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THE CONTROL OF PESTS IN STORED CEREALS

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ABSTRACT

This paper reviews current practices and research into UK storage of cereals, with particular emphasis (100 references) on the control of insect and mite pests during storage.

The presence of insects and mites in stored cereals is undesirable for a number of reasons. They cause direct damage by feeding on the seeds, thus reducing weight and viability. They create pockets of heat and moisture that not only aggravate the pest problem by optimising breeding conditions, but can also prompt fungal germination and consequent microbial spoilage, premature sprouting of the grain and compaction into solidified masses of unusable grain. Additionally, there is a commercial aspect in that many contracts for delivery of bulk grain specify "no live insects" or an acceptance threshold level of mites. Pest presence thus becomes a bargaining point, irrespective of any damage to the grain. Downgrading of the quality, loss of contract, or the incurring of disinfestation, transportation and demurrage charges are the usual result. Regular surveys are required to determine the extent and the importance of pest infestation of storage premises, and to gain information on the storage and control practices used.

Correct storage conditions are necessary for preserving the quality of grain in store, particularly in regard to cleanliness (freedom from old infestations), and the temperature and moisture content of the grain intake. Early DETECTION of pests is essential if remedial action is to be swift and effective. Several detection methods based on trapping and screening, are discussed, together with an assessment of their effectiveness. More work is needed on developing the full potential of detection systems and, importantly, on interpreting their findings in order to choose the most appropriate PEST CONTROL STRATEGY.

Once a pest is found, knowledge of the BIOLOGY (life history) and BEHAVIOUR are

necessary, both for diagnosing the damage potential and for deciding on the most suitable control measure. Not enough is currently known about the behaviour of grain storage pests in the store environment, particularly where pesticides are being used.

CONTROL STRATEGIES are discussed in detail and range from essential hygiene and cleanliness, through careful drying and cooling of the grain on intake, and manipulation of the store environment (temperature, humidity and atmospheric gas composition), to the use of insecticides and fumigants or more pest-specific control agents such as the insect hormones. These treatments may be applied to the surfaces (FABRIC) of the store building or may be ADMIXED with the stored cereal to give longer-term protection. Fumigation confers no protection during storage. Further work is needed on the effects of drying, cooling and aeration on pest populations and on the limitations (if any) of ambient aeration as a means of control. Information is also needed on the doses of pesticide achieved on fabric and cereals in practice and there is considerable scope for improving the application equipment to ensure accurate dosing.

The reviewers conclude that the best storage stratagem is that of INTEGRATING the foregoing aspects of pest detection, aeration of the grain using ambient air, and monitoring of pest presence, and the temperature and moisture of both grain and store. Such an approach can give early warning of problems and it is then possible to remedy the situation before infestation becomes serious, and thus REDUCE THE USE OF PESTICIDE TREATMENT TO THE ABSOLUTE MINIMUM or to do without pesticides altogether.

Certain PROBLEMS arise as a consequence of present control practices dependent on pesticides, most notably the occurrence of pesticide RESIDUES within treated commodities and the RESISTANCE of pest species to pesticides. Other reasons for pest control failure such as inadequate treatment with pesticide are discussed.

With the introduction of the Food and Environmental Protection Act (1985) provision was made for the control of pesticides (Control of Pesticides Regulations) in 1986. These set out requirements for the storage, sale, supply and use of pesticides and in 1988 a statutory system of maximum residue limits was introduced for 64 pesticides on 34 commodities including cereals (but excluding rice). The implications of these requirements are discussed in the light of present pest control practices in grain storage premises.

The review concludes with a final section in which a number of recommendations are made for future research and development to provide solutions to the problems which have been identified.

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DEFINITION OF TERMS

By "pests" the reviewers mean invertebrates such as mites and insects that pose a problem to the grain trade and either the threat or the reality of economic loss, as a result of their presence or activities. These losses may be physical, in terms of a gross weight loss due to damage; or they may be "cosmetic" in that they involve infringement of a contract specifying either "no live insects/mites" or an acceptable level that must not be exceeded. This review does not cover moulds and fungi - except *en passant* as a consequence of insect or mite infestation; nor does it cover vertebrate pests (mammals & birds).

The classic definition of a grain pest is a species of insect or mite that, if allowed to develop unchecked, will reduce the quality of grain by physical destruction or contamination by waste products. This definition has to be modified to include pests whose development will create an environment in which other agents of biodeterioration can thrive and cause damage to the grain. An example of a pest in the first category is the Grain Weevil, *Sitophilus granarius*, which can reduce the weight of grain by 10% in 12 weeks. The Saw-toothed Grain Beetle, *Oryzaephilus surinamensis*, which can reproduce rapidly in grain and create sufficient metabolic heat to start a cycle of grain heating, falls into the second category.

A more practical definition of a pest is an insect or mite whose presence is likely to result in a financial penalty for the producer or seller. Such pests and the situations in which they occur are far more difficult to list. For example, a few insects in a bulk of cool grain would be considered of no importance if the grain were to be used on-farm. However, those same insects could result in grain being rejected when offered for sale into Intervention, resulting in non-recoverable costs of up to £10/tonne for the seller. In the same way, species that cannot harm grain or cause heating may be perceived as pests if the buyer of grain refuses to accept them. This situation may often be complicated by other market forces such as price or level of supply and the acceptability of some species will vary accordingly. Often the only safe advice to offer on the subject is to present grain to the market place with no live insects or mites. Providing control measures to fulfil such advice presents numerous difficulties for advisers and research workers alike and will be commented on in more detail later in this review.

By "control" is meant the application of remedies or changes in storage practice that will result in reducing insect or mite infestation to a non-detectable level, or to a level that will not result in any economic penalty or loss of quality during continued storage.

On some occasions control measures may merely involve taking action that stabilises pest populations at their current level but does not reduce numbers. This can offer cost-effective control in some circumstances, particularly long-term storage. Therefore detection and monitoring of pest presence should be a crucial part of modern store management.

We also need to define two terms used in the application of pesticide to effect pest control, namely <u>fabric treatment</u> and <u>admixture</u>.

Fabric treatment involves the application of pesticide to the structure of the store: walls, ceilings, floors and into cracks and crevices of the building; also application to the outer and inner walls of storage bins/containers; but not to the grain itself or to bagged commodities. Clearly any grain or commodity in direct contact with a treated surface will be contaminated by the pesticide deposit to some extent but the resultant mean levels of residues are likely to be almost undetectable.

Admixture is the technique of mixing pesticide intimately with the grain, usually as it goes into store -by application of dust or spray to the augured seed- but sometimes to the bulk in store, either when it is being turned or transferred to another bin or -exceptionally- by digging-in a dust formulation.

Surface treatment is a limited form of admixture, where pesticide spray or dust is applied to the surface layer of a grain bulk only; it may or may not be mixed in manually to the depth of a few inches.

1. INTRODUCTION

Many species of insects and mites have been recorded in grain stored in the UK. Wilkin and Rowlands (1988) covered this topic in detail in their review but some data are worth repeating here to provide background information about the range of pests that trigger control measures. It is also important to stress that differences between pests may require a range of control techniques because susceptibility to chemicals will vary; similarly, differences in biology may necessitate different approaches to physical control measures.

The stored grain insects can be divided into two groups: those which can be regarded as endemic and those that have been imported into the country via international trade. A common feature of both groups is that neither attack the crop in the field. Therefore, the majority of insect infestations stem from residual populations surviving in stores or being transferred between stores. This transfer is not limited to premises within the UK and there is ample evidence of a constant flow of pests being imported into the country and distributed to farms and grain stores via components of animal feed (Wilkin and Hurlock, 1986). Exceptionally some fungus feeding beetles are found in a wide range of environments outside grain stores, and they may actively move into grain at certain times of the year.

Most of the mites that infest stored grain are also found in a wide range of habitats and may be distributed by the activities of man, rodents or birds. However, there is very little evidence to suggest that any of the damaging pest species are found on the crop in the field.

Detailed listing of the species of insects and mites found in grain stores and stored grain can be found in recent survey data (Griffiths *et al.*, 1977; Prickett, 1988).

Changes in the UK grain trade and elsewhere, many of them as a result of membership of the EEC, have been identified and discussed in a previous review in this series, "The biodeterioration of stored cereals" (Wilkin & Rowlands, 1988). It is necessary in the UK to store grain, both on farms and in specialised premises, sometimes for considerable periods, thus allowing opportunity for damage by insects, mites and fungi. This necessity, coupled with the increase in cereal production, trend toward surplus, and a consequent tightening of quality standards applied by traders and end users, has led in turn to an increased use of grain protectants generally, but particularly in commercial stores where the cost of a prophylactic treatment is viewed as cheap insurance against pest problems. The majority of commercial grain stores (96%) use pesticides, with 91% using some form of fabric and/or grain treatment, such that 54% of the grain passing through commercial stores is admixed with pesticide (Garthwaite *et al.*, 1988).

In the twelve English counties having the largest areas of cereal grown, the percentage of farms storing grain that used insecticides in their grain stores rose from 28% in 1966-67, to 54% in 1984-5 (Taylor & Sly, 1986). On large farms - those growing more than 75 hectares of cereals - the percentage rose from 42% to 76% over the same period.

For all the increasing use of insecticides, only recently has there been any evidence of a decline in infestation rates (Prickett, 1986). In 1977 it was estimated that 13% of farms in the twelve counties were infested with one or more species of the major grain pests (Anon, 1981; Hurlock & Jefferies 1980), *Oryzaephilus surinamensis* occurred in 10% of stores. An examination of 129 farm grain stores in East Anglia in 1980 showed that 8.5% were infested with grain pests, with *O. surinamensis* occurring on 7% (Wilson, 1983). In Wales in 1986 of 102 premises (95 were farms) *O. surinamensis* was found in 10%. More recently during 1987, a survey of 742 farms in England (Prickett, 1988) showed infestation by *O. surinamensis* to be around 5%, though some of this decline may have been due to the severe 1986-87 winter. Mites were found in 72% of the farm stores during this latter survey.

Surveys of commercial grain stores have not sought any information on infestation rates, only on pesticide usage. Thus in 1977-8 it was calculated that 21.6 tonnes of active ingredient were used proportional to the total 6M tonnes of grain in store. In 1985-6 the corresponding figure for 18M tonnes of grain was 55.1 tonnes. During 1988 a survey of infestation in commercial grain stores was carried out, jointly funded by the HGCA and by MAFF.

Taylor & Sly (1986) estimated that of the 23M tonnes of grain harvested in 1984, 90% was stored for a period of time in a farm grain store. With a store infestation rate of 10% for *O. surinamensis* alone, this suggests that over 2M tonnes were at risk, equivalent to the total tonnage of grain requiring phytosanitary inspections prior to export from the UK in 1984-5 (Wilkin & Hurlock, 1986).

Currently the "grain trade" seem complacent about the rejections of grain due to insect presence. Representatives on a recent MAFF/AFRC Research Consultative Committee (Smith, 1988) affirmed the response to a limited trade questionnaire that rejection of grain by merchants due to insect presence is now "probably less than 1%". The MAFF survey of farm grain stores indicated farmer awareness of a rejection rate by buyers of about 4-5% (Prickett, 1988). Intervention stores attributed 16% of rejections to insect presence in 1987-8. Decrease in the interception of infestated grain destined for export from the UK is apparent in the change from a 22% infestation level in 1981 to about 5% in 1986.

The improvement (reduction) in the overall rate of rejections is probably due to the widespread use of pesticides in both prophylaxis and disinfestation of premises.

However, other chemical and non-chemical methods can be employed to prevent or to control infestations in stored grain, and public pressure for pesticide-free cereal products will surely contribute significantly to the concern about the widespread use of contact insecticides in grain stores. Legislation, both within the EEC and as a result of the Food and Environment Protection Act (1985), which sets Maximum Residue Limits for pesticides in cereals and cereal products under the Control of Pesticides Regulations (1986) may add to the inducements to find alternatives to chemical control.

Some alternatives have long been available but are often intrinsically more expensive to carry out than a fabric treatment or an admixture with pesticide costing but a few pence per tonne.

Storage structures can be cleaned and the incoming grain can be dried and cooled, and maintained at low temperatures via ambient aeration using the chill of the English winter. This can reduce infestation to an extent that only surface application of pesticide may be necessary. Such a strategy is satisfactory for grain stored for on-farm use, where a few surviving insects pose no threat, but the ability of beetles to survive exposure to temperatures well below their breeding thresholds, can allow sufficient survival to create marketing problems. In any case reduction in moisture content is one of the most expensive control options. Extensive replacement of the oxygen in the storage atmosphere by carbon dioxide, nitrogen or burner gas (modified atmospheres) has shown potential for controlling infestation, even at low temperatures. It can also be competitive in price, certainly with fumigation, but needs further development as a practical technique. Fumigation is costly and often difficult to use successfully except in purpose-built structures, but can be very effective for dealing with existing infestations or for emergency treatment as a "last resort" and there is little or no residue.

Few of these techniques are as cheap, as easy to use or as effective as contact insecticide treatments, so that grain protectants will continue in widespread use for the foreseeable future. The best way forward to reduce the prevalence of pesticide residues and restrict use of protectants, is to integrate the physical and chemical control methods into a store management strategy based on early detection of pests and close monitoring of grain temperature and moisture, adjusting these by ambient aeration. Pesticide application can thus be restricted to the absolute minimum.

2. REVIEW OF CURRENT PRACTICES

The review of "The Biodeterioration of stored Cereals" (Wilkin & Rowlands, 1988) discussed fully the changes in cereal production and grain storage during the past fifteen years. There has been an increase in storage capacity for cereals both on farms and in commercial stores to cater for increased cereal production. The EC intervention system of market support has become more important, so that many producers work automatically to Intervention standards in terms of grain quality. The Intervention requirements in terms of specific weight, limits on impurities and on moisture are generally relatively easy to understand, but a requirement for consignments of grain to be free from live pests can present serious problems. The adoption at Intervention stores of rigorous sampling and assessment techniques to detect live insect pests have exerted a major influence on storage practice. Installation of adequate drying and cleaning facilities and the general awareness of measures that can be taken to reduce storage pest problems has resulted in a reduction of the grain rejected by merchants due to insect presence. However, pests still present a constraint on sales into Intervention as in 1987-1988 the incidence of pests in grain offered to Intervention stores rose and infestation accounted for 16% of the 1,143 loads which were rejected, even with the limited success of pest detection on intake (see below).

Current storage practice, involving on-farm drying and aeration nevertheless tends to rely heavily on the use of pesticides to prevent infestation (Wilkin and Hurlock, 1986) to the extent that more than 50% of farm stores and 96% or more commercial stores are treated with pesticides.

(a) DETECTION AND MONITORING.*

The objective of grain storage, whether on farm or in large centralised commercial premises, is to maintain cereals or cereal products such as milled wheat/flour in a stable and unchanged condition.

A wide range of insect pests can attack or spoil stored foods and because many of these species have very different dietary and environmental needs, successful control requires an informed approach targetted on specific pests and pest problems.

*This section includes pest detection in processed food stores.

Broad scale 'blanket' treatments of materials and stores with persistent pesticides may kill many insects but such treatments may not only be ineffective because some insects survive, but will increase pesticide residues in food and the environment. Similarly, routine fumigation of cereal products should effectively kill insects but the effect of some fumigant gases on stored materials, such as flour and malting barley, and the possibility of residues in food or tainting may also give rise to concern.

Because insect infestations are insidious and may remain undetected until serious damage has occurred, many control programmes rely on widespread application of pesticides as an insurance against the possibility of pest presence.

Reliable early warning of insects and monitoring of their numbers by the development of efficient insect detection techniques can be used as the basis of store management systems. Integrated use of insect detection and targetted pesticide application can prevent damage and reduce pesticide usage overall.

(i) <u>The role of detection</u>

Large numbers of insects of almost any species are unacceptable and require remedial action because it is likely that if insects are easy to find, damage has already occurred. The pest status of different insect species varies widely and at low levels of infestation, so the acceptance or lack of tolerance of insects present depends upon the pest species, the commodity at risk and environment. For example, the presence of one book louse *Liposcelis bostrychophilus* may not cause serious concern in a flour mill warehouse, whereas the discovery of a single live grain weevil in a 20 tonne lorry load of grain submitted for Intervention storage in the UK will result in the load being rejected.

The temperature and humidity of the storage environment will also determine the importance of pest presence. Storage of grain or cereal products at low temperatures may mean that detection of small numbers of insects may not cause serious concern because the environment is unfavourable for their development. However, if equivalent numbers of the same species were found in a warm store without temperature regulation, urgent action would be required.

The relationship of insect species to the material at risk is an important factor. A few carpet beetle larvae, *Anthrenus verbasci*, would probably be ignored in a flour mill whereas the same insects could cause panic in a textile store.

It follows that practical and effective pest detection relies upon knowledge of the ecology, behaviour and potential of the pest species for causing economic or physical damage, together with information on the material at risk and the storage environment.

(ii) Detection techniques

Visual inspection of commodities and their environment still remains the most widely used approach for finding insects. At best, an experienced observer with considerable time at his disposal can be extremely effective: at worst, high levels of infestation can remain undetected until very serious damage has occurred. Because visual inspection is time consuming, labour intensive and very subjective, methods have been developed to increase the efficiency of insect detection.

Physical traps

The earliest of these is probably the spider's web. Although an indicator of bad hygiene, pest insects trapped in webs can be the first sign of a problem. Sticky traps developed for public health and hygiene insects have been successfully adapted for use in stores. Vertically suspended "fly-papers" have been used in food stores for moths (*Ephestia* sp) and because they will trap insects which blunder into them they can be useful for pests which fly actively. However, they soon become ineffective in dusty atmospheres and may be unacceptable in food processing areas. Horizontal sticky traps normally with tent-like covering flaps are very effective for trapping cockroaches (*Blattella germanica* and *Blatta orientalis*) (Barak *et al.*, 1977) and have been adapted for use in food stores with varying degrees of success. Although the adhesive in some traps will successfully catch roaches it does not retain some of the smaller beetle species which may also be deterred from entering the trap. Covered traps with a more suitable adhesive could perform a useful role particularly if enhanced with a suitable attractant.

Pitfall traps have been used for many years to estimate populations of ground-living insects (Southwood, 1966). The principle of a sunken pit into which insects fall was developed for the surface of grain bulks in Germany in the

1960's. Pinniger *et al* (1986) and Cogan and Wakefield (1987) describe the evaluation of 1 pint plastic beer mug pitfall traps and commercially produced probe traps for detection of the major stored grain pests *Oryzaephilus surinamensis*, *Sitophilus granarius* and *Cryptolestes ferrugineus*. Probe traps originally devised by Loschiavo (1973) are plastic cylinders perforated with holes which are inserted below the grain surface.

Insects fall into the probe through the holes and their trapping action is therefore similar to that of pitfall traps although they trap insects moving through grain rather than those wandering on the surface. Cogan and Wakefield (1987) demonstrated that the use of both pitfall and probe traps in large grain bulks increased the chances of detection of the major grain pests by at least tenfold compared to conventional spear and sampling techniques.

Electric grid traps which utilise a UV light source to attract some insect species are marketed for the control of flying insect pests. They can effectively trap and kill any flying insect which blunders into the grid and examination of the catch tray under one of these traps can reveal hitherto unsuspected pests.

Traps with attractants

Honey and jam traps have been used for many years to attract and kill ants and wasps and this principle of attracting insects to a food lure can be successfully applied to many storage insect pests. Traps enhanced with food lures have been described by Levinson and Levinson (1977) and Pinniger *et al* (1984) described the evaluation and successful use of a perforated plastic mesh "bait bag" containing wheat, groundnuts and carobs (locust beans). The food in these bait bags was chosen to encompass a range of food preferences of storage insect pests and the combination of attractant food and refuges within the trap has resulted in over 60 different species of warehouse and food store pests being found in bait bags placed in a wide variety of environments. Hodges *et al* (1985) have successfully developed the bait bag principle by substitution of brown rice in the bags for detection of pests in Indonesian rice stores.

Corrugated card Storgard™ traps which have a central pitfall containing cereal oil have been described by Jones (1987), and a covered trap with a sticky insert to trap beetles has been developed (Wyatt *et al.*, 1988). Evaluation of these traps with other attractants will be described later.

Studies on insect pheromones have resulted in many proposals for traps enhanced with pheromone components or analogues (Burkholder and Ma, 1985; Pinniger and Chambers, 1987). Pheromones have different functions in controlling insect behaviour. "Sex" pheromones are produced by one sex and initiate a reproductive behavioural response in the other. The response may be stimulation, attraction, search, copulation, or any combination of these. "Aggregation" pheromones may be produced by one sex and usually attract both. However, the function and role of some of these aggregation pheromones is not fully understood and it is a mistake to underestimate the complexity of pheromone behavioural responses.

Pheromones appear to offer a means of attracting and detecting insects at very low population levels but successful laboratory assays may not be confirmed in practical use because of the habits of the pests and the nature of the environment. The value of traps baited with sex pheromone lures for the early detection of flying moths *Ephestia* sp in mills and food factories has been described by Cogan and Hartley (1984). Although Storgard™ traps with aggregation pheromone lures have been much less successful for the detection of Rust-red flour beetles, *Tribolium castaneum* (Newton, 1987), Wyatt-Wynn traps with a pheromone lure comprising fewer chemical isomers have proved very effective in detecting flour beetles in a malting. It is therefore worthwhile reviewing the examples of successful use of traps in storage strategies in more detail.

(iii) Detection strategy in practice

There are a number of clear examples where trapping programmes have led to improved control of insects.

Traditional night inspection for cockroaches in hospitals and prisons has relevance for food store premises, and is a difficult task which is hampered by constraints of staff shortages; security or patient care. Although full inspection cannot be dispensed with for the initial determination of population spread and density which is needed to plan a treatment, it can be usefully supplemented by use of sticky traps placed at strategic points throughout the site. The numbers of insects caught on subsequent occasions at these points after the insecticide treatment are then used to determine the rate of decline of the cockroach population and the possible need for retreatment. Because of their value sticky traps have been adopted by most professional servicing companies and they are now an essential part of commercial control operation, including use in food store premises.

The success of pitfall and probe traps for the detection of grain insects has led to their adoption by commercial grain traders for regular monitoring of large bulks of grain. On many occasions *Sitophilus granarius*, *Oryzaephilus surinamensis* or *Cryptolestes ferrugineus* have been found in traps well before they have been detected by conventional spear and sieve sampling (Cogan and Wakefield, 1987). This early warning enables the storekeeper to implement cooling or fumigation strategies and prevent infestation developing into a hot spot. Fumigation of grain bulks is often used to control infestation and in a recent case conventional sampling pronounced a treatment a success whereas beetles caught in pitfall traps showed that insects had survived the treatment (Cogan, personal communication).

Moth traps designed around TDA (Z,E-9,12-tetradecadienyl acetate) pheromone lures have been used by the food industry for a number of years. It has been shown that the successful operation of detection and monitoring programmes depends upon regular and accurate trap recording together with an understanding of the storage environment. Reichmuth *et al* (1978) and Cogan and Hartley (1984) have shown that infestation in flour mills, warehouses and food processing plants can be dramatically reduced when trap catch information is used to implement cleaning and pesticide treatment targetted on specific areas.

For example, a large chocolate manufacturer operates a system of intensive cleaning and treatment of machines adjacent to any trap which contains one or more *Ephestia* adults. This strategy has been successful in reducing customer complaints of infested chocolate. The difficulties of inspection at some mill and food production areas have placed increased reliance on trap catch for the assessing of *E. kuehniella* infestation. Accurate monitoring of populations coupled to strategic cleaning and use of pesticides have eliminated the need for annual methyl bromide fumigation in some mills.

The identification and evaluation of dominicalure, the aggregation pheromone of the lesser grain borer *Rhyzopertha dominica* has resulted in the production of commercial lures (Cogburn *et al.*, 1984). But it is the use of dominicalure in traps for detection of the closely related larger grain borer *Prostephanus truncatus* which has proved to be of greater value. The spread of this devastating pest across Africa has been monitored by the use of dominicalure traps to give local advisers early warning of the presence of the beetle so that control programmes can be implemented (Hodges, 1986). Tests are currently in progress to evaluate Trunc-call 1 and 2, the pheromone components of *Prostephanus truncatus*.

(iv) Future developments

There are many factors which influence the successful development and commercial adoption of a trapping technique. Developments in trap design or identification of sex pheromones may produce exciting results in laboratory tests but there is a very large gap between this stage and that of commercial exploitation. Specificity and complexity of the lure or trap design will determine whether many cheap traps or a few complex traps can be deployed in the detection strategy. Jones (1987) describes other factors which may influence successful commercial exploitation of detection systems including the importance of perceived value of a trap by a customer.

A number of techniques and discoveries which show considerable potential need further development if they are to proceed from laboratory assays and exploratory field trials. The series of macrolide lactone aggregation pheromones associated with *Oryzaephilus* sp and *Cryptolestes* sp (Oehlschlager *et al.*, 1988) are currently being evaluated for use in traps but a major factor which influences the feasibility of using these pheromones is their chemical complexity (Chambers, 1987). Seven different complex stereospecific macrolide lactones are produced by five different beetle species. Inter and intra specific behavioural responses coupled with the difficulties of synthesis may effectively preclude the commercial use of these pheromones.

Although it has been shown that the catch of flour beetles in the Wyatt-Wynn trap is dramatically increased with the inclusion of a *Tribolium* pheromone lure, there is no increase in catch of other beetle species, some of which may even be repelled. Therefore, the sex and species specificity of many of the insect pheromones coupled to their disappointing performance in some field trials has given encouragement to the continuing development of food lures including those based on carob volatiles. Identification of the attractant volatiles produced by carobs offers the possibility of a broad spectrum attractant for a wide range of food store pest species (Chambers, 1987).

Effective lures need to be developed, together with traps which are commercially viable to produce and sell and this is dependent upon demand from the grain storage and food industries. Pressure from the public for higher standards and lower levels of infestation coupled with reduced levels of pesticide use and residues, may lead to progress based on a better understanding of the benefits and advantages of storage strategies based on detection systems.

(b) PHYSICAL METHODS

All of the pests of stored grain found in the UK have definite requirements of temperature and moisture if they are to complete and perpetuate their life-cycles. Work by Storey *et al.*, (1983) and Hagstrum and Milliken (1988) showed that insect infestation in US wheat was directly related to the moisture content of the grain. Wheat with a moisture content above 13% was 5 times more likely to be infested than at 10% or less. Hence, reduction in moisture, even within the range prevalent in the UK, may be advantageous in suppressing or slowing the development of some pests. Generally the moisture levels necessary to restrict insect development are so low that moisture content control does not present an economic method of insect reduction within the UK, although it is feasible for mites (Stenning and Wilkin, 1989). Indeed, the intervention standard for moisture prevents fungal growth and allows only marginal mite development. However, many insects require temperatures above 18°C and even the most cold tolerant of UK grain pests, *Sitophilus granarius* can only breed if the temperature is above 12°C (Howe, 1965). Control of grain temperature in store therefore has great potential for reducing or restricting infestation problems.

(i) Cooling

Cooling grain during storage has been employed for some time as a method of reducing the risks from insects during storage. In the UK, the climate after the harvest period is such that night time temperatures are almost always lower than the temperature of the grain, thus offering the option of using ambient air for grain cooling. This process of aeration is now well developed (Burges & Burrell, 1964, Burrell, 1974; Nellist, 1986). Although the basic principles of aeration are well understood, in practice the technique is often not used to its full potential. Storekeepers usually opt for cooling grain to about 15°C; a temperature that will prevent all insect pests breeding except for *S. granarius*, and even this species will take 90 days to complete a generation. However, it is possible to cool grain to much lower temperatures (Armitage, 1986) and to gain further benefits in preventing infestation. It has also been shown that many stored product beetles will die during prolonged exposure to temperatures of below 5°C (Armitage, 1986).

One reason that, in practice, cooling is not continued to low grain temperatures may be that storekeepers consider the technique too costly in relation to the likely benefits. A practical difficulty is often related to the manual control of aeration fans. Here the decision whether to turn on the fans has to be taken relatively early in the evening and this cannot then be changed until the following morning. This results in inefficient cooling as air at the wrong temperature may frequently be used or valuable aeration time may be lost. There are a number of simple electronic controllers available to turn aeration fans on and off. These are usually based on comparing the ambient temperature with the current grain temperature and activating the fans if there is an appropriate differential. However, there are few data on the effective use of these devices. Current research at Slough, funded by the HGCA is helping to provide such data as part of an integrated strategy (see section 2(d)). The recent MAFF visiting of farm grain stores (Prickett, 1988) indicated that 60% of farms had installed aeration equipment.

Moreover, aeration cannot effectively control the temperature of the periphery of a grain bulk so that insects may migrate to the warmer parts of the bulk and escape the lethal effects of very low temperatures. It is possible that this difficulty could be overcome by using localised applications of a pesticide.

Another obstacle that is raised against the use of aeration is the danger of wetting the grain when cooling with moist air. In practice it is almost impossible to cause a significant increase in moisture content using a properly designed aeration system to blow air through grain with a moisture content of 14% or more. The volumes of air needed to cool grain are very small (10cu m/tonne), and cool air has a limited capacity to hold water. Therefore, the relative humidity of the air used to cool grain can largely be ignored. The exceptions are for very dry grain and if air is sucked through the grain, when some dampening of the surface layers may occur.

(ii) Drying

UK grain is often harvested at moisture contents that dictate immediate action to prevent development of fungi. As mentioned above, drying to 16% will restrict fungal growth provided the temperature is kept below 15°C, but a moisture content of less than 14% may be needed to stop development of mites. Drying to reduce insect development is not considered an economic reality (Howe, 1965).

The recent MAFF investigation of farm grain stores (Prickett, 1988) indicated that 46% of farms used grain dryers, though the type was not specified. The data also indicated that only 81% of farmers growing more than 75 hectares of cereals had drying facilities. This may indicate a failure to distinguish between bulk drying and aeration systems. In general, some drying (or alternative action to prevent immediate deterioration) will be needed throughout most of the UK, two years out of three. These techniques are discussed more fully by Wilkin & Rowlands (1988) but - briefly - involve two types of drying: High-temperature (where air heated by fossil fuel is blown through the grain, McLean (1980)); and Low-temperature, which uses near-ambient aeration with large volumes of air to absorb moisture from the grain until equilibrium is attained. Thus, air at 65-70% relative humidity will dry grain to about 15% moisture at autumn daytime temperatures.

Both systems have disadvantages. High-temperature drying raises the temperature of the grain despite integral cooling, and grain goes into store several degrees above ambient temperature, enough to allow insects to develop. Low-temperature drying requires more overseeing, is slow (4 days to remove 1% moisture) and does not dry uniformly, so that mould and mite development can occur before drying is completed (Armitage *et al.*, 1982).

(iii) Cleaning

Cleaning of both store premises and the incoming grain helps to prevent subsequent infestation problems. In the 1988 survey of farm grain stores, some 30% were cleaned mechanically and 66% manually. Non-cleaning (3%) was confined to smaller farms. Whether this cleaning is effective is another matter, and the need to pay attention to likely hidden pockets of infestation, cracks and crevices and even to areas outside the store where residual insect populations can shelter is discussed under 2 (a) above. It is not unknown for insects to migrate from a store prior to cleaning, and to return after cleaning! (Anon, 1975). Unless the cleaning is very conscientious and effective, a pesticide treatment of the fabric is necessary (see 2 (c)).

Some 31% of farms in the 1988 survey used a grain cleaner. Cleaning of the grain is an emotive subject as many contracts allow for a relatively large percentage of dust and debris without penalty so that economics may dictate not cleaning. However where feasible, cleaning reduces infestation potential (Howe, 1965). Examination of the screenings may help detect presence of pests, particularly in the case of mites (Wilkin, 1975). In addition, it seems likely that the current trend toward improved grain quality will continue; thus future contracts may specify far lower levels of non-grain material. Cleaning before drying will also reduce drying costs and may improve dryer performance.

(iii) Controlled or modified atmosphere storage

The principle of reducing the oxygen content of intergranular air space to less than 2% or raising the carbon dioxide level above 45% will prevent biodeterioration and pest development. The principle is extremely old, and in modern form is in use in many countries throughout the world, though its use in Australia seems to be declining.

In the UK the principle is used in fruit storage, but its potential for use in farm and commercial grain stores has still to be demonstrated as cost-effective. This hinges on provision of cheap supplies of carbon dioxide or other inert gas, or upon development of a suitable hydrocarbon burner to provide enough gas for replacing store atmosphere and for topping-up as necessary, depending on the degree of sealing of store or container. It has to be said that many stores currently being used would need considerable modification in regard to sealability before modified atmosphere storage became feasible. Currently these topics are the subject of research at the Slough Laboratory and the parameters were discussed fully in the earlier review (Wilkin & Rowlands, 1988).

(iv) Other methods of physical control

The inability of insects and mites to tolerate extremes of temperature or humidity can be exploited in methods of control. For example, insects die given only short exposure to temperatures above 55°C. Mites succumb to lower temperatures, particularly if the relative humidity is low. In Australia, a major programme of research has been completed to develop equipment and operating procedures for the thermal disinfestation of grain (Evans *et al.*, 1983). The principle of the method is to use hot air blown through a fluidized bed of grain to raise the temperature of each kernel to 55 or 60°C for a few minutes. This process kills all stages of insects without having any major effect on the quality of the grain. Currently, the process is being held as a strategic reserve control measure that could be used at export terminals if other methods of control cease to be effective. The costs of the energy used by

the method make the system far more expensive than alternatives such as fumigation with phosphine or admixture of a contact insecticide. However, it does provide a fall back method in the event of resistance or residue requirements rendering the conventional methods unacceptable.
The Australian technique heats grain using fossil fuel but it is also possible to disinfest thermally with rapid heating methods such as microwaves or dielectric heating. Such techniques have been shown to be effective (Wilkin and Nelson, 1987), but the high cost of the apparatus and energy needed would appear to confine the technique to high value products such as confectionery and nuts.

Cooling to temperatures below 0°C will kill insects and mites but, either temperatures of below -10°C, or long exposures are needed. Surprisingly, this method is not widely employed in countries such as the USA where winter climate in large areas should allow grain to be readily cooled to sub-zero temperatures.

In the UK this method of disinfestation is now becoming recognised but is only suitable where grain is held in store for 6-8 months. Theoretically, grain could be cooled without dependence on climate, by use of refrigeration units. However, the energy costs make this option unattractive.

(c) CHEMICAL METHODS

These are discussed in some detail by Wilkin & Rowlands (1988), and fall into the categories of fumigation or insecticide/ acaricide treatment - both of the fabric of grain stores or containers, and admixture with the grain itself. Conventional pesticides may be involved, or there is increasing promise for admixture shown by a group of insect hormone analogues of extremely low mammalian toxicity.

(i) Fumigation

Fumigation is used for the rapid disinfestation of commodities <u>in situ</u> and is often used as an emergency measure when, for example, grain becomes infested which must either be sold immediately or kept for long-term storage.

The technique involves applying a chemical in gas form -as distinct from an aerosol (fog, mist or smoke). Crucial elements in the success of a treatment are the gas-tightness of the store (or sheeting enveloping the stored commodity) and maintaining the effective concentration of gas for the right period of time to control the infestation.

The toxicity of a fumigant to a pest is influenced by both the gas concentration (c) and the time (t), for which that concentration is maintained, and in designing fumigation techniques it is necessary to know the product (ct) required for successful control in practice.

1. The so-called liquid fumigants (applied as a liquid): carbon tetrachloride and ethylene dichloride, are not now permitted. In many storage situations phosphine is then the only suitable fumigant available.

2. Methyl bromide is a very effective fumigant but can only be used for grain bulks where a circulatory system is available. It is used for bagged stacks under gas-proof sheets and in specially-designed fumigation chambers.

3. Phosphine is applicable in most circumstances, and is used in the form of aluminium or magnesium phosphide formulated as pellets, tablets, discs, sachets or plates. There are also some sheets called "blankets" which contain many sachets of phosphide put together, and these can be unrolled to cover a commodity. Pellets or tablets are usually thrust into a bulk via a probe at pre-determined levels. Phosphine is then generated by the atmospheric moisture present and the formulations also contain compounds yielding carbon dioxide or ammonia to reduce the flammability.

Pest species differ greatly in susceptibility to phosphine and the ct concept (above) does not apply. The exposure period cannot be shortened by increasing the dosage rate as is the case with other fumigants; in fact the longer the exposure can be maintained the better.

4. Fumigation is a once-off disinfestation; there is no future protectant effect.

(ii) Fabric Treatment

Fabric treatments usually include all applications of insecticide to the structure of the grain store which do not directly treat the grain. The insecticide can be distributed in the store in a number of ways.

1) Space treatment:- treatment of the whole internal volume of the store.

a) With smoke generators.
b) With a mechanically generated fog.

2) Residual treatment:- direct treatment of surfaces of walls, floors and bins etc.

a) With a water-diluted insecticide spray.
b) With a ready-to-use dust.
c) With a ready-to-use low volume spray.

The use of these treatments and their limitations are discussed on pages 29, 39.

(iii) Admixture

Admixture treatments involve the application of a contact pesticide, usually a chemical with a residual action, directly to grain. The pesticide is applied evenly to a bulk and this usually necessitates moving the grain with a conveying system. In many countries, including the UK, limitations are placed on the maximum residue levels (MRLs) that may be present in grain when it is sold. Application rates are, therefore, set at levels that will ensure that these MRLs are not exceeded.

The chemicals used for admixture are highly active against insects and the application rates usually range between 4 and 10g per tonne of grain. The pesticide must be applied to the grain as it is being moved along a conveying system in a carefully controlled manner at a rate that is related to the grain flow. One of three types of formulation can be used.

a) Dusts:- Ready diluted dry formulations, typically containing 2% active ingredient. These are applied to the grain using a vibratory feeder that can be adjusted to give a range of output rates.

b) Sprays:- These are supplied in concentrate form and diluted as emulsions of pesticide in water on site. The concentrates may contain 20 to 95% active ingredient but are diluted to around 1% in water before being sprayed onto the grain. The rate of output of the sprayer must be adjusted to suit the rate of grain flow.

c) Ready to use liquids:- The pesticide is supplied ready diluted in solvent to about 10% active ingredient and this is sprayed onto the grain using specialised spraying equipment. With this type of formulation the operator does not have to dilute a pesticide concentrate. Such types of pesticide formulation are widely used in Europe but are not currently available in the UK.

One exception to the need to move grain to apply an admixture treatment is when only the surface layers of a bulk are treated. In such cases, the pesticide can be applied to the surface as a dust or a spray and then distributed through the surface layers by raking or digging. Such treatments are only of use against localised infestations in a limited number of circumstances.

Admixture is discussed further on p.29 and 41 <u>et seq</u>.

(d) INTEGRATED STRATEGIES

There are benefits to be obtained from careful integration of the best aspects of cleanliness and hygiene, pest detection techniques, monitoring the store environment (temperature and moisture of the grain) during storage under the pest control regimes of careful drying and cooling; pesticide use (fumigation or insecticide/acaricide admixture) can thereby be kept to a minimum.

The requirement to sell pesticide-free grain, demands early detection of an incipient pest problem so allowing time to adapt the storage conditions or possibly to disperse hot spots by turning/cleaning the grain before the pest numbers develop to a serious level.

On the other hand, a pragmatic approach, viewing the use of pesticides as an occasional necessity but sensibly wishing to avoid un-necessary contamination of the grain with residues, still has advantage in terms of cost-effectiveness for the integrated use of these techniques.

Obviously it is in the interests of the cereal trade, food and beverage manufacturers and the consumer, to reduce the widespread dependence on prophylactic pesticide treatment. But if the storekeeper/farmer, whose livelihood is tied-up in the quality of the stored grain in his charge, is to be reassured that he can safely abandon reliance on the insurance value of routine pesticide applications to both store and commodity, then such integrated strategies need to have been "de-bugged" under pilot-scale research conditions, put to practical trial under a variety of storage situations, and lastly - but by no means least - to be shown to be not just as reliable as prophylaxis, but also to be as cheap as "normal practice", and preferably cheaper.

In accordance with this philosophy the HGCA has underwritten an extensive programme of research at the Slough Laboratory to provide these very answers. To this end a pilot-scale (120 tons) trial has been undertaken in which the basic parameters of such an integrated strategy are being tested under the most adverse circumstances that can be achieved. In trials completed so far the grain had been warmed to a high post-harvest temperature, infested with several species of storage insects at known levels, and cooled using ambient air ventilation, including a comparison of differential fan controls on the speed and cost of cooling. Insect populations in the bins (and around the store) have been measured by a variety of techniques including bait bags, pitfall traps and probe traps (see 2 (a)) enabling comparison of conventional sampling and trapping techniques as well as the latest developments. Temperature and moisture content of the grain and the temperature of the store environment have been monitored continuously, and observations made of the prevailing external temperature. Various pesticide treatments were to be examined as well as different methods of application, but in the event have not so far proved necessary.

At the time of writing the experiment is still in progress and it would be premature to make conclusions. However, some generalities can be stated as follows:-

The temperature and level of infestation of the grain at the start of the experiment were close to the worst possible case likely to be encountered in practice. Despite this, a standard ambient air cooling system was able to reduce the grain temperature to a level below the breeding temperature of most of the UK grain insect pests within two weeks at the centre of the bins and three weeks at the side. This cooling also reduced the equilibrium relative humidity of the grain and thus arrested mould growth. However, a further 8 weeks passed before the temperature could be reduced to below 12°C to prevent *S. granarius* from breeding. It seems likely that the temperature may have been sufficiently high during the first 11 weeks of the trial to have allowed this insect to complete a generation, although this was not confirmed by the trapping results.

There was a very significant difference in the number of hours of aeration used by the two fan controllers to achieve similar grain temperatures. The 4°C differential was far more economical, using only slightly more than one third of the aeration hours of the 2°C differential, although both controllers gave similar grain temperatures. Even the 2°C differential would be much more energy-efficient than manual control of the fans, which is the normal practice. Therefore, the use of these simple control systems could offer major savings in the running costs of aeration systems.

The size of bin used in these trials (6 x 25 tonnes) should not have affected the rate of cooling as this is dependent on the rate of airflow per tonne. The smaller size of the bins did ensure even airflow, but on the other hand did not offer the insulating properties of a larger bulk. A rise in temperature at the centre of the bins that was recorded toward the end of the experiment was probably a consequence of mild weather and unlikely to have been so pronounced in a larger bulk.

The methods of trapping used in the trial gave a good picture of the population of *O. surinamensis* but were less good for *C. ferrugineus* and poor for *S. granarius*. There seems to be a correlation between trap catch and temperature of the grain, with diminishing numbers being caught as the temperature fell. This could be related to a reduction in insect movement with falling temperature. This relationship deserves further investigation as Surtees (1965) suggested that *O. surinamensis* was more active at 15°C than at 20°C.

There was an increase in the numbers of insects caught in the surface layers of grain after the start of aeration. This probably indicates that the *O. surinamensis*, and perhaps, *C. ferrugineus*, migrated to the surface in response to the cooling front moving up through the grain. If this is the case then these insects would be much more accessible for control with localised application of pesticides. The trapping result for *S. granarius* did not show the same trend but this could be partly due to the trapping methods being less effective for this species.

The catches of insects in the bait bags outside the bins indicated that *O. surinamensis* wandered most actively from the bins. However, unlike the results obtained by Armitage and Stables (1984), there was no correlation between insects leaving the bins and the use of the aeration system. This could be because Armitage and Stables used an encircling sticky band to collect insects which might have caught a higher proportion of the escaping insects, but might also reflect different outside and grain temperatures.

A detailed statistical analysis of the temperature records and trap catches will be carried out when the trial is concluded. Information is being collected from various large commercial stores and, together with 20 years meteorological data, will provide a means of validating and extrapolating from the results of the laboratory trial. Costing information will also be collected so that the potential savings can be quantified. All data will be summarised into a model that will help determine the most cost effective storage strategy.

(e) USE OF PROPHYLACTIC TREATMENTS

The concept of using contact pesticides to protect both grain storage premises and the grain itself from insect and mite pests was initially intended only **as a minor use** on farm premises, particularly insofar as admixture was concerned (Green, 1971). Whereas it was not then forseen that the cereal industry would increase production to the levels grown and stored today, it began to be clear with entry into the European EC that not only would production increase dramatically, but that the standards acceptable to grain traders would rise. The financial implications of the change in quality standards, and in particular the contractual requirements of "no live pests" have been discussed at length elsewhere (Wilkin and Rowlands, 1988). Grain trading is in the hands of hard-headed businessmen, and they readily grasped the implications for dealing in parcels of grain of enforceable quality standards.

If proper attention is paid to store hygiene and if the grain and the store are maintained cool and dry, then insects, mites and fungi will not cause problems. However in practice (and short of the integrated control strategies advocated by Slough), **it is impossible to guarantee pest-free grain unless pesticides are admixed**, (Pinniger, 1975). Fabric treatments allied to good store management can reduce infestations to very low levels, but to be certain of no pest problems occurring and so to protect the commodity, admixture is required.

Since pesticide treatments are relatively cheap - of the order of a few pence per tonne - this prophylactic treatment of both store and grain represents very cheap **insurance** to the responsible storekeeper. Certainly far cheaper and far less trouble than leaving the grain to look after itself when, if problems develop, there is the costly nuisance (manpower and time) of turning or moving the grain, having loads rejected by the buyer or - worse - exporter (involving return transport or demurrage charges) and incurring the necessity of an in situ insecticide or - even more expensive - fumigation treatment. All this would be in order to eliminate infestation detected either by the buyer (disastrous for dealing confidence/goodwill) or apparent to the vendor just as he is ready to despatch the grain.

To a certain extent, this cheap insurance prophylaxis militates against the strict maintenance of good store hygiene, in that it becomes easier and cheaper to treat routinely with pesticide on intake to a store, than to be scrupulous about cleaning and about monitoring the store for temperature/humidity warnings of trouble developing. The storekeeper's view may legitimately be that admixture reduces the need for costly cleaning before storage, and for monitoring while the grain is in store. Except where resistance is prevalent, to a large extent a correct pesticide application will deal with any infestation that might otherwise develop.

The ADAS Pesticide Usage Survey Group studied farm and grain stores in 1983-4 and reported that 23 million tonnes of grain were harvested (1984), of which 90% was stored for a period in a farm grain store, and over 50% of which was still on the farm at the end of November. Less than 10% of the grain was admixed with pesticide, but 50% of the farms used insecticide fabric treatments, amounting to an estimated 12 tonnes of pesticide (of which 10 tonnes was pirimiphos-methyl). The 1988 MAFF survey of farm grain stores (Prickett, 1988) showed similar levels of 10% on-farm admixture and 52% fabric treatments.

The same ADAS Unit surveyed commercial grain stores in 1986, surveying a total of 8 million tonnes of grain of the total estimated 18M tonnes in store during 1985-6. They found that admixture accounted for 71% of the total quantity of active ingredients used in stores and that multiple treatments occurred at 8% of the premises visited. More than 36% of the total grain surveyed was treated by admixture with pesticides or received fumigation, compared with 6% in the 1977-8 survey.

A Slough Laboratory limited survey of commercial grain stores in 1983 (Wilkin *et al.*, 1983) indicated that 76% of the stores were using grain protectants (i.e. for prophylaxis) and that 28% of the stores were treating all grain on intake.

(f) LEGISLATION AND CONTROL OF PESTICIDES+

(i) Glossary of terms

Acceptable daily intake (ADI): The amount of a chemical which can be consumed every day for an individual's entire lifetime in the practical certainty, on the basis of all known facts, that no harm will result. The ADI is expressed as milligrams of the chemical per kilogram body weight of the consumer.

The ADI is based on the no-effect level (see below) in the most sensitive animal species or, if appropriate data are available, in man. It invariably includes a safety factor of x10 to x100.

Studies from which no-effect levels and hence ADIs are derived, are conducted with the technical chemical so that any toxicological effects of its impurities are included in the assessment. Account is also taken of metabolites which may influence the toxicity of the residue reaching the consumer.

No-effect level: The highest level of continual exposure to a chemical which causes no detectable adverse effect on morphology, functional capacity, growth, development or life span of individuals of the target species which may be animal or human.

No-effect levels used by the Joint FAO/WHO Meeting on Pesticide Residues in estimating ADIs are normally based on doses given in food or drink or by stomach tube.

+ statements and definitions in this section are consistent with, or identical to, those used in Osborne *et al.*, (1988).

Maximum residue limit (MRL): The maximum concentration of a pesticide residue likely to occur in or on a food commodity, either resulting from the use of the pesticide according to good agricultural practice directly or indirectly for the production and/or protection of the commodity concerned, or arising from environmental sources, including former agricultural uses. The MRL is expressed as milligrams of the residue per kilogram of the commodity unless otherwise stated.

Good agricultural practice: The officially recommended or authorised use of pesticides under practical conditions at any stage of production, storage, transport, distribution and processing of food, agricultural commodities, and animal feed bearing in mind the variations in requirements within and between regions, which take into account the minimum quantities necessary to achieve adequate control, applied in a manner so as to leave a residue which is the smallest amount practicable.

Limit of determination: The limit of determination is the lowest concentration of a pesticide residue or contaminant that can be identified and quantitatively measured in a specified food, agricultural commodity, or animal feed with an acceptable degree of certainty by a regulatory method of analysis.

(ii) Maximum residue limits

The Codex Alimentarius Commission (CAC) was established in 1962 to implement the Joint FAO/WHO Food Standards Programme. One purpose of the programme is to protect the health of consumers and to ensure fair practices in the food trade.

Codex is advised on matters relating to pesticides by the Codex Committee on Pesticide Residues (CCPR) at which Governments discuss MRLs for pesticides in commodities moving in international trade. In this way it is hoped to avoid serious inconsistencies in MRLs between countries. Also the FAO "Panel of Experts on Pesticide Residues in Food and the Environment" and the WHO "Expert Group on Pesticide Residues" hold joint meetings (usually referred to as JMPR, Joint meetings on pesticide residues) to assess health hazards which may be posed by pesticide residues in foods. Toxicological data are evaluated with a view to establishing acceptable daily intakes (ADIs) for man.

Maximum Residue Limits (MRLs) however are agreed by CCPR on the basis of good agricultural practice and lists of MRLs for a wide range of pesticide/food combinations are published from time to time. It must be emphasised that the MRL should not be considered as a measure of safety and this applies particularly to commodities such as cereals where any attempt to reconcile MRL and ADI must take into account degradation of the pesticide during storage of treated grain and losses of pesticide which can occur during processing. Many countries which have established legislation to control pesticide residues in food have adopted the Codex MRLs as a basis for control.

Even though an MRL has been recommended by CAC it does not follow that it is appropriate to, or acceptable by, all countries. National patterns of diet and agricultural practices and attitudes to the presence of pesticide residues in foodstuffs have resulted in the adoption of MRLs significantly different (and usually lower) from those recommended by CAC.

In 1986 the European Commission published the Directive on Cereals (CEC, 1986) in which limits were set for certain pesticides in cereals and the UK was obliged to implement these by the end of June 1988. Certain pesticides (eg pirimiphos-methyl) used in the UK to control infestation in stored cereals were not included in the list and limits were set for a large number of pesticides not permitted in the UK for use on cereals, although some may be used on grain storage structures.

(iii) The Food and Environment Protection Act (FEPA), 1985

Until recently control of pesticides in the UK has been supported by a voluntary agreement between Government Departments and the agrochemical industry (the Pesticide Safety Precaution Scheme). For reasons not relevant to this review, it was decided that this arrangement was no longer acceptable and that a statutory system would be introduced. The Food and Environment Protection Act (FEPA) was introduced in 1985 and provisions for the control of pesticides were made under Part III of the Act.

(iv) The Control of Pesticides Regulations 1986

These set out the requirements for the storage, sale, supply and use of pesticides and in June 1988 a statutory system of maximum residue limits was introduced. The first consultative document setting out the general principles of a statutory system of control was issued in October 1986. The second consultative document published in April 1988 proposed specific maximum residue limits for 64 pesticides on 39 commodities and these were embodied in a Statutory Instrument on 1st August 1988 (1378/88). In cereals (excluding rice) the MRLs ($mgkg^{-1}$) are as follows:-

ALDRIN and DIELDRIN	0.01
CAPTAFOL	0.05
CARBARYL	0.5
CARBON DISULPHIDE	0.1
CARBON TETRACHLORIDE	0.1
CHLORDANE	0.02
*CHLORPYRIFOS METHYL	10
DDT	0.05
DIAZINON	0.05
1,2-DICHLOROETHANE	0.05
DICHLORVOS	2
ENDOSULFAN	0.1 (except maize, 0.2)
ENDRIN	0.01
*ETRIMFOS	10
*FENITROTHION	10
HEXACHLOROBENZENE	0.01
$\alpha+\beta$-HEXACHLORO CYCLOHEXANE	0.02
γ-HEXACHLORO CYCLOHEXANE	0.1
HEPTACHLOR	0.01
HYDROGEN CYANIDE	15
HYDROGEN PHOSPHIDE	0.1
INORGANIC BROMIDE	50
*MALATHION	8
MERCURY COMPOUNDS	0.02
*METHACRIFOS	10
METHYL BROMIDE	0.1
PHOSPHAMIDON	0.05
*PIRIMIPHOS-METHYL	10
PYRETHRINS	3
TRICHLORPHON	0.1

A distinction can be drawn between those pesticides (indicated with an asterisk) which are approved for use on grain in the UK for which the MRL is set on the basis of good agricultural practice and many of the others for which the MRL is set at the limit of determination.

(v) Residue monitoring in cereals

Experimental studies on the fate of pesticide residues such as those carried out at the Slough Laboratory, are only a guide to what may happen in practice and for a realistic evaluation recourse has to be made to surveys or monitoring studies. Several expert groups had been responsible for monitoring pesticide residues in UK food until in 1977 the Working Party on Pesticide Residues (WPPR) was established and charged with maintaining surveillance of the residues arising from the use of pesticides in the UK for agricultural, food storage and industrial purposes. There was also a requirement to monitor residues in imported foodstuffs. The first Report of the WPPR (Anon, 1982) and the second (Anon, 1986) show that in general pesticide residues in cereals tend to be well below Codex MRLs. A full account of the first survey of residues in samples of wheat obtained from stores associated with flour mills reported by Bailey *et al* (1982) showed that low levels of gamma-hexachlorocyclohexane (γ-HCH), malathion and carbon tetrachloride (CTC) were found. One sample contained CTC and another contained 1,2-dichloroethane at levels which were above the Codex Alimentarius guide-line levels. A second survey of residues in wheat was carried out in 1982 for wheat samples obtained from a selection of commercial stores. Residues of organophosphorus insecticides were usually well below the relevant MRLs, with only one sample approaching the appropriate Codex MRL. The insecticide most frequently found was pirimiphos-methyl with chlorpyrifos-methyl and fenitrothion being found in a small number of samples. Malathion was not detected. Fumigant residues were well below those found in the first survey. Pirimiphos-methyl was the pesticide most frequently found in wholemeal flour (29%) and this is broadly in line with the incidence of the same insecticide in wheat (38%). The proportion of samples of bran containing pirimiphos-methyl was 43% and residues were generally higher than in wholemeal flour but still well below published MRLs.

The overall pattern of residues in cereals and cereal products indicates that residues in cereals are usually below 1 $mgkg^{-1}$ and that processing to products other than wholemeal flour and bran will tend to reduce the residue levels.

The monitoring studies so far conducted by the WPPR have tended to focus, especially in the case of cereals, on the pesticides known to be used on stored grain in the UK. These were mainly the six organophosphorus insecticides for which a collaboratively studied method (Anon, 1980) was available. Similarly for fumigants the method of Heuser and Scudamore (1969) had also been collaboratively tested (Anon, 1974) by the Committee for Analytical Methods. Until 1986, however, the WPPR had to rely on market intelligence in deciding which pesticides should be monitored because there were no statutory UK maximum residue limits, although those drawn up by the Codex Alimentarius Commission were used as presumptive standards.

A recent paper by Wilkin and Stanley (1989), gives a useful review of the WPPR report for 1985-8 and a detailed discussion of the pesticide residues detected in wheat, flour and other wheat products.

3. PROBLEMS ASSOCIATED WITH, AND ARISING FROM, THE CONTROL OF PESTS

(a) DRAWBACKS

Problems that can arise in the control of pests include the obvious one: failure to control, and two consequences specifically linked with the use of pesticides: resistance and residues. (A detailed review of pesticide residues in UK grain was carried out by Osborne *et al.*, 1988). Resistance may be one of the factors contributing to control failure, but is seldom the sole cause, although it is the potential of resistance for making control with chemicals problematical or impossible, that gives cause for concern.

Where control is attempted by manipulation of the storage environment (eg by physical methods; drying, cooling, modified atmosphere) failure must result from not achieving the required conditions either throughout the bulk/store, or more often in isolated pockets. Where a remaining pest population in the building fabric has not been removed by scrupulous cleaning of the store or by the application of pesticide, proper maintenance of the store and commodity environment should still prevent that pest population developing, and at best should ultimately kill those attempting to become established within the bulk.

There are records of resistance to CO_2 in insects (Navarro *et al.*, 1985; Donahaye, 1986) and it is also feasible that some species could develop physiological characteristics that enhance their survival at low temperatures.

Chemical control failures may also be due to the store environment or to the commodity being too cold or too hot leading to condensed moisture on surfaces, or to active moisture (free cellular water) within the commodity. All these factors can contribute to breaking-down the pesticide applied, or to reducing the intrinsic toxicity of the compound. With fumigation - and to a lesser extent control using modified atmospheres - the gas-tightness of the bin, silo or building is crucial. To be effective, the appropriate concentration of lethal gas must be maintained for the minimum exposure period to achieve control of insect pests. When considering treatments of the store fabric, the nature and sorbent/chemical properties of the various surfaces will dictate the successful life of the treatment. For example, many organophosphorus compounds applied to alkaline substrates such as plaster or concrete will be rapidly hydrolysed to non-toxic materials. This can be offset in some circumstances by coating or sealing the surface, for example with carboxymethyl cellulose (Tyler & Rowlands, 1967).

Insect behaviour also makes a significant contribution to the effectiveness or otherwise of pesticide treatment, which is why the Slough Laboratory has always considered behavioural studies to be an integral part of pest control efficacy assessment (Pinniger, 1983).

Measurement of efficacy is itself a highly complex matter. In the case of fabric treatments they are often conveniently approximated in the laboratory, (and indeed, sometimes in practice) by confining insects on the treated surface and measuring their response after a given exposure period but although this allows for the nature of the surface (substrate) treated and temperature and humidity effects, it still takes no account of refuges (such as a bulk of untreated grain!) in practice, and is therefore rather simplistic.

In the admixture situation, assessment of insect mortality on small lots of treated grain under controlled conditions of temperature and humidity may perhaps be less flawed, but the "real" situation will doubtless contain pockets of untreated grain or grain at higher temperature/moisture which will again provide a refuge/respite situation, let alone any consideration of untreated areas of the store itself (Pinniger, 1974; Samson, 1985).

In a grain store which has been treated with insecticide, the success of the treatment is often determined by the ability of surviving insects to move from a refuge (ie cracks and crevices in the fabric) across a treated surface to gain access to untreated foodstuffs or to other refuges. It is not uncommon for storage pests to shelter outside the building (under tree bark etc) during a treatment (perhaps fumigation) and only re-enter when the treatment is completed and the new grain harvest is being taken into store. The interacting factors which govern this survival include both those dependent on the treatment, such as disturbance, avoidance, resistance, speed of action and persistence of the insecticide and also those which may be independent of the treatment, such as migration, refuge-seeking and response to physical changes of light, temperature and humidity (Pinniger & Wildey, 1979).

Failure to achieve an adequate or even pesticide deposit (ie the recommended dose) on building/bin surface or stored product is probably a common cause of pest survival. Under-dosing can also facilitate selection of resistant individuals in an insect/mite population where the potential for resistance exists within the gene pool.

(b) APPLICATION OF PESTICIDES

By comparison with the sophisticated technology marketed for application of pesticides to growing crops, the machinery available for pesticide fabric treatments or for admixture with grain is crude. The user is also severely limited by the formulations available (see earlier).

(i) Fabric

Treatment of the grain store structure with insecticide can be by the use of smokes or fogs as space treatments or by application of residual sprays or dusts to the building "fabric".

Space treatments are usually easy to apply and take less time to apply than a thorough treatment with a residual insecticide. Although the clouds of fog or smoke may look very impressive, the deposits of insecticide achieved on surfaces are generally very low and are not likely to persist for any length of time. Consequently many insects may survive such treatments when they are used as the sole form of control in a grain store. However, when smokes or fogs are used in addition to residual treatments, they can provide an effective means of dispersing insecticide to kill insects in areas like roof voids, elevators and delivery bins which would otherwise be out of reach or inaccessible to conventional sprays.

Although most insecticides approved for use as residual treatments in grain stores are formulated as dusts or water dilutable sprays, there is also a low-volume spraying system which utilises a ready prepared formulation of permethrin, resmethrin and fenitrothion. This system is easy to use and treatment times are much shorter than those required for conventional treatments but although the initial kill of insects may be satisfactory, the deposit is not large enough to persist and kill insects which may subsequently emerge from refuges.

Dust treatments usually persist well and although they are most effective for treating cavities and dead spaces it is very difficult to apply an even deposit to walls and other vertical surfaces.

Most insecticides approved for fabric treatments are formulated as wettable powders or emulsion concentrates, and given a good formulation and proper attention to instructions for mixing and dosage (allowing for factors like "run-off") and the sorbency and effect of the different building surfaces on persistence, these "residual treatments" should be moderately successful. A further problem comes in deciding which of the 17 or so pesticides cleared for application to store fabric, should be used. Efficacy data are now required under the FEPA and these together with published work by the Slough Laboratory (eg Pinniger, 1975) should facilitate the user's choice for his particular circumstances.

The success of such treatments in terms of dose achieved on the store fabric is seldom if ever monitored in commercial or everyday use. However, under experimental conditions on farm and grain storage sites, some assessment is possible by analysing the doses impinging on strategically-placed targets such as filter paper. This technique measures the dose achieved, but not its effectiveness at killing insects - though this can be done by extrapolation from laboratory bioassay, making due allowance for temperature and humidity effects (Barson, 1983; Samson, 1985). To predict the effective life, these data can then be related to laboratory tests on the appropriate substrates (concrete, wood, tile, metals) (Pinniger, 1975).

Insects and mites sheltering in cracks and crevices or in residues which cannot be reached by the direct spray will only be killed by the pesticide when they wander over the treated surface. Only a small proportion of the pests wander at any given time and it is important to treat a store several weeks before new grain is brought in to give the pesticide some time to work. Large numbers of dead insects are sometimes found after a treatment and although these may be impressive, they should not be taken as an indication of complete success. A very large kill indicates a heavy infestation. This increases the risk of sufficient survivors being left as a continuing threat and needs follow-up cleaning and respraying.

Judging the success of such a treatment by assessing any remaining infestation should be an integral part of good store management, but this is seldom done in commercial practice although it can be monitored quite effectively by the use of bait bags to detect hidden insects (Pinniger, 1975).

Apart from the reports and publications of the Slough Laboratory, there are no published data on the fabric doses achieved in grain stores in practice.

(ii) **Admixture**

In many cases insecticidal dust is shovelled or discharged by hopper into a grain flow, or stack. The dust rises in clouds (as indeed it does every time the grain is moved) forming both a hazard to the operator, and a deposit in other parts of the building - often on neighbouring (perhaps "untreated") bins. Dust-hopper discharge into a flow of grain (e.g. from an auger) readily blocks and may not be metered or geared to the grain flow.

Similarly the delivery of a spray nozzle fed from a tank of diluted emulsion is rarely linked directly to the grain flow; it relies instead on the operator estimating the rate of grain flow and setting the sprayer accordingly. In practice the grain flow is rarely constant, yet modern sensor beams should make this a simple enough achievement. Moreover the diluted formulation may not be agitated and may settle out so that the pesticide delivered varies in concentration with the degree and rate of settling.

Many spraying set-ups can at best treat only the top layers of a grain flow, which are subsequently mixed with those (untreated) beneath. Grain may be three inches deep on a conveyor moving at 50 tons/hour and there may be 10- to 1,000-fold differences in amounts received by grains under such a regime (Rowlands, 1975). Tyler and Rowlands - cited by Green (1969) took samples of grain being sprayed at the discharge point from an auger into a 50 ton grain bin. In a typical 25g sample they found that all 548 individual grains had indeed received some insecticide spray, but that the doses ranged from 0.1ppm to 424ppm.

The implications of this uneven treatment have not been fully investigated. Work by Minett and Williams (1971) suggested that uneven application of malathion to wheat improved the persistence of that chemical. However, variation in the doses achieved in the even and unevenly treated grain, casts some doubt on their conclusions. Unpublished work from the Slough Laboratory has shown that uneven applications of pirimiphos-methyl or chlorpyriphos-methyl at ratios of up to 1 treated grain in 300, have no deleterious effect on the efficacy of the pesticides. More laboratory and practical work is needed on this topic but such work would be expensive in terms of cost and resources because of the large numbers of samples needing analysis.

Many of the formulations provided for storage practice are unsuitable or were developed for other (more lucrative) uses (eg cotton). Grain storage - even on a world-wide basis, is still a minor use with little potential to yield large profits for pesticide manufacturers or those designing application equipment. There is, however, considerable scope for developing suitable formulations for food storage practice; in particular the development of dusts or other particulate formulations that can be screened out during cleaning before processing into food, and that will not allow translocation of the pesticide into the treated grains (Desmarchelier, 1985).

The Codex Alimentarius Commission (CAC, 1985) give international guidance on acceptable daily intake of pesticide residues based on good agricultural practice, and formulate maximum residue levels (MRLs) for certain raw and processed crops. The Codex MRLs for grain may well represent internationally accepted levels in exported cereals. Under the FEPA regulations in the UK (see earlier) MRLs have been set for raw cereals, and it is now necessary to consider the dose achieved in practice, not only from an efficacy point of view (ie will it control insects for a satisfactory period of time, leaving a minimal residue behind in the grain?) but also in relation to the statutory MRL.

Crucial among our lack of data is information on the doses actually achieved on grain by farmers/storekeepers when aiming for a particular recommended level. As mentioned above, poor equipment, bad stability of formulation, inadequate mixing of diluted emulsion during spraying, constipation in dust applicators, uneven flow-rate of the grain being treated, losses (particularly of dust) after treatment, spray drift... all these factors conspire against the achievement of an accurate and appropriate dose.

(iii) Fumigation

Problems arise through the unsuitability of most stores or grain containers for fumigation - ie they leak. With fumigants, which confer no subsequent protection against re-infestation, it is essential to maintain an effective concentration of gas for long enough to kill all the pests present. Temperature is, again, a crucial factor; much longer exposure times being required during winter conditions. Distribution of the gas throughout the grain bulk to deal with pockets of infestation is also important where no residual protectant is employed and in the case of floor-stored bulks of thousands of tonnes, obtaining adequate distribution of the gas can be a major problem. Furthermore, there are for all practical purposes only two fumigants currently available for use - methyl bromide and phosphine, the liquid fumigants having been withdrawn. Of these two, methyl bromide is difficult to distribute through a grain bulk without propoer circulatory equipment, though current research with methyl bromide-carbon dioxide mixtures and with a mixture of methyl chloroform and methyl bromide (as a replacement for liquid fumigant mixtures) has demonstrated vastly improved distribution of methyl bromide through grain bulks in presence of these "carriers". Phosphine distributes reasonably well and even better in mixture with carbon dioxide, but is threatened by pest resistance. Dramatic control failures have resulted (from malpractice) overseas, and although not a perceived threat in this country at present, the possible importation of resistant strains cannot be dismissed.

(iv) Uniformity of application

This can be checked, within limits, for fabric treatments to ensure that the appropriate mg/sq footage has been achieved, but there has been no experimental work on the relationship between application of formulated pesticide and efficacy, or whether an uneven -or irregular- treatment is more effective. However Wildey (1983) observed that part-treated arenas (areas of exposure with or without artificial refuges where there were untreated areas alongside higher dose areas to give the same overall dose as "evenly-treated" arenas) produced higher insect mortality than did evenly-treated arenas. He also showed that beetles could demonstrate a choice/preference for lower-dosed areas within an arena, and that lower-dosed areas would then become repellent if untreated areas were made available. He was able to link these repellency reactions with the physical composition of the wettable-powders evaluated, which in addition to the active ingredient also contain sorbent carriers, fillers, dispersants, wetting agents and stabilisers. Some of his findings would apply to dust formulations which contain some identical ingredients, but he did not demonstrate repellency by emulsifiable concentrate formulations.

With admixture on the other hand, although for many years it was <u>assumed</u> that even dosing was a prerequisite for effective treatment it is only comparatively recently that this has been studied on either laboratory or practical scale. The results have been somewhat conflicting.

Tyler and Green (1968) and Tyler *et al.*, (1969) carried out laboratory trials in which wheat and barley were treated with malathion. They compared treatments in which every grain was dosed in a small bulk, with treatments where the same overall dose was achieved by including a few highly-treated grains among a majority of untreated grains. The results indicated that the uneven dosing was more effective on wheat, but that there was no difference between the treatments with barley. The concept of a deliberately uneven treatment (ie small percentage of highly treated grains) was then tried out at the pilot (tonnes) scale by Minett & Williams (1971, 1976) who found that there was little difference in effectiveness (with malathion) between "even" treatments and those where only 1% or 2% of grains were treated to give the same overall dose. Uneven dosing prolonged both the residual life of the malathion and its effectiveness. However, Anderegg and Madisen (1983), and Anderegg (1984) found little difference in effectiveness between such treatments with malathion. Henderson (1989) has recently carried out laboratory assessment of even and uneven treatments of pirimiphos-methyl and chlorpyrifos-methyl in wheat, and again concluded that there are no obvious advantages (in terms of pest control) in uneven distribution of the pesticide. There are no obvious disadvantages either.

The reason is not hard to find. It is that within the grain bulk the residues will re-distribute over a period of storage. This was demonstrated on a laboratory scale, where equilibrium is usually achieved in a matter of days, by Rowlands (1967) and subsequently on a tonne-scale, where re-distribution can take months, by Minett & Williams (1971, 1976).

(v) Consequences of treatments

In addition to redistribution through the grain bulk, the residues of admixed insecticide are, in the process of moving through the tissues of each individual grain and in being metabolised by the grain and fungal enzymes present, being redistributed within each grain and are concentrating in certain grain tissues.

It is necessary to understand briefly what happens to the insecticide after it is applied to grain, and a considerable volume of work on this topic has been done by Rowlands and co-workers (e.g. Rowlands, 1975, 1986) and has been discussed extensively elsewhere (Osborne *et al.*, 1988).

Uptake of pesticide from emulsion spray is rapid (hours) whereas comparatively slow from dusts (weeks). There are transport systems within the grain which will move pesticide about regardless of the sites of application. In living grains the pesticide is attacked and metabolised by a variety of cereal and fungal enzymes, usually breaking down to less toxic derivatives. Dead grains accept pesticide less readily than live grains and any transfer is passive;

furthermore any loss of pesticide from dead grains is chiefly by volatilisation. The moisture content, age, temperature and variety of the grains all affect the initial rate of uptake of pesticide and also the rate and the nature of any metabolic degradation.

(c) PESTICIDE RESIDUES

(for a thorough review of pesticide residues in cereal grains see Osborne, 1988).

(i) Problems of occurrence

In general terms, fumigation does not lead to problematical residues since they are lost by volatilisation, particularly during processing (Fishwick, 1988).

The main consequence of pesticide admixture and of grain in contact with pesticide-treated surfaces, is that the grain is going to contain a residue of one pesticide and its metabolites-possibly of several; for with the increase in grain trading , a parcel of grain may possibly be treated more than once; possibly with different compound. This problem of multiple treatment was not readily apparent (though suspected) at the time of the Report of the Working Party on Pesticide Residues (which covered the years 1982-5 (Anon, 1986), but multiple residues do feature in the next report (Anon, 1989) albeit at reassuringly low levels. Of course they are only apparent where different pesticides have been used for prophylactic treatment.

A further problem is that the residues of parent insecticide or metabolites translocate within each grain, and are concentrated mainly in the outer layers of the caryopsis of grain (i.e. the bran fraction of wheat). There are Codex MRLs (see Chapter 2 (f)) for the flour and bread produced from stored wheat, and this tendency of residues to concentrate in the bran and in wholemeal bread suggests that any residue problems are likely to be associated with "health food products". Thus, Wilkin & Fishwick (1981) and Fishwick (1988) measured residue levels in wholemeal flour and bread following experimental treatment of wheat with several grain protectants. They showed for example, that approximately 55% of pirimiphos-methyl and 39% of methacrifos present in flour survived the baking process. Residue levels in wholemeal flour from wheat treated at rather less than the maximum recommended doses, were above the Codex MRLs for chlorpyrifos-methyl and malathion, and similarly with pirimiphos-methyl residues in bread.

The practice of mixing UK wheat with imported grain for breadmaking will not necessarily lead to any reduction in residue. Though many parcels of grain are still pesticide-free, Working Party and other past surveys have shown that where they occur, residues of malathion and pirimiphos-methyl are more frequent and at higher levels in imported cereals. In any case in the UK the grist milled to produce breadmaking flours now incorporates up to 70% or more of UK wheat.

Chapter 2(f) discusses the legislative aspects of residues. At present there are UK MRLs for raw cereals but not for cereal products.

(ii) Problems of analysis/assessment

Residues and persistence of pesticides are measured by both bioassay (with insects, mites or other organisms) and by physico-chemical methods of analysis that are usually highly specific for a particular pesticide. It is important to appreciate that they measure different phenomena and that the information produced from each method is complementary in understanding what is happening to a pesticide treatment (i.e. residue) rather than being alternatives. "Chemical" analysis measures the overall amount of recoverable (i.e. extractable) insecticide within a sample, and possibly some of the metabolic products. Bioassay gives an indication of the availability and toxic effects of that residue to the organism used in testing.

Most chemists and biologists engaged in considering insecticide residues in grain and in attempting to correlate chemical and bioassay figures will be familiar with the anomalies where good control has been achieved in practice but chemical analysis of the samples withdrawn from the bulk indicate virtually no insecticide present; or where analysis shows a good level of pesticide residue persisting, but which is not killing either insects in the bulk, or those put on samples in laboratory bioassay. This topic, which hinges on the nature and availability of the residues has been mentioned above, but is discussed fully by Rowlands (1986) and by Osborne *et al.*, (1988).

Clearly the EC Directive on insecticide MRLs in cereals significantly extends the number of pesticides for which WPPR monitoring studies will have to be undertaken. Certain organophosphorus insecticides, such as diazinon, can be readily included within the currently used method (Anon, 1980) but further collaborative testing would be required to validate the method for compounds such as trichlorphon which are known to present problems when analysed by gas liquid chromatography. Similarly, in the case of fumigants it will not be possible to monitor ethylene dibromide at 0.01 $mgkg^{-1}$ using the currently used general screening method and it is highly probable that hydrogen cyanide and hydrogen phosphide will each require separate methods. These few examples point towards the more general requirements for analytical methods which will have to be met.

The analysis of samples on which recent monitoring studies have been based has presented a very large workload. There is a need for methods which are more broadly based in terms of the number of pesticides which can be included.

Previous monitoring studies have shown that the majority of samples examined for residues of fumigants have contained small or not detectable residues and a rapid screening procedure for insecticides, based on headspace analysis, particularly if fully automated, could therefore be advantageous. Unequivocal identification of any residues will often be required, particularly if the levels approach statutory limits which may precipitate monitoring for enforcement purposes. The availability of the newer, cheaper 'benchtop' mass spectrometers should make this technique available to a wider range of laboratories.

The development of uniform and accurate methods of analysis and the demonstration of their reliability by collaborative studies will impose even more demands on costly analytical resources. Whenever possible, advantage should be taken of methods already evaluated by the Association of Official Analytical Chemists (1984). Codex Alimentarius Commission (CAC, 1985) have published a guide to those analytical methods which have been evaluated by the Working Group on Methods of Analysis. These methods are offered on an advisory basis but are believed to be applicable to the determination of pesticide residues for statutory purposes. Nevertheless, collaborative testing of these methods may still be required.

(d) RESISTANCE TO INSECTICIDES

In the present context resistance is defined as occurring where insects have the inherited ability to survive a discriminating dose of insecticide designed to kill all normal or susceptible insects in a sample.

Resistance so detected by laboratory tests does not necessarily indicate a failure to control pests in a practical situation, though many of the strains tested by MAFF have come from sites where advice has been sought .... ie there is an undefined problem in control. Even on a world-wide basis, there is surprisingly little documented evidence of resistance causing control failures, although they do occur (Prickett, 1986).

The degree of "overkill" (that is, the margin of control) when using a recommended dose against insect populations with resistant individuals present, varies considerably with the insect species and the pesticide used. For example the recommended dose of fenitrothion would probably be adequate to control saw-toothed grain beetles even if high levels of resistance were present, whereas control of grain weevils with malathion could be so marginal that slight resistance would spell failure.

(i) The World Situation

New instances of resistance to pesticides continue to arise among stored product pests (Champ, 1986) and to be spread around the world by trade. From involving 14 species in 1979, the figure has risen to 23 in 1981 and 31 in 1985 (18 beetles, 7 moths and 6 mites) and the pesticidal compounds involved number some 102, which can be broken down into 18 organochlorine, 43 organophosphorus, pyrethrum and 14 synthetic pyrethroids, 5 carbamates, 5 juvenile hormone analogues, 1 organotin, 1 organosulfite and 12 fumigants including CO_2.

A few of these instances are of academic interest only, but most are of practical significance.

Since the wide-ranging FAO Survey of resistance in storage insects in 1972-3, few data have been published on the European situation, other than in the UK. One exception is the survey of malathion and gamma-HCH resistance in six species of stored product Coleoptera in the Federal Republic of Germany (Rassmann, 1978). This survey, in which samples were apparently collected in 1975-6, demonstrated the presence of malathion resistance in *Sitophilus granarius*, and gamma-HCH resistance in four of the six species involved. In France, malathion was the major contact insecticide used to protect grain until 1975, at which time pirimiphos-methyl and chlorpyrifos-methyl began to be used (Buquet, 1978). Whether the introduction of these compounds was prompted by the existence of malathion resistance in Europe is not clear.

(ii) Origins of resistance in the UK

The saw-toothed grain beetle (*O. surinamensis*) is the most serious pest causing damage to UK cereals in store and can be used as an indication of the changing situation.

During 1971-3, 74 strains of *O. surinamensis* collected in the UK were subjected to malathion discriminating-dose tests and no resistance was detected (Dyte *et al.*, 1973, 1976a, 1976b). In 1974, samples from 151 inland sites, consisting mainly of farms and provender mills but including some other storage facilities, were collected and one population was found to contain malathion-resistant individuals (Green, 1975). This site was a warehouse in London which was known to have traded in imported commodities from a ship subsequently shown to be infested with resistant *O. surinamensis*. The warehouse goods were fumigated with methyl bromide and monitoring with bait-bags indicated that all insects had been eradicated (Anon, 1978a). The investigation of *O. surinamensis* infestations was continued and by the end of 1976, 507 samples from inland sites and 166 samples from ships and containers had been tested. Of the samples from cargoes, 39 proved resistant to malathion, whereas only one inland sample was resistant (Anon, 1978b). This sample came from a farm grain store and the population was subsequently eradicated with pirimiphos-methyl (Anon, 1978a). Thus although there was a danger of a large influx of resistant strains, port surveillance to intercept these strains and prevent their establishment inland, appeared to be successful.

However, the inspection of a large proportion of imports which had been maintained from 1956 to 1976, and since 1974 had been coupled with discriminating-dose tests for resistance, was severely curtailed after 1979. Since 1981, fewer than six resistant strains have been intercepted each year, suggesting that many have been imported undetected. Further evidence of an influx of malathion-resistant strains of *O. surinamensis* comes from a comparison of the incidences of resistance at inland sites. Between 1973 and 1978, 1003 strains were tested of which two per cent were resistant; during the

1984/5 harvest 31% of 74 strains tested were resistant. Also, 39 per cent of 28 strains tested were resistant to pirimiphos-methyl. It must be noted that the figures for 1984/85 may be slightly exaggerated because the sampling was mostly restricted to farms where the farmer had identified a problem and had requested assistance. The earlier samples had been from farms known to store grain, regardless of whether a control problem existed. Nevertheless the battle to exclude resistant strains from the UK was lost.

(iii) Current situation in the UK

In 1988 a wide ranging survey of UK farm grain stores was undertaken by MAFF. (Prickett, 1988). The first part of the report gives details of the 109 items of information collected at each of the 742 grain stores visited in 1987. 9.7% of the farm grain stores inspected had one or more of the major beetle pests of stored grain (*O. surinamensis*, *C. ferrugineus* or *S. granarius)* of stored grain present. 51.9% of the grain stores had psocids present and 71.6% had mites. Beetles from 58 farm grain stores were tested for resistance to organophosphorus insecticides. Resistance was widespread in *O. surinamensis* and most populations showed cross- or multiple resistance to a number of compounds, with 20% of the population showing resistance to four or more insecticides. The most frequent combination of resistances was to chlorpyrifos-methyl, methacrifos and etrimfos (9 populations) with resistance to chlorpyrifos-methyl and methacrifos, and to etrimfos and methacrifos a close seconds (8 populations). One population had resistance to malathion, fenitrothion, pirimiphos-methyl, chlorpyrifos-methyl, methacrifos and etrimfos. 10% of the *O. surinamensis* populations were resistant to phosphine. There was little evidence of organophosphorus resistance in *C. ferrugineus* where only 4 out of 111 tests, which involved 5 insecticides and samples from 22 farms, had a positive result. 10% of the 426 farms from which mites were collected had mite populations which were resistant to pirimiphos-methyl. *Acarus* spp. accounted for 85% of the resistant populations.

A survey of pest presence and control measures used, together with testing of insect and mite strains for resistance, in 483 commercial grain stores was carried out in 1988-9, jointly funded by HGCA and MAFF. This will yield further data on the extent and importance of resistance in the UK when the strains collected have all been tested.

The selection pressure for insecticide resistance in the UK can be gauged from a recent survey of pesticide usage in farm grain stores in England and Wales

(Taylor and Sly, 1986). The percentage of sites storing grain which used pesticide doubled from 28 in 1966-7 to 56 in 1984-5. This doubling was not reflected in the total quantities of active ingredient applied, but during this period there was a move away from using gamma-HCH, malathion, and fenitrothion, towards pirimiphos-methyl and chlorpyrifos-methyl.

This change in the popularity of compounds, which is mostly a change from malathion to pirimiphos-methyl, may explain why the quantity of active ingredient used remained more or less constant whilst the proportion of sites using insecticide doubled. The recommended application rates of pirimiphos-methyl for treating grain and for spraying surfaces are 44 per cent and 67 per cent of the rates for malathion, respectively. Thus, with the same weight of active ingredient, twice as many sites could be treated with pirimphos-methyl compared with malathion.

As judged from this data, the selection pressure for resistance to organophosphorus insecticides has doubled in the UK in the last two decades. So far, resistance to methyl bromide and the halogenated hydrocarbon fumigants has proved to be of little consequence in economic terms. However, the picture is very different for phosphine and reports are now to hand from outside the UK of fumigation failures arising from, or directly linked with resistance. High levels of resistance have been recorded among strains from all over the Indian sub-continent, and from parts of Africa. Some resistant populations have been imported into the UK and other countries from these areas. The spread of highly resistant strains is likely to increase in future unless measures are taken to stop the phosphine misuse which has caused the resistance to appear.

At present resistant populations can still be controlled by phosphine by increasing the length of exposure under gas-tight conditions, but standards of sealing need to be very high, and becomes problematical at the lower temperature encountered in the UK.

(iv) <u>Future strategies</u>

Because of the cheapness and effectiveness of admixture as a "guaranteed" control technique it is evident that use of contact insecticides on grain and in grain stores will continue for the forseeable future. However there are a number of ways in which the amount of pesticide used can be reduced, so reducing the consequent residues, but with implications for resistance.

1. Rapid and timely detection of hidden or unperceived infestation would enable realistic decisions to be made on "spot" treatments and on the timing of applications, so reducing the need for "blanket" or "insurance" treatments.

2. Improvements in grain-handling and pesticide application equipment would enable pesticide to be used more effectively, allowing lower dosage rates and better-timed and more accurate application.

3. Much could also be gained from a better understanding of the movement of pesticides in grain bulks, especially if the formulation applied can be tailored to enable easy removal of any pesticide left at the end of storage.

4. Better targetting of specific pesticides towards the pest involved, through careful study of the toxicology, could allow lower doses of active ingredient to be used whilst maintaining efficacy. For example *Rhyzopertha dominica*, is much more sensitive to the synthetic pyrethroids such as cypermethrin than to the organophosphorus pesticide pirimiphos-methyl (Wilkin and Binns, 1988). In some cases a combination of two or more highly active but specific compounds could yield a broad spectrum pesticide that could be used at a dose much lower than the individual doses of any of the ingredients.

Problems with resistance can also only effectively be negated by decreasing the widespread use of pesticide admixture, though again (as in 2. above) accurate application of the recommended control dose with its inherent "overkill" should reduce the development of resistance. Some of the strategic approaches suggested by resistance studies are not acceptable to the grain industry however; for example:

1. Use of low doses or leaving an untreated refuge area would reduce the selection pressure for resistance, but would also leave live insects!

2. Use of integrated control techniques involving predators. This requires the establishment and maintenance of a pest-predation reservoir and also conflicts with the requirement for "insect-free" grain, regardless of the

damage potential of different species.

3. Dilution of the residual (resistant) population with susceptible insects is clearly not acceptable.

However, the following strategies do offer some potential:-

1. Fabric treatments utilising the highest permitted dose combined with refuges would cause regression of existing resistance genes. A problem is to ensure that refuges are untreated in order to allow susceptible insects to survive. In practice this is not feasible because residual treatments in stores are not able to achieve an even application of insecticide to all the exposed surfaces while leaving totally untreated areas. Therefore elimination of refuges, which are the single most important contributory element of residual insecticide treatment failure, coupled with a lower dose prophylactic treatment of grain to avoid the problems caused by the remaining live insects is the current MAFF strategy.

2. Use of mixtures of unrelated pesticides has some potential in a situation that is not complicated by cross-resistance.

RESEARCH NEEDS AND RECOMMENDATIONS

Clearly, however, in addition to pinpointing the need for continued studies on all facets of pesticide residues in grain, and on resistance to pesticides in storage insects, these problems are best solved in the longer term by placing greater emphasis on safe storage and control of pests by non-chemical methods.

The areas needing future study can be conveniently grouped as hereafter:

Baseline Information

1. Need for a continuing survey of grain storage practices on farms, in commercial stores and in food processing.

2. Need for monitoring the occurrence and spread of resistance and to investigate problems in control.

3. Assessment of the true application rates achieved by farmers and storekeepers admixing pesticides.

Detection of Pests and Problem Diagnosis

1. Development of attractants and lures to improve insect trapping methods.

2. Develop physical methods of pest detection (eg NMR, NIR) particularly for use in moving grain flows.

3. Need for developing guidelines on the meaning of insect and mite trap catches/population estimates and determining appropriate control strategies.

4. More work on the behaviour and the development of the pests in the store environment; particularly in situations of pesticide use or where the store environment is being modified.

The Storage Environment and Pest Control

1. Investigate the control of insects/mites at the periphery of grain bulks during cooling.

2. Assess the effect of different drying methods on grain temperatures and on pest populations.

3. Investigate the consequences of grain aeration/cooling on the ability to detect pests.

4. Investigate the effect of mechanical and/or manual grain cleaning on pest populations.

5. Investigate the influence of the store environment, temperatures, refuges etc on pest survival of insecticide treatments.

Control Strategies

1. Establish the suitability of modified atmosphere storage for UK farm and commercial grain stores.

2. Need for more pilot, and full-scale studies of integrated strategies for pest management with minimal reliance on pesticides.

3. Need for increased work on alternative novel pest control agents (such as insect hormones and anti-hormones) that will prevent establishment/ development of key pest species but which will be of low or zero-toxicity to the consumer.

Pesticide Application

1. Development of adequate application machinery that will allow more accurate treatment during admixture.

2. Assessment of the significance to control and to residues of uneven dosing during admixture.

3. Investigation of more suitable pesticide formulations that will combine effectiveness of control with minimal contamination of the grain.

4. Study means of enhancing the translocation of fumigant gases through grain bulks -eg with use of carbon dioxide or an inert gas.

Pesticide Residues

1. Need to develop broader-spectrum methods of analysis to reduce costs, time and expertise required.

2. Need to develop rapid ("yes/no") methods of analysis for use in trade situations.

3. Need to develop appropriate bioassay methods and to integrate these more with chemical methods in understanding the success or failure of pesticide treatments.

4. Need to identify and to understand the formation/accumulation of pesticide residues within treated commodities.

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