hormone mimics	Australia (JH-1, hydroprene, methoprene, DMF, Bowers' 2B)	Dyte et al. (1975a), Amos et al. (1977), Hoppe (1981)
Piperonyl butoxide	Australia	Dyte et al. (1975b)
Tributyltinacetate, diflubenzuron.	Australia	Carter (1975)
Tribolium confusum		
DDT	F×25. Canada	Kumar and Morrison (1965)
Lindane	F×8. World-wide 23/24 countries	FAO Survey 1972–73, Attia (1984a)
Bioresmethrin	F×14, fenoxythrin F×2. Australia	FAO Survey 1972–73, Attia (1984a)
Malathion	F>×160. World-wide 27/33 countries	FAO Survey 1972–73, Attia (1984a)
Bromophos	F×2, chlorpyriphos methyl F×3, cyanophos F×4, diazinon F×17, dichlorvos F×15, fenitrothion F×16, iodofenphos F×3, methacrifos F×2, pirimiphos methyl F×4, tetrachlorvinphos F×4. Australia	FAO Survey 1972–73 Attia (1984a)
Carbaryl	F×9	FAO Survey 1972–73
Oryzaephilus surinamensis		
DDT	F×6. Australia	FAO Survey 1972–73, Attia (1984a)
Lindane	F>×24. World-wide, 46/56 countries	FAO Survey 1972–73, Attia (1984a)
Pyrethrins	F×3×4^{a}. Australia	FAO Survey 1972–73
Bioresmethrin	F×8, F×2×4^{a}, cismethrin F×2^{a}, fenoxythrin F×5. Australia	FAO Survey 1972–73, Anon. (1978d)
Malathion	F×40. Central USA, El Salvador, Guadeloupe, Brazil, UK, Cyprus, Turkey, Iran, Iraq, Malawi, Israel, India, China (Taiwan), Japan, Australia, New Caledonia	FAO Survey 1972–73, Navarro et al. (1981), Anon. (1978c, 1981c,f,1), Brun and Attia (1983)
Bromophos	F×17, chlorpyriphos methyl F×2 Am×3.7, diazinon F×11, dichlorvos F×8, fenitrothion F>×500 Am×53, fospirate F×2, iodophenphos F×30, methacrifos F×1.8 Am×5.7, pirimiphos methyl F×37 Am×19, tetrachlorvinphos F×12. Various countries including Australia	FAO Survey 1972–73, Dyte et al. (1975c), Heather and Wilson (1983), Brun and Attia (1983), Attia (1984a)
Carbaryl	F>×14. Australia	FAO Survey 1972–73, Attia (1984a)
Dioxacarb	F>×3	Anon. (1978d)
Oryzaephilus mercator		
Lindane	F>×89. USA, Caribbean, Sardinia, UK, Gambia, Senegal, Kenya, Mozambique, Botswana, Swaziland, Burma	FAO Survey 1972–73
Malathion	F×1.9. USA, Jamaica, Trinidad, UK, Gambia, Sardinia, Senegal, Swaziland	FAO Survey 1972–73, Anon. (1978c)
Cryptolestes ferrugineus		
Malathion	F. UK	Anon. (1981m)

Table 4. (cont.) Field occurrences of resistance to residual pesticides in pests of stored products.

	Type of test, highest resistance factor and countries involved (F = film, T = topical, Am = admixture, D = dipping)	References
Latheticus oryzae		
Malathion	F. Kuwait	Blackman and Peckover (1975), Anon. (1978c)
Trogoderma granarium		
Malathion	Tunisia	Yana (1967)
Callosobruchus chinensis		
Lindane	F×93. India, South Korea	Tyler and Evans (1981)
Callosobruchus maculatus		
Lindane	F×56. Senegal, Uganda	Tyler and Evans (1981), Evans (1986)
Caryedon serratus		
Lindane	T×3. Gambia	Dyte and Forster (1970a)
Dieldrin	Am×15. Gambia	Parkin and Forster (1968)
Zabrotes subfasciatus		
Lindane	F×160. Colombia, Mexico, Uganda	Tyler and Evans (1981), Evans (1986)
Dermestes maculatus		
Lindane	F×12. USA, UK, Argentina, Brazil, Gambia, Ghana, Nigeria, Lebanon, Pakistan, India, Bangladesh, Hong Kong, Australia	Binns and Tyler (1978), Binns and Pemberton (1981), Anon. (1981c)
Malathion	F×4.5. UK, USA	Tyler and Binns (1975), Anon. (1981c)
Attagenus megatoma		
Dieldrin	Australia	FAO Survey 1972–73
Clothes moths and fur beetles		
Chlorinated hydrocarbons	USA	Odeneal (1961)
Ephestia cautella (larvae)		
DDT	T×52. Australia	Attia (1976)
Lindane	T×17. Australia	Attia (1984a)
Endrin	T×62, dieldrin >×49. Australia	Attia (1976)
Pyrethrins	T×3.3. USA	Zettler et al. (1973)
Malathion	T>×259. USA, Cyprus, East Africa, South Africa, India, Australia	Godavaribai et al. (1962), Joubert and de Beer (1968), Zettler et al. (1973), Attia (1976, 1981a), Attia et al. (1979), Anon. (1981c)
Chlorpyriphos	T×1.7, diazinon T×15, dichlorvos T×2.5, fenitrothion T×9, monocrotophos T×2.3 methyl parathion T×3, pirimiphos methyl. Australia T×13. Australia	Attia (1976, 1981a), Attia et al. (1979)

Table 4. (cont.) Field occurrences of resistance to residual pesticides in pests of stored products.

	Type of test, highest resistance factor and countries involved (F = film, T = topical, Am = admixture, D = dipping)	References
E. kuehniella (larvae)		
DDT	T>×51.	Attia (1984a)
Lindane	T×14. Australia	Attia (1984a)
Dieldrin, endrin	Australia	Attia et al. (1979)
Malathion	T>×244. Australia	Attia et al. (1979, 1981)
Plodia interpunctella (larvae)		
DDT	T>×42, lindane T×14, chlordane T>×206, endrin T×74, dieldrin T>×53. Australia	Attia (1977, 1981), Attia et al. (1979)
Pyrethrins	T×2.5[a]. USA	Zettler et al. (1973)
Malathion	T>×260. USA, Australia, Kenya, Nigeria, Argentina, Republic S. Africa	La Hue (1969), Zettler et al. (1973), Armstrong and Soderstrom (1975), Attia (1977, 1981), Attia et al. (1979) Beeman et al. (1982), Cogan (1982), Zettler (1982),
	F, adults. U.K.	Anon. (1981n)
Diazinon	T×9.7, dichlorvos T×3.6, fenitrothion T×8.6, naled T×2, methyl parathion T×2, pirimiphos methyl T×4.8. Australia	Attia (1977, 1981), Attia et al. (1979)
Sitotroga cerealella		
Lindane	Sri Lanka	Fernando (1967)
Malathion	Brazil, USA	Anon. (1981c)
Tinea pellionella		
Dieldrin	×100. Australia	FAO Survey 1972–73
Tineola bisselliella		
Mitin FF	×2. Germany FR	Kühne and Becker (1965)
Acarus chaetoxysilos		
Pirimiphos-methyl	Am. UK	Anon. (1981j), Stables and Wilkin (1981)
Etrimphos, chlorpyrifos-methyl, methacrifos	Am. UK	Anon. (1981j), Stables and Wilkin (1981)
Acarus farris		
Lindane	Am. UK	Anon. (1981a)
Pirimiphos-methyl	Am. UK	Anon. (1981j), Stables and Wilkin (1981)
Etrimphos, chlorpyrifos-methyl, methacrifos.	Am. UK	Anon. (1981j), Stables and Wilkin (1981)
A. chaetoxysilos × *A. farris* hybrids		
Pirimiphos-methyl	Am. UK	Anon. (1981j), Stables and Wilkin (1981)
Etrimphos, chlorpyrifos-methyl, methacrifos	Am. UK	Anon. (1981j), Stables and Wilkin (1981)

Table 4. (cont.) Field occurrences of resistance to residual pesticides in pests of stored products.

	Type of test, highest resistance factor and countries involved (F = film, T = topical, Am = admixture, D = dipping)	References
Acarus siro		
Lindane	Am. UK	Wilkin (1973), Anon. (1978a, 1981a,i)
Dieldrin	D. UK	Anon. (1978a)
Propargite	Am. UK	Stables (1980)
Bioresmethrin	D. UK	Anon. (1978a)
Glycyphagus destructor		
Lindane	Am. UK	Wilkin et al. (1975), Anon. (1978a, 1981a,i)
Dieldrin	D. UK	Anon. (1978a)
Propargite	Am. UK	Stables (1980)
Bioresmethrin	D. UK	Anon. (1978a)
Tyrophagus palmarum		
Pirimiphos-methyl	Am. UK	Anon. (1981j)

[a] Synergised with piperonyl butoxide

[b] Australia and South Africa are the only countries where *R. dominica* has been reported resistant to malathion synergized with triphenyl phosphate. Subsequently such resistance has been reported from New Caledonia (Brun and Attia 1983).

[c] Resistance factors obtained by topical application to *T. castaneum* have been found to be approximately 70% lower than those obtained from exposure to films of insecticide (Anon. 1981h).

independent, changes in behaviour patterns that reduce to exposure to treated surfaces (Pinniger 1975) or other doses of toxicant.

Resistance to Residual Insecticides

A summary of the resistances to residual insecticides and related compounds is given in Tables 3 and 4. Table 3 gives data on laboratory-selected resistances and Table 4 gives a listing of the resistances that have been recorded in the field. Data from the FAO Global Survey of Pesticide Susceptibility of Stored Grain Pests are included, as are the other resistances determined from each species in tests for 'cross-resistance'. Fig. 2 is reproduced from Champ and Dyte (1976) to illustrate resistance patterns of representative strains carrying the malathion resistances known to be present in stored grain beetles.

The various resistances have been discussed in detail in earlier listings and texts (Dyte 1974; Champ and Dyte 1976; Champ 1979, 1984a, 1986; Champ and Turner 1980a). The most significant recent changes have been the greater frequency of reports of malathion and other OP compound resistances among the major pest species and the increasing occurrence of resistance to synthetic pyrethroids.

Early records of malathion resistance in the *Tribolium* spp., *Rhyzopertha dominica*, and some of the phycitid moths were specific to malathion and only included OP compounds that could be degraded by carboxyesterases. This was short-lived and all species now appear to have resistance to a wide range of OP compounds.

Because of the widespread occurrence of malathion resistance, malathion usage is declining and has been abandoned in some areas. The problem is compounded by the differing susceptibilities to the current generation of OP compounds and the synthetic pyrethroids of resistant strains of the predominant pest species, particularly *Sitophilus oryzae* and *Tribolium*

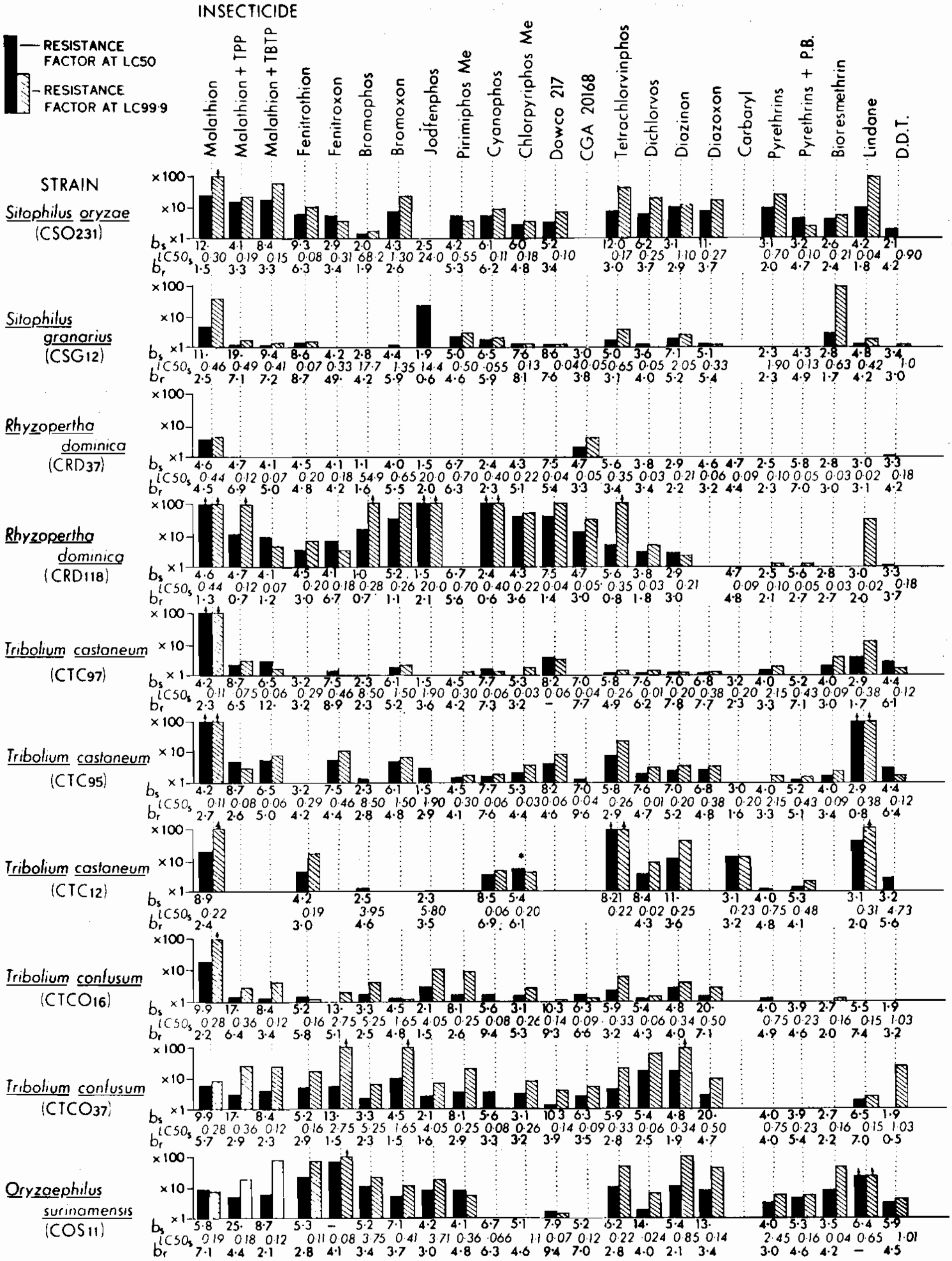

Fig. 2. The resistance patterns of representative strains carrying the malathion resistances known to be present in stored grain beetles (from Champ and Dyte 1976).

castaneum, and the multi-resistant strains of *Rhyzopertha dominica.* The former group of species can be controlled by the OP compounds, fenitrothion, chlorpyrifos-methyl, etrimphos, or pirimiphos-methyl; whereas carbaryl or the synergised pyrethroids, bioresmethrin, fenvalerate, permethrin, IR-phenothrin, or pyrethrins are necessary for control of the *R. dominica* (Bengston these proceedings). Methacrifos and deltamethrin are the only materials that currently control all typical resistant strains.

Reports of OP-resistance in *Oryzaephilus surinamensis* have increased. This species appeared to have been effectively suppressed by malathion for a considerably longer period than the other major pest species. Control failures associated with documented resistance have now been reported with fenitrothion (Heather and Wilson 1983) and the pest appears to be on the increase.

Cryptolestes ferrugineus has been included in the list of resistant species from England (Anon. 1981m). This cosmopolitan species, which assumes its greatest importance in cold countries, has frequently been associated with control failures following use of malathion but has not been reported resistant previously. This can probably be attributed to difficulties in handling and identifying individual live specimens with consequent delays in developing appropriate testing procedures.

Sitotroga cerealella has also been added to the list of malathion-resistant species (Anon. 1981c).

Table 5. Occurrence of laboratory-selected fumigant resistance in pests of stored products.

	Generation tested and resistance level	References
Sitophilus oryzae		
Hydrogen cyanide	F36	Lindgren and Vincent (1965)
Carbon dioxide	F_{10} ×3.3	Dias and Navarro (1983), Navarro et al. (1986)
Sitophilus granarius		
Methyl bromide	F_{50} ×7.8[a]–×17	Bond and Upitis (1972) Anon. (1974b)
Phosphine[c]	F_{28} × 3[b]	Monro et al. (1972)
Hydrogen cyanide	F_{25} ×3	Lindgren and Vincent (1965)
Mercury	F_{10} ×350	Blackith and Gorringe (1953)
Carbon dioxide	F_7 ×3.3	Bond and Buckland (1979)
Tribolium castaneum		
Methyl bromide	F_3 ×1.6	Winks (1979)
Phosphine	F_2 × 6.5 F_{10} ×12[d] F_{16} × 5.9[d]	Winks (1969) Kem (1975) Saxena and Bhatia (1980)
Ethylene dibromide	F_6 ×4	Anon. (1974b)
Tribolium confusum		
Hydrogen cyanide	F_7 ×1.7	Gough (1939)
Methyl formate	F_{35} ×3	Anon. (1959)

[a] Monro et al. (1961) reported the following cross resistances in these selection lines as indicated —
F_{12} — phosphine ×13, chloropicrin ×2.2;
F_{27} — hydrogen cyanide ×2, ethylene dibromide ×3, acrylonitrile ×4.7, ethylene oxide ×4.8.

[b] Monro et al. (1972) reported a ×2.7 cross resistance to chlorpicrin at the F_{18} selection.

[c] Rajak and Hewlett (1971) reported a ×2 phosphine resistance in a pyrethrin-selected strain.

[d] Winks (1986) does not accept these records as true resistance but rather 'reduction in variability of a strain.' See Figure 1 in this text also.

Two further bruchids, *Callosbruchus chinensis* and *C. maculatus*, have been shown to be resistant to lindane (Tyler and Evans 1981) which has been used as a protectant for beans almost since its introduction some 40 years ago. These late records, however, probably only reflect lack of earlier testing. Other recent records of lindane resistance are from *Acarus* mites collected during surveys of farm stored grain in England (Anon. 1981a,i). More extensive testing has revealed resistance also to pirimiphos-methyl, etrimphos, and chlorpyrifos-methyl in the various *Acarus* spp. and to pirimiphos-methyl in *Tyrophagus palmarum* (Anon. 1981j).

Resistance to Fumigants

The resistances to fumigants are summarised in Tables 5 and 6. Table 5 gives data on laboratory-selected resistances and Table 6 gives a listing of resistances involving six fumigants and nine species that have been recorded in the field. As previously, data from the FAO Global Survey are included.

The various resistances have been discussed in

Table 6. Field occurrences of fumigant resistance in pests of stored products.

	Areas of occurrence	Highest level recorded	References
Sitophilus oryzae			
Methyl bromide	Kenya	a	FAO Survey 1972–73
Phosphine	Guyana, Portugal, UK, Kenya, India, Yemen, Indonesia	×2.5	FAO Survey 1972–73, Anon. (1978b)
Sitophilus zeamais			
Methyl bromide	China, Brazil, Trinidad, Guyana, Malaysia, Zimbabwe	×1.4	FAO Survey 1972–73
Sitophilus granarius			
Methyl bromide	Malta	×1.6	Howe (1962)
Phosphine	Argentina, Canada, UK, Poland, Spain, Cyprus, Iran, Turkey, USSR	×2.4	FAO Survey 1972–73, Anon. (1978b)
Rhyzopertha dominica			
Methyl bromide	Greece	a	FAO Survey 1972–73
Phosphine	Guadeloupe, Guyana, Jamaica, Argentina, Greece, Libya, CAR, Mozambique, India, Bangladesh, China (Taiwan), Australia	×100	FAO Survey 1972–73, Bell et al. (1977), Attia and Greening (1981), Attia 1984b, Dyte et al. (1983), Mills (1983), Tyler et al. (1983)
Tribolium castaneum			
Methyl bromide	Canada, USA, UK, Malawi^{b}, Ethiopia, Bahrain, China, Australia	<×1.5	FAO Survey 1972–73, Winks (1979), Anon. (1978b)
Phosphine	USA, Guyana, Montserrat, UK, Greece, CAR, Somalia, Malawi, Syria, India, Bangladesh, Nepal, China, Japan, Australia	>×16	FAO Survey 1972–73, Anon. (1978b), Attia and Greening (1981), Dyte et al. (1983), Mills (1983), Attia (1984a,b)
Hydrogen cyanide	USA	×1.4	Lindgren and Vincent (1965)
Ethylene dibromide	Canada	×2	Bond (1973)
Tribolium confusum			
Methyl bromide	Canada, USA, Argentina, UK, Finland, Germany F.R., Greece, Spain, Ethiopia, Cyprus, Iran, Iraq, China, Japan, Australia	>×1.5	FAO Survey 1972–73, Anon. (1978b) Winks (1979)

Table 6. (cont.) Field occurrences of fumigant resistance in pests of stored products.

	Areas of occurrence	Highest level recorded	References
Phosphine	Canada, USA, Jamaica, Argentina, UK, Finland, Germany F.R., Spain, Greece, Cyprus, Iran, Iraq, Japan, Australia	×3	FAO Survey 1972–73, Anon. (1978b), Attia and Greening (1981), Attia (1984a)
Hydrogen cyanide	USA, Australia	×1.4	Lindgren and Vincent (1965), Winks (1979)
Ethylene dibromide	USA	×1.8	Lindgren and Vincent (1965)
Oryzaephilus surinamensis			
Methyl bromide	USA, UK		FAO Survey 1972–73, Anon. (1978b)
Phosphine	USA, UK, Bangladesh, Australia	×40	FAO Survey 1972–73, Anon. (1978b), Dyte et al. (1983), Mills (1983), Tyler et al. (1983), Attia (1984a)
Ethylene dichloride — carbon tetrachloride mixture	Italy, UK[c]	×2.5, ×2	Dal Monte (1969), Anon. (1981e, k), Dyte et al. (1983)
Cryptolestes ferrugineus			
Phosphine	Bangladesh, India, UK	×14	Dyte et al. (1983), Mills (1983), Tyler et al. (1983)
Trogoderma granarium			
Phosphine[d]	India	?	Borah and Chahal (1979)

[a] Discriminating dose test only.
[b] Not confirmed by laboratory tests.
[c] The three strains involved were also resistant to methyl chloroform.
[d] Winks (1986) questions the adequacy of the data of Borah and Chahal as evidence for resistance.

earlier listings and texts (Champ and Dyte 1976; Champ 1976, 1979, 1984a, 1986; Champ and Turner 1980a; Dyte et al. 1983; Bond 1984). The most significant recent records are of high level resistances to phosphine in *Rhyzopertha dominica, Tribolium castaneum, Oryzaephilus surinamensis,* and *Cryptolestes ferrugineus* from the field in Bangladesh (Dyte et al. 1983; Mills 1983), and of laboratory-selected carbon dioxide resistance in *Sitophilus oryzae* (Navarro et al. 1986).

Earlier records of phosphine resistance had involved most major pests of stored grain but were of a low order in the most strains tested. The highest levels were in *Tribolium* and *Rhyzopertha dominica* approximating x10. The appearance of the new highly resistant strains from Bangladesh adds a new dimension to pest control as a realisation of predictions that substandard fumigations with phosphine could result in resistance with consequent failure of fumigation in the field.

The resistance to carbon dioxide in *S. oryzae* was recorded from laboratory selection, as was the earlier record from *S. granarius* (Bond and Buckland 1979). The resistance has not been recorded in the field where treatments are carried out with high atmospheric contents of carbon dioxide and changes in tolerance would be manifested as longer times to achieve kills rather than concentration effects. The appearance of resistance in the field will seriously jeopardise the usefulness of carbon dioxide as the detention of a commodity for prolonged periods may be economically unacceptable.

There appears to be no change in the resistance status of methyl bromide. Although there are records of low level resistances in numerous species, there are still, after 50 years of extensive use and misuse, no records from the field of control failure that can be attributed to resistance. Resistance does not appear a significant threat to this material.

Containing the Resistance Problem

Resistance is widespread and involves all major residual pesticides and most of the important pests of cereal and cereal product storage. Control failures in the field have been unequivocally associated with resistance and have forced the use of materials such as malathion to be abandoned in some areas. In summary, it can be assumed that resistance to residual pesticides is a world-wide problem affecting or threatening in some measure the efficacy of all pest control programs involving residual pesticides.

Control failures with fumigants have also been common and, in many instances, it has been possible to attribute these failures to obvious causes, such as lack of suitably gastight enclosures.

The spread of resistances both within national grain and seed distributional networks and in the international grain trade is a matter of considerable concern. The problem was highlighted in the report of the FAO Global Survey of Pesticide Susceptibility of Stored Grain Pests (Champ and Dyte 1976) and has been emphasised in subsequent publications (e.g. Dyte 1979). The emergence of high level phosphine resistances such as has occurred in Bangladesh gives new significance to warnings of the potential disasters that can occur if such resistances are allowed to spread. The dependence of many countries on phosphine as the mainstay of their pest control programs is jeopardised and, as a consequence, their ability to maintain buffer stocks of grain and to export to buyer standards of insect freedom.

The significance of pest infestation generally in international trade has been outlined by Champ and Winks (1982). They considered the various methods of providing clean grain to buyers by pre-export treatments and in-transit fumigation in the context of national regulation of grain quality and international obligations both contractual and through the International Plant Protection Convention. This convention exists as a cooperative effort between trading partners to limit the spread through international trade of plant pests and diseases. Conformity with the requirements of the convention provides a basis for limiting the spread of insect pests and hence of their resistances.

Within national grain industries, FAO and others have now provided the test methods for detecting resistance to contact insecticides and fumigants in the major pests. The techniques enable the contribution of resistance to control failures to be identified and permit early detection of low level resistances where their presence is obscured by the minimum doses necessary for control being less than the doses applied in practice. The test methods also provide a convenient method for continuous monitoring of the resistance status of field populations, and where high levels of pest control are required, they are essential to reveal resistances before damage materialises or significant contamination of the commodity occurs.

There is a growing awareness of the need to define local pest control problems, including the tolerance of each major pest to the pesticides in use, and to plan countermeasures for resistance. The impact of resistance has undoubtedly been lessened considerably where such action has been taken. Unfortunately, there are many situations where this has not taken place, jeopardising the adequacy of local control measures and intensifying the general problem with resistance. While there is major dependence of pesticides, as there will undoubtedly be for the forseeable future, efforts to counter resistance will need to be maintained or increased as circumstances dictate, and to this end, the use of the various monitoring techniques is strongly commended to facilitate rational planning of the pest control programs involved. Indeed, resistance to certain pesticides is so common in some species, as for example in *Tribolium castaneum,* that it can now be regarded as a normal attribute of the species. Because of this, resistance must be an integral consideration at all stages of research and development from basic biological studies through to planning of control programs.

In general, pest control programs using chemicals should aim for complete kills to minimise the chance that resistance will develop. If less than complete kills are acceptable, non-chemical methods should be sought. It should be realised by all concerned that protection of grain against pests in storage, can only be based on the well-tried and proven principles of sound storage practice, if the impact of pesticide resistance is to be minimised and long-term efficacy of controls is to be achieved. The principles have been clearly understood for a very long time and it is mandatory that all controls be based on them.

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Modelling of Strategies to Overcome Resistance to Pesticides

H.N. Comins*

Abstract

Mathematical models of insecticide resistance that have been developed for several divergent purposes are described. The most detailed models attempt to include resistance in economic decision models, assigning a future cost to the development of resistance. Such models are currently of limited use, because of the unknown initial resistance gene frequency, effective dominance, and field selection rate. At the other end of the scale, simple genetical models can be used to demonstrate some consequences of the basic nature of resistance selection, as revealed by the study of existing cases. These models have shown the importance of avoiding unnecessary pesticide applications, and of minimising the pest population growth rate by alternative means, such as integrated pest management or, in the case of stored-products pests, refrigeration of grain. Similarly, the potential growth rate of pesticide-surviving subpopulations is important; hence, rigorous hygiene can help to delay resistance problems. These models have also highlighted the helpful effects of effective recessiveness, refugia, and immigration. At an intermediate level of modelling complexity, one can consider how pesticide treatments can best be arranged to minimise resistance development, consistent with a particular level of pest damage. Such models offer potentially useful insights in selecting dosage levels and in managing the use of multiple pesticides. Nearly all current models are restricted to the selection of single resistance alleles, because of the genetic complexities of multi-allele models. However, multiple allele selection is an important future direction for resistance modelling.

MODELLING of pesticide resistance has now continued for a number of years. This activity has been encouraged by the difficulty and economic danger of performing field experiments on resistance. However, the experimental data on resistance, although extensive, are not sufficiently coherent that resistance modelling can be properly validated in any particular case. Thus, the continued elaboration of theoretical models may soon cease to be useful (Taylor 1983). In this paper I therefore review what has been achieved by resistance modelling, and consider where modelling effort might be focused in future.

Modelling of resistance is based on standard population genetics theory (Crow and Kimura 1970). In particular, the change in gene frequency of a monofactorial resistance gene in a random-mating, synchronous-generation, diploid pest population, from generation n to generation $n + 1$, is given by

$$\varphi_{n+1} = \frac{w_{RS}\,\varphi_n(1-\varphi_n) + w_{RR}\,\varphi_n^2}{w_{SS}(1-\varphi_n)^2 + 2w_{RS}\,\varphi_n(1-\varphi_n) + w_{RR}\,\varphi_n^2} \qquad (1)$$

where φ_n and φ_{n+1} are the gene frequencies in the nth and $(n + 1)$th generations, and w_{SS}, w_{RS}, and w_{RR} are the genetic fitnesses of the susceptibles (SS), heterozygotes (RS), and homozygotes (RR).

Aside from the question of dispersal (for which equation 1 is not valid), the main problem in resistance modelling is to estimate the fitnesses w_{SS}, w_{RS}, and w_{RR}. By dividing equation (1) by w_{SS},

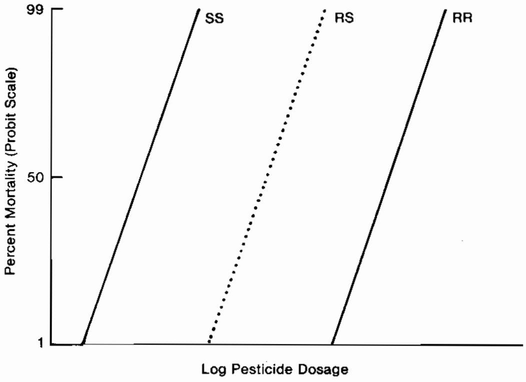

Fig. 1. Standard dosage-mortality curves for monofactorial resistance; susceptible (SS), heterozygote (RS), and homozygote (RR) mortality are plotted on a probit scale as a function of log pesticide dosage.

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top and bottom, it can be seen that only the relative fitnesses w_{RS}/w_{SS} and w_{RR}/w_{SS} are required. One way of estimating these quantities is to use the dosage-mortality relationships which are obtained from standard laboratory procedures for characterising resistance (Fig. 1) (Brown 1971). Although some early models of resistance use these mortalities directly as measures of fitness (i.e. relative fitness = 1 − mortality), there are several ways in which this simple relationship fails to estimate fitnesses in the field.

One important source of error is that the dosage-mortality lines are derived from the application of a standard dose directly to the cuticle of the insect. In the field it is very difficult to approach this situation. There are almost always some insects which are physically protected from the pesticide, are outside the treated area at the time of application, or are in a non-susceptible life-stage. The dosage variability may also be increased if the pesticide is repellent. Furthermore, the standard tests relate only to mortality within a specified period. Pesticides may also have sublethal effects, which are relevant to estimating genetic fitness (McKenzie and Whitten 1982, unpublished data). Longstaff and Desmarchelier (1983) demonstrate these effects for rice weevil.

Resistant individuals may differ from susceptibles in other than their response to pesticides (Curtis et al. 1978). In models, the intrinsic fitness difference (termed 'back-selection') is generally assumed to be independent of the pesticide treatment. However, it is possible that it may vary as a result of other actions in an integrated pest management program (for example, resistant individuals might be more prone to predation, or more affected by intraspecific competition at high population densities). In this regard, it should be noted that estimates of back-selection obtained from laboratory resistant strains (Inoue 1980; Muggleton 1983; Pitt 1984) may be an underestimate of that acting in the field, since the genetic background of a laboratory strain has been selected in a population almost homozygous for resistance (Curtis et al. (1978) discuss techniques for direct estimation of back-selection in the field). It can be shown theoretically that some fitness modifiers favouring the resistant genotype are selected only when resistance is more common than susceptibility, so such modifiers would be at a low frequency in an almost wholly susceptible field population (McKenzie et al. 1982).

These effects remain a difficulty for computer simulation models which attempt to model the rate of change of resistance in particular field populations (Greever and Georghiou 1979; Guttierez et al. 1979; Tabashnik 1985). However, simple conceptual models have been constructed which include most of them. These models have produced a number of simple concepts to be applied to resistance management. Some of them have evidently affected actual control practice. In the next section, I briefly summarise some of these results; fuller accounts may be found elsewhere (Conway and Comins 1978; Comins 1985; Georghiou 1983; Taylor 1983; May and Dobson 1985).

Simple Resistance-Management Concepts

The contents of this section are summarised in Table 1, which lists factors which accelerate or retard the evolution of resistance.

Table 1. Factors which simple genetic models have shown to be important for delaying or accelerating the spread of resistance. A minus sign denotes a delaying factor; a plus sign an accelerating factor.

Low pesticide dosages	(−)
Refugia	(−)
High population growth rate	(+)
Effective recessiveness	(−)
Susceptible immigration	(−)
Susceptible release	(−)
Alternating pesticides	(−)

The most obvious ways to retarding resistance are to use *low pesticide dosages* and to not treat large sections of the population (i.e. leave *refugia)* (Georghiou and Taylor 1977). This means that the susceptible fitness w_{SS} does not differ much from w_{RS} or w_{RR}, and φ_{n+1} is not much different from φ_n in equation (1). Unfortunately, it also means that there is a low kill rate of susceptibles, which may not provide adequate control. A low kill rate of susceptibles can be made compatible with adequate control of *reducing population growth rate* by non-pesticide means. These means include integrated pest control measures, such as introducing predators (Croft 1982). In the case of stored grain pests, population growth rate can be reduced by refrigerating grain (Heather 1981; Longstaff 1984; Thorpe et al. 1982) and by hygiene techniques, such as cleaning out storage facilities between uses.

Simple genetic models show that the rate of resistance selection is largely determined by heterozygote fitness (see later). Therefore, the rate of resistance selection is reduced if the dosage is high, causing *effective recessiveness* of the resistance gene (Wood and Mani 1981). This goal is in conflict with that of using low pesticide dosages; however, it is in principle compatible with the alternative idea of leaving refugia. To use both strategies requires that part of the population be treated with a high dose while the remainder receive a dose insufficient to kill susceptibles. This sharp dosage definition may be achievable in some circumstances (e.g. dipping cattle with non-residual acaricide; Sutherst and Comins (1978), but it is difficult to arrange in many other agricultural systems.

Models show that the dilution of residual treated populations by *susceptible immigration* retards the evolution of resistance (Comins 1977a; Taylor and Georghiou 1979; Taylor et al. 1983). Similarly, *releasing susceptible insects* (generally adult males) can be beneficial if they do not represent a pest problem in themselves (Curtis and Rawlings 1980; Wool and Manheim 1980) (this may require a particular time of release). There is a possibility that sophisticated genetic techniques (such as using meiotic drive genes) will provide a stronger effect of the released insects than simple dilution (Whitten 1970; Wood 1981).

Finally, simple models of multiple pesticide use suggest that *alternating pesticides* causes back-selection to operate more effectively (Georghiou 1983; Pimentel and Bellotti 1976). This is best done with agents from different chemical groups, in order to avoid the problem of cross-resistance. In stored product systems, fumigants and asphixiating gases (N_2 and CO_2) present alternatives to organic pesticides which are not available in cropping systems. The much stronger resistance delaying effect of *redundant killing* (killing of individuals resistant to one pesticide by a redundant dose of another) has been claimed for multiple pesticide strategies (Georghiou 1983). Recent research (described below) suggests that more careful management is required to exploit this effect.

Developing Intuition

Feller (1971) describes the role of intuition in the development of scientific theory (in particular, mathematical statistics) by the maxim 'today's intuition is yesterday's most advanced result'. In this section, I argue that resistance modelling can be advanced by developing an intuitive interpretation of the existing results, so that new results can be fitted in coherently, rather than generating confusion (Whitten and McKenzie 1982). Such intuition should provide heuristic principles (i.e. approaches which usually succeed, but may sometimes fail) for predicting, for example, at what part of the insect life-cycle (Fig. 2) pesticide should be applied, in the presence of particular kinds of intraspecific competition.

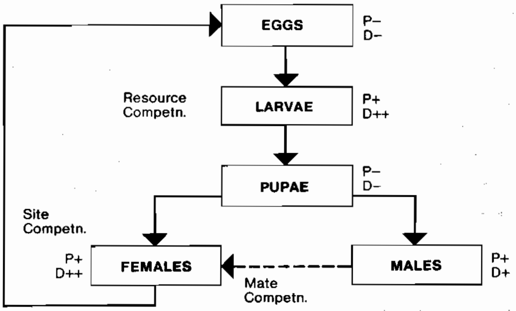

Fig. 2. Typical insect life-cycle, showing life-stages more or less susceptible to pesticide (P+, P–), and more or less damaging to crops, stored products, and public health (D++, D+, D–). Also shown are the types of intraspecific competition (resulting in density-dependent population dynamics) acting on the various stages. Density-dependent induction of parasites, predators, and diseases can occur at any stage.

The intuition described here is limited to the population dynamical and genetic aspects of resistance. Thus, I consider the question; 'how can resistance be delayed as long as possible, consistent with maintaining a particular level of control?' It is also possible to include economic aspects in simple resistance models, and to consider trade-offs between reduced control and increased rates of resistance development (Comins 1977b, 1979a). I think this kind of model is less likely to affect decision-making, because of the difficulty of predicting the absolute time-scale of resistance. However, such considerations may well be incorporated in detailed models of particular pest systems.

The fundamental case to be considered (most suitable for discussions of 'moderation' strategies in Georghiou's (1983) terminology) is that of an effectively dominant monofactorial resistance gene, subject to rapid selection (i.e. w_{SS} is significantly less than w_{RS} and w_{RR}, as compared with the marginal fitness differences generally assumed in evolutionary theory). In this case, it can be shown that the time for resistance to develop is closely predicted by the 'heterozygote selection approximation' to equation (1), in which the selection of homozygotes is ignored. The simplified equation that results is

$$\varphi_{n+1} = (W_{RS}/W_{SS})\varphi_n \qquad (2)$$

This approximation is equivalent to the intuition that, since the resistance gene is nearly always rare (because of the high selection rate, which gives a small time interval between noticeable resistance and loss of control), a resistant individual is almost certain to mate with a susceptible. The resulting offspring include no RR homozygotes. An additional property of this mating is relevant to extending the intuition; namely that half of the offspring are RS heterozygotes and the remainder are susceptibles, the same ratio which prevails in the parents. Thus, genetic recombination during reproduction has no effect on the proportion of RS heterozygotes in the population. It is therefore possible (Comins 1979b, 1985) to regard the resistant individuals as comprising an independent sub-population, which only interacts with the susceptible population through intraspecific competition (including indirect forms, such as stimulation of predator functional response).

It can now be seen why I have emphasised competition mechanisms in Figure 2. According to the intuition just developed, the RS sub-population growth rate cannot be directly affected by pesticide, since the resistance gene is assumed dominant. Therefore, the only means of reducing the RS growth rate (short of exotic genetic techniques) are enhancing competition by susceptibles, and reducing population growth by non-pesticide means (affecting both RS and SS population equally).

Applications

We now consider some applications of the 'competition-biased' view of population dynamics just developed. One obvious question, since the most obvious form of competition (resource competition) equates to economic loss, is what will happen if pesticide application abolishes intraspecific competition and predation altogether, by reducing pest numbers to very low levels. The answer is that, in this case, further increasing pesticide levels within the treated area can only retard resistance, by possibly making resistance less dominant (see discussion of 'saturation' later). Note that this action may increase the frequency of resistance more rapidly (as predicted by standard refuge models), but it does not increase the absolute number of resistant individuals, which is a more important quantity from the control point of view.

These results suggest that in designing pesticide moderation strategies one should be careful to consider when and where intraspecific competition will occur as a result of the moderation. For example, in the Queensland *Heliothis* control program (Davies 1984), care is taken to restrict pyrethroid use to a single generation. According to the present view, the sexual recombination at mating is of little consequence to resistance development; the important events at this time are mate competition and egg-site competition, and the dispersal of the adults. I believe the control strategy should be reappraised in this light.

The intuition can also be applied to the use of susceptible immigration and the release of susceptible males (Curtis and Rawlings, 1980; Wool and Manheim 1980). In the latter case, the effect on the resident RS sub-population is presumably through mate competition only. However, it is evident that this competition affects only half of the RS sub-population (the males) and can therefore only select against resistance by a factor of 2. Any reduction in RS sub-population growth rate resulting from resource competition will have an economic cost, unless it occurs elsewhere than in the crop or grain-store.

A curious point which follows from our intuitive view is that encouraging pest *emigration* from treated areas into untreated areas can have an effect in controlling resistance. This of course assumes that they and their offspring do not return, meaning in practice a large surrounding untreated area and a sufficient back-selection pressure in the absence of pesticide.

Finally, I would suggest that the population dynamical concept of 'intrinsic growth rate' be applied to resistance models. In its original context this referred to the rate of growth of low density populations free of intraspecific competition and predation. I propose applying it instead to the rate at which a population would grow if pesticide ceased to be applied. It is therefore equal to the current population growth rate of the RS sub-population (provided resistance is dominant). Also, since the susceptible population growth rate is zero at equilibrium, the intrinsic growth rate is roughly equal to $1/(1 - K)$, where K is the pesticide mortality rate required for control (some difference being introduced by immigration).

The time for resistance to develop is determined by three things in the effectively dominant case: the initial gene frequency φ_I prior to pesticide use, the intrinsic population growth rate r (as defined above), and the rate of back-selection per unit time b (back-selection is more commonly expressed as a factor per generation):

$$T_R = (-\ln\varphi_I)/(r - b) \tag{3}$$

(See May and Dobson 1985; Comins 1977b). This equation explains why pest species or local populations with high reproductive rates and numerous generations develop resistance more rapidly. Note that, since r is the growth rate of the RS sub-population, it is not directly affected by pesticide application. It is determined by the residual effects of intraspecific competition and predation, as well as by any non-pesticide control measures that are applied, such as refrigerating grain.

Generalisations

Georghiou (1983) divides pesticide application strategies for resistance management into three categories; moderation, saturation (i.e. high dosage rates to kill resistant heterozygotes), and multiple attack. According to the intuition just developed, pesticide saturation is a fundamentally different resistance-delaying technique to moderation, since it attacks the resistant sub-population directly, rather than relying on the indirect effects of intraspecific competition. In its ideal form, saturation consists in ensuring that every susceptible which is killed by pesticide is exposed to a large dose, so that it would also have a high probability of dying if it were a resistant heterozygote. In practice it is difficult to achieve the required splitting of the population into heavily dosed victims and undosed survivors, except perhaps in certain special cases (Sutherst and Comins 1978). More commonly there is a trade-off between the advantages of killing heterozygotes with high dosages and the resultant breakdown in the 'moderation' technique, due to greater leakage of pesticide into refuges.

Since the resistance factors of the available resistance genes are generally unknown, pesticide saturation represents a gamble with certain losses against uncertain gains. In general, the spread of some resistance genes may be delayed by heterozygote mortality, while the spread of others (with higher heterozygote resistant factors) is accelerated due to reduced competition from susceptibles. For considering this case, the previous intuition may be generalised to include the simultaneous growth of several independent RS sub-populations (see later for discussion of the independence assumption). Comins (1979b) discusses the costs and benefits of pesticide saturation in these terms.

Georghiou's third control category is multiple attack; that is, the use of two or more pesticides concurrently. It has already been pointed out (Table 1) that simple resistance models predict a back-selection advantage from any kind of multiple attack. In addition, multiple attack strategies in which use of the two pesticides is positively correlated (i.e. individuals receiving a high dose of pesticide A are likely to receive a high dose of pesticide B) promise the advantage of 'redundant kill' (Comins 1985). In its most optimistic form this strategy supposes that, in the absence of cross-resistance, pesticide B will have the same effect on the A-resistant heterozygote sub-population as a non-pesticide mortality (e.g. predation), and vice-sersa for pesticide A on the B-resistant heterozygotes. This could lead to very low resistance selection rates.

Apart from the danger of cross-resistance, Curtis (1985) and Mani (unpublished data) have pointed out that the frequency of doubly resistant heterozygotes can increase rapidly, even if neither single-resistant heterozygote is selected. This question is studied further elsewhere (Comins 1986, in press). It is shown that, for highly pleiotropic selection, the concept of independent selection of resistant heterozygote sub-population must be augmented to include selection of doubly resistant heterozygotes (for which additional selection factors can be calculated). Such second-order sub-populations must be regarded as subject to an additional back-selection in each generation, equal to the proportion of recombination between the two component genes (a factor of 1/2 if they are on separate chromosomes). It is concluded that redundant killing may be useful if either the population is so small that doubly-resistant heterozygotes are absent, or a less than 50% pesticide kill per

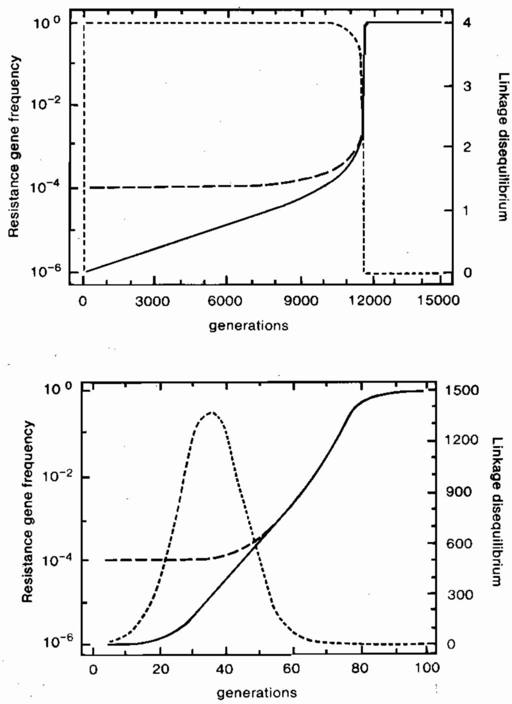

Fig. 3. Selection of two pesticide resistance genes (solid and dashed lines) by the ideal multiple-pesticide control program in which one part of the susceptible population suffers no mortality and the rest suffer 100% redundant mortality (that is, 100% mortality would occur as a result of either pesticide, but both are used to kill singly resistant heterozygotes as well). Linkage disequilibrium (dotted line) is defined here as the frequency of the doubly resistant haploid divided by the product of the frequencies of the A and B resistant haploids, minus one. (a) 40% of population treated, 60% unaffected; (b) 60% of population treated, 40% unaffected. These examples assume that both resistance genes are effectively dominant.

generation is sufficient for control (because only a limited area is cropped, or because of alternative control measures) (Fig. 3). Note that doubly resistant heterozygotes may similarly be important in one-pesticide 'saturation' strategies, if two multiplicative resistance genes are each unable to give a sufficient resistance factor by themselves. The evolution of resistance involving mutations of regulatory genes (Plapp and Wang 1983) may also be described in these terms.

Conclusion

Resistance modelling has produced a number of isolated simple rules for delaying the spread of pesticide resistance (Table 1). However, in the absence of experimental verification it cannot be expected that many more such principles remain to be discovered. It is argued, therefore, that the best way forward is to try to systematise current knowledge in an intuitive concept of resistance development, involving the growth of a resistant heterozygote sub-population. This approach allows the consideration of complex life-cycles without actually constructing models (for example, we can see that male immigration is most effective just before an episode of mating competition).

The role of further theoretical work is seen as the extension of the existing intuition into new areas. Two such extensions are considered here: the idea of multiple independent resistant sub-populations for considering the effect of high pesticide dosages, and the idea of doubly resistant sub-populations for considering the effect of multiple pesticide attack.

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Quality Control and Methods of Application of Pesticides to Stored Grain

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Abstract

There are many application techniques for insecticides, including drips and sprays of either concentrates or aqueous dilutions, and dusts. Each has its advantages and problems. A brief description of recent advances in the development and application of microgranular formulations is followed by a detailed discussion of current usage of liquid formulations for bulk grain and criteria for their effective use. Quality control comprises the techniques and programs that are undertaken to ensure that success in general usage will equal that obtained in supervised trials. It is partly an art and partly a science. It is most successful when research and management accept responsibility for commercial failures. Quality control criteria should be adequate, straightforward, and suitable for the storage and the workforce. They should be assessed by research into routine usage, especially failures. Quality control failures with protectants are caused mainly by poor hygiene and bad formulations or application techniques. Quality control techniques include hygiene schedules, analysis of formulations, and preharvest testing of application equipment.

PARAMETERS that are important in protectant usage (such as efficacy, reliability, and worker safety) depend on the whole system, and the various aspects of usage are interrelated. For example, coverage of grain with protectant depends not only on the proportion of grain sprayed, but on the mixing achieved in the inloading equipment. Thus, a more even mixing is obtained by applying undiluted protectant, at the rate of 16 ml per tonne of grain, before the inloading auger, than by applying a spray, at the rate of 1 l/t, after grain has passed through the auger (Desmarchelier and Wilson 1981; Desmarchelier 1984). Another example of the need to adopt system analysis is the effect of increasing the number of particles in a given spray volume by decreasing particle size. Such decreases are likely to increase evenness of coverage, which may be an advantage, but also have the disadvantage of increasing atmospheric concentrations.

One corollary of this need to adopt a system approach is that it is necessary to evaluate an application technique in the commercial situation, and not merely in the laboratory.

Involvement in commercial applications must also go further than a 'once-off' evaluation of a technique. There needs to be a continuing feedback between commercial application and research. Such interactions are required for detection of resistance and to explain and eliminate failures. Evaluations of commercial usage are also necessary to validate research conclusions on, for example, desired rates of application. Because laboratory data are limited, and because of complex interactions between temperature, moisture, chemical degradation, toxicity, and insect behaviour, it always remains possible that a recommendation, although based on good research, is inappropriate for conditions that exist in storage. That is, not only are research conclusions validated by success in commercial usage, but investigation of commercial usage provide guidelines for research.

Diluted Solid Formulations

Grain protectants are applied in many ways. The principal methods of application to bulk grain during bin loading are either diluted solid formulations ('dusts') or 'liquid' formulations that are, or flow like, liquids.

Solid formulations are typically obtained by impregnating 40 micron carriers with 1–5% of a chemical, w/w. Although carriers are usually

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minerals, such as talc or kaolin, organic materials, such as pyrethrum marc, are sometimes used.

People who store small quantities of grain often use diluted solid formulations to avoid pumps and concentrated formulations. Where application to every grain is important, as with fungicidal seed treatment, solid formulations are preferred because good mixing can be obtained and visually assessed. Dilute solid formulations are seldom applied to bulk grain because of the 'dust problem' generated from admixture of 500–1000 g of carrier per tonne of grain.

This picture could change because of recent advances that have reduced problems with diluted solid formulations, and have revealed major advantages. The technique of producing — and applying — solid formulations of any particle size has led to widespread use of fine dusts or coarser microgranules in general agriculture, particularly in Japan (Uejima 1980). This technology is available to stored-product entomology. It has also been shown (La Hue 1977, 1978; Desmarchelier 1985) that certain microgranular formulations are more effective than conventional formulations. Preliminary results from my laboratory on the optimal amount of carrier for a given level of protectant suggest that current rates of 500–1000 g/t are unnecessarily high by an order of magnitude. The carriers investigated in my laboratory that gave increased protection were also those that retained the protectant. This permits physical removal of residues either immediately before or during processing.

Other possibilities for dilute solid formulations have been discussed in my other paper in these proceedings.

I will conclude this discussion on solid formulations by referring to the sale, especially in developing countries, of dusts containing much less than the stated strength of active ingredient. The buyer has a simple solution to this problem, and it applies to all formulations, whether of protectants, fumigants, or inert atmospheres. The solution is to enter into purchase contracts specifying concentrations, and to confirm these by analysis of samples.

Liquid Formulations for Bulk Grain

Protectants are usually applied to bulk grain as liquids, either in concentrated form or as aqueous 'dilutions.' There are an enormous number of variations in systems for delivery (e.g. pumps, gravity-feed, pressurised air) and application (fine or coarse spray, drip, nebulisation).

I will outline what I think is important for application of liquids to bulk grain, based on my experience, on the data from commercial use available to me, which are mainly Australian, and from published data, which are mainly concerned with laboratory studies, or accounts of supervised trials.

Hygiene

The industry experience in Australia is that application of protectants to grain in dirty premises will not be effective, and grain is not permitted to be received into unhygienic storages. Closing a storage for receival is a drastic step involving considerable financial losses to farmers, and the preparedness of the industry to take such steps illustrates the importance given to hygiene.

There is a substantial body of scientific evidence to support these industry conclusions. For example, a small refuge, which may only contain a few adults, will contribute a continuing source of infestation through migration. This source will result in the detection of live insects in stored grain, especially in cases where protectants kill progeny but not adults, as is the case with aged deposits of organophosphorus insecticides and *Rhyzopertha dominica* (Champ et al. 1969).

The situation of continuing migration into a storage where insecticidal efficacy is decreasing will inevitably result in exposure to discriminating doses, thereby increasing the chance of resistance. Presenting insects with a choice between insecticidal and non-insecticidal grain may also select for behavioural resistance, as observed in *Tribolium castaneum* (Pinniger 1975). In summary, hygiene is the first thing to be considered in the use of protectants, preferably during the design of the storage complex (Bond 1975).

Interval Between Harvest and Application

The Australian industry prohibits late deliveries of grain and Australian farmers receive payment at a time related to delivery, which is a motivation (Ajibola Taylor 1975) to deliver grain as soon as possible. One reason for this preference for early deliveries, usually within 24 hours of harvest, is that the success rate of protectant application decreases with increasing intervals between harvesting and delivery.

The scientific evidence behind such observations is the general inability of protectants to control immature stages of *R. dominica* and *Sitophilus* species. Grain containing such stages will continue to contain live insects until such time as immature stages have emerged and been killed. In other words, protectants are effective as prophylactic treatments to control low levels of infestation, often after development to a susceptible stage, and also to control low levels of reinfestation. They cannot disinfest grain quickly. The Australian practice of receivals immediately after harvest is therefore an integral part of the system.

Evenness of Application

There is a considerable body of literature on what are achievable, permitted, or even desirable levels of unevenness of application. For example, the 'sandwich' method of alternating layers of grain and malathion dust was recommended at an early stage in the use of this insecticide (Turtle 1961) as it is a very convenient method, especially in the absence of mechanical equipment for grain movement. In other studies (Tyler et al. 1968; Kane et al. 1970; Minett and Williams 1971; de Lima 1975) it was shown that good control was obtained with liquid protectants in situations where coverage was uneven.

Minett and Williams (1971) claimed that there was an optimal degree of unevenness of application with malathion, that is, that residues should be concentrated on 1 or 2% of the grains. The claim that this concentration increased the persistance of malathion, as compared with more even coverage, has been disputed by Anderegg and Madisen (1983), who worked with [^{14}C] malathion. Minett and Williams (1981) also found that the persistence of fenitrothion was the same in commercial storages whether applied as a dilute aqueous spray or as a concentrate.

The work of Minett and Williams (1971) on malathion distribution showed that application to 0.1 or 0.2% of grains gave less control than application to 1 or 2% of grains, presumably because insects were able to avoid insecticide when only 0.2% of grains had been treated. Pinniger (1975) sounded a cautionary note on the subject of deliberately uneven application by showing that provision of refuges reduced the efficacy of protectants. Subsequent work has shown that the effect of refuges depends both on species and on insecticide (Prickett and Ratcliffe 1977).

This dependence on species and insecticide is not surprising because the efficacy of uneven application relies on the probability of insects coming into contact with lethal doses (de Lima 1975), which in turn depends on the repellancy of insecticides (Pinniger 1975) and on insect movement (cf. Green et al. 1970), which is affected by temperature, moisture, species, sex, stage, density, disturbance, and boundary conditions (Surtees 1965).

Desirable patterns of distribution of residues are those that control every species, and over all conditions found in practice. Because such conditions of, for example, insect behaviour and movement are neither known nor able to be determined quickly, it is necessary to correlate infestations and distribution patterns in commercial storages, in order to determine whether more even distribution results in better control under the wide range of conditions found in commercial storages. An example of the Australian experience is the predominance of *R. dominica* in small (1 m^2) pockets of low residues in no preferred location, whereas *T. castaneum* is seldom found in such pockets but rather at the top of grain piles, especially in aerated storages. The explanation for these observations lies with the 'sluggish' movement of adult *R. dominica* and the habit of some emerging larvae entering the crevices and cracks in grain where eggs are preferentially deposited (Potter 1935), in contrast to the wandering habits of *Tribolium* larvae (Surtees 1965). Thus, *T. castaneum* is more likely to leave a refuge, provided perhaps by failure to treat a pocket of grain, than is *R. dominica.* It may well be that the limits for permissible levels of unevenness are those set by the need to control low densities of eggs and larvae of *R. dominica* in cracked or broken grain, as these are conditions where the susceptible stage, the larval stage, may come in contact with only a very limited number of grains.

At present, there is no objective industry criterion for evenness of application that is acceptable for all feasible circumstances. There is a need for such a criterion and for studies on optimal levels of distribution. It must be based on single, not composite samples, in order to detect systems which deposit insecticide only in certain layers or on one side of a heap. Evenness should be assessed as soon after application as possible, in order to minimise variation caused by different thermal or moisture regimes (Desmarchelier and

Elek 1978). We are currently investigating a criterion based on the coefficient of variation in single samples of 40 g. There is evidence that if the coefficient of variation is less than 20% (Desmarchelier and Wilson 1981) good results will be obtained, and evidence that high values of 80–100% result in serious infestations (Desmarchelier, unpublished results). I recommend this criterion as a useful one, but it is one that will certainly be modified.

The possibility also exists of integrating uneven application with schemes that either utilise or modify insect behaviour. Such schemes are successfully used to control moths in warehouses, and include coupling of insecticides to pheromone traps. The use of baited traps to control Coleoptera in empty storages would also seem not only to be feasible but to remove the selection pressure arising from the current practice of structural sprays. In bulk grain, it might also be possible to attract insects to irregular deposits (e.g. with heating or pheromones) or force insects to move through insecticidal layers (e.g. with forced air flows, or with low levels of carbon dioxide). To be useful, such treatments would need to be an improvement on existing procedures by requiring less insecticide, or to use a formulation in insecticidal layers that could be removed from the grain.

Malfunctions

Malfunctions, such as pump stoppages during grain flow, lead to unevenness of application. A criterion for malfunction is that it should not lead to unacceptble unevenness of application in lodged grain. Thus, failure to apply protectant to 50 kg of grain would probably have no effect where such grain is lodged thinly across a wide area, but would lead to infestation if lodged in a bag.

It is very difficult to avoid malfunctions, and their minimisation requires attention to equipment, maintenance, education, and supervision.

Safety

Safety may be considered under two aspects: consumer and worker safety. The criterion for consumer safety (that levels not exceed the maximum residue limit (MRL) at time of processing) is generally insensitive to localised variations in residue levels in stored grain, because of their averaging during outloading.

Such local variations could, however, cause problems where parcels of grain, for example, bags, are taken for individual consumers.

The criterion for worker safety is avoidance of excessive average or threshold levels of atmospheric concentrations. These concentrations depend on the extent and fineness of spray drift, on volatilisation from spillages and grain and on ventilation. Volatilisation will result in a relative increase of more volatile components such as solvents, which should be measured and, ideally, reduced or eliminated. I would also like to report that the addition of quicklime to spillages is an effective way of trapping chemicals, enabling easy removal and also causing degradation of protectants.

Quality Control

Much of the discussion on protectant application was concerned with techniques and programs to ensure that commercial applications followed good agricultural practice, that is, that they achieved the maximum possible success rate, given existing technology and knowledge. Such techniques and programs are 'quality control'.

General Criteria

Some examples of quality control are hygiene schedules, which require the worker to tick a list of areas to be inspected, and the pressure test, to assess suitability for fumigation. These criteria are good ones because they are straightforward, precise, intelligible to the work-force and adequate, at least on existing knowledge.

Although precise and adequate instructions are essential, quality control also depends on such human qualities as training, experience, and dedication. It is therefore not possible to outline a detailed set of instructions that will automatically lead to good quality control. In my opinion, however, improvements in quality control depend very much on one subjective factor, and that is the importance attached to it by scientists and management. Where management is too busy to interest itself in pest control improvements, or scientists have more important things to do than implementing their ideas, quality control will suffer. Acceptance of quality control as a joint responsibility of science and management is essential if improvements in grain storage are to be made.

Protectant Criteria for Quality Control

In the light of the discussion on quality control, the earlier discussion on application of liquid protectants could be reformulated into quality control criteria, as follows:

1. Adopt a system approach;
2. Apply protectants only in hygienic storages;
3. Apply protectants as prophylactic treatments;
4. Ensure that the coefficient of variation in single samples be less than a certain value;
5. Avoid equipment malfunctions that would result in violations of 4;
6. Keep residue levels to individual consumers below the MRL; and
7. Keep atmospheric concentrations of protectant and solvent below permissible levels.

How do these criteria meet my criteria for quality control, namely the criteria that they be straightforward, precise, intelligible to the workforce, and adequate for the purpose?

Some criteria can and should be made precise by inserting particular values such as 10 mg/kg for the MRL for fenitrothion on wheat, or by substituting criteria such as 'apply 6 and 12 mg/kg for grain to be stored respectively for less or more than 3 months' (Bengston and Desmarchelier 1979). The criterion for evenness of application is currently too imprecise, but more precise criteria are being evaluated. The criterion for malfunctions also needs to be quantified for existing types of storages to criteria such as 'avoid non-application to grain that lasts more than 30 seconds.' A further criticism of my criteria is that those for evenness of application and avoidance of malfunctions require detailed instructions for mixing, calibration, and equipment maintenance, that is, they are not sufficiently straightforward. One solution to such problems is modern technology currently in use, such as coupling the pump, and even the volume delivered, to grain flow. The other solution is to have operators who, to use their own words, 'watch the pump like a hawk.'

Although the number of things that need to be checked is large, quality control in the use of grain protectants has the great advantage of universality. Thus, evaluation of a system will be valid for similar situations, or for later uses. For example, the Australian industry removed all major systematic errors of application by evaluating storage types where infestation occurred regularly, and by improving the systems until such regularity of infestation disappeared. It was not necessary to evaluate all criteria in every storage, nor is it necessary to re-evaluate annually.

I will conclude my discussion on quality control by referring to the analytical chemist, who should check formulations, assess variability of residue deposits, and ensure that values do not exceed MRLs. It is therefore important that measurements are not only accurate, but seen to be accurate. This can be achieved by regular participation in collaborative analytical programs, where samples are analysed by various collaborators and values assessed with the aim of improving procedures and ensuring the lack of systematic errors. Such programs have been of great benefit in determination of protectant residues, and that would certainly be of value for other relevant measurements, such as those of phosphine and water content.

Conclusions

There are many ways of applying protectants, and choice of method depends on the situation. Whatever method is adopted, it is possible and necessary to adopt criteria that lead to good agricultural practice, that is, to optimal results in commercial usage given existing knowledge and technology.

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Framework for Use of Pesticides

Session Chairman's Summary

D.J.B. Calverley*

THIS session followed that covering the background of pesticide research, with its heavy concentration on the mechanism and causes of resistance to both fumigants and residual pesticides. The session started with an outline by *Bengston* of the various strategies for using chemicals as part of the procedural framework termed 'good storage practice.' It is convenient to postpone discussion of his paper until later in this summary. *Champ* then defined the present degree and extent of resistance among insect species and the insecticides involved. He stated that where storage facilities and techniques or management are not ideal, pesticides applied to the commodity or storage environment provide the only economically feasible protection against attack. The objective is not to reduce large pest populations to manageable proportions, but to obtain complete freedom from insects in the foodstuffs.

Apparently this objective cannot be achieved. The dosing of insects with residual pesticides and fumigants leads through a process of selection, to the development of resistance and this resistance now poses a continuing threat to the conservation of food stocks. One difficulty in resolving the problem is a need to stay within FAO/WHO Maximum Residue Levels (MRL). Whilst it was later argued that high dosage rates of insecticides may not necessarily ensure greater kill or reduce population numbers, nobody has questioned whether presently accepted MRL are appropriate in serious cases of resistance and, in view of the arbitrary method by which they are calculated, whether MRL should be challenged.

Champ suggests control measures should achieve complete kill to prevent selective resistance occurring. He stressed the importance of hygiene and the maintenance of good storage practices to reduce the numbers of insects present and thereby the probability of resistance developing.

FAO and others have now provided the test methods for detecting resistance to contact insecticides and fumigants in the major pests. *Champ* stressed very heavily the need for resistance monitoring to be integrated into all R & D programs on biological studies of stored products pests and for monitoring resistance in all pest control activities to facilitate the rational planning of pest control programs. Commendable and justified though this is, it will place very great stress on organisational and human resources in developing countries where the work is most needed.

Comins presented a theoretical paper in which he considered the question of insecticide resistance on the basis of insect population genetics. He presented factors which simple genetic models have shown to be important for delaying or accelerating the spread of resistance. Factors delaying resistance included:

1. Low pesticide dosage rates or the leaving of refugia to ensure a low kill rate of the susceptible population.

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2. Any mechanism which causes effective recessiveness of the resistance gene.
3. The dilution of residual insecticide treated populations by immigration of a susceptible population or by releasing susceptible insects.
4. Alternating pesticides using materials from different chemical groups in order to avoid the problem of cross resistance.

The factor accelerating the spread of resistance is high population growth rate which should, as far as possible, be reduced by means other than pesticide use. These include integrated pest control measures such as the use of predators, strict attention to hygiene and good storage practices, and aeration with ambient or refrigerated air to reduce grain temperature.

Few of these factors have any real meaning in terms of immediate practical application, except for any appropriate measures that might limit the rate of growth of an insect infestation. This again emphasises the importance of hygiene as a fundamental basis for pest control management.

However, the work is clearly of considerable importance. If pesticide resistance is a genetic phenomenon and on the basis of genetic developments observed in insects and other species in different situations there is no reason to think it is not, genetic manipulation of populations of resistant insects may be the only way to combat it. There is obviously some way to go before genetic manipulation of the kind we are looking for becomes possible. *Comins* argues that the first important step forward is to try to systematise current knowledge into what he calls an intuitive concept, which I think is a short cut to constructing a model, involving the growth of a resistant heterozygote sub-population. He also suggests further theoretical work.

In view of the unknowns in this work, the lead time to a practical application is an imponderable. We should therefore convert his argument for more work into a strong recommendation and support.

Bengston and *Desmarchelier* presented complementary papers on practical techniques for pest management control. Both strongly emphasised the essential place of hygiene in any pest control operations, a recurring theme for more than a generation now. It is disturbing that it needs to be continually repeated.

Bengston's review was characterised by its emphasis on sound, proven strategies but, as did *Desmarchelier's* paper, it presumed that integrated use of chemicals begins at the intake to a central storage installation (with the exception of reference to field infestations). Much of the grain in the humid tropics is harvested on small farms and starts its storage period in a farmer's store. It would have been pertinent for the review to have included consideration of what treatment, if any, should be given on the farm, in order that any initial treatment is timely and effective. Investigations into this should be included in *Bengston's* recommendation for research into field infestation. Perhaps the only contentious aspect is the reference to treatment of bag stacks with a residual insecticide, a procedure which was subsequently challenged by others.

Desmarchelier considered the reasons why on-farm or commercial operations do not achieve the success of supervised trials. He cited poor hygiene and bad formulations or application techniques, all of which come under the umbrella of 'management.' Good management, the need for high standards and the opportunities for frequent exercise of poor standards are stressed throughout this paper. However, the methods for quality control and application of pesticides are in the context of Australian conditions. Even within ASEAN, the delivery by farmers of crops to parastatal marketing boards is unlike Australian farmers' practices. While the paper contains much valuable information and guidance for these marketing boards, it would be more helpful if it included consideration of marketing operations north of the Antipodes.

Desmarchelier's protectant criteria for quality control are sound and valuable but I do not share his extreme concern for the need for absolute simpleness of operations. I am, however, concerned at the requirement for the maintenance of quality standards which may be hard to justify in the face of keen competition for scarce management, skilled technical staff, and physical resources.

Treatment Techniques

Grain Protectants

M. Bengston*

Abstract

Grain protectants are defined as insecticides that are incorporated directly into the grain mass. They have the major advantage of providing protection against insect attack right up to the time of consumption, but the safety requirements in regard to residues severely restrict the number of candidate compounds. Properties, formulations, and uses of the more important compounds are described and the application rates for 9 months storage of wheat in Australia are given as a basis for comparison.

Malathion applied at a rate of 18 mg/kg was the first widely used protectant, but its value has been reduced by the development of malathion-resistant strains. Chlorpyrifos-methyl 10 mg/kg, etrimfos 8 mg/kg, fenitrothion 12 mg/kg, or pirimiphos-methyl 4 mg/kg, each control most species except multi-resistant strains of *Rhyzopertha dominica.* Bioresmethrin 1 mg/kg plus piperonyl butoxide 10 mg/kg, carbaryl 8 mg/kg, fenvalerate 1 mg/kg plus piperonyl butoxide 10 mg/kg, permethrin 1 mg/kg plus piperonyl butoxide 8 mg/kg, 1R-phenothrin 1 mg/kg plus piperonyl butoxide 10 mg/kg, or pyrethrin 3 mg/kg plus piperonyl butoxide 30 mg/kg each control multi-resistant strains of *Rhyzopertha dominica.* Deltamethrin 1 mg/kg plus piperonyl butoxide 10 mg/kg or methacrifos 20 mg/kg currently control all typical resistant strains.

Development of grain protectant treatments is described. It first requires surveys to determine the resistance status of typical strains and to provide test insects for laboratory evaluation of candidate compounds. Field experiments with commercial quantities of grain involve both assessments of natural infestation and laboratory bioassay of treated grain with resistant insects. Successful compounds are then evaluated under industry conditions in a minimum of 20 storage units before introduction into large-scale use.

GRAIN protectants are defined as pesticides which are incorporated directly into the grain mass to protect it against insect and mite attack. Application rates are generally chosen so that residual protection is provided right up to the time of consumption. This residual protection is often a major advantage in the operation of grain storage systems. Protectants are generally safe to use and need only simple equipment for their application.

Clearly, some level of protectant residues will be present in the finished product so candidate protectants must be of low toxicity. This severely restricts the number of candidate compounds. Detailed discussion of the topic is outside the scope of this paper but the maximum residue limits recommended by the Codex Alimentarius Commission of the United Nations (Anon. 1978) are acceptable to many nations. The Codex decisions are updated annually and the current ACIAR program concerns only such compounds. The Codex limits are calculated so that intake by humans is less than 1% of that which produces any detectable symptom in test animals.

Development of a new candidate grain protectant takes a minimum of 7 years though of course accepted compounds may be adapted to a region quite quickly. This time frame includes the time for the necessary long-term toxicology studies and for international agreement on residue limits necessary for export trade. Because of this lengthy time span, and because of the probability of further insecticide resistance, workers in Australia have adopted a policy of developing and promoting international agreement on a range of compounds in the hope that this can be done in advance of the actual requirements of the storage system.

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Methods of Application

Grain protectants are usually applied as sprays directed into the grain stream during movement of the grain. Clearly this is most efficient where grain is handled in bulk. However, it may be practicable in bag handling systems during rebagging operations and, with additional effort, before bagging. The grain protectant is commonly diluted with water and sprayed into the grain stream at the rate of 1 L/t. Other systems involve ultra low volume application requiring little or no water. In the drip feed system, for example, tiny quantities of the concentrate are dripped directly into the grain stream through microcapillary tubes.

The residual life of malathion was increased and good insect control achieved by treating only one grain in a hundred of experimental grain bulks (Minnett and Williams 1976). It should be emphasised that the treated grains were distributed evenly throughout the mass. In practice, the use of small pumps with coarse spray nozzles and low pump pressure produces large spray droplets and gives good results whilst minimising spray drift.

With small quantities of grain, the protectants may be incorporated as dusts with simple mechanical stirring, although adequate mixing may be difficult to achieve. With larger quantities of grain, exposure of workmen to dusty conditions may become a problem. In addition, some dusts are abrasive and cause accelerated wear in machinery bearings. Nevertheless, dust formulations are valuable in specific circumstances.

There has been some use of a range of alternative application techniques including slow-release strips (Muda, unpublished data), thermal aerosols, and mechanical and gas propelled aerosols. In general, these remain experimental.

Ideally, grain protectants are applied to uninfested grain at the commencement of storage with an application rate chosen to give complete protection from infestation throughout. The application rate must be adjusted for the length of storage and for storage conditions. Both the rate of breakdown and also the biological acitivity of grain protectants vary with storage temperature and moisture as discussed in the papers by Desmarchelier and Samson in these proceedings.

Historical Uses

Historically the admixture of ashes, dust, sand, sulfur, and a range of inorganic salts was practised in many parts of the world since early times (Majumder and Muthu 1960). Plant products were also used in specific regions (Jacobson 1958) and pyrethrum extracts have been used at least since the mid-19th century. Many of these treatments and a range of compounds including food additives have been or are being re-evaluated. The list includes insecticidal clays (Venugopal and Majumder 1964), dusts (White et al. 1966; Ebeling 1969), oils (Messina and Renwick 1983), citrus oils (Su 1972a, b), *Mentha spicata* (Kayshyap et al. 1974), neem (*Azadirachta indica*) (Muda 1984; Cox 1981), capric acid (House and Grahm 1967), tricalcium phosphate (Bano and Majumder 1968), and sorbic acid (Dunkel unpublished data).

Since the 1940s many of the synthetic organic insecticides including DDT and lindane were tested as grain protectants, but were of little use because of residue problems.

Malathion and Dichlorvos

The major use of grain protectants commenced in the early 1960s following the recognition of the suitable properties of malathion for this purpose (Strong and Sbur 1960, 1961; Floyd 1961; Bang and Floyd 1962). Many workers in many countries contributed to its introduction. The use of malathion is now being restricted because of the widespread development of malathion-resistance, which was surveyed extensively by FAO (Champ and Dyte 1976).

Dichlorvos, although not conforming strictly to the definition of a grain protectant, has many properties complementary to malathion. It has a short residual life and when incorporated into the grain stream it is useful in disinfesting grain without producing high residues (Godavaribai et al. 1960; Green and Tyler 1966; Champ et al. 1969; Desmarchelier et al. 1977). It is particularly effective against moth species little affected by malathion and for this purpose may be conveniently applied as slow-release strips (Conway 1966; La Hue 1969; McFarlane 1970) or aerosols (Bengston 1976).

Alternatives to Malathion

With the development of malathion resistance, chlorpyrifos-methyl (Bengston et al. 1975; Morallo Rejesus and Carino 1976a, b; La Hue 1977a, b; Quinlan et al. 1979), fenitrothion (Champ et al. 1969; Bengston et al. 1980), and pirimiphos-methyl (Bengston et al. 1975; La Hue 1975, 1977b; McDonald and Gillenwater 1976; Quinlan et al. 1980) were tested and are being used in many countries. Although a low level of cross-resistance is present in many species, effective control is exercised at acceptable dose rate.

Control of Bostrychids

The most significant exceptions are the bostrychids *Rhyzopertha dominica* (Fabricius) and *Prostephanus truncatus* (Horn). Multiresistant strains are not effectively controlled and either natural pyrethrins or a synthetic pyrethroid — bioresmethrin (Bengston et al. 1975, 1980, 1983a) or fenvalerate (Bengston et al. 1983a, 1984) or (IR) phenothrin (Bengston et al. 1983b, 1984) or the carbamate carbaryl (Bengston 1980, 1983a; Davies and Desmarchelier 1981) must be used. Since these materials are not effective against other common species at practicable doses they must be combined with an organophosphorus material to provide control of the entire pest complex. The synthetic pyrethroid materials are all synergised by the addition of piperonyl butoxide (Bengston 1979).

General Purpose Protectants

More recent studies have shown that the organophosphorus material methacrifos is effective against all strains including the multiresistant *R. dominica* (Renfer et al. 1978; Bengston et al. 1980) and it is now gaining acceptance. It has a relatively short half-life on grain so that residues in the finished product are low but application rates must be fitted more precisely to the storage condition.

The synthetic pyrethroid deltamethrin is also effective against currently prevalent strains of the complex (Bengston 1984; Bengston et al. 1983b, 1984). This compound is persistent on grain and use of suspension concentrate formulations has been necessary to avoid respiratory irritation to workmen exposed in the treatment area. Piperonyl butoxide synergises its action but must be applied separately to avoid increasing the respiratory irritation (Bengston, unpublished data).

Other Compounds

Several other compounds are either in limited use as grain protectants or are in various stages of development and approval. Bromophos has some acceptance as an alternative to chlorpyrifos-methyl but is not as effective against some resistant strains. Etrimfos is under development as an alternative and is generally effective (Bengston, unpublished data).

The insect growth regulators methoprene and hydroprene (Amos and Williams 1977), dimilin (McGregor and Kramer 1976), and many others (Strong and Dickman 1973; Kramer and McGregor 1978a, b; Loschiavo 1978) are promising for specific purposes. Several are specially active against *R. dominica* and methoprene is now undergoing field evaluation for control of that species (Bengston, unpublished data).

Development of Candidate Compounds

The development of grain protectant treatments needs to be related to the specific circumstances of the grain storage system and requires a blend of laboratory and field studies. It is a major advantage for the decision makers in the storage network to be associated with the field testing program.

Since resistant strains are a major factor in the efficacy of current materials, surveys to determine the resistance status of prevalent strains are an important pre-requisite. Collection of samples and laboratory procedures outlined in the FAO methods are recommended (Anon. 1974). Typical resistant strains of the major pest species must be maintained in culture in sufficient numbers to provide material for bioassays. In general it is necessary to maintain these cultures under selection with insecticide to ensure that the resistance level is maintained.

The acute toxicity of candidate compounds may be compared in a variety of ways but the FAO resistance test methods yield a rapid initial comparison provided the compounds are not volatile. Bioassays in insecticide-treated grain with a range of insecticide concentrations provide valuable estimates of relative potency of candidate compounds and give initial indications of the likely field application rates. Experience has shown that simple pipetting of diluted insecticide into small quantities of grain yields valid data and avoids the surprisingly high losses of insecticides which may occur with attempts at laboratory spraying.

More promising compounds are then subject to detailed laboratory investigation extending over a typical storage interval, usually a year. Samples of treated-grain stored under controlled conditions are bioassayed at regular intervals. The criteria for assessment depend on the insect species and the compound but generally include an assessment of adult mortality at one or more times and an assessment of F_1 and F_2 progeny. As is well known the susceptibility of insects varies with stages of development.

The optimum conduct of such laboratory experiments demands a high level of technical skill and a detailed understanding of the principles involved (Busvine 1971). The design and analysis of appropriate experiments depends heavily on the statistics of probit analysis (Finney 1971).

It is vital that the preliminary laboratory work identify the most promising compounds and yield realistic estimates of the minimum effective doses likely to be appropriate in the field. Although the topic is outside the scope of this paper it is essential that target application rates are verified by chemical analysis and that residue levels in finished products are adequately assessed.

Field testing of materials requires treatment of grain in the actual storage system. Experimental grain bulks usually need to contain a minimum of 500 t of treated grain to ensure that grain temperatures are typical of those in larger grain masses which may differ markedly from ambient and from those in smaller bins. Experiments with bagged grain may involve smaller quantities, but they need to relate as closely as practicable to conditions in the actual storage system.

The major method of assessment of the treatments depends on laboratory bioassays of treated grain using test insects of typical resistant strains. The presence of natural infestations and damage (if any) in experimental grain bulks in the field should be recorded and may indicate a failure. However, the absence of infestation may be an unreliable criterion since typical resistant strains may be absent from the particular storage or locality.

The final stage of field testing should involve pilot usage ideally in a minimum of 20 storages, representative of the various parts of the storage system (Desmarchelier et al. 1981). This stage allows evaluation of aspects such as compatibility of formulation with a range of water types, suitability of formulation for the application system, dust problems, etc. It also evaluates the candidate compounds against the actual range of resistant insects since success in 20 storages is a good criterion of success in the entire system. Another important aspect of the pilot usage stage is that is allows many storage operators and system managers to become familiar with the properties, uses, and limitations of grain protectants and thus encourages their correct use.

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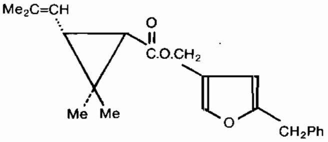
Appendix. Properties of Common and Candidate Grain Protectants

Bioresmethrin

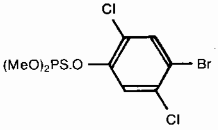
1. *Trade name.* Bioresmethrin
2. *Chemical name.* 5-benzyl-3-furylmethyl (+)-*trans*=chrysanthemate
3. *Structural formula.*



4. *Physical properties.* A viscous yellow liquid which on crystallisation forms an off-white solid. Specific gravity 1.050 at 20°C. Soluble in most organic solvents but substantially insoluble in water.
5. *Chemical properties.* Decomposed by light but its photo-stability is greater than that of pyrethrins; stable to temperatures met under most normal storage conditions; medium persistence on grain.
6. *Formulations used.* Emulsifiable concentrate containing piperonyl butoxide at concentrations 10 times that of the bioresmethrin.
7. *Insecticidal activity.* Limited activity against most species at economic doses but specifically effective against *Rhyzopertha dominica.*
8. *Fields of use.* As a grain protectant when synergised with piperonyl butoxide and combined with an approved organophosphorus insecticide such as chlorpyrifos-methyl, fenitrothion, or pirimiphos-methyl.
9. *Application rate.* 1 mg/kg bioresmethrin combined with 10 mg/kg piperonyl butoxide for 9 months protection of wheat in Australia at 30°C and 55% RH.
10. *Toxicity.* Acute oral and acute dermal toxicity very low (LD_{50} rats, > 8000 mg/kg and > 10 000 mg/kg respectively). No toxic manifestations seen after feeding high doses for 90 days to dogs.
11. *Safety directions.* Avoid contact with skin and eyes. Wash concentrate from skin and eyes immediately. Wash hands and exposed skin after use and before eating, drinking or smoking.
12. *Symptoms of poisoning.* None observed.
13. *First aid.* If swallowed induce vomiting. Use Ipecac Syrup (APF) if available.

Bromophos

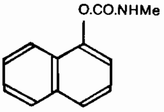
1. *Trade name.* Nexion
2. *Chemical name.* *O*-4-bromo-2,5-dichlorophenyl *O,O*-dimethyl phosphorothioate
3. *Structural formula.*



4. *Physical properties.* White crystals; m.p. 53°C; soluble in most organic solvents; slightly soluble in alcohol; almost insoluble in water.
5. *Chemical properties.* Stable in aqueous suspension; hydrolyses in alkaline medium. Medium persistence on grain.
6. *Formulations used.* Emulsifiable concentrate and wettable powder.
7. *Insecticidal activity.* Generally more effective than malathion but less effective than fenitrothion; relatively ineffective against *Rhyzopertha dominica* and *Trogoderma granarium.*
8. *Fields of use.* Approved for addition to grain in Mexico, United Kingdom, Spain, South Africa, and a number of other countries.
9. *Application rate.* Not used in Australia.
10. *Toxicity.* Very low acute oral toxicity (LD_{50} rats, 4000–8000 mg/kg); extremely low dermal toxicity. Long-term studies indicate no unusual toxic manifestations other than cholinesterase inhibition.
11. *Safety directions.* Concentrate is poisonous. When handling concentrate and preparing spray, use rubber gloves and face shield. Avoid breathing mist or spray and avoid contact with skin and eyes. On completion of each spraying, wash thoroughly with soap and water. Wash contaminated clothing before re-use. Do not eat or smoke while spraying.
12. *Symptoms of poisoning.* Headache followed by increased salivation, drowsiness, nausea and vomiting, mental confusion, and abdominal cramps. May be a feeling of tightness in the chest and difficulty in breathing. Pupils of the eyes contract and vision is blurred. Diarrhoea may occur. If poisoning is severe, twitching develops followed eventually by generalised convulsion. Coma follows.
13. *First aid.* If poisoning occurs, contact a doctor or Poisons Information Centre. If swallowed, induce vomiting. Use Ipecac Syrup (APF) if available. After vomiting give one atropine tablet (0.5 mg) every quarter hour until dryness of mouth occurs. If poisoned by skin absorption, remove contaminated clothing and wash skin thoroughly. Give atropine tablets as above.

Carbaryl

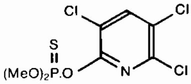
1. *Trade names.* Sevin, Septene
2. *Chemical name.* 1-naphthyl methylcarbamate
3. *Structural formula.*



4. *Physical properties.* White crystalline powder, poorly soluble in water and most organic solvents; m.p. 142°C; low volatility.
5. *Chemical properties.* Stable to light, heat, and hydrolysis under normal storage conditions; non-corrosive; medium persistence on grain.
6. *Formulations used.* Suspension concentrate.
7. *Insecticidal activity.* Minimal effect at normal rate of application against most pests of grain. Highly effective as a contact insecticide and stomach poison against *Rhyzopertha dominica.*
8. *Fields of use.* In conjunction with an organophosphorus grain protectant insecticide, for admixture with grain.
9. *Application rate.* 8 mg/kg for 9 months protection of wheat in Australia at 30°C and 55% RH.
10. *Toxicity.* Acute oral toxicity moderate (LD_{50} rats, 400 mg/kg). Acute dermal toxicity low (LD_{50} rats, 4000 mg/kg). Not readily absorbed through skin. Symptoms of intoxication quickly disappear.
11. *Safety directions.* Concentrate is poisonous. Avoid contact with skin and eyes and avoid breathing vapour. When handling the concentrate and preparing the spray, use rubber gloves and face shield. If eyes are contaminated, flush with water. Do not eat or smoke when spraying.
12. *Symptoms of poisoning.* Watering of eyes and mucous membranes, headache, nausea, nervousness, vomiting, blurring of vision, dizziness, and difficulty in breathing.
13. *First aid.* Atropine is an antidote. If swallowed, give two atropine tablets (0.5 mg). Repeat each half hour until dryness of mouth occurs.

Chlorpyrifos-methyl

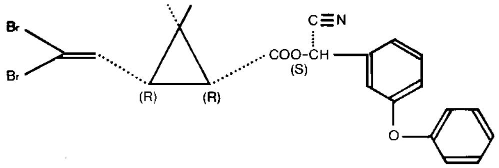
1. *Trade name.* Reldan
2. *Chemical name.* *O,O*-dimethyl *O*(3,5,6-trichloropyrid-2-yl) phosphorothioate
3. *Structural formula.*



4. *Physical properties.* Colourless crystals with a slight mercaptan odour; m.p. 45°C; readily soluble in most organic solvents, poorly soluble in water.
5. *Chemical properties.* Stable under normal storage conditions; stable under neutral conditions but readily hydrolysed under both acid and alkaline conditions; medium persistence on grain.
6. *Formulations used.* Emulsifiable concentrate.
7. *Insecticidal activity.* Controls most species, but is relatively ineffective against multi-resistant *Rhyzopertha dominica.*
8. *Fields of use.* For admixture with grain, generally in conjunction with a pyrethroid insecticide, or carbaryl.
9. *Application rate.* 10 mg/kg for 9 months protection of wheat in Australia at 30°C and 55% RH.
10. *Toxicity.* Acute oral toxicity low to very low (LD_{50} rats, 1650–2100 mg/kg), acute dermal toxicity very low. Chronic toxicity studies show no significant manifestations other than cholinesterase inhibition.
11. *Safety directions.* Concentrate is poisonous. When handling concentrate and preparing spray, use rubber gloves and face shield. Avoid breathing mist or spray and avoid contact with skin and eyes. On completion of each spraying wash thoroughly with soap and water. Wash contaminated clothing before re-use. Do not eat or smoke while spraying.
12. *Symptoms of poisoning.* Headache followed by increased salivation, drowsiness, nausea and vomiting, mental confusion, and abdominal cramps. May be a feeling of tightness in the chest and difficulty in breathing. Pupils of the eyes contract and vision is blurred. Diarrhoea may occur. If poisoning is severe, twitching develops followed eventually by generalised convulsion. Coma follows.
13. *First aid.* If poisoning occurs, contact a doctor or Poisons Information Centre. If swallowed, induce vomiting. Use Ipecac Syrup (APF) if available. After vomiting, give one atropine tablet (0.5 mg) every quarter hour until dryness of mouth occurs. If poisoned by skin absorption, remove contaminated clothing and wash skin thoroughly. Give atropine tablets as above.

Deltamethrin

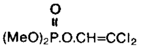
1. *Trade name.* K-othrine, Kothrin, Deccis
2. *Chemical name.* (S)-d-cyano-m-phenoxybenzyl (1R,3R)-3-(2,2 dibromovinyl)-2,2-dimethyl-cyclopropane carboxylate
3. *Structural formula.*



4. *Physical properties.* A crystalline powder, white to slightly beige in colour; m.p. 98 to 100°C. Soluble in many solvents but almost insoluble in water. Very low vapour pressure.
5. *Chemical properties.* Relatively stable when exposed to light and highly persistent on grain. Decomposed by strong alkalis.
6. *Formulations used.* A suspension concentrate.
7. *Insecticidal activity.* Effective against most species and currently resistant strains of stored product pests.
8. *Fields of use.* Admixture with grain in combination with piperonyl butoxide synergist. Separate application may be necessary to avoid respiratory irritation.
9. *Toxicity.* Acute oral toxicity moderately low (LD_{50} 129 mg/kg in rat); acute dermal toxicity low (> 2940 mg/kg).
10. *Safety directions.* Avoid contact with skin and eyes. When handling concentrate, wear impermeable gloves, boots and face shield. Wash hands before eating, drinking, and smoking.
11. *Symptoms of poisoning.* May cause skin irritation in certain individuals and also respiratory irritation.
12. *First aid.* Remove contaminated clothing immediately and wash contaminated skin thoroughly with soap and water. In case of eye splash wash eyes immediately with water for at least 15 minutes. If swallowed induce vomiting with Ipecac Syrup (APF) and refer to doctor for gastric lavage with care to prevent aspiration. Treat symptomatically.

Dichlorvos

1. *Trade names.* Vapona, Nuvan, Mafu
2. *Chemical name.* 2,2-dichlorovinyl dimethyl phosphate
3. *Structural formula.*

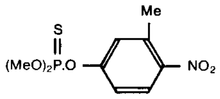


$$(MeO)_2\overset{\overset{O}{\|}}{P}.O.CH{=}CCl_2$$

4. *Physical properties.* Colourless to amber liquid; poorly soluble in water; moderately soluble in kerosene; miscible with organic solvents; slightly volatile.
5. *Chemical properties.* Stable to heat; hydrolysed by alkali; corrosive to iron and steel; short persistence on grain.
6. *Formulations used.* Emulsifiable solutions, solutions, aerosols, and resin based slow-release strips.
7. *Insecticidal activity.* Contact insecticide with fumigant and penetrant action. Specially effective against moths.
8. *Fields of use.* For admixture with grains at rate of 6–12 g/tonne to control active infestation; controls most stored product pests including moths and immature stages inside grain. Application to the surface of grain masses or to the airspace above is effective for moth control.
9. *Application rate.* 6–12 mg/kg for disinfestation of wheat in Australia at 30°C and 55% RH.
10. *Toxicity.* Acute oral and acute dermal toxicity high; care needed in handling concentrates; resin-based strips present low hazard.
11. *Safety directions.* Concentrate is poisonous. When handling concentrate and preparing spray, use rubber gloves and face shield. Avoid breathing mist or spray and avoid contact with skin and eyes. On completion of each spraying, wash thoroughly with soap and water. Wash contaminated clothing before re-use. Do not eat or smoke while spraying.
12. *Symptoms of poisoning.* Weakness, headache, tightness in chest, blurred vision, non-reactive pinpoint pupils; salivation, sweating, nausea, vomiting, diarrhoea, and abdominal cramps.
13. *First aid.* If poisoning occurs, contact a doctor or Poisons Information Centre. If swallowed, induce vomiting. Use Ipecac Syrup (APF) if available. After vomiting, give one atropine tablet (0.5 mg) every quarter hour until dryness of mouth occurs. If poisoned by skin absorption, remove contaminated clothing and wash skin thoroughly. Give atropine tablets as above.

Fenitrothion

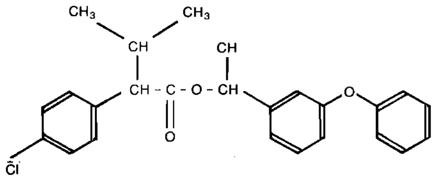
1. *Trade names.* Sumithion, Folithion
2. *Chemical name.* *O,O*-dimethyl *O*-3-methyl-4-nitrophenyl phosphorothioate
3. *Structural formula.*



4. *Physical properties.* Brownish yellow liquid, practically insoluble in water, but soluble in most organic solvents; poorly soluble in petroleum solvents.
5. *Chemical properties.* Hydrolysed by alkali, otherwise stable. Medium persistence on grain.
6. *Formulations used.* Emulsifiable solutions, wettable powders, and dusts.
7. *Insecticidal activity.* Controls most species but is relatively ineffective against multi-resistant *Rhyzopertha dominica.*
8. *Fields of use.* For admixture with grain, generally in conjunction with a pyrethroid insecticide or carbaryl.
9. *Application rate.* 12 mg/kg for 9 months protection of wheat in Australia at 30°C and 55% RH.
10. *Toxicity.* Acute oral toxicity moderately low (LD_{50} rats, 250–500 mg/kg); acute dermal toxicity low.
11. *Safety directions.* Wash hands, arms, and face before eating or smoking.
12. *Symptoms of poisoning.* Headache followed by increased salivation, drowsiness, nausea and vomiting, mental confusion, and abdominal cramps. May be a feeling of tightness in the chest and difficulty in breathing. Pupils of the eyes contract and vision is blurred. Diarrhoea may occur. If poisoning is severe, twitching develops followed eventually by generalised convulsion. Coma follows.
13. *First aid.* If poisoning occurs, contact a doctor or Poisons Information Centre. If swallowed, induce vomiting. Use Ipecac Syrup (APF) if available. After vomiting, give one atropine (0.5 mg) tablet every quarter hour until dryness of mouth occurs. If poisoned by skin absorption, remove contaminated clothing and wash skin thoroughly. Give atropine tablets as above.

Fenvalerate

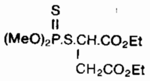
1. *Trade name.* Sumicidin
2. *Chemical name.* α-cyano-3-phenoxybenzyl 2-(4-chlorophenyl)-3-methylbutyrate
3. *Structural formula*



4. *Physical properties.* A yellow viscous liquid. Soluble in many solvents but almost insoluble in water. Very low vapour pressure.
5. *Chemical properties.* Relatively stable when exposed to light and highly persistent on grain. Decomposed in strong alkali.
6. *Formulations used.* An emulsifiable concentrate containing piperonyl butoxide at concentrations 10 times that of the fenvalerate.
7. *Insecticidal activity.* At economic application rates it is effective against only *Rhyzopertha dominica.*
8. *Fields of use.* As a grain protectant when synergised with piperonyl butoxide and combined with an organophosphorus insecticide such as chlorpyrifos-methyl.
9. *Application rate.* 1 mg/kg fenvalerate combined with 10 mg/kg piperonyl butoxide for 9 months protection of wheat in Australia at 30°C and 55% RH.
10. *Toxicity.* Acute oral toxicity moderately low (LD_{50} in rats, 450 mg/kg), acute dermal toxicity low (3700–5000 mg/kg).
11. *Safety directions.* Avoid contact with skin and eyes. When handling concentrate wear impermeable gloves, boots, and face shield. Wash hands and exposed skin after use and before eating, drinking, and smoking.
12. *Symptoms of poisoning.* May cause facial numbness in certain individuals.
13. *First aid.* Remove contaminated clothing immediately and wash contaminated skin thoroughly with soap and water. In case of eye splash, flush eyes immediately with water for at least 15 minutes and refer to doctor. If swallowed refer to doctor for gastric lavage with care to prevent aspiration. Treat symptomatically.

Malathion

1. *Trade name.* Malathion, Grain-Guard, Malapreme
2. *Chemical name.* *S*-1, 2-bis (ethoxycarbonyl) ethyl *O,O*-dimethyl phosphorodithioate
3. *Structural formula.*

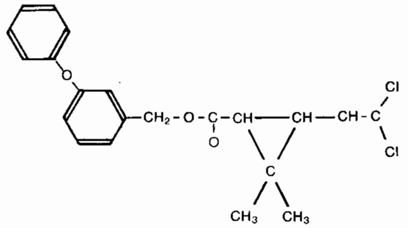


$$(\mathrm{MeO})_2\overset{\overset{\mathrm{S}}{\|}}{\mathrm{P}}.\mathrm{S}.\underset{\underset{\mathrm{CH_2CO_2Et}}{|}}{\mathrm{CH}}.\mathrm{CO_2Et}$$

4. *Physical properties.* Colourless to light amber liquid with high specific gravity (sp. gr. 1.23); poorly soluble in water (145 ppm), miscible with many solvents but of limited solubility in petroleum oils.
5. *Chemical properties.* Stable in neutral solution, but unstable to both acid and alkali, corrodes iron; technical grade has strong odour; medium persistence on grain.
6. *Formulations used.* For use near grain, only formulations based on premium grade malathion should be employed. Emulsifiable concentrates, dust, and wettable powder.
7. *Insecticidal activity.* Formerly effective against most species but malathion-resistance is now widespread and invalidates its use in many localities.
8. *Fields of use.* For admixture with grain as a grain protectant.
9. *Application rate.* 18 mg/kg for 9 months protection of wheat in Australia at 30°C and 55% RH.
10. *Toxicity.* Oral toxicity very low (LD_{50} rats, 2800 mg/kg); dermal toxicity very low (LD_{50} rabbits, 4800 mg/kg); chronic toxicity very low.
11. *Safety directions.* Concentrate is poisonous. When handling concentrate and preparing spray, use rubber gloves and face shield. Avoid breathing mist or spray and avoid contact with skin and eyes, and on completion of each spraying, wash thoroughly with soap and water. Wash contaminated clothing before re-use. Do not eat or smoke while spraying.
12. *Symptoms of poisoning.* Headache, lachrymation, salivation, laboured breathing, vomiting, marked tremors, diarrhoea, and convulsions.
13. *First aid.* If poisoning occurs, contact a doctor or Poisons Information Centre. If swallowed, induce vomiting. Use Ipecac Syrup (APF) if available. After vomiting, give one atropine tablet (0.5 mg) every quarter hour until dryness of mouth occurs. If skin contact occurs, remove contaminated clothing and wash skin thoroughly. Give atropine tablets as above.

Permethrin

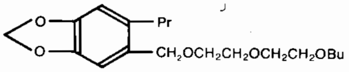
1. *Trade names.* Ambush, Permethrin 25:75
2. *Chemical name.* 3-phenoxybenzyl (±)-cis,trans-3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropanecarboxylate
3. *Structural formula.*



4. *Physical properties.* A viscous liquid. Soluble in many organic solvents and almost insoluble in water. Very low vapour pressure.
5. *Chemical properties.* Relatively stable when exposed to light and highly persistent on grain. Decomposed in strong alkalis.
6. *Formulations used.* An emulsifiable concentrate containing piperonyl butoxide at a concentration 10 times that of the permethrin.
7. *Insecticidal activity.* At economic application rates it is effective against only *Rhyzopertha dominica.*
8. *Fields of use.* As a grain protectant when synergised with piperonyl butoxide and combined with an organophosphorus insecticide such as chlorpyrifos-methyl.
9. *Application rate.* 1 mg/kg permethrin combined with 10 mg/kg piperonyl butoxide for 9 months protection of wheat in Australia at 30°C and 55% RH.
10. *Toxicity.* Acute oral and acute dermal toxicity are low (LD_{50} in rats $>$ 4000 mg/kg for both).
11. *Safety directions.* Avoid contact with skin and eyes. When handling concentrate wear impermeable gloves, boots, and face shield. Wash hands and exposed skin after use and before eating, drinking, and smoking.
12. *Symptoms of poisoning.* Not recorded.
13. *First aid.* Remove contaminated clothing immediately and wash contaminated skin thoroughly with soap and water. In case of eye splash, flush eyes immediately with water for at least 15 minutes and refer to doctor. If swallowed give milk or water and do not induce vomiting. Refer to doctor and treat symptomatically.

Piperonyl butoxide

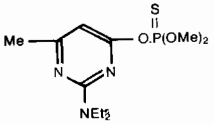
1. *Trade name.* Various.
2. *Chemical name.* 5-(2-(2-butoxyethoxy) ethoxymethyl) - 6 - propyl - 1,3 - benzodioxole.
3. *Structural formula.*



4. *Physical properties.* Pale yellow, odourless oil; soluble in most solvents including petroleum oil.
5. *Chemical properties.* Non-corrosive; resistant to light and to hydrolysis, stable in most use situations.
6. *Formulations used.* Used with natural pyrethrins or synthetic pyrethroids usually in the ratio 10 parts piperonyl butoxide to 1 part natural pyrethrins or synthetic pyrethroids in solutions, dusts, and aerosols.
8. *Fields of use.* As a synergist for pyrethrin and synthetic pyrethroid insecticides in all applications except moth control.
9. *Application rate.* Generally 10 mg/kg for 9 months protection of wheat in Australia at 30°C and 55% RH, but varies according to pyrethroid used.
10. *Toxicity.* Acute oral toxicity very low; chronic toxicity very low.
11. *Safety directions.* No particular precautions required.
12. *Symptoms of poisoning.* None.
13. *First aid.* None.

Pirimiphos-methyl

1. *Trade name.* Actellic
2. *Chemical name.* *O*-2-diethylamino-6-methylpyrimidin-4-yl *O,O*-dimethyl phosphorothioate
3. *Structural formula.*



4. *Physical properties.* Straw coloured liquid with low vapour pressure; very soluble in most organic solvents but practically insoluble in water.
5. *Chemical properties.* Hydrolysed by strong acids and alkalis; does not corrode brass, stainless steel, or plastics but slightly corrosive on unprotected steel and tinplate.
6. *Formulations used.* Emulsifiable concentrate.
7. *Insecticidal activity.* Effective at low concentrations against most beetles, weevils, and moths but relatively ineffective against *Rhyzopertha dominica.*
8. *Fields of use.* For admixture with grain generally in conjunction with a pyrethroid insecticide or carbaryl.
9. *Application rate.* 4 mg/kg for 9 months protection of wheat in Australia at 30°C and 55% RH.
10. *Toxicity.* Acute oral toxicity low (LD_{50} rats, 1200–2050 mg/kg); very low acute dermal toxicity; somewhat more toxic to birds than other species; chronic toxicity studies reveal no significant effects other than cholinesterase inhibition.
11. *Safety directions.* Concentrate is poisonous. When handling concentrate and preparing spray, use rubber gloves and face shield. Avoid breathing mist or spray and avoid contact with skin and eyes. On completion of each spraying, wash thoroughly with soap and water. Wash contaminated clothing before re-use. Do not eat or smoke while spraying.
12. *Symptoms of poisoning.* Headache followed by increased salivation, drowsiness, nausea and vomiting, mental confusion, and abdominal cramps. May be a feeling of tightness in the chest and difficulty in breathing. Pupils of the eyes contract and vision is blurred. Diarrhoea may occur. If poisoning is severe, twitching develops followed eventually by generalised convulsion. Coma follows.
13. *First aid.* If poisoning occurs, contact a doctor or Poisons Information Centre. If swallowed, induce vomiting. Use Ipecac Syrup (APF) if available. After vomiting, give one atropine tablet (0.5 mg) every quarter hour until dryness of mouth occurs. If poisoned by skin absorption, remove contaminated clothing and wash skin thoroughly. Give atropine tablets as above.

Pyrethrins

1. *Trade name.* Various
2. *Chemical name.* Complex mixture of pyrethrins I & II, cinerin I & II
3. *Stuctural formula.* Complex
4. *Physical properties.* Technical product consists of dark brown oil extract; insoluble in water; miscible with most solvents; strong, characteristic odour.
5. *Chemical properties.* Unstable to sunlight; rapidly degraded by alkalis; residual activity short, except in dry grain.
6. *Formulations used.* Solutions and emulsifiable concentrates containing piperonyl butoxide at concentrations 10 times that of the pyrethrin.
7. *Insecticidal activity.* Rapid knock-down effect due to paralysing action on wide variety of insects; particularly effective against *Rhyzopertha dominica.*
8. *Fields of use.* As knock-down spray or aerosol. In conjunction with an organophosphorus grain protectant insecticide for admixture with grains.
9. *Application rate.* 3 mg/kg pyrethrin combined with 30 mg/kg piperonyl butoxide for 9 months protection of wheat in Australia at 30°C and 55% RH.
10. *Toxicity.* Acute oral toxicity moderately low; dermal toxicity low; unrefined extracts may produce allergic reactions.
11. *Safety directions.* No particular precautions required.
12. *Symptoms of poisoning.* Some people may be allergic or suffer minor respiratory irritation.
13. *First aid.* If poisoning occurs, contact a doctor or Poisons Information Centre. If swallowed, induce vomiting. Use Ipecac Syrup (APF) if available.

Application of Fumigants for Disinfestation of Grain and Related Products

H.J. Banks*

Abstract

Although now an old technique, fumigation remains one of the most useful approaches to the control of insects infesting grain and related products. Moreover, it is a technique for which there is often no feasible alternative, as it can be applied without disturbing the grain and at moderate cost. This paper describes the results of recent research on the use of fumigants and consequent improvements in fumigation practice.

Studies of the physical forces acting on storage structures have revealed the main environmental factors that govern the retention of gas in storages under fumigation. By sealing and painting storages to minimise the influences of wind and temperature variation, in particular, it has become possible to retain fumigants for long periods. Phosphine can now be used efficiently in structures that hitherto could not be treated, so that there is no survival from an infestation. In Australia, low dosage rates of phosphine combined with very long exposure periods are used whenever possible, a regime supported by laboratory findings on the response of insects to phosphine.

Recent research into fumigation techniques has resulted in several new ways of applying phosphine, has highlighted the problems of removal of fumigants after treatments, and has enhanced the potential for use of mixtures of fumigants with carbon dioxide. The use of such mixtures can assist both the biological action and the distribution of fumigant within the treatment enclosure. There is a need to investigate alternative fumigants and to develop ways of accelerating the action of methyl bromide and phosphine.

FUMIGATION is an old and widely used technique for disinfestation of stored products (Bond 1984). In many situations it may be the only feasible process for insect control as it does not require the commodity to be moved. Neither may it need specialised apparatus, electricity, or manpower. It can often be the cheapest and most effective process available.

A detailed understanding of some of the constraints on the use of fumigation has been obtained recently. Research has provided background information on the biological response of insects to fumigants, the fate of fumigants in grain, and the ways that fumigants are lost from the system under treatment. This knowledge has led to development of new ways of application of fumigants and to a recognition of ways of optimising current techniques.

This paper presents some recent research findings on the biological action of fumigants and behaviour of gases in semi-sealed enclosures and the consequences of this information for practical fumigation. Developments in techniques for applying fumigants are reviewed. Discussion is restricted to the use of methyl bromide (CH_3Br) and phosphine (PH_3) although the techniques used for these gases may often be easily adaptable to other fumigants.

The basic research that has led to changes in the way fumigants are now being used can be viewed in two distinct parts: research on the biological response and research on the movement and containment of gases. Much attention has been given to the exposure time required and associated biological responses, both of which are often limiting factors in the use of phosphine. The physical dispersion and distribution of the fumigants within storages and removal of gas from storages have also been investigated in detail. The use of CH_3Br is often limited by these factors.

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Dosage Rates and Biological Action

Recent recommendations (Heseltine 1973; Winks et al. 1980) for the exposure period required for fully effective fumigation with PH_3 have been based on *Ct*-products of 150 gram-hours/m^3 achieved over a minimum of 5 days exposure at greater than 25°C. If *Sitophilus* spp. are present, a minimum of 7 days exposure is needed (Winks et al. 1980). Dosages required in large sealed storages to meet this *Ct*-product are 2.5 g PH_3/m^3 and 1.5 g PH_3/m^3, respectively. These exposure periods are much longer than those stipulated previously (see Anon. 1972). The increased exposure period results from a recognition that some developmental stages, notably eggs and pupae, of stored products insects are very tolerant of phosphine and not all of these tolerant stages may be killed by higher dosages at short exposure times. Development is said to continue during exposure to phosphine (Reynolds et al. 1967). The long exposure allows tolerant stages to develop into susceptible stages (Fig. 1) and thus much reduces the dosage required. A long exposure period has other advantages. The nature of the response of insects to phosphine is such that length of exposure is a more important variable than concentration [i.e. $n < 1$ in the expression $C^n t = k$, relating concentration, C, and time, t, to a parameter, k, constant for a particular response such as level of mortality (Winks 1984)]. A long exposure makes it possible to take advantage of this fact and allows the dosage of phosphine applied to be reduced. It also ensures that the release of phosphine from the aluminium phosphide formulation has finished and that there is minimal undecomposed phosphide residue.

In the Australian bulk grain storage system, very low dosages of phosphine are used if a very long exposure time can be allowed, e.g. in long-term, up-country storages, providing that they are well sealed. Typically, application rates of 0.5 g PH_3 per tonne of grain are used in PVC-covered bunker storages in New South Wales and 0.3 g PH_3 per tonne of grain in some large, sealed sheds in Western Australia, both with exposure periods of at least 20 days. These treatments take advantage of the importance of time for the action of phosphine and have been found to be highly effective in practice, a single treatment giving many months storage free of insects (Banks and Ripp 1984).

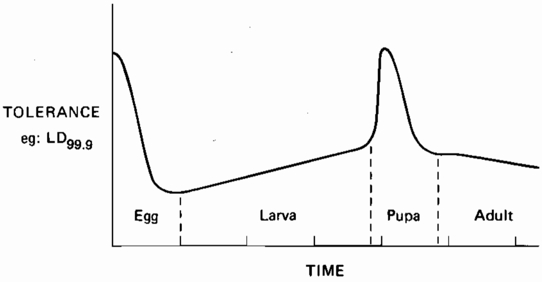

Fig. 1. Diagrammatic representation of the change in tolerance of an insect to phosphine during development (figure courtesy of R.G. Winks).

The use of mixtures of gases appears to have some potential to allow reduction of application rates or exposure periods. CH_3Br dosage schedules have remained unaltered for many years and are typically aimed at 200 gram-hours/m^3 for temperatures from 10–20°C and 150 gram-hours/m^3 above 20°C, both over about 24 hours (Anon. 1970, 1975). An increased dosage and exposure period of 400 gram-hours/m^3 over 48 hours is required (Anon. 1982) to eliminate larvae of *Trogoderma granarium* Everts in diapause. It has been shown that some reduction in CH_3Br dosage is possible if it is added with carbon dioxide (CO_2). Mordkovich (1982) used a mixture containing about 5% CO_2, while Williams (1982) found 20% to be effective in enhancing CH_3Br toxicity. Both workers claimed that only about half the normal CH_3Br dosage is required for an effective treatment.

In some instances there may be scope for reduction of exposure time if CO_2 is added with PH_3. PH_3/CO_2 mixtures in air act more quickly than pure PH_3 in air against some stages of *Rhyzopertha dominica* F., *Tribolium* spp., and *T. granarium* and no less fast than pure PH_3 in air against other stages of these species or against the very tolerant eggs and pupae of *Sitophilus* spp. (Desmarchelier and Wolhgemuth 1984).

Mixtures of CH_3Br and PH_3 do not appear to have any advantage as regards biological action compared with the materials used alone (Bond and Morse 1982). Although only a small advantage can apparently be gained in biological action from use of mixtures, mixtures can be useful as they may also improve fumigations by assisting gas distribution, as discussed in the next section.

Gas Distribution

Fumigation may not be completely successful even though a normally adequate quantity of fumigant is added and the correct exposure time has been used. Such failures may be caused by increased tolerance of the insects present to the fumigant, but a more common reason at present is defective technique, usually associated with poor distribution or retention of gas. Most of the causes of these problems [e.g. wind (Cotton et al. 1936), temperature and barometric effects (Chabrolin and Montlaur 1937), and chimney effect and convective mixing (Oxley 1948)] have been recognised for many decades but it is only recently that they have been studied quantitatively with specific regard to fumigation.

Fumigant may be lost from the gas phase of the fumigation enclosure either by sorption or leakage. Both processes may reduce the concentration of fumigant substantially and can give rise to conditions under which a treatment may fail. Sorption processes are difficult to control and an allowance is made when setting application rates if a fumigant that is subject to substantial sorption (e.g. CH_3Br) is used. This allowance varies with the commodity under fumigation (Anon. 1975) since different grains, pulses, and other stored products have widely differing sorptive capacities. There is little sorption of PH_3 on grains and no allowance is required for this gas. Data on sorption-desorption phenomena are reviewed in the paper entitled 'Sorption and desorption of grains: mathematical descriptions' in these proceedings.

There are several forces acting on a system under fumigation which can cause leakage of fumigant from the system (Table 1). Some of these may individually cause sufficient loss to render a treatment ineffective unless adequate precautions are taken to reduce their effect. Others which are on their own insufficient to cause failure, may act in concert to cause excessive loss of gas.

A mathematical model predicting the rate of gas loss caused by various forces from some typical enclosures has been presented by Banks and Annis (1984a). Wind-induced pressures and the chimney effect are the dominant causes of gas loss from poorly sealed systems, while thermal expansion and contraction within the headspace cause most leakage from well sealed systems. Sealing reduces the effect of the former influences, while insulation and provision of a white heat-reflecting coating to the fumigation enclosure reduce the effect of the latter.

Table 1. Natural forces causing gas loss from enclosures under fumigation.

Temperature variation — in the headspace
— in the grain bulk
Barometric pressure variation
Wind
Chimney effect
Permeation and diffusion

Adapted from Banks and Annis (1984a). Contributions to the observed total loss from a system from individual forces vary with the storage size, type, and load. Some estimates are given in Banks and Annis (1984a).

The model shows that there is a level of sealing of an enclosure at which the expected losses from wind and the chimney effect are reduced to a magnitude similar to that expected from temperature variation within the enclosure. This level has been adopted in Australia as the standard to which structures should be sealed before they are considered satisfactory for fumigation. Structures meeting this standard give a pressure test (see Banks 1984) with a decay time for a pressure halving (e.g. 500–250 Pa excess pressure) of more than 5 min when the structure is filled to capacity. A similar standard is in use in Japan (Akiyama 1984). Pressure testing has become an important part of the routine conduct of successful fumigations in Australia.

Newer Methods of Fumigant Application

Both CH_3Br and PH_3 are often applied in a manner that leads to a high risk of failure, notably in very leaky systems. Such failures should be avoided as they may contribute to the development of resistance to the fumigant. The emergence of substantial resistance to PH_3 in Bangladesh (Tyler at al. 1983) is attributable to the frequent use of fumigation in leaky structures in situations where ineffective treatments could have been predicted. The modifications to existing practice, described in subsequent sections, are designed to improve fumigation and the chances of eliminating infestation, often with reduction in the quantity of chemical used and therefore in residue-formation. The need for frequent retreatment, often required at present, is avoided since there is very little or no survival of insect pests. In many cases, because the behaviour of the gas is more closely controlled, the safety of the process is improved.

Methyl Bromide Treatments

A system of covering stacks of bagged grain with PVC sheets to produce a well sealed fumigation enclosure has recently been described (Annis et al. 1984). The system differs in important details from the widely used one known as 'fumigation under gasproof sheets.' The enclosure is made by chemically bonding the cover sheets to a floor sheet, rather than by simply weighting down the sheets to an untreated and often leaky floor. A pressure test is used to confirm that the enclosure is properly sealed or to indicate if further sealing is required. This system has not yet been used with CH_3Br, but it is clearly an advance over the current practice where no floor sheet is used, the seal between the cover and the floor is often poor, and the cover sheet may be holed and leaky.

When CH_3Br is applied to bulk grain, some method of forced distribution is usually required. Without this, the gas concentration in some parts of the bulk may by inadequate for insect control, while in others it may be excessive, leading to high residues and inefficient gas usage. Recently, the use of CO_2 to assist distribution of CH_3Br has been investigated. Adequate distribution of CH_3Br has been achieved in silo bins, either by adding solid or gaseous CO_2 with CH_3Br into the headspace (Calderon and Carmi 1973; Viljoen et al. 1981; Hah et al. 1981) or adding a CO_2/CH_3Br mixture into the base of the bin (Williams et al. 1984). In the first case, the dense CO_2 sets up gas currents that convey the fumigant down through the grain. The second system relies on the gas mixture to displace the air in the storage evenly and to convey the CH_3Br to regions not easily reached using simple forced recirculation. CO_2 does not affect the rate of physical sorption of CH_3Br (Gilby 1983). In practice the use of CO_2/CH_3Br mixtures leads to decreased residue formation and shorter ventilation times because less CH_3Br is required (Mordkovich 1982).

Phosphine Treatments

PH_3 treatments of bag stacks could be improved in the same way as CH_3Br treatments because they often suffer from similar defects. However, with PH_3 use, such improvements are more important. Effective PH_3 concentrations must be maintained for much longer periods than those required for CH_3Br. Moreover, PH_3, being less strongly sorbed, is more easily lost from the system under treatment by natural ventilation.

In the past, there was a belief that PH_3 could be used effectively in poorly sealed systems and that it was possible to compensate for leakage by increasing the dosage applied. This approach is now known to be unsound (Winks et al. 1980). There are many conditions under which the gas concentration in some regions in a leaky storage will never reach effective levels. The fumigant is continuously diluted or displaced by the air that enters the system through the leaks (e.g. see Banks and Annis 1984b).

Development of ways of sealing large stores (see Ripp et al. 1984) has permitted successful use of methods of application of PH_3 to bulk grain that would be quite inappropriate in leaky systems. PH_3-generating formulations are usually added to bulk grain in a way designed to give an even distribution of the formulation (e.g. by placing formulations in the grain stream when loading). However, it is unnecessary to place the formulation evenly throughout well-sealed systems, as the natural convection currents present in grain bulks, assisted by diffusion, are usually sufficient to give an even distribution of the gas after a period of mixing. In Australia, large, well-sealed bulk grain storage sheds and squat cylindrical bins are now dosed by placing the PH_3-generating formulations on the grain surface or on the walkways by the loading conveyors that run just under the roof ridge. In bunker storages, the PH_3-generating formulations are applied just beneath the plastic membrane cover (Banks and Sticka 1981). An even concentration is achieved by about two weeks after application, and minimum exposure periods, usually at least of 20 days, are set to allow all points to reach an effective concentration of the fumigant.

The simple, surface-application technique is inappropriate in two particular situations: silo bins with a height-to-diameter ratio of more than 2:1, and ships holds. In both, convective mixing may be insufficient to give a good distribution of PH_3 and inadequate concentrations may occur in the lower regions of the grain bulk (Banks and Annis 1984b; Hah et al. 1981; Reichmuth 1983; Zettler at al. 1984). It is necessary to mix the gases within the system to avoid this problem.

Formerly it was thought that PH_3 could not be recirculated using a fan because of the risk of explosion (Monro 1969, p. 251). However, the flammability properties of this fumigant have been reinvestigated recently (Green et al. 1984) and it is now apparent that it may be recirculated safely provided certain precautions are taken. These include the use of very low rates of recirculation, typically two volume changes of gas or less per day, low-power recirculation fans, having fan tip speeds of less than 40 m/s, and duct work of a size such that pressure loss through the system is not more than 10 kPa (Green 1983). Recirculation of PH_3 in silo bins has been described by Cook (1984) and Boland (1984), and in ships by Zettler et al. (1984). Recirculation may be useful in well sealed storages to ensure rapid and thorough mixing in less time than required with natural convection, thus shortening the total treatment time needed to achieve an adequate *Ct*-product throughout the system.

In China, distribution of PH_3 in silo bins may be assisted by adding CO_2 into the headspace during release of PH_3 from a preparation placed on the grain surface (Guan, Y., personal communication). Alternatively, natural convective mixing can be enhanced by providing an external blackened duct running from the headspace to the base of the grain bulk (Boland 1984). Heating of this duct by solar radiation causes a circulation of gas through the duct, acting as a 'thermosiphon,' thus producing rapid mixing of the gases within the storage.

The various methods for applying phosphine to silo bins are shown in Fig. 2.

Wohlgemuth et al. (1976) used a mixture of PH_3 and CH_3Br to treat palm nut expeller cake in a barge at low ambient temperature. The treatment took advantage of the different properties of the two fumigants. CH_3Br is active against insects at low temperatures but has poor penetrating abilities. It was thus able to treat the surface of the bulk and accessible regions of the barge. PH_3 is active only at higher temperatures (>15°C) and penetrates well, and thus disinfested the warm interior of the cargo. This kind of approach using mixtures of fumigants may be useful in many situations where a single fumigant may be ineffective, notably where there are extremes of temperature in the enclosure under treatment.

Prospects for Development

Although considerable progress has recently been made towards rational and efficient use of PH_3 and CH_3Br, some problems remain. The long exposure periods necessary for completely effective treatments with PH_3 are inconvenient and a method of decreasing the exposure period to three days or less would be most welcome. The need to use well sealed systems if perfect results are to be achieved is also inconvenient. However, it may be possible to relax the sealing standard

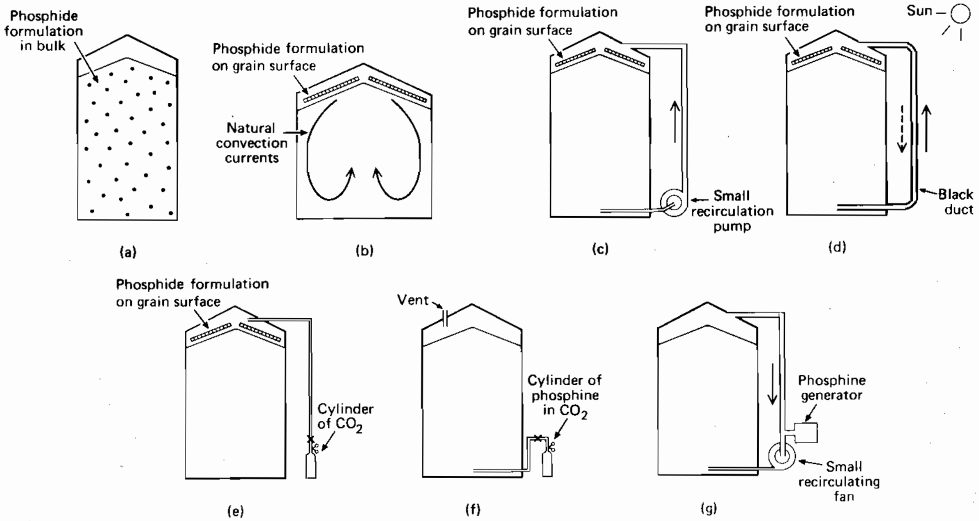

Fig. 2. Methods of application of phosphine to silo bins: (a) even distribution of phosphide formulation throughout the bulk; (b) surface application in a squat bin with gas distributed by natural convection; (c) recirculation of gas generated from a surface application; (d) recirculation of gas by 'thermosiphon' (circulation may reverse at night); (e) assisting the distribution of phosphine generated in the headspace using carbon dioxide; (f) continuous introduction of phosphine from a compressed gas source (phosphine/carbon dioxide mixture); (g) external generation of phosphine coupled with forced distribution. Details for method (e) are not available, method (f) is under investigation, and method (g) is speculative only.

somewhat if a system for replacing the PH_3 lost by leakage can be devised. Continuous input of PH_3 from cylinders during the exposure period has been suggested (Winks et al. 1984) (see Fig. 2). It may also be possible to compensate for loss by adding successive dosages of phosphide formulation to the system so that PH_3 is evolved continuously during the exposure. The prospects for use of PH_3 in poorly sealed systems seem slight, partly because of the known effects of natural ventilation and partly because of the possible health risks involved.

There appears to be some potential for the use of some form of generator of PH_3 that can produce the gas outside the system under fumigation at a controllable rate. Such a generator could be used to produce defined concentration-time regimes for PH_3 in storages. Currently, the concentration-time profile for PH_3 is limited by the release characteristics of phosphide-based formulations and the exposure regime produced may well not be the most biologically efficient. A PH_3 generator based on adding acid to a mixture of zinc phosphide and sodium bicarbonate is in use in China (Champ et al. 1981).

The main problem remaining in the use of CH_3Br concerns not how to apply the gas but how to remove the gas after the exposure period is complete. With the trend of reducing allowable concentrations of CH_3Br in workspaces, it is becoming more difficult to reduce the residual CH_3Br in treated grain to acceptable levels within a commercially reasonable time. Under Australian conditions, a CH_3Br treatment of bulk grain may take 3 days in total: an exposure of 1 day and then two more days with ventilation before the grain can be moved. The limiting factor to removal of the gas is the rate at which it is desorbed from the grains. The rate cannot therefore be increased by increasing the fan power and ventilation rate through the system. The rate of removal of PH_3 is similarly limited (Noack et al. 1984). However, Snitko and Levchenko (1973) noted that degassing is 25–30% quicker when CH_3Br is used in conjunction with CO_2. This resulted from the lower dosage that could be used because of the presence of the CO_2. It is an important reduction under conditions where fumigations must be completed as rapidly as possible. The use of mixtures would therefore seem to have potential for reducing the total time required for a fumigation.

Conclusions

This paper has surveyed some of the recent advances in the techniques used for the two common fumigants CH_3Br and PH_3, and has given some of the recent research results that form the rational basis for the newer methods and that provide an explanation of why some systems in use are defective. There is still scope for improvement in ways of using these two fumigants, notably in finding ways of shortening total treatment times without loss of effectiveness, but with proper application the efficacy of treatments can now be very good. New fumigants must now be developed so that if the grain storage industry is denied the use of the ones it now relies on, a change can be made quickly and without disruption. It has often been said that there can be no new fumigants since the range of compounds of sufficient volatility is restricted by the simple chemical properties of the lighter elements. However, it may be that with our current knowledge of the ways in which gases behave in storages and the biological responses of insects to toxicants some chemicals with suitable properties will be found. Alternatively, the use of some fumigants discontinued because of their inconvenient properties will be revived and ways of applying these fumigants easily and effectively will be found, perhaps based on systems recently developed for PH_3 and CH_3Br. Hydrogen cyanide is an obvious candidate for this re-development.

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Fabric Spraying for Pest Control in Grain Storage

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Abstract

The results of trials on the effectiveness of spraying the walls of warehouses, bins, or containers with various insecticides are described, the objectives of such spraying being first to disinfest the surface and second to leave a residual deposit. The nature of the sprayed surface has more effect on the persistence of insecticide deposits than differences between insecticides. All insecticides are more persistent on plywood or galvanised iron than on rough concrete. Pyrethroids and carbaryl are more effective than organophosphates against *Rhyzopertha dominica*, while the organophosphates are more effective against *Sitophilus* spp. Azamethifos is effective for much longer than several other organophosphates on concrete and iron surfaces. Wettable powders are generally more persistent than emulsifiable concentrates but are less easy to apply. It is advisable to choose formulations which are safe to apply, inexpensive, and can be used to achieve complete coverage.

THE application of insecticides to the walls of warehouses, bins, or containers has two objectives: firstly to disinfest the surface; and secondly to leave an effective residual deposit. The fabric spraying will therefore by keyed into the pest control program either (a) to clean up warehouses or silos before intake of new stocks, or (b) to fit in with the fumigation or spraying of the stock in storage.

How long the treatment will be effective depends on many factors: the insecticide, the formulation, the sprayed surface, the temperature, the susceptibility of the pests, and the time for which the pest is in contact with the treated surface. However, the results of trials seem to indicate that the nature of the surface is much more important than the differences between the insecticides. All insecticides are more persistent on smooth, neutral surfaces than on rough, alkaline surfaces such as concrete. Furthermore, the results of trials depend on the toxicity of the insecticide to a particular species (usually *Tribolium* spp.) and on the length of exposure time of insects to the surface. For example, long exposure times (several days) may give positive results for slow-acting insecticides which may appear to be inactive in short (several hour) exposures. Predictions of the persistence of treatments are therefore often based not on practical efficacy but on the results of confining test insects to treated surfaces for varying lengths of time. The results of these bioassays may not give an adequate picture of the usefulness of residual sprays, but they do sort out one treatment in comparison to another.

Pinniger (1983) has addressed this problem in a review of the methodology of bioassay of the effects of residual deposits. He concludes:

> '. . . the main problem encountered is that the data available on individual insecticides are not standardised because not all insecticides or formulations are tested in the same way. Many manufacturers or distributors naturally give priority to the testing of their own products and understandably may selectively present the results of comparative tests which show these products in the best light...
>
> In the final analysis, the available data should be carefully examined and the implication judged with regard to a particular need or use. Candidate products which show promise should then be tested in properly conducted practical trials. These should include the monitoring of population levels before and for a period after treatment and assessments of the kill of insects, insecticide deposits achieved and the length of effective life of the treatment. Subject to satisfactory results from these trials, the material should be used in practice with critical appraisal of its performance at regular intervals.'

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Persistence of Insecticides on Concrete

In general, organophosphorus or pyrethroid insecticides persist much longer on wood, plywood, or metal than on concrete or cement. Malathion is less persistent on concrete surfaces due to its greater lability to alkaline hydrolysis and loses its toxicity within a few days on alkaline concrete, cement, or whitewash. It has been shown that sizing of the walls or the addition of sodium carboxymethyl cellulose will extend the life of malathion on concrete from less than 1 week for an emulsion formulation and less than 4 weeks for a water-dispersible powder to 14 weeks for both formulations (Tyler and Rowlands 1967).

Applied to concrete warehouse surfaces at 1–2 g/m^2, malathion emulsifiable concentrate (e.c.) persisted 2–5 weeks and tetrachlorvinphos e.c. for 5 weeks, measured by the effect of 24 hours exposure of *Tribolium castaneum* to the surfaces (Cogburn 1972). On dusty, aged concrete, at low temperatures of 10–12°C, malathion e.c. and bromophos wettable power (w.p.) were equally effective against *T. confusum* for 10–33 weeks at application rates of 1.46 g/m^2 (Watters 1970). Fenitrothion, pirimiphos methyl, chlorpyrifos methyl, and permethrin are generally slightly better than malathion and may give protection for a few weeks on concrete in favourable conditions. In a recent trial, 1 g/m^2 of fenitrothion and pirimiphos methyl wettable powders remained effective for at least 6 weeks on an emulsion-painted cement wall at average temperatures of 30°C and above. The treatments were evaluated by confining test insects in funnels on the walls for 5 hours.

Williams et al. (1982) compared carbaryl flowable suspension, pirimiphos methyl and fenitrothion e.c. formulations, and azamethifos w.p. on concrete blocks kept in the headspace of a silo. The blocks were bioassayed by 24 hour exposures to *Rhyzopertha dominica, T. castaneum,* and *Sitophilus oryzae.* Against *R. dominica,* only carbaryl and azamethifos were effective at 8 weeks. An application of 1 g/m^2 of azamethifos was active for 24 weeks. Only azamethifos was effective against *T. castaneum* and *S. oryzae* for more than 1 week on concrete. The same authors in similar experiments compared permethrin, deltamethrin, fenvalerate w.p.s, and a fenitrothion e.c.. Permethrin and deltamethrin were effective on concrete for 24 weeks against *R. dominica.* Applications of 0.5 g/m^2 permethrin, 0.05g/m^2 deltamethrin, or 1.0 g/m^2 fenitrothion were all equally ineffective on concrete when bioassayed against *S. oryzae* and *T. castaneum.*

Wallbank (1982) carried out bioassays on the totally sprayed walls of silos. The treatments were 0.5% azamethifos wettable powder, 1% fenitrothion e.c. alone and 1% fenitrothion plus 1% carbaryl flowable suspension. Insects were exposed on the surface in polypropylene cups for 20 hours. Azamethiphos at 0.5% was 100% effective against the three species for at least 26 weeks. Carbaryl was effective for at least 6 weeks against *R. dominica.* Fenitrothion alone gave reasonable control of *T. castaneum* and *S. oryzae* up to 13 weeks.

These experiments indicate that azamethifos is much more effective on concrete against all the species. It is unfortunate, however, that azamethifos wettable powder was compared with emulsifiable concentrate formulations of the other organophosphates.

Persistence of Insecticides on Wood and Metal

Insecticides are much more persistent on wood, and malathion e.c. has been shown to be effective for over 20 weeks on plywood and fibre board and to remain active through 16 weeks (1 g/m^2, 3 hour exposure) up to 52 weeks (2.5 g/m^2, 24 hour exposure) (Tauthong and Watters 1978).

In experiments already referred to, Williams found carbaryl and azamethiphos w.p.s effective for 32 weeks on wood against *R. dominica,* and fenitrothion and pirimiphos-methyl e.c.s and azamethifos w.p. effective for more than 16 weeks against *S. oryzae* and *T. castaneum* on iron and wood. Azamethifos was the most persistent. Pyrethroid wettable powders (deltamethrin, 10 and 50 mg/m^2; permethrin and fenvalerate, 100 and 500 mg/m^2) were effective on wood and iron at all levels for at least 32 weeks against *R. dominica* (Williams et al. 1983). The effectiveness of the pyrethroids was similar to, or slightly less than fenitrothion emulsifiable concentrate (1 g/m^2) against *S. oryzae* or *T. castaneum* on wood and iron and generally persisted for 16–24 weeks. White et al. (1983) showed that on galvanised steel and plywood, 0.5 g/m^2 of fenitrothion e.c. gave 100% mortality for 4–8 weeks (1 hour exposure), 8 weeks (3 hour exposure) and 16 weeks (6 hour exposure) at 30°C. The test insects were *T.*

castaneum and *Cryptolestes ferrugineus*. Malathion was slightly more effective than fenitrothion.

Carter and Chadwick (1978), measuring the effectiveness against cockroaches of permethrin 25% in 30 minutes exposure, found that 200 mg/m^2 was 100% effective for 2.5 weeks on cement and plaster and for 52 weeks on plywood. Permethrin was initially 10 times as effective as fenitrothion — LC_{50} 10 mg/m^2 versus 110 mg/m^2 for fenitrothion w.p. — and decayed 20 times slower. Permethrin may be less effective against *Sitophilus* spp. or *Tribolium* spp. (cf. Williams et al. 1982).

When insecticides are applied to painted surfaces, their effectiveness may or may not be extended. Malathion e.c. and bromophos w.p. have been shown to persist similarly on painted and on unpainted concrete (Watters 1970). In one experiment fenitrothion and chlorpyrifos-methyl lost all activity within one day on painted plywood, although on plain plywood activity remained. The pyrethroids tend to react with some gloss and emulsion paints, resulting in a very rapid loss in activity.

Choice of Insecticide Formulation

In situations where silos have a large turnover of wheat and not very much exposed surface, the effectiveness of residual treatments can only be gauged by experience. The choice of insecticide to use may, to a large extent, be a matter of availability and price, and the manufacturer's directions for use should indicate the concentrations necessary to achieve the protection required. Of the available formulations, there can be no doubt that wettable powders or suspension concentrates give the most effective residual deposits on most, if not all, types of surfaces. The differences between the effectiveness of wettable powder and emulsifiable concentrate deposits of the synthetic pyrethroids, e.g. permethrin, is very great. Wettable powders can be unsightly but the development of highly micronised, easily suspensible powders has given very fine and less visible deposits. However, emulsifiable concentrates are often preferred because they are easier to mix and apply.

In choosing between an organophosphate and a more expensive but more persistent synthetic pyrethroid, the greater deposit obtainable with the organophosphate may be considered preferable in some circumstances and not others.

In Australia, the standard fabric treatment is fenitrothion or a fenitrothion carbaryl mixture, the latter where there are resistant *R. dominica* (bioresmethrin is not stable and too expensive for surface treatments). The rates approved are 1.0% fenitrothion with 1.0% carbaryl or 0.5% azamethifos, all applied at 5 l/100 m^2. Laboratory trials have shown azamethifos is very effective against resistant *Oryzeaphilus surinamensis* and much more persistent than fenitrothion. Azamethiphos at 0.25 g/m^2 is said to be effective for 37–46 weeks on metal surfaces against *S. oryzae*, *R. dominica*, and *T. castaneum*, compared with 15 weeks effect by fenitrothion, and 0.5 g/m^2 is said to be effective for 6–8 weeks on concrete against *T. castaneum* and *R. dominica* (Williams et al. 1982).

Azamethifos is used in Australia where there have been persistent problems with insects such as resistant *O. surinamensis*. Experience of bulk handling authorities shows that these problems have been controlled by these treatments and that in some older storages persistent problems have been remedied. Unfortunately, azamethifos (0.5%) costs about three times as much as the fenitrothion/carbaryl mixture.

Safety Considerations

For indoor spraying, compounds with high mammalian toxicity cannot be used without causing hazard and distress to spraying operatives and other storage personnel. Organochlorines are not longer considered suitable and pyrethrum and the earlier generation of synthetic pyrethroids are too sensitive to light for residual spraying. A number of organophosphorus compounds — azamethiphos, chlorpyrifos-methyl, fenitrothion, and pirimiphos-methyl — are available in the medium to low toxicity range, together with the carbamates, carbaryl and propoxur. The residual synthetic α cyano pyrethroids still cause irritation when applied with piperonyl butoxide synergist. In Australia, deltamethrin requires full protective clothing. The smell of the deposit has been strongly objected to in the case of chlorpyrifos-methyl and yellow stains are sometimes produced on white surfaces by fenitrothion/carbaryl mixtures. These effects are very important because the operator may have to apply the materials in confined spaces and any smell or irritation is very off-putting.

The initial change from organochlorine to organophosphate as the insecticide to use in indoor treatments resulted in some short-term toxic symptoms. It is most important to use full protective clothing and to give workers regular cholinesterase checks.

Application Methods

Although there may be no truly residual sprays on concrete, the effect of knocking out the resident population in crevices and cracks may so severely reduce the population that build-up is slow and an apparent residual effect is achieved. Insecticides are much more effective on clean surfaces and it is standard practice to thoroughly wash down empty silos with high pressure hoses before applying residual treatments.

Warehouse spraying is not an operation calling for refined application techniques or small, finely applied deposits of expensive materials. The main requirement is to apply insecticide generously and thoroughly into every crevice and around every beam and girder with a relatively inexpensive organophosphorus insecticide (fenitrothion or pirimiphos-methyl, for example) applied at 0.5–1 g/m^2 of active ingredient and repeated as necessary by means of a spraying pump (or hand sprayer with extension lance in very small stores). Motorised knapsack sprayers have too much air blast so that it is difficult to achieve an even cover and not always possible to point the spray in the desired direction. Spraying pumps deliver liquid at a high rate but it is difficult to avoid run-off or to prevent splashing. The motorised sprayer and the spraying pump are excellent for getting a good blast on the target and into the corners and crevices. Good coverage is the prime requirement.

The rate of kill of organophosphates is greater than that of pyrethroids (pyrethroids may give a quick knockdown but that is of doubtful value for surface treatments as it may allow recovery). The lease expensive spray will be fenitrothion or a fenitrothion/carbaryl mixture for control of *R. dominica*. Such mixtures are the wisest choice for wall spraying whilst the persistent pyrethroids should be used for more precise applications. Residual wettable powder deposits should remain active for up to 6 months on wood, 4 months on metal, and a few weeks on concrete.

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Use of Pesticides in Bag Storage of Grain

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Abstract

External treatment of bag stacks of grain with insecticides is recognised as an unsatisfactory method of storage pest control that may, in the longer term, increase the problems with insect pests. Alternatives to it are discussed. They include: in-bag fumigation; bag-by-bag admixture treatments; pretreatment of bag materials; layer-by-layer spraying of stacks; covering stacks with plastic sheets then fumigating; total enclosure of the stack with plastic covers and treatment with phosphine or carbon dioxide. Most of these procedures are difficult to carry out. The best solution seems to lie either in a change to bulk storage or in the use of closable bag stores which can be fumigated effectively and kept reasonably free from reinfestation.

THE combined effects of high temperature and relative humidity, intense reinfestation pressures, and poor quality open storages present a challenge to methods of control of infestation in stored cereals which has been recognised as one of the major problems to be faced to achieve adequate nutrition in all countries. It is clear from other papers to this seminar, that there are chemical and non-chemical pest control methods which can be adapted to bulk storage. The situation with bag storage is far less clear. Whereas admixture of insecticides to bulk grain by spraying or dusting is a widely established method, no really satisfactory method of admixture of insecticides with bagged grain has yet been devised. Compared with admixture, the external treatment of bags or bag stacks with insecticide is much less effective and in the type of situation where storage of grain in bags is most common, only very effective treatments would be able to prevent infestation of the commodity.

Because it is difficult to maintain high quality in commodities such as milled rice in bags in the tropics, many countries are urgently considering a change from bag to bulk storage. However, bag storage is more adaptable to the facilities and handling methods of small communities, whereas bulk handling is a large-scale operation. On the whole, the bag system is more tolerant of high moisture content on receival because the moisture movements which are so harmful in bulk storage are less likely to occur. The serious consequences of mould development mean that it would be unwise to adopt bulk storage practices until it was certain that the resources were available to cope with any problems. These resources are unlikely to be available for many years and therefore some bag storage is likely to be practised for some time to come. We should still therefore consider what can be done to improve the present bag storage methods. This paper describes the various approaches that have been made in this regard.

It appears from the literature that little research has been done in this area over the last few years. Much of the published work describes small-scale studies with small sacks, treated and exposed in laboratory conditions. Whilst this is a useful and necessary means of sorting out possible treatments, the large-scale follow-up work in the warehouse has very often not been done. It is much more difficult to work on a large scale, but those with the opportunity to do so should attempt to carry out field trials, particularly where these trials naturally follow from the small-scale trials. Unfortunately, there is generally very little feedback on the use of techniques from operational staff, and research staff tend to lack the resources to gather data from routine operations. The key to all effective pest control should be scientific evaluation based on the acquisition of working data. In all areas of pest control, measurements of fumigants or deposit rates of insecticides and of biological effectiveness are important. It is not easy to measure residual effectiveness on surfaces either by chemical means or by insect bioassays,

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and the methodology of this type of evaluation needs to be reviewed (Pinniger 1983).

In-bag Fumigation

In-bag fumigation is mainly a technique developed for use in on-farm, small-scale storage. The availability of fumigants for in-bag fumigation was reviewed by Webley and Harris (1977). It was pointed out at that time that many of the useful fumigants are potentially dangerous poisons. Methallyl chloride has many of the properties required for in-bag fumigation (Taylor 1975), but is also doubtful on grounds of mammalian toxicity. Peirrot and Ducom (1981) have shown that carbon tetrachloride is much less effective than insecticide admixture with pirimiphos-methyl and other dusts. This is likely to be true for less toxic fumigants such as trichloroethane. The withdrawal of ethylene dibromide and carbon disulphide due to toxicity and carcinogenicity has left the technique reliant entirely on phosphine. Hindmarsh (1977) showed that storage of hybrid maize seed in polythene-lined jute sacks with an aluminium phosphide pellet was better than admixture with organophosphorus insecticides. Proctor and Ashman (1972) carried out trials with in-bag fumigation of confectionery ground nuts exported from Zambia to the United Kingdom. Each sack was lined with 128 µm polythene film. An aluminium phosphide pellet was dropped in and the liner then bunch tied. Although the technique was successful, it was not adopted by the trade. Problems with splitting liners, fears of sweating in sealed bags, and the general lack of control and difficulty in maintaining uniformly well-treated bags were operational drawbacks. It seems unlikely that there will be much development of this technique.

In-bag Admixture Treatments

A normal spray admixture is not possible whilst the commodity is bagged, yet to empty bags, treat the commodity, and then re-bag involves considerable labour and handling. There are, however, many situations where there is sufficient time for bag-by-bag treatment and for these situations the continuous flow duster was developed by the U.K. Tropical Research and Development Institute. The duster allowed the automatic dusting of the contents of a bag as the bag was tipped through the duster into another bag. Some problems were experienced with bridging and uneven distribution, but the duster was further developed by the ICI Company in a series of tests on the application of pirimiphos-methyl dust.

There are many receival situations where commodities are re-bagged or put in bags for the first time. In Southeast Asia, farmers sometimes take back their own bags and the commodity goes into the standard, marketing authority bag. In India and Pakistan, farmers deliver in bulk and bagging starts at the receival centre. In other situations, crops are delivered in small (less than 1 bag) lots and are accumulated for standard bagging. This is where admixture treatments can be organised. It has been shown that crops can be treated in drums with internal baffles like cement mixers; dust is added and a very even distribution is obtained with just a few turns by hand. This method has been used to evenly dust butter beans exported from East Africa and no doubt could be adaptable from small drums of 200 L up to sophisticated treating and bagging facilities. In many cases, inert dust could be used. Paddy could be protected in this way, and of course paddy husk ash makes a very effective insecticidal inert dust. The major difficulties with admixture are likely to be in determining the dosage rate which will be effective over the storage period, in minimising workers' contact with insecticidal dusts, and with residue problems if storage periods are short.

Conventional Stack Spraying

Malathion and lindane have customarily been used for regular spraying of bag stacks. For example, Inder Singh (1972) listed weekly spraying of stack surfaces with malathion and pyrethrins. It is understood that fortnightly spraying with malathion/pyrethrins mixtures is still standard practice in godowns in India and Pakistan. Sometimes the spraying has been less frequent, with intervals of 1, 3, or even 6 months. As a general rule, the longer the interval, the higher the dose applied.

Monthly spraying with malathion gave incomplete protection against *Tribolium castaneum* (Green and Kane 1959) and did not prevent reinfestation by *Ephestia cautella* (Schulten 1970) either after twice-weekly or monthly spraying of bags. Three-weekly spraying of pyrethrins in Kenya controlled *E. cautella* but not *Sitophilus oryzae* or *T. castaneum* in bagged wheat (McFarlane and Sylvester 1969). Fortnightly spraying with malathion and monthly spraying with pirimiphos-methyl, each of 0.5 g/m^2, gave no significant benefit in the medium term storage of milled rice (McFarlane 1980). Indeed, it has been widely recognised that malathion has assisted the development of *Ephestia* spp. by preferentially killing the moth's predators.

Where insecticides are not used, there may be a complex of insect species but sometimes not very much damage, because of the occurrence of natural (= biological) control. On the other hand, where insecticides are frequently used, there are fewer species but these species may be a major problem. Unfortunately, biological control with natural enemies does not yield insect-free grain and cannot always be relied on.

The treatment of bag surfaces with insecticides is not an area that has recently attracted very much research interest. There have been flurries of activity associated with the change of insecticide from organochlorine to organophosphate and organophosphate to pyrethroid, but no real breakthrough in either case. The bag/insecticide deposit has to form an effective seal against the passage of insects. In the case of jute bags, there is no effective barrier provided by the untreated bags. However, for multiwall paper, woven polythene, polythene film or even close-weave cotton bags, the barrier provided by the material is sufficient to enable the treatment with insecticide to exert its effect.

Much of the literature relates to treatment of small bags in laboratory-scale trials. These small stacks are sprayed or the bags are dipped in insecticide. The concentration of insecticide resulting from dipping is usually not given, but it is likely to be high. On a large scale, therefore, the dipping might be expensive in terms of insecticide used and hazardous to handlers of bags. The dipping of small polypropylene sacks in 2 or 4% pirimiphos-methyl protected maize for about 3 months (Morallo-Rejesus et al. 1975). The same authors found chlorpyrifos-methyl also was an effective sack treatment. Treating the commodity, however, with pirimiphos-methyl dust was more effective (Morallo-Rejesus and Eroles 1976). Caliboso (1981) describes tests in which jute minisacks were dipped in or dusted with deltamethrin. The dusting was more effective, but neither treatment controlled *Rhyzopertha dominica* and the dipping was also not very effective against other species.

Sarkar et al. (1984) used the pyrethroid fenvalerate applied as a spray to 4 kg jute bags at 1 to 1.5 g/m^2. There was 100% mortality of *T. castaneum* exposed to the bag surface 1 month after treatment. However, the deposit had very low toxicity after 3 months. It is not clear if the treatment would prevent insect penetration. Singh and Chahal (1975), evaluating insecticides on small pieces of gunny bag sprayed in a Potter tower, found pirimiphos-methyl most effective. Kumar et al. (1982) considered that pirimiphos-methyl was better than fenitrothion, malathion, or methacrifos. Doharey et al. (1981) also found that pirimiphos-methyl on bags at rates up to 450 mg/m^2 gave complete mortality for 30 days and was more effective than malathion or pyrethrins. Kumar recorded the mortality of insects on the bag surfaces but there was little control of insects on the commodities involved, wheat and rice.

Kuppuswamy and Subramanian (1976) sprayed gunny bags in the laboratory to protect red gram. Phoxim seemed to be most effective. Pandey et al. (1979) found that dipping jute sacks with 0.5% phoxim was effective for 5 months. Prakash et al. (1983) found that admixture of etrimfos gave much better protection than bag treatment.

In Egypt, Al Saffar et al. (1982) found pirimiphos-methyl at 300–700 mg/m^2 to be very effective on PVC, cotton, and paper for 7 months, but for only 2 months on jute. Moustafa et al. (1979) conducted laboratory trials which indicated that organophosphates are more effective on cotton than on jute.

The interpretation of many of these tests depends on the exposure time. Often the barrier effect is not tested; the surface is simply used for bioassay. Generally, jute is a very poor surface. Insecticides like pirimiphos-methyl and phoxin seem to be most effective, but generally the persistence and effectiveness of the treatments are not encouraging.

The treatment of bag surfaces is particularly effective with polypropylene or multi-wall paper bags. This is because insecticide is not lost by absorption into the fibres to the same extent as in thicker hessian bags, and because it is more difficult for insects to penetrate the surface, giving more time for them to pick up the insecticide. Very persistent effects of this kind are to be expected with the synthetic pyrethroids.

It has been shown in laboratory experiments (Webley 1981), that insecticides can migrate onto the adjacent commodity from the sprayed surface, giving considerable protection during the time that the insecticide persists on the commodity. This type of effect is commonly found with organophosphorus insecticides. The movement of insecticide from the bag surface to the commodity takes place not at the time of spraying but afterwards, and is related to its volatility. It was shown that insecticides with high vapour pressures, such as methacrifos and chlorpyrifos methyl, could completely fumigate the contents of a small pack without need for admixture (Table 1). The insecticides are also effective against insects resting on the bag surface.

Table 1. Development of internal infestations in bags of maize and cowpeas treated with various insecticides (Source: Webley 1981).

Treatment	*Callosobruchus chinensis* F_1	*Callosobruchus chinensis* F_2	*Sitophilus oryzae* F_1	*Sitophilus oryzae* F_2
Control	1562	8500+	2136	541
Permethrin	1520	6056	1982	519
Bromophos	1366	417	1064	102
Fentrothion	1492	52	614	35
Pirimiphos-methyl	963	4	674	28
Chlorpyrifos-methyl	783	1	308	23
Methacrifos	216	2	5	1

Table 2. Comparative efficacy of surface treatment of polypropylene and jute bags with fenitrothion and pirimiphos-methyl after 45 and 54 weeks storage (Source: Giles, personal communication).

	Survival (live adults/kg)			
Treatment	Polypropylene (45 weeks)	Jute (45 weeks)	Polypropylene (54 weeks)	Jute (54 weeks)
Fenitrothion[a]	1.3	2.0	34.7	54.8
Fenitrothion[b]	1.8	3.0	19.8	48.3
Pirimiphos-methyl[a]	1.2	25.7	10.5	46.2
Pirimiphos-methyl[b]	1.0	8.7	9.5	61.8
Control	58.0	63.7	72.8	58.2

[a] Initial layer-by-layer treatment, then every 3 weeks at 0.5 g/m^2.

[b] Initial layer-by-layer treatment, then every 6 weeks at 0.5 g/m^2.

The superiority of spraying on woven polypropylene is shown in the results presented in Table 2, from trials in Zambia (Giles, personal communication).

Pyrethroids persist on the surface (Table 3) and give negligible residues in the grain (Table 4), in contrast to the organophosphorus compounds which give high residues in the grain. However, the residues in the grain are active and may prevent insect development, whereas the insects may not be affected in grain in pyrethroid-treated bags (Table 5). In related trials, the pyrethroids permethrin and deltamethrin were much more persistent and effective on the polypropylene surface than were fenitrothion or pirimiphos-methyl.

The effect of insecticides in these trials is therefore that they are much more effective on polypropylene. Organophosphates migrate into the commodity and this can increase the effectiveness. Pyrethroids remain on the surface and are effective there for longer. As surface

Table 4. Residues on grain in bags after spraying of bag surfaces (Source: Webley 1981).

Insecticide	Application rate to bag surface (mg/m^2)	Residue on grain immediately after spraying (mg/kg)	Residue on grain after 8 or 12 weeks (mg/kg)
Pirimiphos-methyl	500	0.6	3.8 (8)
Fenitrothion	500	1.0	3.6 (8)
Permethrin	83	0.1	0.1 (12)
Deltamethrin	12.5	0.05	0.05 (12)

Table 3. Persistence of insecticide deposits on woven polypropylene, expressed in terms of percentage survival of 40 test insects (20 *Tribolium castaneum*; 20 *Sitophilus oryzae*) at 0–12 weeks after treatment (Source: Webley 1981).

	Application rate	% survival 0–12 weeks after treatment				
Insecticide	(mg/m^2)	0	2	4	8	12
Pirimiphos-methyl	500	100	92	48	2	0
Fenitrothion	500	100	100	63	15	0
Permethrin	41	100	100	100	100	100
Deltamethrin	6.2	100	100	100	100	92

Table 5. Development of *Tribolium castaneum* and *Sitophilus oryzae* on grain in bags sprayed with various insecticides (Source: Webley 1981).

Insecticide	Application rate to bag surface (mg/m^2)	Mortality (%)		F_1 emergence (No. of individuals)
		2 days	16 days	
Pirimiphos-methyl	500	50	50	0
Fenitrothion	500	47	50	0
Permethrin	83	0	1	130
Deltamethrin	12.5	0	1	166
Control	0	1	1	122

treatment may give rise to residues, the surface treatment of foodstuffs stored in permeable containers must be restricted to contact insecticides of low mammalian toxicity. Alternatively, the insecticide used must be known to decompose quickly enough in the commodity to harmless or non-persistent residues. The localisation of persistent residues in particular parts of cereal grain and other seeds is a further factor to be considered in deciding whether or not surface treatments should be applied to commodities in permeable containers. In most seeds, chemical residues will tend to accumulate in fatty or protein-rich parts, especially in the germ and bran. Tests to determine actual residue levels in individual products are advisable. Insecticidal treatment of the most vulnerable commodities, such as milled rice and flour, is generally not permitted. It may, however, be necessary to accept small residues to get the desired protection.

There has been a marked change in the availability of insecticides for storage treatment and the era of lindane and melathion is almost over. The choice is now generally between the organophosphorus insecticides, pirimiphos-methyl, fenitrothion, bromophos, and chlorpyrifos-methyl at an application rate of 0.5 or 1 g/m^2, or a synthetic pyrethroid, such as permethrin, applied at a rate of about 100 mg/m^2.

Several technical factors have to be taken into account. These include the nature of the commodity, in particular its susceptibility to chemical contamination, the kind of infestation that is to be controlled, and the level of local infestation pressure. In addition, the level of possible insecticide residue that will be acceptable in the commodity and, equally important, the level of pest control 'interference' with routine bag-stacking operations, are management issues that must be considered.

Treating bag surfaces with insecticide is effective providing the surface is one on which the insecticide is active and persistent. The treatment must be applied to all bags as the stack is built. Spraying of the external surface of a stack cannot prevent insects flying into the centre of the stack. Therefore, external stack spraying is a palliative only and cannot prevent reinfestation unless there is a barrier to keep insects out of the stack. If insecticides are to be used effectively, there must be layer-by-layer or individual bag surface spraying as the stack is built. This may then be followed by capping sprays at intervals. This calls for the development of a method which effectively treats each bag as the stack is built, but which will not result in undue exposure of the handlers. This is not an easy task. An electrostatic sprayer suited to automatic operation, giving each bag the required treatment as it moves up the elevator but eliminating drift and minimising worker exposure, could be considered.

Covering with Cloth Sheets

Conventional insecticidal spray treatments appear to be ineffective for preventing the build-up of infestation in tropical conditions unless applied very frequently and at a high dosage rate. Moths and beetles can penetrate sacks by flying past the external sprayed surfaces. This can be partly overcome if stacks are covered with protective covers as an alternative to stack spraying. Increased protection is obtained with smaller residues on the grain if the stacks are covered with sheets of muslin, cotton baft, or light hessian cloth. Insecticide is sprayed on the outside of these covers rather than on the stack itself. The cloth must completely cover the stack with an overlap on the floor to be reasonably effective against beetles.

Schulten (1973) covered stacks with hessian sheets which were sprayed every 4 weeks with actellic or reldan at 500 mg/m^2. Alternatively, chlorpyrifos has been applied every 10 weeks at 3 g/m^2. The method has been used effectively in the Sahel with cotton covering sheets. Hayward (1983) states that impregnation of cotton sheets is an effective and low cost method and requires only 25% of the quantity of insecticide required for conventional storage. The main disadvantage is the extra cost and effort needed to make and handle the covers. There is also the possibility that the covers may themselves harbour dirt and infestation if they are not properly maintained. Sheets need to be well maintained or they may interfere with the normal use of the warehouse and heavily contaminated sheets may be a problem to handle. There are thus operational difficulties to be overcome.

Covering with Plastic Sheets

Many of the difficulties experienced with cotton sheets do not occur with coverings of light-weight polythene film. These films do not need to be sprayed with insecticide and can be repaired or discarded if they are torn. Light-weight polyethylene sheets left in place after fumigation have been used to provide very effective protection against reinfestation in several countries. This method was recommended by McFarlane in Jamaica in 1961. In a more recent account (McFarlane 1980), the technical and economic feasibility of using various forms of permanent sheeting for this purpose has been discussed, with particular attention to the management aspects. For impermeable sheets to be used as permanent covers on stacks of bagged grain, it is essential that adequate safeguards should be provided against the risks of moisture translocation and condensation. The sheeted commodity should be dry and fumigated at the outset and not subject to extreme daily fluctuations of temperature. There may be some concern about the possibility of sweating and moulding of the bags close to the sheet. In the Indian subcontinent, wheat and paddy is stored under waterproof covers for very long periods, with an arrangement for lifting covers on dry days to allow ventilation through the stack. With a properly planned management program and adequate monitoring of physical conditions in the sheeted enclosures, this system can provide economically effective protection of the stored grain with minimum use of chemical pesticide (McFarlane 1980).

The system avoids the need for insecticide spraying and can incorporate an initial fumigation and a final fumigation at the end of the storage period. Good quality fumigation sheets would not be appropriate but a cheap plastic film would be adequate and its use to protect a stack for several months should be economically justifiable.

Experiments have shown that this type of storage can be carried out without moisture migration problems, but more work needs to be done on this aspect. A common experience in the

Table 6. Comparative costs of alternative programs of quality control for bagged, milled rice (Source: Webley 1981).

Program	Cost of materials[a] (% of commodity value)	Probable weight loss[a] (%)	Total cost (%)	Additional costs
1. Initial fumigation[b]	0.1			
Regular surface spraying	0.05			Cleaning operations
Final fumigation	0.1			
	0.25	2.0	2.25	
2. Initial fumigation[b]	0.1			Improved store management
Retention of sheet as protective cover (usedfor two seasons)	0.1			
	0.2	nil	0.2	

[a] Costs and losses relate to 2000 t stacks stored for 6 months and required to be free of live insects and insect waste matter at the time of discharge.

[b] Fumigation costs are for phosphine at 1.5 g/m^3. Spraying costs are for malathion at 0.5 g/m^2 every 2 weeks or pirimiphos-methyl at 0.5 g/m^2 every month.

tropics is that fermentation may occur in the time required for phosphine fumigation and in these circumstances it is absolutely essential to remove the impermeable sheets as soon as possible. McFarlane has compared the costs of the two approaches (Table 6) and they are seen to be comparable. The main questions are to what extent the covers interfere with normal warehouse operations, whether the use of covers may cause moisture problems, and whether such covers may actually provide a harbourage for insects if not used properly. Use of impermeable covers requires more care. The final development of this type of cover is the fitted gas-tight cover used with phosphine or carbon dioxide, as described by Annis and Graver in another paper in these proceedings.

Pre-treatment of Bag Materials

Pre-treatment of paper and cardboard with pyrethrins was used in the 'Cooperkote' process to protect foodstuffs. Highland and co-workers in a series of papers (Highland 1983; Highland et al. 1984) have described the use of pyrethrins and permethrin to protect multi-wall paper bags. Permethrin or synergised pyrethrins considerably slow down the penetration of bags by insects, but do not entirely prevent entry of insects such as *R. dominica*. This method has not to my knowledge been used on polypropylene and the use of the pyrethrins treatment on blended cereals packaged as food aid has been stopped due to lack of demand for the treated material.

Use of Liners or Impermeable Bags

Morallo-Rejesus and Javier (1981), working with small sacks (6 kg) of milled rice, found there was a clear advantage in using a paper liner inside woven polythene sacks.

Hindmarsh (1977) has described the successful storage of maize seed using polythene liners, and Wilkin and Green (1970) have described the use of polythene sacks for control of insects in grain.

Lee and co-workers (1977) at the Singapore Institute of Standards and Industrial Research concluded that bagged milled rice could not be kept for longer than 6 months, because of yellowing and undesirable increases in FFA. Repeated fumigation with methyl bromide gave unacceptable bromide residues but phosphine, even at high dosages (6 g/t), was not sufficiently effective. It is concluded that milled rice should be stored in sealed, impermeable, heavy polythene bags at less than 14.5% moisture content.

Closable Bag Stores

The concept of total store fumigation, in which an entire storage structure and its contents are disinfested by one fumigation, has been advocated and can offer many advantages if the storage structure is sufficiently gastight or can be made so. Otherwise, the system is generally less effective and therefore less economic than fumigation of individually sheeted bag stacks.

One of the major advantages is that the store can be filled. Often it is impossible to carry out fumigation under sheets due to the lack of access. In the type of store where a high filling ratio is expected and goods tend to remain for long periods, total store fumigation offers considerable advantages. It is not suitable for open warehouses in continuous use where fumigation under sheets is easily organised and less disruptive of the daily work schedule. Generally, it is the smaller, compact, solid-roofed concrete warehouses in which total store fumigation is carried out. However, there is a very great danger that these stores will not be properly sealed, and repeated fumigations in conditions which do not give complete kill of the insect population may lead to the development by insects of resistance to fumigants such as phosphine (Tyler et al. 1983). Development of resistance of this type would have very serious consequences for future stored product protection. Sealing is difficult even in custom-built premises. It has been shown that a good Ct product can be obtained in mud brick stores with very thick walls which are easily resealed (Webley and Harris 1979). However, phosphine passes comparatively quickly through the average store walls so that even if doors and windows are well sealed, leakage will still be very rapid. The application of two coats of polyurethane or rubberised paint can substantially improve gastightness of such stores if all the cracks have first been filled. All doors, windows, ventilators, and other openings must be taped. Generally, this type of store will not be sufficiently well sealed to pass a standard pressure test and it is important that standard methods of leak testing should be developed and used before fumigation is carried out. Top up or double dosing is being advocated for some of these leakier stores and it is possible that continuous flow fumigation could be advocated on a long time scale. Total store fumigation can solve many problems and it is expected that there will be developments in this area.

A somewhat similar case to this is the use of sealed bag stores, e.g. butyl rubber bag stores. Generally, this type of store has not been developed because its life seems to be too short in tropical use.

It is probably true to say that total store fumigation with phosphine is the most attractive of the many options which have been discussed, just as closed storage with phosphine or inert atmosphere fumigation is the most favoured option for bulk storage. If this is the way that bag storage goes, design and sealing specifications must be introduced to make it work. It probably has more future than the continued use of insecticide sprays on bag stacks.

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Use of Carbon Dioxide and Sealed Storage to Control Insects in Bagged Grain and Similar Commodities

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Abstract

Disinfestation of bag-stacked raw and processed grain, and commodities such as coffee beans, seeds, and spices, is normally carried out by fumigation with phosphine or methyl bromide under 'gasproof' sheeting. The sheeting is removed after fumigation and a combination of store hygiene and spraying the outer surfaces of the stacks with contact pesticides is relied on to prevent reinfestation. This combination is usually inadequate to prevent insect populations increasing to an extent where refumigation becomes essential. In tropical conditions, a bag-stacked commodity may require several costly and inconvenient fumigations during the course of long-term storage. If methyl bromide is used, repeated fumigation may lead to unacceptable fumigant residue levels.

A well sealed fumigation enclosure permits a reliable disinfestation using a single dose of carbon dioxide (CO_2). This gas has some advantages as a fumigant: it does not produce harmful residues, it is relatively safe to use, and it does not have to be imported. An enclosure sealed to the standard required for successful CO_2 treatment also acts as a substantial barrier to reinfestation. This paper discusses a series of experimental and semi-commercial treatments using the CO_2/sealed stack method of storage. These have shown that the treatment is reliable for long-term storage and has advantages over the conventional methods. To achieve reliability, particular attention must be given to sealing the enclosure.

IN tropical countries, most large stocks of grain, grain products, seeds, spices, and other commodities are stored and handled in jute or woven polypropylene bags. These bags form a convenient basis for a manual or partially automated system of handling and storing such commodities in stacks. However, the use of bags creates problems for efficient pest control, especially when used for long-term storage. In bag-stacks, intimate mixing of non-gaseous pesticides with the contained commodities is very difficult. In general, such treatments are restricted to spraying the exposed surfaces of the stack. The only practical method of disinfecting a bag-stack in situ is by fumigation.

The current practice of fumigation is to use methyl bromide or phosphine in a process widely known as 'fumigation under gasproof sheets'. In this process the stack is covered by a sheet of PVC or polyethylene and the margins of this sheet are held in contact with the floor by a series of long flexible weights (Anon. 1974). Floor sheeting is not normally used, but it is recommended when the floor is known to be leaky (Anon. 1983). The fumigant is administered, and after the defined exposure period is complete the cover sheeting is removed. Thereafter, the stack is unprotected from reinfestation by insects from both nearby untreated stacks and the general storage environment. A combination of store hygiene and the use of contact pesticides is used in an attempt to reduce reinfestation. These pesticides are used to treat the surfaces of the store structure and, as mists or fogs, to reduce flying insects. Surface spraying of stacks is often carried out in an attempt to form an insecticidal barrier to prevent reinfestation of newly fumigated stocks (Anon. 1983). For a variety of reasons these treatments frequently fail. Consequently, when bag-stacks are stored over long periods, repeated fumigations become necessary.

Well-sealed fumigation enclosures may offer several advantages over the loosely sealed gasproof sheeting used in current practice. The loss rate of fumigant can be reduced sufficiently to allow an even distribution of fumigant to occur before loss by leakage (Banks and Annis 1984). Thus, appropriate regimes of concentrations and time can be predictably and reliably achieved. An enclosure that is well sealed against gas loss is also likely to be a substantial barrier to insect entry if left sealed during the whole storage period. A good

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seal may also reduce the entry of water vapour when attempting to store materials drier than their equilibrium moisture content with the ambient relative humidity (Annis and van Someren Greve 1984). The sealing of permanent structures for the treatment and storage of bulk grains using low oxygen and high carbon dioxide atmospheres has been considered elsewhere (Banks and Annis 1980; Banks et al. 1980).

This paper considers the use of carbon dioxide (CO_2) and sealed plastic sheeting for the long-term storage of bagged commodities as a particular example of the use of well-sealed enclosures for the post-fumigation storage of infestable commodities. A very similar technique to the one discussed, but using nitrogen rather than CO_2, is reported to be used routinely in some Chinese storages (Qianyu 1984). Discussion here is based on a series of experimental and semi-commercial applications of this technique carried out since 1978.

Methods

Over the course of the trials reported here, the use of CO_2 has been developed from a procedure which was barely satisfactory to one which appears to give a reliable treatment on most occasions. During this period, the overall procedure has remained unchanged but individual techniques have been developed to progressively overcome problems found in the earlier trials. The procedure consists of five distinct stages. In order of occurrence, these are: stacking, sealing, testing the seal, adding CO_2, and long-term storage (commencing in a high CO_2 atmosphere, but with progressively lower concentrations as the initial charge leaks out). The methods given below provide a general description and show how the final techniques were arrived at. For a more complete description of the currently used procedure see Annis et al. (1984).

The details of the various treatments discussed are summarised in Table 1. Specific treatments will be referred to by the trial number given in that table.

Stacking

The floor where the bag-stacks were to be built was covered with plastic sheeting, polyethylene in trial 1 and 0.6–0.8 mm unreinforced PVC in all other trials. In trials 1, 2, and 8, the stacks were built with palletised loads by fork lift truck. A layer of bituminised building paper was used to protect the floor sheets from damage by the wheels of the truck. All other stacks were built manually and the top surface of the floor sheet was unprotected. The bag-stacks were built on either the timber dunnage normally used at the storage site or on standard pallets where these were in common use. The

Table 1. Details of stacks, enclosures, and commodities in storage trials referred to in text.

Trial No.	Site	Year	Reference	Number of stacks	Stack size[a] (m)	Floor sheet[b]	Cover sheet[b]	Side seams	Floor seams	Tonnes	Commodity
1	Sydney	1978	Annis, unpub data	1	4x4x2	PE	PE	adhesive tape	adhesive tape	19.7	Wheat & rye
2	Griffith	1979	Annis et al. 1984	1	11x4x5	0.76 mm UPVC	RPVC	factory welded	solvent sealed	108	Broken rice
3	Jakarta	1980	Annis et al. 1984	4	12x6x4	0.76 mm UPVC	RPVC	factory welded	solvent sealed	177	White rice
4	Dubbo	1980	Annis unpub. data	1	2x1x1	0.76 mm UPVC	RPVC	rolled & clamped	rolled & clamped	1.0	Sunflower & sorghum
5	Jakarta	1983	Suharno et al. 1984	16	10.5x6x4.5	UPVC	RPVC	factory welded	solvent sealed	200	White rice
6	Lae	1983	Annis et al. 1984	3	4.4x2.6x2.4 4.4x2.6x1.1	0.76 mm UPVC	RPVC	factory welded	solvent sealed	2x18 1x9	Coffee beans
7	Lae	1984	Graver unpub. data	4	12x7.3x5.5	0.76 mm UPVC	0.5 mm UPVC	factory welded	solvent sealed	200 to 250	White rice
8	Echuca	1984	Bramall pers. comm.	2	3.8x3.8x1.9	0.76 mm UPVC	1 RPVC & 1 UPVC	factory welded	solvent sealed	approx. 17	Brown rice
9	Mt. Hagen	1984	Graver unpub. data	2	2.8x2.4x2.6	0.76 mm UPVC	RPVC	factory welded	solvent sealed	2x4	Coffee beans
10	Bangkok	1984	Annis unpub. data	2	6x6x4.2	0.4 mm UPVC	0.4 mm UPVC	adhesive tape	adhesive tape	100	White rice

[a] Stack dimensions (length x width x height)

[b] PE — Polyethylene; UPVC — Unsupported Poly-Vinyl-Chloride; RPVC — Reinforced Poly-Vinyl-Chloride.

underside of all the timber used was inspected for protrusions that could damage the floor sheet. The stacks were then built by the method normally used at each site. During stacking, representative samples of the stored commodity were normally taken for assessment of insect infestation and for pre-treatment analysis of moisture content and quality.

Sealing

When stacking was completed, the stacks were covered with a plastic fumigation sheet tailored to the stack size and shape (polythene in trial 1 and PVC for all others). In trials 1, 2, and 10, the side seams and bottom corners (Fig. 1 for details) were cut and sealed at the storage site. Side seams were either taped (trials 1 and 10), or rolled then clipped (trial 2) by the method recommended for joining ordinary fumigation sheeting (Anon. 1983). In all other trials, the top sheeting was factory prefabricated to the stack dimensions and joins were either solvent sealed or heat welded. After ensuring that the top sheet fitted properly, its lateral extensions were sealed to the floor sheeting using tape sealing in trials 1 and 10, rolling and clipping in trial 2, or solvent-based sealing on all others.

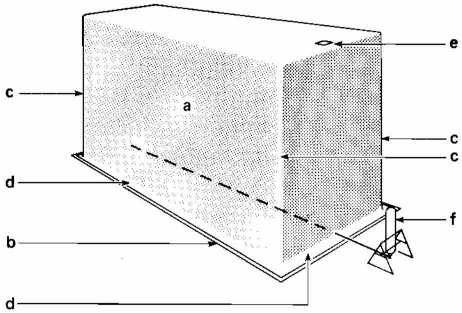

Fig. 1. Diagrammatic view of enclosed stack showing fitted top sheet (a), floor sheet (b), side seams (c), lateral skirt (d), gas escape vent (e) and CO_2 introduction system (f).

Testing the Seal

The enclosure's fabric and seams were first carefully inspected. Special attention was given to corners and places where either the top sheet or floor sheeting had been folded during storage or transport. The fully sealed enclosure was then tested for gastightness by the pressure decay method (Zahradnik 1969). In this test, a vacuum cleaner was used to produce a small differential pressure with respect to atmospheric (approximately –500 Pa). The outlet of the vacuum cleaner was then sealed and decay of pressure with time was observed. The pressures were measured either with an electronic micromanometer or with a water-filled U-tube manometer.

While the enclosures were under slight vacuum, they were further examined for leaks, which were detectable as draughts or by the sound of air passing through them. If leaks were found they were sealed, and a new pressure test carried out. If there were no obvious leaks and the enclosure had a decay time from 250 to 125 Pa of 5 min or longer, the level of sealing was accepted as adequate. When this standard was not reached, the enclosure was examined more closely for leaks and corrective action was taken. Because of poor sealing techniques and the unfavourable ratio of surface area to volume in the early trials (1, 2, and 3), the standard of sealing could not be attained. In these cases the trial proceeded, though with the expectation that the CO_2 concentrations after a single application would not be maintained adequately for a complete disinfestation.

Gas Addition

Carbon dioxide was added to the stacks by a copper pipe which passed through the cover sheets and discharged CO_2 between the floor sheet and the top of the timber dunnage. Holes were made in the tops of the stacks to allow displaced air to be vented during gas introduction. In all cases, CO_2 was delivered to the site as compressed gas either in cylinders or bulk tanks. Carbon dioxide was piped into the base of the stacks either as gas or 'snow' depending on the equipment and types of cylinders available.

In trial 1, gas was taken from upright cylinders with electrical regulator heaters. This was a slow process as the CO_2 solidified once the gas pressure became too low and time had to be allowed for the cylinder to then warm up before gas could be obtained. A manifolded bank of 10 upright cylinders was used initially to deliver gaseous CO_2. Although it took much longer for the cylinders to freeze, gas introduction was still disrupted.

Carbon dioxide was added as 'snow' to all other stacks. This was delivered from bulk tanks in trials 4 and 7, from cylinders fitted with eductor (siphon) tubes in trial 6, and inverted standard cylinders in the other trials. With both types of cylinders the full liquid content was discharged with the valve fully open. The unrestricted introduction of CO_2 from bulk tanks was much more rapid and some experimentation was needed to set an appropriate flow rate.

Whatever introduction method was used, an attempt was made to keep the gas introduction continuous in order to maintain a discrete purging front and, thereby, a high efficiency of purging. Gas introduction was stopped when the concentration of CO_2 leaving the top vent was in the range 70–80%. As soon as the gas flow was stopped the gas inlet and top vent were sealed.

Storage Period

Gas concentrations were measured at regular intervals during the storage period. In trials 6 and 8, additional gas was added when the concentration first fell below 30% CO_2. In the other trials, no further gas was added. At the end of the storage period (Table 2), samples of commodity were taken for assessment of insect infestation and changes in quantity.

Table 2. Storage periods, pressure tests, and gas retention.

Trial No.	Storage period (days)	Pressure test halving time (min.)	Days above 35% CO_2[a]
1	30	3.5[b]	2
2	28	3.2–5.5[c]	9
3	28–133	>9[c]	39–45
4	17	4.0	4
5	120–480	Not stated	42–106
6	182	7–11[d]	27–63
7	330	>5[e]	>20
8	>25	Not stated	6–>19
9	270	>5[e]	<10–>15
10	30–60	3.4[b]	1–2

[a] Based on interpolation or extrapolation of 1st order decay curve.
[b] 250–125 Pa.
[c] 200–100 Pa.
[d] 1000–500 Pa.
[e] 500–250 Pa.

Results

Stacking

When manual stacking was used, the sealed storage method caused little disruption to normal stacking operations but when fork lifts were used (trials 1, 2, 4, and 8) there was an increase in the time taken to complete stacking because of the need to protect the floor sheet from damage. In the small stacks (trials 1, 4, and 8) there was little disruption (about 5 min extra time) but it was significant in the larger stack of trial 2 because the fork lift had to be driven over the floor sheet and special care was needed to avoid damaging the sheet. The increase in stacking time in this case was about 45 min.

The inspection of dunnage took a few minutes per pallet and in most cases it was worthwhile as it revealed protrusions that might have damaged the floor sheet. On two occasions, the floor sheet was slightly damaged by nails that were missed during inspection.

Sealing

In trials 1, 4, and 10, where the cover sheets were tailored to the stacks on-site, considerable difficulty was experienced in forming gasproof side seals. In each of these trials, a different sealing technique was used; single-sided adhesive tapes in trial 1, rolling and clipping in trial 4, and double-sided adhesive tape in trial 10. On each of these occasions, the process was time consuming (up to about 8 hours per stack in trial 10). The seals formed in these three cases were weak and easily damaged.

The prefabricated top sheets were easily handled and fitted over the stacks quickly. In trial 7 and one stack in trial 6, the stacks were built lower than originally planned and the resulting surplus fabric was pulled to the top of the stack and held there with weights. This was a cumbersome operation in the large stacks of trial 7.

Sealing the top sheet to the floor sheet with sealants based on PVC solvents required some skill. Where several stacks were sealed during the course of a single trial, the time taken to complete the sealing decreased and the quality of the seal increased as sealing progressed. Tape sealing of this joint was weak. At all sites, the combined process of covering and sealing took 1 to 2 hours longer than for a conventional fumigation.

Testing the Seal

Proving that the enclosure is sealed to a sufficiently high standard is an essential part of this method. In all trials, pressure testing along with the associated examination of leaks took at least 60 min and required a trained operator and an assistant. In each stack, several pressure tests were needed as leaks were always found during preliminary testing. Attempts to seal leaks either had no effect or increased the pressure halving time.

Except in trials 1, 2, 4, and 10, the enclosures finally achieved the recommended pressure test standard of a pressure halving in more than 5 min (Table 2). The standard was not achieved with the stacks sealed by methods other than a solvent-based sealer. In these stacks, the level of sealing decreased with repeated pressure tests, indicating that the seal was damaged during testing. This problem did not occur with solvent sealed enclosures.

Gas Addition

All the methods used for gas introduction produced an enclosed atmosphere concentration of greater than 70% CO_2, using between 2 and 3 kg (2.4 kg mean) of CO_2 per tonne of commodity.

The simplest way of introducing CO_2 was as 'snow' from eductor tube cylinders. The cylinder was connected to the inlet tube and the cylinder valve opened completely. When all the gas was discharged, the cylinder was exchanged for a full one. The complete cycle from connecting the full cylinder to disconnecting it took about 10 min.

Where cylinders fitted with eductor tubes were not locally available inverted ordinary cylinders were used. This was a more complex task requiring a special frame to hold the inverted cylinder safely and took about 12 min for each cylinder. About 1 cylinder in 10 became blocked when inverted and failed to discharge more than a small proportion of its contents.

'Snow' obtained from bulk supplies (tanker or mini-bulk tanks) was the cheapest way of obtaining CO_2 and fastest method of adding gas to the enclosures. However, the unrestricted rate of application was so fast that it caused excessive cooling of the PVC enclosure close to the CO_2 entry point. This in turn caused the PVC to become temporarily brittle and to be broken by the high velocity gas/snow striking it. It was necessary to adjust the main delivery valve to give flow rates equivalent to those obtained from inverted cylinders. This adjustment was not easily achieved as the valve was designed as a shut-off device and not as a regulator.

Storage Period

Immediately after gas introduction, there was a concentration gradient between the base and the top in all stacks, but this gradient disappeared in 2–3 days (Fig. 2) under the influence of natural mixing. The logarithm of the average concentration of CO_2 in the stacks typically decayed linearly with time (Fig. 3), although in one case (trial 2) the reciprocal of concentration decayed linearly with time.

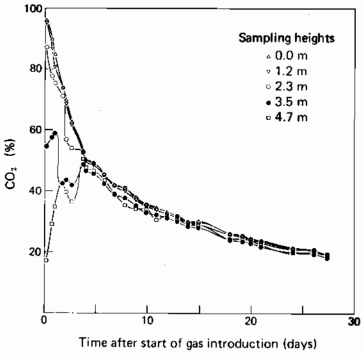

Fig. 2. An example of variation in concentration of carbon dioxide at various heights above floor level in an enclosure (Annis et al., 1984).

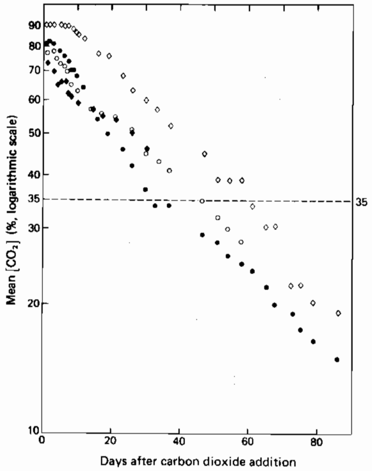

Fig. 3. An example of average carbon dioxide concentrations inside four enclosures after purging: Stack 1 (●), Stack 2 (◇), Stack 3 (○) and Stack 4 (◆). Target CO_2 regime: initial concentration greater than 70%, concentration after 10 days greater than 35%. (Annis et al., 1984).

Where an adequate pressure test had been achieved and a reliable sealing technique had been used on stacks of 100 t or more, the CO_2

concentration was maintained at above 35% for much longer than the required disinfestation period of 10 days (Banks and Annis 1980) (Table 2). With smaller stacks, it was sometimes necessary to add gas to increase the concentration after a few days even if the pressure test had been passed and no obvious reason for the gas loss could be found.

All but three of the enclosures appeared to be as well sealed at the end of the storage period as at the beginning of the treatment. Two covers of the four in trial 7 had holes of a few square centimetres, which were consistent with rodent damage. The holes were found where the surplus material from the over-sized covers was folded and heaped up at floor-level. There was no regular inspection procedure at this site so the time at which the hole appeared could not be determined. In trial 5, 1 enclosure out of 16 was holed, the hole shape being consistent with the fabric having been snagged and then torn. Here there was a regular inspection and the hole was found (but not repaired) about 10 months into the 16 month storage period.

Insect Infestation

With the exception of trials 4 and 9, all stacks initially had live insects present either as a natural infestation or as test cultures. When the 33 stacks with undamaged covers were opened live insects were present only in those of trials 1 (1 stack) and 10 (2 stacks). In these stacks, the sealing was known to be of less than the required standard and gas concentrations were not held above 35% CO_2 for the required period of 10 days. The three stacks with damaged covers all had light to moderate infestations of mixed species of insects.

Quality at Outloading

The most significant change occurring during the storage period was a rise in moisture content of the commodity close to the outer surfaces of the stacks. In the stacks with undamaged covers, this rise occurred only in the outermost 1–2 cm of the outer bags. The only occasions where this increase in moisture led to moulding were in some stacks stored for 16 months and in one stack in trial 6 where very wet dunnage was used.

In the three stacks with damaged covers, there was substantial surface moulding which penetrated up to 0.5 m into the stack. Despite the presence of moulds in these stacks, there was no evidence of aflatoxins. The moulding was worse in the top of the two stacks of trial 7 which had a stepped top portion that extended above the eaves line of the warehouse. In trial 7, there was a total of about 135 t of greyed and moulded rice in the two 250 t stacks. When this material was re-milled, the total loss was about 7.5 t or 3% of the original contents.

The effect of the treatment on other quality parameters was somewhat more variable and, because of differing methods of assessment and a lack of control treatments, it is difficult to assess the significance of the results. Despite this the trials indicate that:—

1. In no case was there a substantial permanent loss in quality or quantity during the storage period. At all of the trial sites, serious quality degradation would be expected if the commodity were left untreated for more than a few months and some degradation would be expected with existing pest control methods.
2. There is some protection from overall quality degradation, e.g. the coffee beans used in trials 6 and 9 were assessed to have suffered less quality loss than beans stored for several months under normal storage methods.
3. In rice, the proportions of broken, chalky, and red grains do not appear to be increased by the treatment.
4. In some rice, yellowing was reduced when compared with rice stored by conventional means (trial 5, Indonesian rice), and in others rice yellowing did not occur (trial 3, trial 7, and Thai rice in trial 5).
5. Greying in rice appears to follow a similar pattern to yellowing, except that if moulding occurs, greying will appear regardless of the treatment (trial 7 and rice from the outer 1–2 cm of 16 month treatment in trial 5).

Discussion

The treatments reported show that if applied correctly, the combined use of carbon dioxide and permanent sheeting will disinfect bag-stacks and protect them from reinfestation for long periods. However, the method is not yet at a stage where it could be recommended as a routine procedure. It will not be recommended until various operational parameters are further investigated. The trials were designed to establish the technical feasibility of the method and to formulate a set of techniques to allow its reliable operation. The experiments were not designed to investigate such parameters as costs, maximum and optimal storage times, limiting factors for effective use, and how to integrate the technique with other appropriate insect control measures. The results could be of assistance in establishing the larger trials needed to investigate such parameters.

The need to re-stack material on to a floor sheet is an operational constraint because it is both time consuming and an inefficient use of storage space. However, this problem could be overcome in routine use by ensuring that all stacks are built on an appropriate PVC floor-sheet. This is not an excessively expensive operation and it should improve the efficacy of conventional fumigations if the carbon dioxide/sealed stack storage method is not used.

The surface area of a stack defines the size of the gasproof barrier and the perimeter of the stack defines the minimum amount of on-site sealing needed. The potential for leakage is therefore related to both surface area and perimeter length. The ratios of both perimeter and area to gas volume are much less favourable to gas retention in a small stack than in a large one. The trials reported here illustrate this phenomenon. Small enclosures, no matter how constructed, presented most difficulties in achieving and maintaining an adequate level of gastightness. Stacks of less than about 100 t frequently needed an additional charge of gas to ensure that the target of greater than 35% CO_2 for 10 days was achieved. This was never the case for the larger stacks.

The sealing methods currently available for use in the field are both time consuming and somewhat unreliable. Thus, as much prefabrication as possible should take place in a workshop equipped with radio-frequency or other heat-sealing machinery. Such machines produce excellent sealed joins but are expensive, and not usually being portable, are not suited to field use. The most reliable treatments were obtained in enclosures correctly tailored to the stack dimensions and fabricated off-site. If the stacks are of a known standard size, the only sealing needed in the field is the junction between the floor sheet and the stack cover. In the trials reported here, sealing this seam with a sealant based on PVC solvent, although time consuming and requiring some specialised skill, gave the most reliable results. An enclosure correctly tailored to the size of the stack not only minimises the need to make sealed joints on site but also prevents areas of folded sheeting. This folded sheeting may form harbourage for rodents and also prevents easy inspection of the enclosure fabric for damage.

All of the methods of supplying CO_2 reported were adequate but each had its advantages and disadvantages. In terms of the cost of gas alone, bulk tanks of liquid CO_2 are the cheapest method of supply. However, if the storage site is too distant from an adequate source of carbon dioxide, the use of bulk carriers may be impractical. The cost of carbon dioxide in bulk may be as little as 20% of the cost when supplied in cylinders. The major problem encountered when using bulk gas was control of its entry rate into the enclosures. However, a suitable gas introduction system could be designed to give an appropriate application rate for routine use.

For small stacks or where bulk gas is unavailable, cylinder gas can be used. Eductor tube cylinders are the most convenient, but since they have a specialised range of applications, they are not always readily available. Standard cylinders containing 28–32 kg carbon dioxide are often available well away from major population centres. Although they occasionally become blocked, these cylinders are best used inverted as they empty completely without any interruption to allow the cylinder to thaw. Upright cylinders could be used for very small stacks or for treatments where the low temperatures associated with 'snow' may cause a problem.

The trials clearly show that if the required sealing standard is reached in a stack of 100 t or more, the concentration of carbon dioxide will be adequately maintained and the stack thereby disinfested. In all 33 treatments reported, reinfestation was prevented except where the membrane was holed during the storage period. Pressure testing and examination of the enclosure for leaks are therefore crucial. While meeting the pressure test standard indicates adequate gas holding, it is essential that all obvious leaks be sealed to make an insect barrier. This means that an examination for leaks *must* be made even if a pressure test of the enclosure exceeds the required standard.

Moisture migration may become apparent under certain circumstances. In most of the trials there was an increase in moisture at the periphery of the stacks. In only a few cases was the increase sufficient to permit mould growth and when this happened there was always an obvious reason for it. Moulding always occurred when there was a large hole in the enclosure, presumably as a result of increased moisture movement resulting from large-scale gas interchange and the effects of reinfestation. Other reasons for moulding were the inclusion of very wet timber in a sealed enclosure, and prolonged (16 month) storage. Large-scale damage of the stored commodity by moulding only occurred in the holed enclosures. If any of the stacks which showed very light moulding had contained a commodity with a high moisture content (all products used were less than 14% moisture content) more extensive and damaging moulding could have taken place. Currently, it would be prudent to restrict use of this technique to drier commodities (equivalent to milled rice with a moisture content of less than 14%).

Since sealed stack storage makes conventional inspection of the commodity impossible without breaking the seal, other methods of monitoring the condition of the commodity need to be developed. The simplest of these is the use of a clear plastic enclosure. Clear plastic sheeting is frequently used for conventional fumigation and although it is not perfectly transparent, live insects and surface moulding can easily be seen through it. The only part of the commodity that seems to be at risk due to moulding is that close to the surface and this area might be monitored for a significant rise in moisture content. Monitoring could be by a grain moisture sensor or by measuring the relative humidity and temperature of the atmosphere in this critical region.

In the majority of these trials, monitoring was mainly restricted to measuring carbon dioxide concentrations. Any sudden drop in concentration would indicate a failure in the sealing. This method is of value only in the early stages of the treatment when there is significant carbon dioxide present. While no sudden drops in concentration occurred during the trials, these measurements were useful in confirming that the disinfestation schedule has been achieved. The easiest method of detecting significant damage to the enclosure during the storage period seems to be regular visual inspection of the areas that may be damaged.

It is not possible to give an accurate cost for the procedure because most of the trials were conducted in a non-commercial environment. It is possible, however, to make certain general statements that may help in costing the method. The area of PVC used to make the tailored enclosure and floor sheet is only slightly greater than that required for a conventional fumigation sheet for the same stack. The cost of fabricating the top-sheet in Australia is between 10 and 15% higher than fabricating the equivalent conventional fumigation sheeting.

The costs of carbon dioxide are variable and range from a maximum list-price of about \$A1.40/kg in single cylinders to about \$A0.40/kg contract price if purchased as bulk gas. Gas requirements for a 100–200 t stack vary between 2.0 and 3.0 (mean 2.4) kg/t. Current recommendations for phosphine are 3–4 g/t and for methyl bromide 38 g/t (Anon. 1983). As the need for refumigation with conventional fumigants is variable it is difficult to compare costs of conventional fumigation with those of a single carbon dioxide treatment.

Conclusions

The combination of carbon dioxide and sealed stack storage can be used for the safe, long-term storage of bagged infestable commodites. The treatment requires a heavy investment of time and effort during sealing and gas addition but for the remainder of the storage period little more is needed than a regular inspection of the fabric for holes, regular rodent control, and store hygiene. This balance of activities makes it most attractive as a method for long-term storage. The trials do not give enough information to determine the minimum storage period for which the method is economically attractive. Neither do they give the maximum safe moisture content for individual commodities in such storage. In determining costs, the CO_2 needed for a single treatment when applied at a rate of 2.4 kg/t must be compared to the cost of several conventional fumigations each at the rate of 4 g/t using phosphine (or methyl bromide at about 38 g/t), plus the cost of contact pesticide treatments at the schedules normally used.

The other benefits of the CO_2/sealed stack method are harder to quantify but they include the use of a locally produced rather than imported insect control agent and lack of chemical residues. From the results reported here, it seems likely that the quality of certain stored products will be better preserved by this technique than following long-term storage in conventional bag stacks.

Provided that the initial phases of sealing, testing, and gas addition are carried out carefully, the method can give reliable long-term storage of bagged commodities with minimum long-term effort.

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Treatment Techniques
Session Chairman's Summary

Valerie F. Wright*

THERE were five papers in the session on treatment techniques. *Bengston* began by defining grain protectants as pesticides which are incorporated directly into what generally are uninfested grain masses to protect them against infestation by pests. They are usually applied as a spray directed onto the grain stream, or during bagging or rebagging. Only 1% of the kernels need to be treated as long as those kernels are evenly distributed in the grain mass. A coarse spray and low pump pressure minimises drift and gives good coverage. Dust formulations are best applied to smaller quantities of grain where adequate mixing can be achieved with minimal exposure of workers.

Malathion, one of the most widely used grain protectants, must now be replaced by alternatives because of insect resistance. Chlorpyrifos methyl, fenitrothion, pirimiphos methyl, and etrimphos should give good control against malathion-resistant strains (except for *Rhyzopertha dominica*). Bioresmethrin, permethrin, fenvalerate, carbaryl, or phenothrin can be combined with an organophosphate to control pest complexes including the bostrychids. Methacrifos and deltamethrin are also gaining acceptance. Determination of resistance in local populations, using FAO test methods, was recommended.

Laboratory experiments are the first stage in evaluation of new materials and these require technical skill and a good understanding of the basic principles involved. Field testing is then necessary, followed by pilot usage to evaluate compatibility of a formulation with local conditions and to allow operators and managers to become familiar with the properties and limitations of the candidate grain protectant.

The discussion on grain protectants included a brief explanation of the testing procedure to obtain mammalian LD_{50} values. Comments were made on whether or not surface spraying of stacks was a useful technique.

Banks, in his paper on fumigation, noted that the technique requires technical skill and understanding of the background principles in order to avoid failures and the buildup of resistant insect populations. Existing methods need to be optimised and new methods developed. CSIRO-recommended dosage rates and times for methyl bromide fumigations were given as 16 g/m^3 for 18 hours and for phosphine (PH_3) 1.5 g/m^3 for 7 days where *Sitophilus* was present and 5 days otherwise.

Failures were defined as any insect survival after treatment. They may be caused by excessive loss of gas, loss from localised areas, or slow dispersion of fumigant. The factors involved in fumigation failure are cyclic temperature variation (which can be minimised by painting storage sheds white), pressure changes and wind (which can be countered only with a complete seal), the chimney effect, and molecular diffusion. Slow dispersion of gas can be countered with an application of carbon dioxide (CO_2) to the headspace when PH_3 has been placed on the grain

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surface. The CO_2 does not take part in insect mortality, but because of its density moves PH_3 down into the grain mass. External generation, flowthrough systems, and multiple dosing were also discussed.

It was clarified during discussion that the CSIRO-recommended fumigation times are longer than the manufacturer recommends, because of the need to kill resistant stages of the insects such as eggs and pupae.

Webley discussed the alternatives to external spraying of bags in stacks. These include in-bag fumigation, bag-by-bag admixture, pretreatment of bag materials, covering stacks with cotton sheets treated with insecticide, fumigation under plastic sheets, and enclosure and fumigation of stacks in plastic envelopes. Storage structures specifically designed for in-house fumigation are another option.

Woven polypropolene bags were shown to be superior to jute bags for control after spraying with an insecticide. Fabric treatment of structures is effective only if adequate coverage is accomplished.

There was some discussion as to whether sealed storage with a CO_2 atmosphere would replace conventional fumigation, discussion which anticipated the next paper in this session. The concensus was that it probably would not. This type of fumigation technique is particularly useful for long-term storage, but research is still needed. This includes: (1) further understanding of toxicological aspects for various insects and commodities; (2) determination of the reliability of the system; and (3) a better assessment of quality and its parameters. Specifications for the plastic sheets needed were discussed.

The paper by *Annis* and *Graver* dealt with the use of CO_2 in sealed storage of bagged grain in stacks, a new technique with much promise. Disinfestation followed by reinfestation is common with other fumigation techniques, but here the permanent plastic envelope acts as a barrier to insects. The technique requires rather stringent and standardised sealing practices. Pressure tests are required, along with continual inspection of the plastic cover for leaks. If dry grain is sealed correctly into a plastic envelope and flushed with CO_2, the storage period can be quite long and the deterioration minimal. Breaks in the seal and holes in the plastic are the most common reason for failure. Moisture migration in this system is not yet understood, but is being intensively researched.

In summarising this session, we can say that although the number of pesticides is limited, future treatment techniques are limited only by how effectively we apply our minds to the problems at hand. We should know the systems we are working in, their limits and advantages, and choose the pesticides and application techniques which are most economical, practical, and effective. Fumigation is the most common strategy at present, with supplementary use of grain protectants where appropriate.

Integration of Chemicals into Storage Systems

Use of Pesticides in Systems for Central Storage of Grain

D.J. Webley*

Abstract

Use of pesticides in the central bulk storage of grain is described. A very high standard of freedom from insect pests is demanded. The two methods of achieving this are the use of residual chemical protectants and the use of fumigants or inert atmospheres in sealed storages. Chemical protectants are easily applied, effective, and do not require a high standard of storage structure or technology. The prohibition of many of the fumigants formerly used for grain storage has led to the use of residual chemical protectants becoming much more wide spread. Their major disadvantages are the tendency of insects to develop resistance to them and the presence of residues. Despite the extensive Codex approval system, countries vary in their acceptance of the use of insecticides, and the presence of residues must be carefully monitored. Sealed storage requires some additional capital cost and there is a greater need to reduce the moisture content of the incoming crop. The validity of this type of storage technique for the humid tropics is still being researched. There is also a need for some form of rapid disinfestation measure in central storage systems. The current options in this regard are discussed.

THE need for a positive system of disinfestation and protection in storage of grain is a universal one. International trade, market pressures, and the higher standards sought by consumers have created a demand for total freedom from pests and diseases on exported grain. In contrast, for their own domestic product, some countries may find it necessary to set lower standards. Nevertheless, complete freedom from infestation should still be the most sensible aim because in warm climates, if infestations are not dealt with quickly, moisture and fungal problems develop and lead to serious quality losses. In extreme cases, where infestation in cereals coming into store in bags in the tropics has not been checked, total loss has occurred because it has become impossible to clean up and save the already heavily infested product.

In general, the cost of pest control measures is likely to be very much less than the losses incurred if the measures are not taken. The cost of pest control by insecticide treatment is in the region of $A1/t (during May 1985, $A1 = $US0.65) compared with the cost of storage and handling at $A15–20/t and a differential between milling and a lower grade of wheat about $A2–8/t. It is therefore in the best interest of the handler to keep the grain at the highest possible standard. Maintaining a 'nil tolerance' of insect pests requires, in addition to effective pest control measures, a highly efficient inspection system. If live insect pests are found, action must be taken and the system must be improved to lessen the possibility of future infestation.

Central Storage Systems

The central systems referred to in this paper are bulk storage systems; bag storage systems have been considered in a previous paper. The paper deals mainly with wheat storage.

The system begins with delivery from the farmer. In Australia, most farmers deliver their wheat immediately after it is harvested. A farmer may hold his crop for subsequent delivery, but this is currently a very small part of the total delivery. In those countries where most of the grain is stored on farm, the actions taken by the farmer to solve his pest problems must be taken into account. It must be more difficult to guarantee quality when this depends on the ability of the farmer to store the grain for long periods and cosmetic solutions to problems have to be guarded against. However,

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in many countries which rely on farm storage, much of this storage occurs in cold winter seasons, and this helps to prevent the insect problems which would occur in farm storage in warmer areas.

The grain is inspected on receival. The inspection must take care of the properties which cannot afterwards by remedied. These are the quality of the grain and whether it meets the standard of the grade into which it is being delivered, the grain variety, its test weight, moisture content, non-millable and foreign matter, and its general appearance and soundness. The inspector or agent must reject damaged grain and any grain above the maximum accepted moisture content, unless there is provision for drying before storage. Before harvest, the stores will have been washed down and sprayed with insecticide, and all on-site maintenance will have been attended to.

Whether grain is received straight from the harvester or out of a farm store, there will be a need for pest control measures to be applied on receival or soon afterwards. The urgency depends on the state of the grain, particularly its temperature and moisture content. Simple use of aeration may be sufficient to keep grain for several months. However, aeration alone cannot usually be relied on as a means of disinfestation, but only as a way of slowing insect development. If conditions allow aeration, the temperature of the grain can be reduced by 10°C in a few days and this has important benefits in reducing moisture migration and in slowing insect development and pesticide decay.

There must be regular inspection during the storage period. This entails a weekly check-up and regular spear inspections every 2 months in flat storage. Bins should be turned and inspected. Any sign of infestation must be dealt with by treatment using one of the methods outlined in Table 1. Early reinfestation would indicate either resistance to the treatment or, more likely, a failure of application. For insecticide treatment, residue checks should assist in diagnosing the cause of failure.

The various methods of pest control currently available and estimates of their costs are given in Table 1. The table distinguishes between two types

Table 1. Alternative methods of stored grain pest control and estimates of their costs (in Australian cents[a])[b]

Control method	Operating cost/tonne chemical	Operating cost/tonne labour	Annual capital cost/tonne	Total
Pest Control Combined with Storage Protection				
Residual Insecticide				
Organo phosphate	9–25	10	1–2	10–30
Organo phosphate + pyrethroid	80–100	10	1–2	90–110
Re-treatment at half rate	40–50	10	1–2	5–60
Closed storage + phosphine				
Bunker	4–8	1–2	—	—
Permanent store	4–8	1–2	40–70	40–80
Closed permanent store + carbon dioxide	30	1–5	40–70	80–120
Aeration				
Aeration alone	8–14	—	30–40	55
Aeration + low levels of insecticide	50	10	30–40	90
Aeration + full insecticide	90–120	10	30–40	150
Aeration with cooling	100	—	200	300
Rapid Disinfestation with No Storage Protection				
Non-residual insecticide — Dichlorvos	10	—	—	—
Fumigation				
Methyl bromide	15	30–110	—	—
Methyl bromide + carbon dioxide	30	—	—	—
Phosphine	12	10	—	—
Thermal disinfestation with fluidised bed	—	55	40	95
Thermal disinfestation with microwaves	75	100	—	175
Irradiation with accelerated electrons	—	35	40	75

[a] During May 1985, $A1 = $US0.65.

[b] Sources: Co-operative Bulk Handling Ltd. (W.A.); Bulk Grains Queensland; Grain Elevators Board (Vic.); Evans et al. (1983); Elder et al. (1984); Yates and Sticka (1984).

of pest control measures: those which are part of a protective storage system and those giving rapid disinfestation to cope with problems on outloading or prior to sale.

Table 1 is not a rigorous analysis of costs, which are very hard to determine as they depend on current exchange rates, costs of energy, the degree of utilisation of the stores, and annual throughputs. The cost of carbon dioxide, for example, is obviously highly dependent on the manner of generation and on the distance from a commercial source. Labour costs depend on the size and location of stores.

The chemical costs per tonne of wheat for use of 10ppm fenitrothion (8.7 cents), 10ppm chlorpyrifos methyl (25 cents), bioresmethrin 1ppm (72 cents), and 1g/m^3 Detia blankets (8.2 cents) were provided by the Wellcome Company. Dichlorvos costs $A10 per litre of 50% w/v concentrate. Carbon dioxide costs $A200–250 per tonne delivered. Electricity is assumed to cost 4 cents/kWh, and natural gas 0.4 cents/MJ.

Table 1 shows that most methods of stored grain pest control have the same order of costs. Thermal disinfectors are assumed to be capable of treating 0.6 million t/annum at a rate of 500 t/hour. Refrigeration is costed as needing 3 kWh of electricity/t/month.

The Australian wheat industry has recognised the value of rapid disinfestation methods being available at terminals to lessen dependence on residual insecticides and has supported research in this area. No biological methods appear in Table 1. Methods in which insects control other species are not consistent with the concept of nil tolerance and would interfere with methods for obtaining complete control.

Research has shown that refrigerated aeration is expensive and because insects can withstand long cold periods — *Rhyzopertha dominica* and *Sitophilus oryzae* have been shown to survive at 9°C for more than 26 weeks — the grain may still harbour infestation. The methods for protective storage therefore come down either to the application of residual insecticides with or without aeration or to a form of closed storage with phosphine or an inert atmosphere. If the latter is to be used, a sealable storage system has to be available on site. If there is no permanent sealable system, either insecticide protectant must be used or temporary sealed storage must be built. In the ideal system, the protective method begins at receival and lasts through the entire storage period, leaving the grain at the end fit for use without further treatment.

Both alternatives i.e. insecticides and sealed storage, are widely used in Australia today. Of the 1984–85 wheat crop, 70% was treated with insecticide and most of the remainder was stored in sealed storage and treated with phosphine or carbon dioxide. The intention of the wheat industry is to keep both these options open but to move towards a greater reliance on sealed storage as opportunities permit.

Before looking at the alternative methods in detail, the requirements should be considered. The method should be reasonably simple to operate and should work in all circumstances against all the likely pests without needing perfect application. It should give control without constant supervision. It should not affect grain quality. Finally, the method should allow some degree of flexibility. Ideally, it should not be necessary to segregate grain to be treated for long or short storage periods, although in the case of insecticide treatments this may be necessary. For rice, where much of the crop is of a similar grade, prior decisions on the length of the storage period may be easier to make than with wheat, for which many segregations have to be made for differences in hardness, protein content, and strength. Storage becomes much more difficult to organise when segregation for storage treatment has to be imposed on the inevitable segregation for type and grade of wheat. Grain stored in closed systems can be used at short notice, whereas full insecticide treatment may prevent immediate use.

Admixture Treatments

There is no doubt that admixture treatments have many advantages, particularly the low capital cost, the ease with which they can be set up, and the fact that this system places the least demand on the storage structure. They have, however, two major disadvantages: resistance and residues. Admixture treatments began in Australia with malathion in the early 1960s due to customer complaints about infestation. Later, resistance to malathion, and the resistance of some species of *R. dominica* to all organophosphorus (OP) insecticides, forced the industry to replace malathion with a mixture of fenitrothion and bioresmethrin. Fenitrothion is now failing to control some strains of *Oryzaephilus surinamensis*, and although other

OPs can exert control, laboratory evidence suggests that resistance to these alternatives may not be far off.

After 10 years, there is no evidence of resistance to bioresmethrin in *R. dominica.* However, the total world usage of this compound against *R. dominica* is small, and the opportunity for resistance to occur has therefore been limited. The expense of this compound has prevented its wider use. If resistance to bioresmethrin did occur, all the alternative pyrethroids might soon follow. Apart from the recent work on methoprene and other insect growth regulators, there is little sign of any replacement for the major insecticide classes.

The use of insecticides is increasing in other countries, mainly due to the pressure to replace liquid fumigants. Until recently, carbon tetrachloride, carbon disulphide, and ethylene dibromide were being used in the United States. There is considerable evidence of the toxicity of these materials and some receiving countries object to the residues of these materials in the hold when grain is being unloaded. Ethylene dibromide was withdrawn in 1984 by the United States Environmental Protection Agency and, as a result of the review of these fumigants initiated by the Agency, both carbon disulphide and carbon tetrachloride will be voluntarily withdrawn before the end of 1985. This will lead to the virtual end of these particular fumigants, although some use of the less toxic ethylene dichloride and trichloroethylene or trichloroethane may continue.

Wilkin has recently stated that, because of the toxic hazards and the fact that fumigation is now restricted to licenced servicing companies, fumigation has become a technique of last resort in the United Kingdom (Wilkin 1985). The technique of shipboard fumigation of grain with phosphine has been developed in the US (Davis 1983). Snelson and Winks (1982) have objected to this procedure on the grounds of safety and efficacy. The method circumvents requirements for phytosanitary declaration of freedom from infestation at time of export. However, while some importers strongly object to fumigant residues when holds are open, others may prefer them to insecticide treatments.

Until recently, malathion was the only major insecticide allowed to be used on stored cereals in the US. However, chlorpyrifos-methyl was registered for stored grain use in the US in 1985 with a maximum residue limit of 6 mg/kg. Also, pirimiphos methyl was recently approved for exported cereals. The US label states 'Actellic may only be used to treat corn, rice, wheat, or grain sorghum intended for export only'. However, manufacturers are hopeful that after several years of trials and some period of experimental use, both pirimiphos methyl and chlorpyrifos methyl may soon be registered for stored grain use in the US, possibly as early as June 1985. The current pirimiphos methyl label allows 6–8 mg/kg on maize and wheat and 9–15 mg/kg on rice.

Canada has less need for insecticide treatments, but some exports are treated with malathion. Insecticide admixture has increased markedly in the United Kingdom due to higher standards imposed by the market and the declining use of liquid fumigants. In a 1982 survey (Wilkin et al. 1983), 75% of stores surveyed used insecticide admixture on at least part of their grain. The most used chemical was pirimiphos-methyl (80%) followed by malathion (26%), fenitrothion (17%), and chlorpyrifos-methyl (3%). Chlorpyrifos-methyl was introduced in 1980. In the United Kingdom, dusts (mainly pirimiphos methyl) were preferred to sprays. However, dusts were more expensive, 20–40 pence/tonne against 10–20 pence/tonne for sprays, and are also less suited to high conveying rates and not available for some insecticides (1 GBP = 100 pence = US$1.46).

Wilkin (1985) states that many recipients of UK grain specify that the grain should be treated as it is loaded onto the ship. The Grain and Feed Trader, April 1985, describes insecticide treatment as being routine on export — 'Immediately before passing onto the ship the grain is treated by admixture of pesticide to kill any insects that may be present, and to provide some residual protection to the cargo in case it has to lie off for a time when it reaches its destination. The equipment is portable and has a unique automatic metering system providing very accurate dosing of the chemical as the grain passes along a belt conveyor. Reldan, Actellic, Satisfar and, if the receiver requests it, malathion, are the main chemicals used.'

In France (Ducom, private communication 1985) there is a reluctance to use fumigants and whereas only 5% of the grain is treated by phosphine fumigation, 50% is treated by insecticide admixture. At export terminals almost all grain is treated with insecticide. Chlorpyrifos methyl at 2.5 mg/kg is used for residual treatments and dichlorvos at 10 mg/kg for short term disinfestation. However, the most frequent treatment is a mixture of chlorpyrifos-methyl and dichlorvos at half the above rates. Pirimiphos methyl at 4 mg/kg and bioresmethrin at 1.5 mg/kg are also permitted, but the latter is not used.

The foregoing overview makes it clear that insecticide admixture is currently very acceptable, although this is not to suggest that those responsible for grain storage would not prefer to use an alternative method, particularly phosphine fumigation. It has already been noted that the combination of aeration with insecticide treatments could result in much lower application rates. In practice, full application rates are generally used and wheat is kept for longer periods in aerated rather than in non-aerated stores. Reliance on insecticide protection is very greatly diminished in aerated stores, and if all stores were aerated it would be possible to reduce the rate of insecticide treatments, at least in a proportion of the stores. The noise of aeration systems has been reported to be a problem in some storages.

Practical Application

The advantages of insecticide admixture are clear, particularly the fact that it may be used with poor storage facilities and makes very little demand for any modification of the simplest working practices. Insecticides are sprayed and dusted on to the moving grain as it passes along a conveyor belt or up an elevator. Application methods are still very simple, the diluted aqueous emulsion being applied with a pump.

Dr Desmarchelier has already spoken at this Seminar on the topic of insecticide application methods. There is no doubt that some upgrading of the insecticide application technology is necessary. It is probable that less insecticide could be used if it were applied more effectively, and particularly if the application rate were more accurately regulated to the amount of grain on the belt. Pumps are switched by mechanical, sonar, or infrared devices which detect grain on the belt and conversely stop the flow of insecticide when the grain flow ceases. By having a series of nozzles switched on sequentially through solenoid valves, it is possible to obtain some measure of regulation of insecticide to grain flow. There is often a big variation in insecticide levels on a mass of grain and this may persist over a storage. Metering pumps can be introduced which meter and mix the insecticide and water and eliminate the current practice of open dilution of concentrate with water. These pumps would be much more expensive, but would reduce the exposure of the operators to solvent and insecticide fumes. Dilution is the greatest source of error.

In considering insecticide application methods, it should be noted that methods which use atomisation, application in carbon dioxide (Wallbank 1981), and ULV methods tend to result in greater losses due to drift and vaporisation. The gravity feed method of Minett et al. (1981), however, simply dribbles the concentrate in a stream on the belt. The method is said to result in less exposure to the workforce and is used at some terminals in South Australia. Some problem has been experienced with it in terms of changes of flow rate with temperature and a metering or pumping device is therefore required. A recent comparison of deltamethrin application by gravity feed and conventional spraying (Webley, unpublished data) showed that the distribution was similar in both cases when 200 g samples were analysed. The coefficient of variation (standard deviation/mean) was 22% for the gravity feed and 20% for the conventional treatment. The gravity feed method, which reduces drift and workforce exposure in the terminal, must be further developed.

Choice of Insecticide

The insecticides currently available for use on stored grain are listed in Table 2. Pirimiphos-methyl and chlorpyrifos-methyl are the most widely used. Pirimiphos-methyl is registered as a grain protectant in many countries including the US, UK, France, and Australia. Chlorpyrifos-methyl is widely registered in Europe as well as in Australia and South Africa. The most persistent are pirimiphos methyl and etrimfos and these are also the most effective against mites. Chlorpyrifos-methyl and methacrifos are most effective against fenitrothion-resistant *O. surinamensis.* Methacrifos is persistent only at low temperatures and requires aeration for long-term protection. The organophosphates are not effective against OP-resistant *R. dominica.* Bioresmethrin at the low rate of 0.5–1 mg/kg, or alternative pyrethroids such as permethrin, give excellent control of this species, with permethrin also being effective against the greater grain borer (*Prostephanus truncatus*). The Australian Wheat Board Working Party on Grain Protectants has been carrying out

Table 2. Insecticides currently used for treatment of stored cereal grains.

Compound	ADI[a] (mg/kg body wt/day)	Codex MRL[b] cereal grain (mg/kg)	Half life (weeks) (30° 75% RH)	Application rates (mg/kg)
Chlorpyrifos-methyl	0.01	10	17–20	2.5–10
Pirimiphos-methyl	0.01	10	50	4–8
Fenitrothion	0.003	10	14–16	6–10
Etrimfos	0.003	10	50	4–8
Methacrifos	0.0003	10	7–8	10–20
Dichlorvos	0.004	2	1	5–12
Bioresmethrin	—	5	38	0.5–1
Permethrin	0.05	2	140	1–3

[a] Acceptable daily intake. [b] Maximum residue limit.

full, silo-scale trials on grain protectants since 1973 and much of the efficacy data supplied to FAO for the approval of these insecticides has been Australian in origin.

Apart from the development of resistance, residues are the other major problem which has to be accepted. All insecticides used have passed through the Codex Alimentarius approval system, with maximum residue limits (MRL) as given in Table 2. In addition, toxicologists in the US Environmental Protection Authority, the Australian National Health and Medical Research Council, and similar bodies elsewhere examine all the data before national registrations are approved. Despite these precautions, some countries are sensitive to the use of insecticides, and this is undoubtedly one of the major pressures for research into alternative methods not relying on residual chemicals. Many countries do not have the necessary legislation to allow this type of insecticide usage or the toxicologists to evaluate its relevance to their conditions.

The Australian Wheat Board runs its own laboratory and thereby carefully monitors residue levels, ensuring that these are always well below the approved limits. Insecticides must be used in a way that minimises residues in the final products. There is very close co-operation in Australia between millers and the Wheat Board and insecticides are not used unless the occurrence of residues has been examined in milling trials. This means that insecticide should be used at full rate only for long storage periods and where the earlier use of the grain is anticipated, lower rates should be applied. This introduces major operational difficulties if the grain is not moved within a short period, i.e. about 3–4 months. Retreatment of grain in a large horizontal shed can be expensive and logistically difficult.

Sealed Storage

The main alternative to insecticide admixture is the use of sealed storage and fumigation with phosphine and carbon dioxide. Participants in the controlled atmosphere symposium in Perth, Western Australia, in 1983 were greatly impressed by the progress that has been made with sealing technology which culminated in the use of carbon dioxide in a 300 000 tonne shed at Kwinana in October 1983.

At the end of 1984, Western Australia had more than 2.1 million tonnes of sealed storage and the project figure by the end of 1985 is 3 million tonnes, about 40% of the permanent storage capacity. In other Australian States, sealed storage is commonplace in metal bins and in PVC-covered bunkers. All new stores are being made to conform to gastightness standards. The methodology of sealed storage has been described by Banks and Ripp (1984) and in many other papers by Banks and co-workers. In 1985, more than 4 million tonnes of wheat were stored in some form of sealed storage. The costs of sealing are shown in Table 3 (Banks and Ripp 1984).

All future storage built in Australia will be sealable, whether it be sealed horizontal storage as favoured in Western Australia, or sealed bins or bunkers, which is the way sealing technology is developing in the eastern States. At present, the amount of grain treated with carbon dioxide is still very low. This is because use of phosphine is still competitive. However, the situation is likely to change with the development of methods for on-site generation of carbon dioxide, currently an area of considerable interest and research.

Fumigation in sealed storage by the method of application of phosphine generators on the surface of, or above the grain is elegant, inexpensive, and

Table 3. Typical Australian construction costs for three storage types, with additional costs of sealing and modification when the storage is initially built.

	Costs ($A[a])		
Storage type	Construction	Sealing	Sealing & modification[b]
Silo bin (concrete cylindrical 2700 t)	125	7.60[c]	7.25
Flat storage (metal roof, concrete walls, rectangular 27 000 t)	55	3.30	3.84
Flat storage with corrugated iron walls		4.0	4.35
Flat storage (metal roof, concrete walls, rectangular 300 000 t)		1.16	1.16
Welded steel bin			1.0

Sources: Co-operative Bulk Handling Ltd, Bulk Grains Queensland, and various sealing contractors.

[a] During May 1985, $A1 = $US0.65.

[b] Replacement of hatches with gastight systems, recirculation ductwork and fans, pressure relief valves, exhaust fans, electrical work as required.

[c] Bulk Grains Queensland gives $6/t for internal treatment of 2500 t concrete bins with high density acrylic.

virtually hazard free. Although initially a number of fires resulted from placing phosphine formulations immediately under very hot PVC sheets, a change of formulation, modification of the technique of inserting it, and choice of the best time of day have eliminated this problem and several years of use have shown it to be successful, at application rates of 0.5 to 1 g/t. Fumigation lasts for at least 28 days. The cost for the formulation is only 4–8 cents/t. Gas concentrations are regularly monitored and the concentrations needed for successful fumigation are well established. Sealed storage gives a very large measure of protection against reinfestation and has the advantage that refumigation *in situ* is possible at any time.

It is a major question whether sealed storage is appropriate for the humid tropics. If moisture migration and condensation occur, moulds and mycotoxins could soon follow. Prevention of this type of damage must be the first consideration for any storage system. The Australian experience seems to indicate that water damage only occurs when there is unchecked infestation or where water ingress has occurred.

During the development of bunker storage technology, water damage has occurred due to badly fitted, poorly sealed covers and when there have been delays in the start of fumigation. No such moisture problems have occurred in sealed horizontal sheds, nor in metal silos containing dry uninfested wheat. Much interest is being shown in the bunker storage method in countries with hot dry climates, for which it is ideally suited. Grain in sealed storage, of course, tends to be hotter than in ventilated or aerated storage. This is not a disadvantage for wheat, but for other cereals cooler storage conditions might be preferable.

Any form of chemical pest control must take into account the attitude of the work-force. In Australia, there are severe limitations on the use of fumigants at many of the major terminals. Workers object to evidence of the presence of fumigation residue, e.g. spent aluminium phosphide fumigant powder. One major advantage of the use of surface application is the avoidance of such residues. The limitations of detector tubes in monitoring the safety of work places is a major problem in the attempt to satisfy the work-force and achieve safe and effective working conditions. Automatic monitoring through the use of photoionisation detection systems is possible but extremely costly and some cheaper, more widely effective methods of specific gas detection at very low concentrations are urgently required. Many of the synthetic pyrethroids are well known for their irritant properties. This is a problem which needs to be solved before these compounds are used. Workers must also be prevented from exposure to fumes and solvent vapours, particularly in closed storages.

Rapid Disinfestation

Insecticide admixture is not ideal for rapid disinfestation before use or export. Dichlorvos is often used quite successfully for this purpose, but it is not desirable in the long term to rely on this method, both because its use has appeared to result in resistance and due to the high mammalian toxicity of the compound.

Bioresmethrin is not suitable for rapid disinfestation for *R. dominica* and there is an urgent need for alternative treatments. Most of the conceivable alternative methods for disinfestation have been well researched. The fumigation methods all take a few days. Carbon dioxide requires a minimum of 10 days and phosphine 7 days to kill all stages of *Sitophilus* spp. The new techniques of phosphine recirculation allow phosphine to be distributed in taller silos from surface or external application, but should not be used to justify shorter exposure periods or the use of phosphine as an instant method.

In the case of methyl bromide fumigation, the need for long aeration periods to remove the persistent residues also means that 3–4 days may be required for the fumigation. The future of methyl bromide is also uncertain on toxicological grounds. The only current method of 'instant' disinfestation is thermal disinfestation. The pilot plant, fluidised-bed disinfestation device described by Evans et al. (1983) is in the final stages of testing. So far, no adverse effect on grain quality has been noted and the method looks very promising. It is expected that a larger, in-line plant processing 500 t/hour may be the next step in the development of this technique. There is also work in Australia with a microwave disinfestor. The current plant is only at the 1 t/hour stage and scaled up costs appear to be discouraging, but the method would have much appeal. It is now believed that these methods should have an in-line capacity so that, if necessary, the whole consignment can be treated as it passes through a terminal. The estimated costs of these methods were given in Table 1.

The Australian Wheat Board has recently looked at disinfestation with accelerated electrons. This method is currently used only by the USSR on imported grain at the Black Sea port of Odessa. The electron accelerator uses very little electricity so running costs are low (Table 1) The main disadvantage is that at the dosage rates used, insects are sterilised but may not die for up to 6 weeks. Other matters which need to be addressed include the resistance of some consumers to the concept of irradiated food, as well as acceptance by silo operating staff.

Conclusion

An attempt has been made to give a brief overview of the current options for pest control in bulk stored grain. It apears that with open storage in warm climates, some use of insecticides plus aeration is necessary and economically viable. However, some form of sealed storage has generally been the final solution of storage problems for long-term storage and it is suggested that greater efforts should be put into investigating the possibilities for sealed storage in the ASEAN region.

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Use of Pesticides for Insect Control in Farm Storage

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Abstract

On-farm storage of grains has been studied in several countries and expert analyses have been published. Constraints to use of pesticides by farmers include: lack of availability, unfavourable cost-benefit, lack of information and knowledge on pesticide use and safety, lack of an effective extension service at farm level, rapid degradation of pesticides under tropical conditions and potential for insecticide resistance. Few data are available on actual use of pesticides by farmers. Three previously unpublished surveys which highlight the constraints to use of pesticides at farm level are discussed. Their findings suggest that future emphasis should be on strengthening extension services, on increasing the effectiveness of traditional control methods, and on reducing residual insect populations through sanitation.

THE emphasis on pesticide usage in developing countries is generally centred on practices in government stores and other large grain storage operations. Through government agencies, personnel working with stored grain can receive intensive training on the proper use of pesticides. Chemical supplies to these groups can be regular, although, in fact, this is not always the case. One or two knowledgeable people can direct the application of residual insecticides or fumigants to large quantities of grain.

Pesticide usage on-farm has received much less attention. Farmers are not conveniently located in one place for training purposes. Extension personnel are often assigned areas so large that they cannot possibly reach all of the farmers, transportation constraints aside. Chemical supplies are often erratic and their potency suspect. Knowledge of new insecticides moves slowly and ideas such as insect resistance and varying degrees of mammalian toxicity are beyond the understanding of farmers with a low education level.

Probably more than 70% of the cereal production in developing countries is stored on the farm. Most is kept for family consumption (McCallum-Deighton 1981). Are farmers using pesticides to protect this food supply? What kinds of pesticides are they using? How are the chemicals applied and in what dosages? Are these chemicals effective? In most countries these questions cannot be answered satisfactorily.

Several studies of on-farm storage of grains in developing countries have been published (Coyne, 1971; Giles and Leon 1974; DeLima 1976; Adesuyi 1977; Boxall et al. 1979; Golob 1981a,b,; and others). Pesticide usage at the farm level has been reviewed by Hall (1977), Schulten (1981), and Mphuru (1982). Reviews include types of pesticide, susceptibility of insect species, residual toxicity, duration of effect, treatment methodologies, alternatives, economics, and future needs. Most of these studies conclude that insecticides are not fully utilised by small farmers. The many constraints involved were also discussed by Hindmarsh et al. (1978).

Background to Pesticide Use on Farms

The traditional grain storage systems can give satisfactory results. Most farmers know how much grain must be produced and stored for family use. This amount includes an estimation of loss to insects. When storage time is short and traditional varieties with inherent insect resistance are grown, the use of pesticides may not be justified. Recent studies, which employed current loss assessment techniques, conclude that because storage losses on farms are lower than previously estimated, the

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introduction of pesticides is not practical under the existing conditions in Malawi (Golob 1984) and Nepal (Boxall and Gillett 1984).

Most authors agree that the introduction of high-yielding but insect-susceptible varieties, will motivate farmers to use pesticides to protect their increased production. As grain production increases, the farmer must have increased resources and information on how to build more adequate storage facilities and how to apply pesticides properly, and there must be a marketing system that gives the farmer incentive to sell. If a farmer has no economic incentive to change practices, then any amount of persuasion and demonstration is lost. Any missing link in overall government policy, such as lack of input from extension, unavailability of pesticide, or a poor transportation scheme, will slow or prevent the advance toward adequate production of sufficient high quality food. Changes in traditional practices should not be made independently (Tyler and Boxall 1984). An integrated approach is needed which includes feasibility studies on the technical, economical, and sociological impact of the change.

Effectiveness of insecticides in stored produce has been studied in several countries in laboratory and experiment station trials, but rarely are these carried out at the farm (Adesuyi 1978; Muhihu 1980; Hindmarsh and Macdonald 1980; Weaving 1981; Bitran et al. 1982; Ayertey 1983; Golob et al. 1983). The results vary depending upon the year, locality, species of insect, pesticides tested, and other conditions. Field trials using infestation from local insect residual populations give the best information on pesticides which can be recommended to the farmers. Treatment failures may occur during trials but reasons for loss of efficacy are difficult to assess. The reason most often given is insect resistance to the specific pesticide. Poor formulation and shelf-life degradation are other possible explanations for control failures. Local insect populations are seldom checked, as they should be, for resistance to the pesticides used in the field trials.

Insect resistance to pesticides is a current problem (Champ 1978). Pest control methods that do not give complete kill are prime systems for building resistance. Boshoff (1980) illustrated how this is related to on-farm storage in the humid tropics. Overall experience in Africa indicates that the exposed crib structure, which is vulnerable to adverse weather, results in rapid deterioration of insecticides. This results in a degree of control only, rather than elimination of insects.

It is understood that many of the insecticides recommended for stored grain degrade more rapidly under conditions of high humidity and temperature than under dry and cool conditions. Poor formulations and old insecticides also expose insects to sublethal doses of active ingredients. Incorrect application techniques compound the problem. The farmer, through poor education, may not be able to read and understand a label on a package of insecticide, if one is present. The farmer must be told by the manufacturer's label or by knowledgeable extension personnel what is safe for use on stored grain. If there is no extension service, no storage specialist, incomplete labelling, and all the concomitant problems we already know exist, the farmer can easily use the wrong pesticide, apply the correct pesticide in an incorrect or unsafe manner, or become confused and decide to use no pesticide at all. Other farmers are unaware of the advantages of pesticide use or are not willing to use them for various reasons. All of these situations occur in developing countries where pesticides are readily available.

Data from surveys which asked farmers about their use of pesticides in stored grain are difficult to find. Because of the lack of information on current practices and efficacy of pesticides in use, a questionnaire was circulated by the Tropical Development and Research Institute to workers in grain storage in developing countries (Taylor and Webley 1979; Taylor 1981). Personnel in 35 countries replied that non-availability, cost, inappropriate packaging, preference for other grain protection methods, and lack of knowledge of modern insecticides were the main restraints on use of pesticides in storage.

Surveys of Pesticide Use on Farms

The initial question remains: What pesticides, if any, are the farmers using? Three surveys from Costa Rica, Honduras, and Pakistan have collected pesticide use information.

(i) Costa Rica

In 1978, 300 Costa Rican farmers were interviewed throughout the country from areas including low and high altitudes, and humid and dry tropics (Reed, unpublished data). Among the farmers interviewed, 54% did nothing to prepare their storage structures (Table 1). Another 24%

Table 1. Preparation of storage structures before harvest by small farmers in Costa Rica.

Treatment	Percentage of farmers sampled
No treatment	54
General cleaning	24
Chemical treatment	22

Reed (unpublished data) 1978. Sample size = 300 farmers.

said that they cleaned the structure before harvest. Sixty-six farmers, 22% of those surveyed, applied chemicals to the structures. About one-third of the farmers stored treated grain. The pesticides that they used are listed in Table 2. Of the 22% using pesticides on the storage structure, 14% were applying malathion and 4% were fumigating with phosphine. Malathion was used on food grains to a greater extent than on the structure. Phosphine was used principally on beans.

Chlordane and aldrin, which have mammalian toxicities higher than pestitides currently recommended for use on stored grain, were applied to storage structures by 44 farmers (67%). The same organochlorine pesticides were used directly on rice, beans, and white maize. Some of the farmers stored maize with the husk intact, but others stored maize without husks. It is fortunate in these circumstances that traditional food processing methods often include washing and removal of the pericarp.

Table 2. Survey of farmer usage of pesticides in grain storage in Costa Rica[a]

	Percentage of farmers using pesticide[b]			
Treatment	Structure	Rice	Beans	White maize
Malathion	14	50	24	18
Chlordane	37	17	4	42
Aldrin	30	33	18	25
DDT	2	—	—	—
Ortho	2	—	—	—
Nuban	2	—	—	—
Phosphine	4	—	40	4
Other	4	—	—	3
Lime	5	—	13	9
No Treatment	78[c]		65[c]	

[a] Reed (unpublished data) 1978. Sample size = 300 farmers.

[b] Some farmers used more than one insecticide.

[c] Percentage of total sample.

Using lime is a traditional insect control measure in Central America. According to a postharvest project in Honduras, lime gives good control if used correctly (Anon. 1984). It is listed here as a chemical control measure. Of the 300 farmers surveyed, 65% used no chemical treatment.

Regional data on pesticide use in Costa Rica show that areas with high populations or large commercial farms have greater numbers of farmers applying pesticides to store grain (Table 3). Information on new agricultural techniques is more likely to be available in these regions.

Although pesticides were readily available in Costa Rica at the time of this survey, there was no special extension program on grain storage practices for the small farmer. The situation may have changed in Costa Rica since 1978, but no new survey data are available to document a change.

(ii) Honduras

The survey in Honduras was taken in 1981–82 (Proyecto Postcosecha, personal communication). Data in Table 4 also show a pattern of non-use of pesticide (25%) and use of the inappropriate chemicals (23%). Of the farmers sampled, 21% applied chlordane, aldrin, or DDT. Malathion was the most frequently used pesticide in spite of the evidence that it is no longer effective. Lime was used by 17% of the farmers sampled. The fact that pirimiphos-methyl is recommended but not available on the market illustrates a basic problem for many developing countries: supplies of pesticides

Table 3. Pesticide usage in Costa Rica by region.[a]

Region	Percentage of farmers who treat stored grain
Central (includes capital city; high population)	48
Pacifico Norte (many commercial farms)	44
Pacifico Central (small farms)	21
Pacifico Sur (small farms)	27
Norte (small and large farms, remote)	30
Atlantico (small farms for basic grains)	20

[a] Reed (unpublished data) 1978. Sample size = 300 farmers (105 applied pesticide).

Table 4. Survey of farmer usage of pesticides on stored grain in Honduras[a]

Treatment	Percentage of farmers sampled	Recommendation
Malathion 4% dust	27	Not recommended; gives 2 mo. protection only
Chlordane	11	Not recommended
Aldrin	4	Not recommended
DDT	2	Not recommended
Parathion	2	Not recommended
Lindane	2	No longer marketed
Phosphine	2	Recommended for use in metal bins
Chlordane + phosphine	2	
Chlordane + salt + water	2	
Malathion + salt + water	2	
Malathion + lime + water	2	
Malathion + salt + lime + phosphine	2	
Lime + water	13	Gives good control at 1 lb/200 ears of maize
Kitchen salt + water	4	
None	25	
Pirimiphos-methyl 2% dust	0	Recommended but not currently available
Fenitrothion 1% dust	0	Recommended but only recently marketed

[a]Anon. (1984) and personal communication. Sample size = 55 farmers.

are not reliable or consistent. The Proyecto Postcosecha is currently evaluating control methods used on-farm in Honduras.

The postharvest project has printed extension materials with recommendations for farm-stored grain. After a description of the storage structure, a series of steps is outlined encompassing preparation of the structure (cleaning, repairing, spraying with insecticide), and harvest practices (drying, selection of sound cobs, calculation of insecticide dose, application techniques, and clean up). Cartoons are provided as a simple explanation of the above practices. The metal silos have been used in Central America for many years but not always correctly. The project is promoting the use of metal bins in conjunction with phosphine fumigation. The approach taken in introducing the bins to a new area is a careful one and farmers receive thorough training in their use. Instructions are attached to the side of the bin so they cannot be lost. Proper grain drying and storage in the shade are emphasised as essential for successful storage in the bin. Most importantly, artisans in the village are trained to manufacture the silos to exact specifications. Improved joints, closures, and sealing methods have been designed. Loans are made available to the artisans through a village committee which oversees the business of manufacturing and selling the metal silos. Originally, a small number of villages cooperated in the project. Cooperators were carefully selected to serve as examples to other villagers. Farmers are now learning to use phosphine in a safe and effective manner.

The farmers using the silos are extremely pleased with the results. Whenever maize is removed from the bin it is inspected. Presence of live weevils is reason to refumigate. Most bins are closed so tightly that the larger and more damaging insects, such as *Sitophilus* or *Rhyzopertha*, cannot enter.

(iii) Pakistan

A 1983 survey of all types of on-farm storage practices in Pakistan was the source of data in Table 5. Thirty-six families comprised of 335 individuals from 17 villages were interviewed. Women in Pakistan farm families are traditionally responsible for the storage of food, especially cereal grains. They have learned from their mothers how to build a storage structure, how to winnow unwanted foreign material, including insects, from the grains, how to decide when the grain needs sun treatment for insect or mould problems, and how to use local plant materials, such as neem. These women receive little or no information about grain storage from external sources. They have no contact with extension personnel or researchers because of cultural restrictions. Husbands or brothers learned about the new techniques, such as phosphine fumigation from landlords, from other men in the village or,

Table 5. On-farm grain storage survey in Pakistan: control measures.

Treatment	Percentage of farmers sampled		Comments
	Punjab	Sind	
Sun-drying	38	40	Combinations of two or three control measures were used by 29% of the farmers in Punjab and 47% of the farmers in Sind.
Neem (green leaves)	—	40	
Mercury + sand	24	7	
DDT dust	—	23	
Phosphine	43	7	
No pesticide	24	19	
No treatment	10	13	

[a]Borsdorf et al. 1983; Wright (unpublished data). Sample size = 36 farmers.

less frequently, from an extension agent. They brought the phosphine tablets home for their wives to use with little explanation given. Sometimes the tablets were carried home in an envelope and not used immediately. Some women believed that phosphine came in powdered form.

Pesticide dealers had varying recommendations for use of phosphine. One dealer was selling tubes with the label in German. Another dealer did not know the recommended dose. He said the instructions were on the tube (in English). The literacy rate of farm women in Pakistan is 4–7%.

The women did not know the dangers of the fumigant or that it was intended for use in a sealed container. Grain is often stored inside the house (sometimes in the sleeping quarters) and fumigated there either in an unsealed bin or in jute bags. Insect resistance to phosphine under these conditions is probably inevitable.

In Pakistan, metallic mercury could be purchased as a grain protectant from a general merchant who sold traditional herbs. Shopkeepers recommended mixing 36 g of mercury with 36 kg of sand or ash for treatment of 100 maunds (about 37 kg/maund) of wheat. The women mixed the mercury into the sand by hand. The sand was then spread either on the floor of the storage structure or mixed with the grain. The sand was winnowed out of the grain before processing. Early in the storage season the winnowed sand was returned to the store, but later it was discarded in the yard. Elemental mercury vapours are toxic to insect eggs and small larvae but not adults (Wright 1944). The vapours are highly toxic to humans and readily absorbed through the skin, gastrointestinal, and respiratory tracts.

The stage is set for insect resistance to become commonplace in developing countries, especially if insecticides are promoted as a foundation of a control strategy without extension information. Early success with insecticides could lead to regular use and misuse. Traditional control and sanitation methods may be ignored or forgotten in the process. Regular use leads to dependence. A stable, in-country chemical industry is required to support this reliance. Regular use can also lead to insect resistance, control failure, loss of food, loss of chemical control method, and loss of confidence in extension personnel. It is important that farmers know how to use insecticides if they are to be promoted.

Critics of the use of pesticides are often seen as a threat to food supply. No method of insect control is likely to be permanent. An integrated program to protect grain stored on the farm is essential. It must include improved traditional methods, reduction of residual insect populations through sanitation, and education for farmers in the basic principles and problems of storing grain. This program must be implemented by a strong extension service with adequate resources to carry out duties at the farm level (Golob 1981a, b, c; and others). However, extension is not often well implemented in developing countries and has few links to research. The postharvest area is often ignored, field programs are understaffed, and personnel are underpaid. Extension efforts often fail to involve women, who in some areas do the majority of farm work, especially in postharvest activities.

The extension workers need to understand the importance of loss prevention in food storage. Training should involve hands-on techniques of insecticide application as well as pesticide safety and alternative methods for insect control. Extension personnel should use in-country grain storage scientists in the assessment of local situations.

It may be practical for extension workers to recommend pesticides for use if: (1) grain production has increased beyond the subsistence level and the purchase of insecticide is economical; (2) increasing the storage period increases the value of the grain on the market or allows grain to be kept longer in better condition; (3) storage losses are high due to some extraordinary circumstances, such as the introduction of a highly damaging pest, for example *Prostephanus truncatus* in Tanzania; (4) sanitation is practiced by the farmers; (5) suitable pesticides are available.

Summary

The use of pesticides for insect control in stored grain by farmers in developing countries is not adequately documented. Recent surveys in three countries show that 25–65% of farmers apply no pesticides to protect stored grain. Farmers who use pesticides often apply inappropriate and highly toxic chemicals to food grains. It is pointed out that a strong extension service with specialists in postharvest systems could alleviate these problems. Pesticides should not be the basis of insect control programs in stored grain, but a part of an integrated approach which allows timely and proper use of pesticides along with other alternatives, including (1) reduction of residual insect populations through sanitation; (2) prevention of the loss of traditional resistant varieties; and (3) improvement of the effectiveness of traditional control methods. We must safeguard the effectiveness of pesticides for future use.

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An Assessment of the Benefits and Costs of Pest Control in Humid Tropical Grain Storage Systems

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Abstract

Entomologists and economists have a mutual role to play in evaluating the benefits and costs of the introduction of pest control technology into storage programs in the humid tropics. In this paper, some simple economic models are examined in order to identify how both private and social costs/benefits can be analysed, using consumer and producer surpluses as measures of economic welfare for both static and temporal economic environments. The analysis demonstrates that storage operations, production and consumption of commodities over time, and pest control technology are interdependent, thereby necessitating a systems approach to determine optimal levels. An operational version of these models requires the specification of the extent to which pest levels affect yields, the nature of the substitution effects among pest control, and other inputs and external costs/benefits of increased pesticide use. These three research areas provide an agenda for future research so that application of the models can proceed towards determination of the most socially efficient pest management program for the humid tropics.

PEST control strategies are often strongly advocated as a means of reducing postharvest losses at the same time that increasing pesticide use will also increase the external costs associated with pesticides. An overall assessment of the impacts on social welfare of alternative pest management methods involves analysing the impact of pest management methods on processors, consumers of product, farmers, those who bear external benefits/costs, and those who pay for pest management. Each of these agents may respond in different ways.

In a static framework of analysis, increasing supply of a product may provide some gains to individual producers but if increased product supply as a result of widespread adoption of improved pest management methods results in lower prices and lower aggregate income then clearly the benefit to consumers of lower prices is offset by the reduced income to producers.

The paradox is that society itself may not benefit from improved pest management methods if the decrease in producer surplus more than offsets any increase in consumer surpluses. In addition, a change to an improved pest management method may result in input substitution effects requiring more intensive management, thereby raising the opportunity costs of management. External costs of pest management may also involve significant damage to the environment, resulting in substantial spillover costs in terms of degradation of air, soil, and water resources. Finally, the resource cost of the improved pest management may be particularly sensitive to changes in the external environment, such as sustained increases in oil and energy prices.

All of these factors must be taken into account in assessing whether society would be better off with or without the introduction of improved management of pests.

In a dynamic economic environment in which storage also takes place, the above factors, viz. producer and consumer surpluses, substitution effects, external costs, and costs of improved pest management, are time-related. Consequently, the leads and lags of adjustments which take place in response to a new pest control technology become important, as do the costs of maintaining inventories.

Optimal storage programs are therefore affected by improved pest management methods depending on the extent to which the stream of benefits and costs is influenced by the new technology. For

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example, a program to store a commodity from one season to another may be influenced by the extent of losses incurred during storage. Prices in successive periods may be higher than they would have been had losses during storage been lower. If storage losses could be reduced, then there would be lower storage requirements, resulting in savings in storage cost.

The main implication of the above discussion is that storage operations, storage costs, production, consumption, and improved pest control technology are all interdependent variables. Consequently, any assessment of the welfare implications of improved pest management must simultaneously analyse production, consumption, and storage in a systems framework by modelling the behaviour of these variables over time.

In the next section, a static or single-period analysis of production and consumption in the absence of storage is made to show how economic welfare changes when technology changes.

Following this simple analysis, a dynamic or time-dependent model is presented to show the implications on economic welfare when storage considerations are involved with or without changes in pest management technology. To make these models operational entomologists must provide further biological information in certain specified areas. An agenda for future research, including the necessity for a close interaction and collaboration between entomologists and economists, completes the discussion.

A Static Model of Economic Welfare

Economists have for some time used the concepts of consumer and producer surplus to evaluate the impacts on economic welfare and distributional effects of a change in consumption or production. In particular, welfare impacts of changes in technology have been analysed by Akino-Hayami (1975).

In Fig. 1, the consumer surplus *(CS_0)* and producer surplus *(PS_0)* are shown for a market in equilibrium at prices P_0 and quantities traded O_0. The surpluses represent the amounts producers and consumers have left after trading takes place and this depends critically on the relative slopes of the demand and supply curves. Figure 1b represents the changes which take place in the distribution of the surplus among producers and consumers when quantities traded expand as a result of an increase in quantity supplied stemming from an improvement in pest control. Consumers gain the area P_0abP_1, while the benefit to producers is the area P_1bd less the loss in producer's surplus, P_0ac. The change in gross benefit is the area *abcd.* To obtain the net effect on social welfare, any spillover costs and resource costs involved in the improved pest control technology must be deducted from the change in gross benefit.

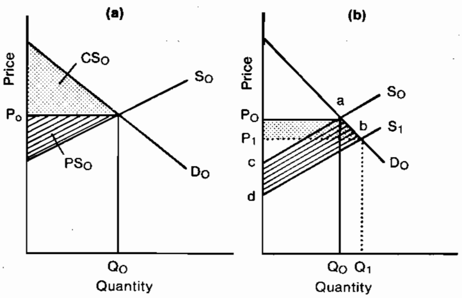

Fig. 1. Model for determining the net benefits stemming from an increase in supply of a commodity.

(a) Distribution of surplus between producers and consumers before change in supply.

(b) Change occurring in distribution of the surplus when quantities traded expand as a result of an increase in quantity supplied stemming from, for example, an improvement in pest control.

See text for explanation of symbols.

The above analysis demonstrates that to determine whether adoption of any new pest control technology will be economic in terms of its net benefit to society as a whole requires comprehen-

Table 1. Summary of benefits and costs in evaluation of pest control technology.

Benefits	Costs
To consumer— lower prices as a result of increased supply.	*To consumer —* potential irreparable damage to resource base stemming from increased pesticide use.
To producer — aggregate income increased by expansion of supply.	*To producer —* (1) increased substitution of management inputs for conventional pesticide control programs. (2) direct resource cost of increased pesticide usage.

sive evaluation of consumption behaviour, responses of producers to changes in pest technology, and spillovers, as well as the direct costs of the new technology. The benefit cost assessment is summarised in Table 1.

Extensions of the Basic Model

The foregoing analysis is suitable for assessing the effects on welfare of a change in technology increasing aggregate supply at the national level assuming that the domestic market remains insulated from the world market.

If the price of the commodity is affected by world market conditions then the analysis needs to be extended to take account of supply response in the rest of the world. Edwards and Freebairn (1982) have developed such a model, which includes regional as well as rest-of-country effects. They consider that the form of supply shifts has an important influence on the aggregate welfare effects. Their analysis suggests that a divergent supply shift (compared with parallel shifts), together with an increased demand, is particularly conducive to the creation of producer losses, a paradox alluded to earlier.

Distribution of Benefits — Who Pays?

At the level of the individual producer, the economic efficiency of any pest control measure depends on whether the extra benefits or returns obtained from control offset the additional costs involved. The point at which extra returns equal extra costs incurred defines the optimum or economic threshold of pest control, a concept first developed by Hedley (1972) and later extended by Hall and Norgaard (1973). It is feasible to define economic thresholds for specific control measures, and particular pests and products. The economic threshold level recognises that there will be some losses above which control becomes uneconomical.

While the individual producer may benefit as a result of his own actions, the aggregate level of which is reflected in the producer surplus, the wider community may in fact incur social costs as a result of the misuse of pesticides inducing pesticide resistance or destroying natural predators. In addition, all producers can benefit (or at least have the opportunity to benefit) from investment in research and development activities which are usually publicly funded. The ultimate distribution of costs borne by the public and producers will be in the same proportion as the benefits, regardless of the initial share of costs. Governments, through intervention in domestic markets to stimulate domestic production by high guaranteed prices relative to border prices, subsidies on fertilisers, seeds or pesticides, and large-scale public funding of spraying programs may themselves create additional social costs requiring greater government subsidy than would be the case without intervention (see Chen and Ci 1982).

Storage and Pest Control Programs

The conceptual framework presented above demonstrates the use of consumer and producer surpluses to analyse welfare impacts of pest control programs at the aggregate level. Because space and time considerations are ignored, the benefits accruing to society from pest control programs will tend to be overstated.

In situations where storage takes place between two time periods, the optimal level of storage is where the price difference between two time periods is equivalent to the cost of storage. This situation is depicted in Fig. 2a. The benefits accruing to the storage programs relate to the changes in consumer and producer surpluses between the two time periods. Thus, in period 1 (surplus), consumer surplus is reduced while producer surplus is increased. In period 2 (deficit), consumer surplus is increased while producer surplus declines with quantity stored. The benefit from storage is therefore represented by the addition of excess demand (D_2–S_2) and excess supply (S_1–D_1). The shaded area (Fig. 2b) represents the benefit resulting from transferring 'a' units from the surplus period to the deficit period. A much more comprehensive analysis within this framework has been published in the World Bank Working Papers series (Anon. 1970).

When storage costs are included, excess supply is reduced. On the other hand, excess supply is further reduced if deterioration occurs during storage. Both these actions seem to reduce the benefits of storage. Benefits from storage are therefore derived from:

- transferring consumption among periods;
- transferring production among periods;
- increasing the overall level of quantity produced and consumed.

The benefits and costs of storage programs are

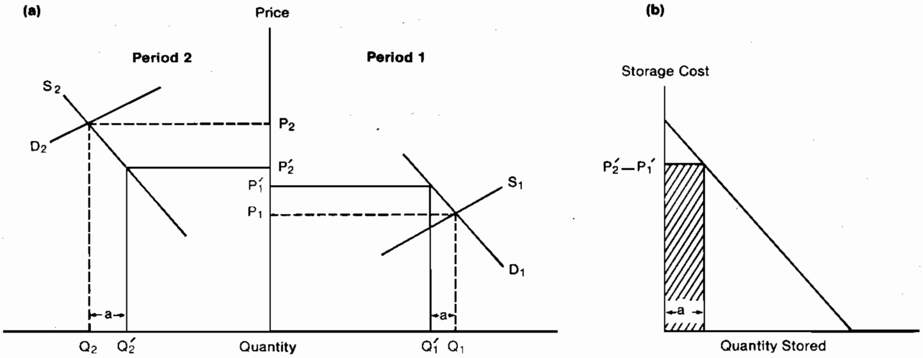

Fig. 2. Two period model of storage benefits, with zero transfer cost. See text for explanation.

Table 2. Elements of costs benefit assessment of storage programs.

Benefits	Costs
Excess supplies	Storage costs
Excess demands	Pest control costs

indicated in Table 2. A model which incorporates all these elements can be used to determine the optimal levels of consumption, production, and storage for given storage operations and supply and demand functions in each period. In situations where demand and supply is elastic, the real income per unit of storage is reduced to a simple analysis of determining the expected price difference, from which must be deducted storage costs and pest management costs for a given storage capacity.

Agenda for Future Research

The objective of any research program in this area should be to work towards a system which determines the optimal levels of storage, pest control technology, production, and consumption of each commodity. All of these variables are interdependent and hence a simultaneous solution to the problem is required. This is indeed a very complex but challenging problem, as was recently recognised by Hedley et al. (1980). The conceptual framework for such an analysis at the aggregate (or regional) level in terms of maximising net social welfare is already widely used by applied economists.

There is a shortage of data in a number of areas, including:

- specification of storage and production functions including pest control;
- incorporation of risk in pest control measures;
- inter-temporal aspects of pest control technology.

Economists typically express production as a function of variable and fixed inputs. Hence, in the case of pest control, production would be expressed in terms of level of pest control. A more realistic production function for pest control is to express yield as a function of pest levels which in turn can be expressed as a function of pest control inputs. The bundle of pest control inputs is substitutable with other productive inputs such as materials, services, labour, and management, as well as varietal selection for pest resistance.

In an inter-temporal environment the relationship between yield and pest level will also include temporal dynamics to take account of the variations in crop yield resulting from variation in pest population level over time. Both these tasks — the quantification of the impact of pest population levels on output and pest control methods on pest populations — are the prime responsibility of biologists. A third and related task for the biologist is to develop models of temporal dynamics of crop yield and pest levels.

On the other hand, the economist is responsible for assessing the substitution effect of pest control methods with other inputs of the farm, the externality costs of pest management programs, and the role of risk in pest management methods.

Finally, both economists and biologists should elicit the support of system scientists to develop a holistic view of pest management. Pest management is only useful and important when it benefits mankind.

Concluding Remarks

Storage programs and optimal levels of pest control technology will differ according to whether the analysis of benefits/costs is in terms of the individual or society as a whole. At the level of the individual producer, storage programs relate to the private benefits in terms of the anticipated net revenue accruing to the producer based on the expected price differences. The actions of a single producer will not influence demand and supply conditions in an industry. However, the actions of the individual producer although profitable may result in spillovers with widespread social and resource costs. These spillovers may include degradation of the resource base, increased resistance of pests to pesticides, and destruction of natural predators.

The holistic view of pest control technology needed to evaluate its impact on net social welfare includes the simultaneous determination of optimal storage operations, consumption and production over time, and optimal pest control. To make models incorporating these variables operational requires the collaboration of biologists, economists, and systems analysts. The problem is complex and recurring, but the challenge of empirical resolution remains.

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Integration of Chemicals into Storage Systems

Session Chairman's Summary

L.J. Fredericks*

THIS session comprised three papers, each dealing with various dimensions of the use and application of pesticides in storage systems.

Webley outlined the Australian system for the protection of bulk wheat to a standard of a nil tolerance for live insects. This was achieved either by the admixture of grain protectants supplemented by aeration, or fumigation in storage with a high degree of imperviousness to gas leakage ('gastightness'). The paper briefly reviewed the use of grain protectants in other countries and also the possible alternative technologies available. In the humid tropics, the use of insecticides plus aeration is necessary and economically viable. As a solution to long-term storage of grains in the tropics, however, more effort is needed to investigate the potential of sealed storage.

Wright discussed the use of pesticides in systems for small-scale storage of grain and described the situation for several countries based on survey data. She emphasised that few resources were available for the study of pesticide use in on-farm grain storage facilities despite its clear importance to reduce grain losses. Traditional storage systems are generally efficient but the introduction of pest-susceptible grain varieties requires an integrated approach for which many problems have to be surmounted. Such an integrated approach would not advocate the use of pesticides as the basis of insect control programs in stored grain. It would include (1) the reduction of residual insect populations through sanitation; (2) prevention of the loss of traditional resistant varieties; and (3) improvement of the effectiveness of traditional control methods. A strong extension service with postharvest specialists would be necessary in assisting small farmers who often apply inappropriate and highly toxic chemicals to food grains.

Ryland stressed the mutual roles that could be performed by entomologists and economists in this exercise. He presented simple economic models to quantify the private and social costs and benefits of pest control technology in storage systems under static and dynamic situations. To determine optimum storage levels a systems approach is necessary, emphasising the interdependence of production and consumption of grains over time and pest control technology. To determine the most socially efficient pest management program for stored grains in the humid tropics, the following data are required: the extent to which pest levels affect yields, the nature of the substitution effects among pest control and other inputs, and external costs/benefits of increased pesticide use. These three areas would constitute the future research priorities for economists.

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An extrapolation of the discussion of the three papers would bring out three main recommendations:

1. For the humid tropics, more research is necessary to evaluate the optimum pest control technologies for grains in bulk storage for short and long periods.
2. It is apparent that insufficient consideration has been given to formulating the appropriate pest control technologies not only for on-farm grain storage but for other storage facilities in the postharvest handling chain.
3. The role of the economist in formulating socially desirable pest control systems for grain storage in the humid tropics is complementary to the research efforts of entomologists and other scientists concerned with this problem.

Conclusion

Summary of Recommendations

IN arranging the program for this seminar, the organisers endeavoured to achieve a balanced presentation that involved all personnel concerned with developing an adequate pesticide technology. It was felt that these personnel should be exposed to the activities of the others and given the opportunity to interact.

The objectives of the seminar were:

(1) to define current pest problems and use of pesticides in humid tropical grain storage systems;

(2) to review the adequacy of the current circumstances in which the pesticides are used, and examine and make recommendations on the constraints to user and consumer acceptance of pest control systems involving pesticides;

(3) to review the relevance of current research on pesticides and identify research needs and priorities;

(4) to review the adequacy of current approaches to pest control and the technologies involved, and identify the directions in which further development should proceed.

On the first day, the pest problems of the countries in the region were identified and current use of pesticides was outlined. The following speakers then examined some of the constraints to use of these pesticides, the general role that pesticides were expected to play, and attitudes to their use in the community.

The papers presented on the second day of the seminar briefly outlined some of the basic research support that is in progress to enable both residual pesticides and fumigants to be used rationally and effectively.

On the following day, the framework in which the pesticides are to be used was established and the major treatment techniques available were critically examined.

On the final day, the seminar discussed how pesticides are integrated into storage systems, both in centralised facilities and on farms. The last paper was a very relevant outline of assessment of cost-effectiveness of the different control measures.

Proposed Action

It was gratifying that the governments of the region have established a viable regulatory process for pesticide use in their countries. *Dr Magallona, Mr Snelson,* and *Mrs Gaston* outlined this very eloquently to us, and I am sure that what they said provides a basis of reassurance that should put to rest any doubts as to the acceptability of pesticides in the region.

A major issue that has emerged repeatedly during the meeting is the necessity for a commitment by all involved in the grain industry to develop and use sound technology that is properly based and conscientiously implemented. I am sure that we all agree with this and will leave here with such a commitment and do all in our power to inspire such a commitment in the others with whom we work.

There will be considerable advantages to the region from the collaborative analytical program being developed in the pesticide studies under the ACIAR Grain Storage Research Program. *Dr Desmarchelier* outlined the proposals for this collaborative program, and participation by groups outside the ACIAR program is commended. Such a program will materially assist the countries participating, both individually and regionally, in developing rational and effective control programs based on pesticides. I would thus encourage any organisations outside those working in the ACIAR program to contact *Dr Desmarchelier* at the earliest opportunity.

The proposal for developing a code of practice for fumigation in the region is commended. There is no doubt that gastightness of structures must be an integral part of this code of practice. The necessity for this was emphasised and supported by reference to the consequences of fumigating in substandard facilities, as in Bangladesh, where high levels of resistance to phosphine have been generated in a range of pest species. Similarly, exposure times are critical and need to be optimised. The recommendation that ACIAR convene a working party to draw up such a code of practice for fumigation in the region will be implemented immediately on receipt of indications of support by the relevant organisations in the region and will involve appropriate representation of all interested parties.

The other various recommendations made by our session chairpersons are contained in the various reports.

There is common ground in the recommendations for increasing the research activities in the region and, in particular, for consolidating a research base within each country's own research organisations, universities, and other training institutions.

The importance of establishing pest monitoring and loss assessment programs has been emphasised. The recommendation for increased pesticide resistance monitoring is timely and should be acted on by all who have responsibility for developing control programs involving pesticides.

Dr Bengston has described how resistance monitoring is an integral part of ACIAR activities in developing integrated pest control programs in the region. Pest management and systems approaches to pest control constitute another theme running through the discussions and recommendations. This is to be commended and, it is to be hoped, implemented by all of us.

It is reassuring to have cost-benefit assessments introduced into our activities. I am sure the one paper on this topic we have had today is the forerunner of an increasing involvement by economists. Certainly, the next seminar in which the ACIAR Grain Storage Research Program is involved will have a full session on socioeconomic aspects.

B. R. Champ
Coordinator
ACIAR Grain Storage Research Program

Closing Remarks

I am deeply honoured to be given this opportunity by the organisers to deliver a few closing remarks at the Seminar on Pesticides and Humid Tropical Grain Storage Systems. There are among the participants persons much more qualified to deliver the closing remarks, of that I am mindful.

I am unsure whether my closing comments are intended to be the final words on the use and application of pesticides in humid tropical grain storage systems. What I am positive about, however, is that they will be the last official words spoken if not heard at this seminar. Within that context I must say that I am happy as it may be foolhardy if not downright dangerous for an economist turned project manager to have to maintain a dialogue dominated by scientists.

In these last four days, we have heard (and probably not all understood) the 29 papers delivered in well-structured sessions. These began with the appropriateness of and constraints on the application of pesticides in humid tropical grain storage systems, then moved in sequence to the background of pesticide research, the framework for the use of pesticide treatment techniques, and the integration of chemicals into storage systems. To a very large extent, this seminar has achieved the three goals set out for it in exposing the subject area to a wider and deeper scrutiny by natural scientists in particular. Such a focus is opportune in view of the increasing productivity and production of grain in the humid tropics and the need to store grain for a longer period than before.

I would like to seek your indulgence in raising a few points which have impinged upon me as a non-scientist participating in this seminar and having some experience with development projects involving grains postharvest handling in ASEAN.

1. There are great benefits that could accrue to our countries by emphasising and practising the relatively simple guidelines in the design and maintenance of grain storage systems to reduce and minimise insect and other infestations. Frequent travel around ASEAN has repeatedly shown that bulk grain storage operators in particular are rather lackadaisical towards precautionary, sanitary, and other measures which could avoid unnecessary losses due to birds, rodents, and other pests. On the other hand, it is ironical that we in the region are struggling to keep abreast of the latest scientific and technological developments in the area of pesticides and stored grain systems.

That being said, I would not deny the significance of undertaking research into the scientific processes and consequences of the use of pesticides in stored grain in the humid tropics.

2. Like other environments, system components have an interrelationship that could influence various outcomes. In the grains postharvest handling system, storage (in particular, bulk storage) represents the next to last point before grain is exported or consumed. If sufficient care has not been exercised to minimise pest infestation at various stages before bulk storage, then in-store bulk systems are overburdened, leading to unnecessary costs and grain losses. Thus the need, stressed by many speakers, for an integrated pest control system.

3. My third point pertains to what economists live on and breathe by — the allocation of scarce resources to points in the post production handling chain associated with the largest losses due to poor handling practices. It is not clear that pesticide research resource allocations in stored grain systems are related to points where most grain is being lost to pest infestation or by other causes altogether. Research priorities and research allocations in non-Asian grains systems may not readily correspond with regional needs (assuming these are known in the first place).

I am relieved, however, that scientists are beginning to recognise the contribution of economists in modelling holistic systems, bringing together scientific, economic, and social variables.

4. More of the seminar papers, it appears, have focused upon or been related to bulk storage systems managed by government agencies. Grain storage within our regional systems is, in effect, decentralised to different points in the postharvest handling chain, and consists of various quantities stored in dissimilar structures and under disparate levels of management. How pesticides behave under varying storage conditions is an eminently researchable topic in our region.

5. Lastly, I am struck by the fact that, barring six papers (four of which describe country situations) the remainder reflect research by non-regional scientists and technicians. Much of the discussion generated by the excellent papers has been prompted by those not from our region. Also, the private sector, which is quite well represented in this seminar, has not articulated or questioned the relevance of the research presented in this seminar to their business concerns.

It may be well worth our while, during our respective journeys home, to ponder why the state-of-the-art thinking and technologies on pests and grain storage in the humid tropics have not evinced regional comment and counterpoint. Is it, as one speaker has pointed out, because of the limited pool of expertise available in the region and the lack of research leadership? Is private trade in the region unmindful of the costs and benefits of new technologies in pest control in grain storage systems? I would like to think that there has been a great deal of discussion by participants from our region outside the formal sessions of this seminar and that this has made up for their 'official silence.'

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