HGCA

HGCA RESEARCH REVIEW No. 3

THE BIODETERIORATION OF STORED CEREALS

by

D. R. WILKIN and D. G. ROWLANDS

Storage Pests Department, Agricultural Development and Advisory Service, Slough Laboratory, London Road, Slough, Berks. SL3 7HJ

September 1988

Price: £7.50

CONTENTS

ABSTRACT

Entry to the EEC has brought UK cereals production into line with that of other Community members, with consequent rises in profitability and in marketing standards. With increased quality and production, there has had to be a concomitant increase in storage capacity both on farm and in commercial stores. The Intervention system of market support has necessarily come more and more into use, so that many producers work automatically to the Intervention standards. The IBAP requirements for moisture, limit on impurities and on bushel weight are relatively easily met, but that of "freedom from live pests" together with sampling and assessment regimes more rigorous than previously, have exerted major influences on storage practice. Adequate drying and cleaning facilities have become necessary and have reduced many of the problems, particularly those associated with fungi. The use of pesticides to control insects and mites has also increased considerably, particularly in commercial stores, where pesticides are seen as cheap insurance against problems.

The present review assesses these factors and the impact they have had in resolving biodeterioration problems, which are also defined, analysed and discussed in some detail. The gaps in research are identified, and the future needs for research are broken down into topic areas. These include: identifying the biological consequences of low-temperature drying; making fuller use of low-volume grain cooling; improving methods of detecting pests in grain bulks, particularly in transit; making full evaluation of the technique of modified atmosphere storage; developing integrated strategies for grain storage where early detection of pests is coupled to physical methods of control, thus minimising use of pesticides; research into improved application methods for pesticides, and into the development of grain protectants based on insect growth regulators; determining the limits of use for phosphine as a fumigant and developing new and improved methods of application. There are also needs for data gathering on the extent of biodeterioration problems in storage practice, monitoring changes in the level of resistance to pesticides in storage insects and mites, and for studies on the nature and development of such resistance.

GLOSSARY OF TERMS

AFRC	Agriculture and Food Research Council
CAM	Committee for Analytical Methods (MAFF)
Codex	Codex Alimentarius Commission, est 1962 to implement the joint United Nations and World Health Organisation Food Standards Programme
DAFS	Department of Agriculture for Scotland
DANI	Department of Agriculture for Northern Ireland
EC/EEC	European Economic Community
FEPA	Food and Environmental Protection Act 1986
FMBRA	Flour Milling and Baking Research Association
IBAP	Intervention Board for Agricultural Produce
IGR	Insect Growth Regulator
JHA	Juvenile Hormone Analogue (Insect)
LD-50	Lethal dose required to kill 50% of a specified genus or population
MAFF	Ministry of Agriculture, Fisheries and Food
MRL	Maximum residue limit (Ref Codex and FEPA)
NIR	Near infra-red spectroscopy
NMR	Nuclear magnetic resonance spectroscopy
RIA	Radio-immunoassays
R & D	Research and Development
UK	United Kingdom (of England, Wales, Scotland and Northern Ireland)
WPPR	Working Party on Pesticide Residues (MAFF)

TOPIC REVIEW: THE BIODETERIORATION OF STORED CEREALS

1. INTRODUCTION

The cereal industry in the United Kingdom has undergone major changes over the last twelve years, largely as a consequence of belonging to the European Community. Total production and absolute value of the crop have more than doubled, so that Britain has exceeded self-sufficiency and has an exportable surplus of the order 6-10 million tonnes. It is now necessary to store grain, both on farms and in specialised premises for considerable periods thus allowing greater opportunity for damage by insects, mites and fungi. This is reflected in a general increase in the use of pesticide grain protectants, particularly in commercial stores where the cost of a prophylactic treatment is viewed as cheap insurance against pest problems. There is also an increased awareness and use of other control methods which do not depend on pesticide treatment, such as the use of low temperature storage, by means of aeration using ambient air and controlled atmosphere storage.

The grain trade is an international business and it is inevitable that storage pests are transferred around the world with transported commodities; this can pose real problems with the importation of insecticide and fumigant-resistant strains, against which the currently available armoury of pesticides may offer poor or greatly reduced protection.

The present review identifies problems that occur, including those that do not lead directly to biodeterioration except in the sense of a lowering of the marketability of the crop (eg the presence of live insects or mites); it also considers the changes that have taken place in grain storage practices in the UK, together with the preventative and remedial control practices. It is particularly concerned to identify areas where knowledge/data are lacking, and to suggest how our current information and awareness can contribute to the design of cost-effective control strategies.

It concludes with some recommendations for future research and development.

The primary source of data for the review is the extensive database of references held at the ADAS Slough Laboratory, together with digest information on current, topical and unpublished research by workers at the same Laboratory. Computer searches of other databases have also been carried out. Selected references are included at the end of the review, but the main bulk of references will be provided as an appendix to the work. In the main the literature search has concentrated on the period 1970-87, but where recent critical or comprehensive reviews of earlier significant work are not available, then the original references are cited.

2. CURRENT STORAGE PRACTICES IN THE UK AND MAIN TRADING PARTNERS

The radical reform of the grain industry over the past 12 years has affected storage practices, both at a farm and at a commercial and marketing level, and has had a fundamental influence on infestation, its control and the attitudes to pests in grain.

Prior to 1975 the cereal industry had evolved only slowly because of the relatively consistent demands of the home market. Almost one third of the country's grain requirements were imported and the majority of home-produced cereal was used as animal feed. Exports were almost unknown and limited to very small tonnages of barley intended for malting. Problems caused by insects, mites and micro-organisms occurred regularly in home-grown grain (Freeman, 1969).

However, as much of the grain was consumed on-farm or sold for animal feed, the main concerns were the weight loss and reduction in palatability caused by infestation (Freeman, 1973; Howe, 1965). The presence of a few insects in grain was often no deterrent to marketing and, in any case, the detection techniques employed at that time were unlikely to have shown up other than serious problems. As a result infestation did not feature highly when storage practices were being considered. A large proportion of the crop was stored on-farm for some period under a wide range of conditions (Butterwick and Ansell, 1972). An overall limit of 16% moisture content (m.c.) was in general use but often provender millers would accept grain with much higher m.c. with appropriate financial adjustment. Hence much grain was stored on-farm at m.c. of 16-20% and advisory recommendations to this effect can be found (Tilley, 1976). As a result, infestation on farms, in commercial grain stores and provender mills was common and there seemed to be limited interest or incentive to improving quality. Serious problems were dealt with on a "fire brigade" basis and lesser problems either went un-noticed or were ignored. The malting industry was the only sector which consistently refused to accept infested grain, but this seemed to have little effect on the general quality of traded grain.

The entry of the UK into the EC resulted in a major change in attitude and triggered a period of rapid development and expansion that is only now tailing off. Surprisingly, there are few papers reviewing the overall effects of Britain's EC membership on the industry and much of the available information is in anecdotal form. However, in 1983 the MAFF commissioned a paper (Anon, 1983) which attempted to predict the market opportunities for UK grain over the five year period following the report. This paper included a good deal of data detailing the changes that had occurred over the previous 10 years and also went on to make a number of predictions, some of which turned out to be extremely perceptive.

During the first 5 years of EC membership, UK grain production increased to the point where home market needs were met as fully as possible and a surplus became available. This increased production had to be accompanied by an increase in storage capacity on-farm and in the form of large commercial storage. There was also a trend towards floor stores or flat storage rather than storage in bins.

The increase in production was coupled with a general rise in the profitability of cereal production as the UK prices were raised in line with EC levels. However, European quality standards were also having an increasing influence on storage and marketing of grain. As production rose towards and beyond self-sufficiency, the influence of the intervention system of market support became more and more intrusive. General quality standards had been set by the EEC for sale into intervention and, with minor variations, these were applied to all member states. The standards as adopted by the UK were not particularly onerous, specifying a maximum moisture content of 15% and limits on impurities and bushel weight, but the standards did demand complete freedom from live pests. Most importantly these standards represented minimum requirements and were not negotiable. The intervention system also imposed a standardised, rigorous (compared to practices then current) sampling and assessment regime which increased the chance of infestation being discovered.

In order to meet these quality standards some improvements in storage systems and in store management had to occur. The need to avoid infestation began to exert real influence on storage practices. Adequate drying and cleaning facilities became essential if grain was to be produced to intervention standards, and these helped to reduce some of the more acute infestation problems, particularly those associated with micro-organisms. The use of pesticides to control insects and mites increased by a large amount, particularly in commercial stores (Papworth & Taylor, 1975; Taylor, 1978; Taylor & Lloyd, 1978; Hurlock & Jeffries, 1980; Wilkin and Wilson, 1983; Garthwaite *et al.*, 1988).

Current Farm Storage Practice

The above changes in quality standards and marketing pressures do not seem to have had a pronounced influence on storage practices on farms. A wide variety of storage systems are still in use and most seem able to deliver grain out of store that is acceptable to the trade. Purpose-built systems range from bins constructed in a variety of materials, free-standing, either outside or within an existing farm building, to multi-purpose floor stores that may be used as grain or potato stores and implement sheds. However, the intervention quality standards do exert a strong influence across the whole cereal market so infestation has become unacceptable in virtually any traded grain. Most of the larger producers of grain now have some form of drying system and are aware of the need to monitor moisture content at harvest, during drying and throughout the storage period.

The widespread use of relatively small bins for on-farm storage often allows infestation problems to be dealt with during storage and without excessive cost. The grain can be turned between bins and a pesticide added to control insects and mites. The moisture content can also be adjusted during the storage period by turning the grain via the drier. However, this facility is limited with floor stores since, because of the scale, it is generally very much more difficult and expensive to move the grain once such a store has been filled. Drying *in situ* is only possible if floor stores are equipped with large capacity air ducts and a powerful fan.

Unfortunately, the overall quality of grain storage on farms is very variable and some grain is still stored in poorly adapted buildings that do nothing to reduce the risks of infestation. Old buildings with numerous structural cracks and dead spaces that cannot be cleaned are still used to store grain that the producer intends to market (MAFF Advisory Reports). If infestation becomes established in such premises it is extremely difficult to eradicate and, as well as adding to the expenses of storage, it may prejudice marketing over several years.

Wilson (1985) provided one of the most recent assessments of insect problems with farm stored grain, but he did not relate problems to storage practices. Other work on mites (Wilkin, 1984) has suggested a decline in problems probably related to the pressure of marketing standards, lower moisture limits and, perhaps, increased use of improved pesticides.

A representative survey of 742 farm grain stores was carried out in England during 1987 by MAFF staff. It suggested that on a tonnage basis the proportions stored were in the ratio: 6 (floor) :2 (inside bin) : 1 (outside bin). Admixture was routinely practised on 6% of the farms, and during the year 10% had admixed pesticide with the grain. Live insect pests were found on 10% of the premises and mites on 72%.

ii. Current Practice in Commercial Grain Stores

Commercial storage has undoubtedly expanded over the last 10 years but there seem to be few published statistics to confirm this supposition. Proposals are in hand for ADAS to carry out a representative survey of current stores in 1988.

Not all the expansion of commercial storage capacity has used purpose-built grain stores. Recently there has been a growing trend to convert existing, redundant industrial premises into grain stores. These can often be converted into floor stores at relatively modest cost. However, grain storage has certain specialist requirements that are not always easy to meet with a low-cost conversion. For example, the ingress of small amounts of water is merely an inconvenience in some industrial premises but may start a cycle of biodeterioration in bulk grain.

From the point of view of infestation and quality, the management of commercial stores has had to respond to many pressures. In general, the industry has been extremely successful in meeting new standards and conditions. Intake inspection techniques are now almost universal and the economic pressures exerted by rejection of infested grain have had a significant effect on attitudes to pests in UK grain. The prophylactic use of drying, cooling and pesticides has increased as has the general awareness of the need to avoid pest problems during storage.

iii. General Aspects of Storage

Some factors of storage have a direct, although unplanned effect on infestation in grain. It is widely postulated that many species of insects and all mites cannot attack completely undamaged grains. However, modern harvesting, drying and conveying techniques seem to cause some damage to many grains. Examination of individual grains under a scanning electron microscope has shown that the seed coat is often cracked in one or more places (Unpublished data, Slough Laboratory). This damage, coupled with a proportion of grains that are broken by combines or conveyers, provides a ready food source for larvae of insects. The germ cap may also be cracked, so allowing mites access to the germ.

High temperature driers effectively remove excess moisture from grain but also raise its temperature. Even driers with very effective cooling sections cannot reduce the temperature of the grain to much less than 5°C above ambient. At harvest time this may result in grain coming off the drier at 25-30°C which must be a very important factor in encouraging the establishment of insect infestations. For example, the Saw-toothed Grain Beetle, *Oryzaephilus surinamensis* (L.) was almost unknown in the UK until the adoption of high temperature grain driers (Armstrong, 1961). Low temperature in-bin or on-floor driers may also create conditions that favour infestation. Generally, such systems will reduce the temperature of the grain relatively quickly to a point at which insects can breed only slowly or not at all. However, they often dry the grain slowly, thus allowing some development of mites and mould before drying is completed. Such systems may be unable to dry the surface layers of grain without over-drying the rest of the bulk and, as a result, may often leave grain exposed to localised but serious infestations of mites or mould.

Generally, little account seems to have been taken of the above points by the designers of harvesting, drying and conveying equipment and there may be some scope for the cost effective reduction of pest problems by the re-designing of equipment.

iv. Current Storage Practices and Their Influence on Infestation

A number of current storage practices or market pressures can be singled out as having a pronounced effect on biodeterioration during storage.

a. Limits on moisture content

Intervention limits for m.c. have ranged between 14.5 and 15.5% and these levels have to be determined according to a standard method of measurement that differs from the techniques used in the UK prior to membership of the EC. The effects of moisture and moisture measurement are dealt with in detail in another H-GCA Research Review (Wilkin and Stenning, in preparation). However, as intervention is the most reliable market, there has been a tendency on the part of farmers and merchants to aim at intervention quality for much of the traded grain. This has reduced the occurrence of serious, visible moulding during storage and may also have limited mite infestations.

b. Size of bulks

As the size of bulks has increased so has the potential for damage from infestation and the difficulties of detecting and dealing with problems. There have been a number of spectacular infestations in large bulks, which have resulted in serious financial loss as well as a reduction in grain quality. However, such cases are the exception as many farmers and storekeepers understand at least the basics of prevent ing infested grain entering store and of taking prophylactic action to prevent the development of insects, mites or moulds.

c. Pesticides

Over the past 10 years several extremely effective contact pesticides have become available for use in grain stores and for application to grain. These chemicals provide low-cost treatments that can be applied by farmers or store personnel and offer a very high degree of security against pests. The use of these chemicals must be regarded as a key feature that has allowed the successful adoption of multi-thousand tonne floor stores and is of particular value when grain is received from many different sources.

d. The introduction of standards which specifically prohibited pests

Any pest insects found in grain offered for sale into intervention results in the load being rejected. Previously, infestation might cause rejection but more likely would result in a small discount. The threat of infested grain being rejected has hardened attitudes towards pests and also made it easier for a wide range of buyers to impose their own pest-free standards.

e. Aeration

The benefits of low-volume aeration of grain during storage have been well known for a number of years (Burrell, 1974). However, over the past 10 years this practice has become much more widely used both at a farm and commercial level. As a result, much grain is stored under conditions that prevent moisture migration, minimise the possibility of insects completing their life-cycles and restrict the rapid development of mites. All these factors have had beneficial effects on grain quality.

v. Storage Techniques Used by Other Major Grain Producers

a. The rest of the EC

The storage practices used in France and Germany (major EC grain producers) have been reviewed by Payne, Wilkin and Medlar (1979); Fleurat-Lessard (1980a) and Mills and Cogan (1982). In general, farm storage is less important and various systems of cooperative or centralised storage have been in use for sometime. The climate in much of France and Germany allows grain to be harvested at lower moisture contents than is usual in the UK so that less drying is needed. A far greater capital investment seems to have been put into the construction and equipping of stores and in Germany in particular, higher operating costs are tolerated. Much grain is stored in concrete silo blocks and considerable attention is paid to intake and outloading facilities as well as access to bulk transportation by rail or water. Floor stores are also widely used but these are usually purpose-built and often have automated filling, emptying and levelling facilities. The infra-structure for grain storage in both France and Germany seems to be the result of direct or indirect long-term planning by government or the EC.

Despite the above points infestation problems, particularly those associated with insects, seem to be more prevalent than in the UK. Not surprisingly there is a lack of published data to confirm this but personal contacts by one of the authors of this Review strongly suggest that insects cause more problems in French and German grain stores than they do in the UK.

b. <u>USA and Canada</u>

Both the above countries are heavily committed to centralised storage although much grain is stored on-farm in the USA. The current world price for grain and the general surplus situation have had major effects on storage practices. Particularly in the USA, capital investment has been low and many silos In the mid west of the USA seem to be using well-worn plant that is operated on a restricted budget. Storage practices and quality standards have not changed over many years, so that even low-cost measures such as aeration, are not used to the best advantage.

However, infestation seems extremely widespread in the USA. The experience of one of the authors in Kansas during 1981 and 82 showed that farm-stored grain on 50 farms visited was all infested to some extent. This situation had been made much worse because of a government policy to encourage the storage of surplus buffer stocks on-farm. Farmers were given a financial incentive to hold stocks of grain on-farm but no incentive to maintain quality. The effects of this policy have probably been very far reaching as it has resulted in vast tonnages of infested grain being distributed throughout the grain storage and transit systems.

The only lessons from North American storage that may be of value to the UK concern the application of quality standards. These, when applied, on a State or National basis, offer ways of manipulating the overall quality of grain produced by a country and tailoring it to fit the requirements of prospective customers.

In Canada, the cold temperatures during the winter months provides an excellent option for pest control and this greatly restricts damage caused by insects.

c. <u>Australia</u>

Grain represents a significant part of Australian total exports and is therefore subject to a substantial amount of governmental support and control.

Some of this support has taken the form of a major R&D input into grain storage techniques. The central government supports a research centre at Canberra that concentrates on national problems and strategic research. In addition, the individual state grain boards support R&D to deal with local problems and to help implement the results from the national research.

Some grain is stored on-farm but most of the storage capacity is in the form of centralised silos. Australia has invested heavily in developing systems of long-term bulk storage to hold surplus stocks until they can be marketed. These may be very large bulk floor stores (100,000 - 200,000 tonnes) or semi-underground, plastic-lined earth bunkers. Control and prevention of pest damage at the lowest cost is regarded as the most important consideration in the design of these stores.

The Australian government has also carried out a number of economic reviews of pest control practice (Johnston 1983) and has used the findings to channel research funds into the most effective projects. The results give an interesting and different view of the value of a variety of research projects. Whilst the results of Johnston's work are not directly applicable to the UK, the technique of assessment would appear to be worth considering for planning and evaluating R&D.

In general there are lessons that need to be learned from the Australian approach to grain storage that could be applied in this country. Their climate favours insects so that there is an enormous potential for loss during storage. However, this has been recognised at all levels within both government and trade, and concerted efforts are made to minimise damage and to present pest-free grain for export.

3. FACTORS AFFECTING THE BIODETERIORATION OF CEREALS

Harvested cereals are intrinsically durable. Properly stored they should suffer no deterioration or loss in quality over many years (Pixton, 1980). Therefore, subject to fluctuations in the harvest and market price, grain in store should represent a stable investment or a secure food supply. However, the increased production in the UK during the past 12 years has not only seen a move away from predominantly animal feed production to grain for human consumption, milling, breadmaking etc, but also the concomitant introduction of much higher market standards and trade requirements (Wilkin 1985).

"Problems and Loss" once meant only physical damage to the commodity, either from mechanical causes or from infestation by rodents, birds, insects, mites or fungi which led to loss in weight and germination, decreased nutritive value, tainting and perhaps the presence of toxins. But this concept has broadened to the extent that the presence of any pest organism is now considered not just undesirable, but unacceptable. Under "pest-free" quality standards, even a few fungus beetles in otherwise excellent grain immediately creates a problem in complying with the contract specification, and can lead to financial penalties. These insects may well be "harmless" or "non-damaging" to grain, but studies have had to be undertaken of their biology and control in order to advise on their elimination from grain (Woodroffe, 1962; Jacob, in press 1988; Thomas and Clasper, 1986).

Financial loss is an obvious consequence of measurable, physical damage but there are also indirect financial losses. These arise from breach of contract, downgrading of grain; loss of goodwill or contract confidence; and costs resulting from demurrage or cost of pesticide treatment if sale/export is to go ahead when live insects/mites are found. Such unexpected items as the return transport costs on a rejected lorry-load of grain, or the additional costs of treatment and/

or re-inspection may well tip the profit/loss balance the wrong way for the seller. Trading in grain is as risky as any other financial speculation, and prophylactic pesticide treatment when taking grain into store is often regarded as cheap insurance by hard-headed businessmen.

i. Problems

Today, problems can be defined as failure to meet the quality standards of the buyer, such as those defined by Home-Grown Cereals Authority, Grain and Feed Trades Association, Intervention Board for Agricultural Produce and similar bodies (HGCA, 1986). They include: freedom from taint (objectionable smells), pest infestation, discolouration, ergot and similar contaminants, excess moisture (above 14.5-16%), impurities (damaged or otherwise fragmented or shrivelled kernels), and pesticide or other undesirable residues. In addition there is the need to fulfil the particular nutritional or physiological criteria for the intended use (eg malting, breadmaking) on inspection by the buyer. Any failure in these respects inevitably constitutes a problem.

The perception of problems will differ according to view point. For example, a farmer producing grain for only farm stock feed may not be concerned about a moderate infestation of insects unless a measurable amount of grain is being consumed by the pests. However, the same farmer may be concerned about mite infestation because of the effects that these pests can have on the performance of stock (Wilkin & Thind, 1984). At the other extreme a store keeper acting for the Intervention Board has no choice but to reject any load of incoming grain in which he detects even a single pest insect. There are, of course, many circumstances that range between these two extremes.

It is also difficult and dangerous to view problems in isolation as there are frequently interactions. A minor ingress of moisture may not at first constitute a serious problem, but if left unattended may lead to the formation of a hot spot caused by fungal heating. This, in turn, may provide suitable conditions for the rapid multiplication of insects, leading to the destruction of many tonnes of grain.

Problems during storage are inevitable if the grain contains sufficient moisture, is at a sufficiently high temperature, is aerobic and contains an inoculum of fungi or a few insects or mites. The physical problems that arise are much the same throughout the world, regardless of the crop, the country and the cause. Only the magnitude of the problem differs and the social or economic consequences for the grower or the community, depending on the climate, the facilities for proper storage and the knowledge and technology to prevent or to deal with such problems as arise (Christensen, 1982).

a. Physical damage

Fragmentation, cracking and other damage to grain can arise from the various mechanical handling processes: combining, conveying, augering, loading and unloading (Adams, 1977) and not only contributes substantially to the "damaged" category in quality assessment, but also provides ingress for many insect, mite and mould problems that could not arise with undamaged grain. Along with such foreign materials as straw, husk debris, and unwanted seeds (wild oats and weeds), damaged grains normally come into the quality category of "impurities", and have a maximum permissible ceiling of up to 12%.

Dust deriving from mechanical damage to grain, particles from bran or endosperm, brush hairs together with chaff and straw particles readily become airborne, constituting an explosion risk. These particles also pose a health hazard, irritating sinuses and mucous membranes and producing allergic reactions in man and animals (Cooper, 1973). Many health problems once thought to be caused by grain dust, are now more correctly attributed to the presence of mites and fungi (Anon, 1970). The problem seems limited in the UK but more pronounced in areas where large-scale silos are situated in drier climates. The filtration/collection of dust arising from the external loading of grain to prevent explosion and a nuisance, can add substantially to the costs of grain handling.

b. Physical conditions

The moisture content and temperature of grain during storage are the most important factors in controlling deterioration. All major agents of biodeterioration are aerobic and have minimum temperature limits below which they cannot develop. Manipulation of the temperature and moisture content of grain during storage must be the most important methods of preventing pest increase during storage. However, they are less effective in guaranteeing freedom from existing live insects and mites because of the ability of many pests to survive for long periods under sub-optimal conditions.

Much grain in the UK is harvested at moisture contents in excess of 16%. Some aspects of moisture have a direct bearing on storage and pests and are, therefore, worth discussing here. The moisture content of grain will govern the treatment a crop receives at or immediately following harvest. Rapid fungal growth is highly likely if the grain is above 16% moisture and so drying (or some other process of preservation) is needed to allow safe storage. Mites will develop at moistures above 14% (depending on the temperature) so the drying process may have to be carried to below this level. Drying may be carried out in one of two ways: high temperature drying which removes moisture rapidly or low temperature bulk drying using large volumes of ambient or near ambient air. Both techniques have advantages and disadvantages and their use can either eliminate the potential for some biodeterioration or encourage some organisms to reach problem proportions (see Chapter 2, General aspects of storage and Chapter 5). However, contractual requirements may override good storage practice, and much grain is stored at moisture contents around 16% because that is specified as the maximum in the contract. Further drying would add substantially to costs as well as reducing the weight of crop sold.

The temperature of grain will affect the development of pests and micro-organisms. At harvest grain may come off the field at 20-25°C because of radiant heating, and high-temperature drying may further raise this value. In addition the temperature is unlikely to be consistent throughout a bulk so that convection may occur and transfer moisture in sufficient quantities to dampen part of the bulk enough to allow fungi to develop. Therefore, some means of evening-out temperatures in large bulks of grain is absolutely essential. Cooling is also highly desirable as bulk grain is an excellent insulator and loses heat only slowly.

All the major organisms of deterioration are aerobic. Fungi and pests cannot develop unless the intergranular spaces in the bulk of the grain contains some oxygen. Unfortunately, they are relatively tolerant of low levels of oxygen and elevated levels of carbon dioxide. Less than 8% oxygen is needed to suppress development and <2% to kill insects and mites and fully suppress fungi.

The means to, and effects of, manipulating temperature and moisture of grain, and its intergranular atmosphere during storage are discussed in Chapter 5.

c. Insects

There are five common pests capable of damaging stored grain in the UK: the Saw-toothed Grain Beetle (*Oryzaephilus surinamensis*), the Rust-red Grain Beetle (*Cryptolestes ferrugineus*), the Rust-red Flour Beetle (*Tribolium castaneum*) (Herbst) and two species of weevils, the Grain weevil (*Sitophilus granarius*) (L.) and the Rice weevil (*Sitophilus oryzae*) (L.). In addition the Lesser Grain Borer (*Rhyzopertha dominica*) (F.) may occasionally occur. Most of these species are of tropical origin and require temperatures above 18°C to complete their life-cycle with optima of 27-35°C. However, they appear to be sufficiently cold-hardy to survive for one year at temperatures below their minimum breeding level (Evans, 1983). The above species can attack grain with all the attendant losses and have the potential for rapid reproduction so that they can complete a generation during the short periods immediately after harvest when grain is warm. The biology, pest potential and damage caused by the above species has been recorded by many authors but much of the key data are recorded in the review by Howe (1965).

The exact routes by which these pests are transported between stores has not been researched but it is assumed that the movement of infested grain or equipment, supplies of animal feed and infested transport all play a part. The insects are known to be attracted to freshly harvested grain and may move over distances of several 100m. Several of the species can fly at tempertures above 20°C but the significance of this in their distribution between stores in the UK is unknown.

Two species of so-called fungus beetle occur commonly in British grain stores: the Hairy Fungus Beetle *(Typhaea stercorea (L.)* and the Foreign Grain Beetle *(Ahasverus advena) (Waltl)*. Both insects can damage grain but only at moisture contents above those normally used for long-term storage.

Although, as described above, there are only a few common insect pests of grain in the UK, there are many insects which may be encoutered in grain and grain stores. These insects include minor pests which feed on broken grain and fine detritus, as well as predators, mould feeders, wood beetles originating from the fabric of the store and field species harvested with the grain which will not breed or survive. Knowledge of the true identity of the species found is thus of paramount importance as it is the key to information on pest status and control strategy.

Rejection of grain due to mistaken or doubtful identity or just because "an insect" is found, is understandable but unnecessary.

When an infestation is discovered the potential for environmental manipulation as a means of control, the most effective chemical control method, the most efficient pesticide and, in some cases, the dosage required, are governed by the species present. The use of species-specific pheromones in control strategies and other biological methods also rely on correct species identification.

As mentioned in the introductory remarks, the presence of insects (or mites) at any stage of their life-cycle immediately constitutes a problem in "developed" countries. Although most contracts specify "no live insects", the presence of dead insects and of insect fragments can be equally undesirable, and not just on aesthetic grounds. Illnesses caused by the presence of insects (and mites) range from the more obvious mechanical irritation of skin, eyes and respiratory tract, to serious allergenic reactions induced both by foreign proteinaceous materials (such as ingested insect fragments) and by chemicals present in discrete insect glands or cells, causing irritation of mucous membranes and the digestive tract (Phillips and Burkholder, 1984).

Storage insects have been shown to transmit infection from contaminated foods. Husted *et al.* (1969) demonstrated that *Salmonella monteride* could be transmitted onto clean grain by the rice weevil.

Other problems caused by the presence of insects in grain are more common and have been the subject of numerous reviews (Adams, 1977). Tyagi and Girish (1975 and 1975a) have published two useful reviews analysing the work of some 200 sources and deducing estimates of the weight loss in a variety of commodities (mostly cereals) due to insect infestation in store. Their data range from the 1870s with Jennerwir separating 10 cwt of grain weevils from 74 tons of Spanish wheat, to the 1970s.

Some insects attack and devour whole kernels or selected parts such as the germ (reducing germination); others require damaged or broken kernels, flour, dust or debris in which to become established (Howe, 1965; Adams, 1977). Yet others, notably the grain weevil, develop within the grain itself, consuming the majority of the endosperm before emerging to mate and continue the breeding cycle.

More important in the UK perhaps than the amount of grain rendered non-viable, consumed or spoiled by attempts at feeding, is the inevitable production of heat and moisture by the insect colonies within the grain. Insect infestation is the most usual cause of initial heating in dry grain (14% moisture or less) because grain metabolism alone is insufficient to induce spontaneous heating at this moisture level (Christensen 1982).

Grain at 15% moisture and above is a good medium for fungal growth and it often happens that insect infestation and the consequent production of metabolic water and moisture migration is closely followed by fungal development, whereupon heat may be generated faster than it can be dissipated (Christensen and Kaufmann 1969), possibly producing tempertures up to 50-55°C, and exceptionally causing charring. Continued high temperatures accelerate the breakdown of proteins and lipids, bringing about loss of germination and nutritive value, discoloration and rancidity.

The gradual cooling that may follow damp grain heating also affords excellent opportunity for insect infestation to develop.

Early detection of low numbers of insects is highly desirable, not only in forewarning of the "cosmetic" problem and possible contract consequences, but also to forestall the possibility of physical damage and spoilage. The insect pests of storage premises are cosmopolitan by nature and if not already present in a grain store, living in residual spillages and sheltering in cracks and crevices, may well be outside or elsewhere on the site, awaiting incoming grain from harvest or supplier.

Many of the pests have been imported into this country from overseas, notably in animal-feed ingredients (Aitken, 1975). Whereas MAFF surveillance and inspection of imported cargoes before 1980 was sufficient to reliably intercept serious infestations (notably saw-toothed grain beetles) coming into the UK, increasing containerisation of imports (especially animal-feed ingredients), their direct transit to inland depots, or even to farm premises, and a marked reduction in staff available for the work, has reduced inspection to a minimum. As a result, imported pests (some of them undoubtedly resistant to pesticides used for their control in the UK) now go direct to animal-feed compounders, mills, other storage premises and even to farms. Lack of disinfestation/cleaning transport and containers between distributors/mills helps the spread of insect pests.

Data from the years 1981-5 (Wilkin and Hurlock, 1986) suggests that one in five containers have infested contents: a regular flow of storage pests into this country. Limited data for the years 1982-3 suggest that 60-75% of the initial recipients - the provender and flour mills and some food manufacturing plants - had detectable infestations. In the case of the major storage pests found, about half could be linked directly with imported cargoes.

The extent to which storage pests occur in farm-stored grain was surveyed in 1977, when there was evidence that some 10-13% of farm stores were infested with one or more major pests (Hurlock and Jefferies, 1980). A limited survey in Eastern England in 1980 (Wilson, 1985) showed little change in species or frequency of occurrence. Coming right up to date, a survey of 742 farm premises undertaken in 1987 indicated an infestation rate for live insect pests of about 10% (Prickett, personal communication).

If the insects in any of these premises prove to be resistant to the pesticides recommended for their control, then that adds a further dimension to the problem - i.e. that of actually controlling them. As already remarked, the use of pesticides for control may well add a third problem - that of pesticide residues in the foodstuff.

It used to be thought that the conditions of a UK winter would prevent most storage pests from over-wintering successfully but, unless aeration is used to keep the grain cool, this is not usually the case. Most storage pests require minimum temperatures of 12-18°C to complete their life cycles - the optimum for propagation being in the range 27-35°C but they can survive at temperatures well below their minimum breeding levels in a state of quiescence until temperatures become warmer.

Moreover where high-temperature grain drying is used for the harvest intake, with moisture levels in the range 16-22%, the grain may go into store at 25°C or higher (Wilkin, 1985) which is ideal for insect development. Conversely, the drying of grain with large volumes of ambient or low temperature air, does not heat the grain and may slow insect development, but drying more slowly allows fungi to develop. This fungal growth can then warm the grain sufficiently to suit the insects.

As remarked in the introduction to Chapter 3 (page 11), so-called non-pest species, by which were meant fungus beetles and other (often accidental) inter-lopers which do not feed on the grain or fragments, are nowadays just as much "pests" as those causing physical damage. In the 1987 Survey, non-pest species such as *Ahasverus* and *Typhaea* were found on 6% and 20% of the farms, respectively.

Rejection or contract penalty may result from finding any live (or sometimes even dead) insects in a sample taken for quality inspection or certification.

d. Mites

Mites are very common pests of stored grain in the UK, such that a survey of 228 premises in 1973-4 disclosed a greater than 90% infestation by mites. Some 90 different species were found, but two: *Glycyphagus destructor* and *Acarus siro* were by far the most common (Griffiths *et al*, 1977). This has been confirmed by the 1987 inspection of farm premises, in which mites were found on 72% of the sites (Prickett, Personal communication). Further-more some of these mites have been found to be resistant to the only group of pesticides currently used to control them.

The extremely small size of individual mites (<0.5mm) makes detection a problem. Often infestation may only become obvious when numbers reach 50,000/kg and the mites can be seen as a brown dust on the surface of the grain or around bins. At this level of infestation some tainting and damage to the grain is inevitable.

As with the insect pests, there are mites which cause no physical damage. Those that do cause damage attack the germ for preference (Solomon, 1966; Wilkin, 1984; Parkinson, Personal communication), thus reducing germination. Heavy infestations can impart a taint to grain which can persist through processing. Infested grain may also have an adverse effect on stock to which it is fed (Wilkin and Thind, 1984) or produce allergenic reactions in workers (Phillips and Burkholder, 1984). "Harmless" mites include scavengers and predators of those that cause damage, but since buyers cannot distinguish between mite species, the same situation pertains as with insects: ie - all live mites are undesirable. In addition psocids (Booklice) which are almost invariably present on UK grain but are essentially harmless, may be erroneously identified as mites.

Opinions differ widely as to what constitutes a mite problem. In fact the inspection standards applied vary considerably and only the Intervention Board (HGCA, 1986) specifies a minimum acceptable level of mite infestation. Sampling and detection of mites and, in particular, interpretation of the findings can be highly variable and problematical.

Grain temperatures in UK stores rarely fall low enough to prevent mites developing, although the process is slowed considerably at 10°C and below. Mites require a relative humidity of 65-70% to breed, which corresponds to grain moisture levels of 14-15.5% depending on temperature. The large quantities of UK grain stored above these moisture contents accounts for the prevalence of mite infestations. The grain at the surface of bulks gains and loses moisture with the seasons and mite infestations during the winter are very common.

Mechanical conveying of mite-infested grain can bring about a substantial reduction in the numbers of live mites, but complete freedom from live mites can only be achieved via an acaricidal treatment (Wilkin and Wilson, 1983) or by drying to 14% moisture or less.

The relationship between mites and fungi in grain is often discussed, but has been very little studied in practical situations. Some fungi are consumed by mites, others may be toxic to them (Solomon *et al.*, 1964) or may simply pass through them undigested (Griffiths *et al.*, 1973). Recent laboratory work by Armitage and George (1986) has shown that mite-infested grain contained less fungal contamination than mite-free grain; though of course the organisms invariably coexist in most practical situations.

e. Fungi

The major problem with fungi is the elementary one of recognising their potential for causing problems! The long and tortuous story of the gradual recognition of the major role in grain spoilage played by - largely invisible storage fungi has been summarised by Christensen and Kaufmann (1969) in their classic text. It is significant that virtually all the problems caused by the presence of fungi on grain: decrease in germination, discoloration, heating, mustiness, increase of fatty acids (rancidity), production of toxins harmful to animal and human consumers, and loss in weight, may occur without the fungi responsible being visible to the naked eye.

The normal classification into field and storage fungi is long-established (Christensen, 1982) and although the field species may affect the appearance and quality of grain coming into store at harvest, they play no part in any subsequent damage incurred during storage. Storage fungi develop on and within grain at a range of moisture contents often found during storage (13.5% and above) although serious problems occur only above 15.5%. The genera involved are mainly *Aspergillus* and *Penicillium*. In passing it should be noted that bacteria and yeasts are not normally a problem in storage since they require free water for development.

Mouldy grain is not readily separated from mould-free grain, unless the pockets of mouldy grain have caked together; what might otherwise be a small problem is magnified due to this difficulty. Stored grain which has not been dried below 14% moisture must be given in-store ventilation if heating due to fungal growth is not to occur Damp grain storage under airtight conditions, where fermentation and the development of some fungal growth generates a carbon dioxide enriched atmosphere (Burrell *et al.*, 1978), is satisfactory for animal feed, but not for grain intended for any form of food processing. Use of fungistats such as propionic acid enables the safer storage of high-moisture grain for animal feed, and may have some bacteristatic effect, as well as possibly affecting the development of insects and mites, but offers no long-term protectant effect against arthropod pests (Wilkin and Thomas, 1970).

Adams (1977) has reviewed the literature appropriate to fungal problems, and noted the correlation between the degree of deterioration, and the condition of the seed: its moisture content and the temperature and period of storage. There are no surprises in his conclusions, and the global picture seems to be one of similar problems occurring, with only the severity varying with the climatic and storage conditions.

f. Pesticides

The use of pesticides to control insect and mite populations in grain, and the problems associated with that use, are the subject of a separate H-GCA Research Review (Rowlands *et al.*, in preparation) and is dealt with, in part, in Chapter 5. Suffice it to say that the problems with pesticides used in grain storage are two-fold. Firstly they give rise to residues in the grain that may be accidental (eg contamination from treatment of the structural fabric of premises) or deliberate (as in admixture). These residues may be persistent and stable, and may survive cleaning and processing, to pass through -often much concentrated in particular tissues- into the final food product.

Moreover, with the increased dealing in grain, individual lots may receive more than one pesticide treatment leading to excessive or multiple residues. Secondly, they may be ineffectual, thus causing needless residues. Reasons for their lack of effectiveness can be due to inadequate or inappropriate application (either to grain or fabric) (Wilkin, 1985); to the fact that the low temperatures of many grain stores in the UK, notably in winter, are not optimal for the pesticidal action (Barson, 1983); or to resistance to the pesticide used, or to similar compounds (Prickett, 1987).

g. Type of cereal

Species and varieties of cereal vary in their susceptibility to biodeterioraton but surprisingly little work has been done on this aspect of storage within a context that can be applied to the UK. For example, there are marked differences between the three main cereals, wheat, barley and oats, yet the difference in their susceptibility to attack by insects is not known. Varietal differences may also affect the susceptibility to insects (Mills, 1972).

4. ASSESSMENT OF THE LOSSES ATTRIBUTABLE TO BIODETERIORATION

There is a very large literature on the topic of loss assessment in stored cereals, particularly with reference to developing countries where pest organisms are ubiquitous and where the means of preventing escalation of damage may be neither affordable nor available (Adams, 1977).

In more temperate and prosperous countries, detection of pests, close monitoring of the storage conditions (notably temperature) and early warning or recognition of the problem normally leads to remedial measures. Assessment of the maximum damage potential under UK conditions is seldom if ever possible and certainly is not an economically viable experiment! Some form of action is normally taken long before irreparable damage has occurred.

The losses produced by stored product insects and mites in laboratory experiments give a good indication of the maximum potential of these pests to destroy food if left unchecked. Grain weevils were able to reduce the weight of wheat grains by more than 10% over a 6 week period (Hurlock, 1965) and similar losses were recorded for the mite *Tyrophagus putrescentiae* (Zdarkova and Reska, 1976). Work on the energy budget of the Saw-toothed Grain Beetle suggests that an individual will consume the equivalent of two-thirds of a wheat grain during its life (White and Sinha, 1981).

Such losses are unlikely to occur on a large scale in the UK since it would be reasonable to expect that infestations would be detected and controlled before appreciable weight losses had taken place. There are exceptions when significant losses do occur and even moderate infestations must result in some weight loss, although usually this would be too little to be measured reliably.

The estimates of loss discussed in published papers and reviews are mainly losses of weight and quality. Where unqualified figures for loss are quoted they may be for insect or fungal damage (quality) rather than a weight loss. A damaged grain may suffer a total loss in quality or be non-viable, yet retain enough substance and food value to constitute only a partial nutritional or weight loss. Once again, the quality of life and subsistence of the country or region in which the grain is stored will determine the importance or the impact of such a loss. Grain whose condition was the subject of caustic bargaining in UK grain markets and perhaps ended up as an animal-feed ingredient, would certainly be acceptable as top quality grain for the consumer in less fortunate countries.

A comprehensive survey of total economic loss caused by insects, mites and moulds in UK grain has never been undertaken. Such an exercise would have to take account of factors of national interest such as the value to the country of grain exports and reduced imports, as well as the cost of prevention and control, and the damage and loss. If this study were undertaken the Australian model described by Johnston (1983) could prove useful in defining the data to be collected and the methods of analysis.

A limited assessment of the costs of pest control was made in 1986 by Wilkin (unpublished data) who requested information on costs from 50 commercial storekeepers. This gave a range of 30p to £3.50 per tonne for the costs of controlling and preventing pests.

A major problem in using the literature is that many of the reported studies for the very obvious and economic reasons mentioned above do not derive from normal post-harvest practice but rather from small-scale trials or even from "glass jar" experiments in the laboratory, intended to simulate bulk storage conditions.

5. PREVENTION AND CONTROL PRACTICES

At a 1969 Symposium on control of insects in stores of home-grown grain, Freeman (1969) reiterated earlier expressions of surprise that storekeepers -and particularly farmers- were still not taking the very elementary precautions necessary to prevent biodeterioration of their valuable crop.

Although other factors change greatly with time, these simple preventive measures have remained unaltered and the same surprise can be echoed, nearly 20 years on. The requirements are:

1. Use of suitable premises for storage (ie that exclude rain, rodents, birds; that are away from animal-feed stores; provision of facilities for turning/conveying/handling/ aeration if appropriate).

2. Cleaning of the structure of those premises between grain intake (harvests) - with particular attention to crevices and the removal of grain residue.

3. Segregation of old and new grain stocks where carryover cannot be avoided.

4. Cleaning of transport/containers/sacks that go to other sites or stores, or convey freshly-harvested grain.

5. Grain should be stored at 15°C or cooler, and 15% moisture or less.

Limitations on any of the physical factors or exclusion of pests will prevent any pest or mould damage during storage. On this basis it is possible to control all organisms of biodeterioration by manipulating the conditions of storage. However, although such techniques are rightly of great importance, it is often not practical to place total reliance on their use. Economics of storage or marketing may dictate a moisture content that is not sufficiently low to prevent fungal or mite development. Although climatic conditions in the UK permit temperatures to be reduced sufficiently rapidly after harvest to ensure that insects cannot complete a generation, they may survive long periods at low temperatures. Therefore, there is a need on occasion, to supplement physical control measures with a range of chemical control agents.

The contractual requirement for "pest free" grain may increase the dependence on chemical control since although physical methods may prevent pests reproducing, they often take many months to kill all stages. Once again the economics of storage may set limits to drying, cooling and the type of store, that mitigate against total eradication of pests unless a chemical is used.

i. Non-chemical prevention and control measures

Pesticides are used largely on grounds of cost and convenience. However, the public demand for food free from residues, the need to protect the environment, incipient problems due to pesticide residues in food and the continuing development of resistance to pesticides by grain insects and mites, make non-chemical control methods more important now than ever before.

Physical techniques in which the storage environment is made unsuitable for the development of arthropod pests and moulds, or indeed lethal to them, are amongst the most useful. Drying, cooling, cleaning and the exclusion of oxygen are basic techniques which have been applied with a varying degree of success and commitment since man started storing grain, and must form an integral part of good grain storage practice (Armitage, 1986). The benefits, particularly those of using ambient aeration, and the future research needed to make them more efficient and economical are outlined here.

a. Drying

In the UK, grain is usually harvested at moisture contents that necessitate drying to prevent infestation, principally by fungi and mites.

The objectives of drying are to reduce the moisture content of the grain to a level at which deterioration will not occur and to a level below the minimum specified by a potential buyer. A moisture of 16% will generally restrict fungal growth, provided the temperature is kept below 15°C, but less than 14% may be needed to prevent the development of mites. Most of the insect pests found in UK grain can complete their life-cycles at moistures well below 14% so drying is not a practical method of insect control.

Two techniques are used to dry grain; a short exposure to high-temperature (45-100°C) air or long exposure to large volumes of air at or near ambient temperature. The first technique requires the grain to be passed through a drier before storage but the second usually makes use of adaptations to the actual store.

High temperature drying:-

Air is heated by the combustion of a fossil fuel (exceptionally straw) and blown through the grain. The process is described by McLean (1980). It offers an easily controlled method of removing moisture from grain and can cope with a large range of moisture contents. The temperature of the drying air and the speed with which the grain passes through the drier, can be regulated to give the required final moisture content. The method demands a relatively high capital investment and has a high energy consumption per unit of moisture removed. Despite these disadvantages the method is growing in popularity, probably because it is fast, reliable and well understood.

Although the technique is widely used it does have one major disadvantage in relation to pest control. The drying process inevitably raises the temperature of the grain and, although driers have a cooling section, the dried grain will go into store several degrees above ambient temperature: sufficient to allow insects to complete their life-cycle. In general this problem seems to go largely unnoticed by the manufacturers of driers, who concentrate on improving the thermal efficiency and drying performance, but put little effort into improving cooling.

Low temperature drying:-

Grain at a fixed moisture content and temperature will be in equilibrium with air of a specific relative humidity. If the relative humidity of the intergranular air is lowered, the grain will lose moisture and this principle is used in low temperature drying when large volumes of air at a lower equilibrium relative humidity are blown through the grain. The air will absorb moisture from the grain until it reaches equilibrium. Generally, air at close to ambient temperature is used. Raising the air temperature increases its drying potential but can only be used to a limited extent if excessive drying at the bottom of the bulk is to be avoided. Air at 65-70% relative humidity will dry grain to about 15% moisture content and this relative humidity can often be achieved in ambient air during daytime in the autumn merely by the small temperature rise caused by the action of the fan. Low temperature or slow drying systems may consist of specially designed drying bins with the appropriate ducts and fans to blow sufficient air through the grain. Alternatively, the grain may be stored on a floor contained between bulkheads and over air ducts connected to a fan. In both cases the drying facility may also be the permanent storage container. The rates of airflow needed range between 0.02 and 0.05 m^3 per second per tonne.

The system generally is less costly to install than a high-temperature drier and has potentially lower running costs, typically 45p per tonne per % moisture. The technique does require a high level of management if it is to be successful and low temperature drying is a relatively slow process. It will take at least 4 days to remove 1% of moisture. The drying does not occur uniformly throughout the grain but the lower layers dry first and the surface last. This latter problem can be compounded by very high atmospheric relative humidities or grain moisture contents. As a result substantial growth of mould and development of mites can occur before drying is completed (Armitage *et al.*, 1982). Some development of mites is inevitable with low temperature drying.

Current practices involve automatically switching off the fans when the relative humidity rises above the target equilibrium, or alternatively switching on heaters or de-humidifiers to adjust the relative humidity. The first technique may be economical, but unfortunately the insects and mites do not switch off their activity when the fan switches off. The second and third approaches, using supplementary heat may seem more expensive, but simulations have shown that the increase in drying efficiency reduces costs (Armitage, personal communication).

The rate of development of certain major mite pests has been determined and studies on others are in progress (Cunnington, 1976, Parkinson, personal communication). However, more work on the damage caused by the different populations may help determine what comprises an economically acceptable infestation level. The relative humidity (r.h.) threshold for different fungal species has also been well documented, but the speed of development has not. Work citing mycelial growth in mm per day cannot be applied to practical storage. The only biological basis for the airflow currently used for slow drying is the appearance of visible mould (Kreyger, 1972), a variable, and unreliable method.

A different approach has been suggested by Armitage (1986), who described fungal growth in bin and laboratory studies using the dilution plate technique which is both quantitative and qualitative. Extensive studies at a range of r.h.'s. and temperatures are needed to determine the speed of development of different fungi. This will not help determine what is a "safe" level of fungal presence, so that separate laboratory studies will be needed to quantify damage such as germination loss. The results of this work should assist in the design of more efficient drying systems and allow the operating conditions to be set more accurately. For example, having established the rates of development of mites and fungi and their acceptable threshold, the time available for drying and appropriate airflow can be defined taking into account season and grain moisture content. Unfortunately, mites and moulds interact (Armitage and George, 1986). In particular, mites inhibit some fungi, either passively with a secretion, or actively by feeding. If it is the latter, the fungi are still growing and causing damage and the mites are merely masking their presence. If it is the former, they are acting as an antimicrobial agent. In either case it casts doubt on the wisdom of extrapolating results from studies of either organism in isolation.

The principles established by such laboratory scale investigations and the resulting improvement to slow drying, need to be extended to testing on a farm scale in different seasons. It is astonishing how few publications have described mite and fungal changes that occur during low-temperature drying.

b. <u>Cooling</u>

The temperature of grain will have a fundamental effect on its safe storage. Insect pests need temperatures above 12-18°C to complete their life cycles and mites breed slowly below 10°C. Reducing temperature also lowers the equilibrium relative humidity.

Unfortunately, bulk grain is an excellent insulator and cools only slowly by natural means. Large bulks rarely enter storage at an even temperature so that convection currents may develop which redistribute moisture. This process can result in part of a grain bulk that has been dried to a safe level, gaining sufficient moisture to support rapid mould growth.

Low temperature drying will reduce the temperature of the grain but, as stated earlier, high-temperature drying results in grain going into store at several degrees above ambient. Even if grain is harvested at low moisture content and does not need drying, radiant heat from the field may have raised its temperature to 25°C or more - well above the minimum needed for insect development. Some form of post-harvest cooling system must therefore be regarded as essential.

The most cost-effective way of cooling grain is to use ambient air, concentrating on the night-time periods of low temperature (Burrell, 1974). Much smaller volumes of air are needed to cool grain than to dry it (10cu.m./tonne/hour for cooling compared to 100cu.m./tonne/hour for drying) so both capital and running costs are low. The small amounts of water contained in the relatively small volumes of cold air needed to cool grain also make it unlikely that the use of such cooling sytems will increase moisture contents greatly, so ambient relative humidity can often be ignored.

Commonly used strategies for cooling grain (McLean, 1980) aim to even out temperatures within a bulk as soon as possible and then to reduce the temperature to below 15°C. Further cooling may be carried out but it is unusual for grain to be cooled below 10°C. However, UK night temperatures during the autumn and winter offer the possibility of reducing grain temperatures to 5°C or lower. When these temperatures are achieved mites do not breed (Armitage, 1980) and fungal development is inhibited. Laboratory trials have shown that many insects die given prolonged exposure to such temperatures (Armitage and Llewellin, 1987) but there are a lack of field data on the behaviour of insects under these conditions. Laboratory tests using unacclimatised insect stocks that have been bred under controlled conditions for many generations cannot be regarded as a satisfactory way of assessing insect survival at low temperatures.

Once cooled, bulk grain is slow to reheat and, if multi-year storage was envisaged, the majority of the grain in large bulks could be expected to remain cool through the summer months following winter cooling.

An alternative to using ambient air to cool grain is to employ a mechanical chiller. This comprises of a refrigeration unit which cools ambient air before it is blown through the grain. The method does allow grain to be cooled at any time of the year but at much greater expense. The use of such units in the UK would seem to be of very limited value.

c. Cleaning

The presence of broken grain, grain dust, weed seeds etc. aids the development of pests. Such debris provides a ready food source for larvae and also impedes airflow of cooling and drying systems. However, many contracts allow relatively large percentages of dust and fine material without penalty so economics may again be in direct conflict with good storage practice. The removal of 5% dust from grain will cost more than £5.00/tonne in lost weight and this may often not be recoverable.

Where cleaning is economically viable (cleaning before drying can reduce energy costs and improve drier performance and reducing admixture may qualify for bonus payments on grain sold into intervention), it will help to reduce the susceptibility of grain to pests. Examination of the cleanings removed from incoming stocks of grain at a commercial store might provide a reasonable method of assessing insect levels, but probably not for detecting very low levels of infestation. However, it is not known if any cleaning system currently in use will remove all pests and thus disinfest grain.

The extra mechanical damage associated with additional cleaning and conveying will itself add to the number of broken grains which facilitates attack by insects and mites. However, it will reduce mite populations by more than 90% (Wilkin, 1975) and will kill or remove over 90% of free-living insects (Armitage, personal communication).

ii Controlled or modified atmosphere storage

If the oxygen content of the intergranular airspaces is reduced to less than 2% or the carbon dioxide level raised to more than 45%, all biodeterioration will cease. This phenomenon has been used in grain storage throughout the world for centuries. It still has important applications for modern grain storage.

The effects of low-oxygen/high-carbon dioxide atmospheres on insects and mites are well researched (Storey, 1979; Banks, 1984) but practical applications are more limited. In some countries, notably Argentina and Australia, underground bunkers have been used with great success. The grain was hermetically sealed under sheets and covered by earth. The oxygen content of the atmosphere within the bunker was depleted by the respiration of the grain and any pests. The resultant low level of oxygen eventually killed the pests. This method will, provided the sealing is near perfect, minimise serious damage from occurring but it will not always ensure complete freedom from pests nor prevent some damage.

Where a higher degree of pest control is required positive steps must be taken to modify the atmosphere within the store. This can be done by flushing with carbon dioxide or nitrogen, or a gas from which oxygen has been removed by combustion. Such techniques can only be successful if some effort is made to seal the store and/or a near continuous input of gas is maintained. Practical trials in the USA (Bell and Wilkin, 1985), and under commercial storage in France (Fleurat Lessard, 1986) and Australia (Banks, 1984) show that the technique can be both effective and economic. So far the method has not been used commercially in this country and there are a number of difficulties that would need to be overcome before it becomes a practical proposition. Modified atmospheres kill insects most rapidly at temperatures of 25°C or above. Much grain in the UK is stored at 15°C or below. At these temperatures it might take three weeks exposure to a low oxygen atmosphere to kill the larvae of grain weevils. Most research has been carried out with relatively dry grain and the higher moisture contents found in the UK may result in the grain adsorbing carbon dioxide which will reduce the concentration in the atmosphere in the grain, thus reducing the effectiveness of the treatment. However, grain at moistures of more than 15% respires actively and may produce more carbon dioxide than it adsorbs. This respiration will also assist in lowering the oxygen content.

The technique has a number of attractions for use in the UK. Work in the USA (Bell and Wilkin, 1985) suggests that the operating costs of a low-oxygen combustion generator are comparable with the costs of using contact pesticides. The treatments leave no residues in the grain, but, it is unlikely to be applicable to many current storage premises and, where it is used, may require extensive sealing if it is to be effective.

iii Chemical control measures

Chemical control measures can be broadly divided into two categories:- contact pesticides
fumigants.

Each use requires specific properties in a candidate chemical.

Contact pesticides that are used to treat grain stores and grain must possess the correct blend of biological activity and either low mammalian toxicity or short residual life. Currently 22 chemicals have been approved for use on the structure of grain stores but only 6 can be applied directly to the grain.

Those approved for use on the fabric of stores include: bendiocarb, bioallethrin, bioresmethrin, bromophos, chlorpyrifos-methyl, cypermethrin, dichlorvos, etrimfos, fenitrothion, gamma-HCH, iodofenphos, malathion, permethrin, pyrethrins, pirimiphos-methyl, D-phenothrin, tetramethrin. Those for admixture to grain: chlorpyrifos-methyl, etrimfos, fenitrothion*, malathion, methacrifos and pirimiphos-methyl. Fumigants are chemicals that are volatile at normal temperatures. They are mostly rapidly-acting general poisons, are effective against all forms of life and disperse through a grain bulk by diffusion. This means that they can be applied at a limited number of points and will then spread through the bulk. However, fumigants must be contained within the grain bulk by sheeting or sealing if they are to be effective. Once a bulk is unsealed the gas will be lost and no residual protection is provided. The following fumigants are approved for use by trained operators: carbon tetrachloride, ethylene dichloride, methyl bromide and phosphine. Of these, ethylene dichloride may no longer be approved from 1989, when a UK derogation to an EC withdrawal directive expires. A large question-mark also hangsover the future of carbon tetrachloride.

*There is no extant label for fenitrothion, so effectively it is no longer approved for admixture in the UK.

a. Contact pesticides

Currently, and for some years past, the control of stored product pests in the UK is and has been based largely on the use of contact insecticides. This convention has come about because of the expansion and refinement in pesticide design, and research into usage and methods of application appropriate to the storage situation. Chemicals are now available that are highly "selective", and that exhibit a very low mammalian toxicity yet show great efficiency in killing insect and mite pests. Such chemicals tend to be inexpensive at the doses needed to control pests, making their prophylactic or disinfestation use extremely cost-effective. Earlier pesticides such as those of the organochlorine group, were highly effective against some arthropod pests, but were also comparatively toxic to mammals and, more importantly, they were very stable and readily stored/concentrated - not just in the organisms deliberately or unwittingly treated, but also in the ecosystem. Modern pesticides have to be biodegradable and much less stable, such that they do not pose any major threat to the environment.

Control of stored product pests using pesticides is carried out in one or two ways:-

Fabric Treatment

Contact insecticides may be applied to the structural fabric of a building or to containers used to store food. Wandering insects contact the treated surfaces and pick up a lethal dose of pesticide. Such treatments are used to prevent the spread of infestation between batches of goods and to protect uninfested commodities from any pests that may have been present on the structure of the store. Fabric treatments are widely used as prophylactic measures by servicing companies and by staff in the food storage and processing industries. In many cases they are the only chemical treatment that can be used.

Admixture

Contact insecticides may be applied directly to raw cereal grains and oilseeds. This can disinfest the product and also offer protection from reinfestation for several months. Such direct admixture of pesticides with cereals and oilseeds is now used extensively by the grain industry. This method has been spectacularly successful in reducing the levels of endemic infestation in British grain and has allowed the industry to cope with an enormous expansion in production and much higher quality standards relating to pest infestation, and also to develop a major export market where freedom from pests is a prerequisite. This improvement in the quality of grain has been achieved at relatively little cost to the industry.

The success of these conventional pest control techniques was directly related to the research and development effort expended during their introduction. Apart from product development work within the pesticide companies, the majority of the R&D in the UK has been carried out by the ADAS Slough Laboratory. Within the past ten years the registration of grain protectants has required increasingly more stringent data to be provided by the manufacturers, and much of this too has emanated from Slough. Until recently this was provided by the ADAS Slough Laboratory free of charge, or as an independent assessment.

The performance of the chemicals currently approved under the Control of Pesticides Registrations, 1986, is detailed by Thomas *et al.* (1987) and Tigar and Pinniger (in press, 1988). The method of application consists of adding an accurately metered amount of pesticide to grain as it is passed along a conveyor, with the rate of application closely matched to the rate of conveying. Pesticides may be applied as either dusts or as water-based sprays using simple apparatus. The technique is inexpensive, current costs range between 20p and 50p/tonne, and can be used by farmers and storekeepers without the need for specialist servicing companies. The method can be used to disinfest grain but is most cost-effective when the pesticide is applied as the grain first enters storage.

b. Fumigation

The technique is used for the rapid disinfestation of commodities in situ and is often undertaken as an emergency measure when, for example, grain becomes infested which must either be sold immediately or kept for long-term storage. It is unfortunate that poor storage conditions (the usual cause of infestation) also conspire to make satisfactory fumigation more difficult.

In the majority of stores in the UK the only fumigants used today are the liquid fumigants carbon tetrachloride and ethylene dichloride, and solid aluminium phosphide (phosphine). Methyl bromide can be used for bagged grain in sacks under gas-proof sheets but it is not suitable for bulk grain unless some means of air circulation to distribute the gas through the bulk is available, for example in purpose-built deep silos at ports and transit areas. The main appeal of liquid fumigants is ease of application. Many will remember use by farmers of watering cans to pour carbon tetrachloride on top of stacked grain. But, in 1980, the Advisory Committee on Pesticides deemed it wise to restrict application of liquid fumigants to professional operatives who should have adequate means of personal protection. Crucial factors in the success of a treatment are the air-tightness of the store, chamber or stack, and the maintenance of the right concentration of gas for the period necessary to deal with the pest concerned. **Fumigation confers no protectant effect;** once disinfested the bulk is liable to reinfestation if the primary source has not been dealt with. The toxicity of a fumigant to an insect or mite 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. Extensive studies on the toxicity of fumigants to insects and mites under varying conditions have been carried out at the ADAS Slough Laboratory and the data accumulated have been used to work out dosage schedules for commercial use (Bell & Rowlands, 1983).

c. Resistance

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). The pesticidal compounds involved number 102, which can be broken down into 18 organochlorine, 43 organophosphorus, pyrethrum and 14 sythetic pyrethroids, 5 carbamates, 5 juvenile hormone analogues, 1 organotin, 1 organosulfite and 12 fumigants including CO_2.

Some of these instances are of academic interest only, but many 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.

In the context of diagnosis and monitoring, 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 in the laboratory, does not necessarily indicate a failure to control pests in a field population, though many of the strains tested by MAFF have come from sites where advice has been sought and where there was an undefined problem in control.

The degree of "overkill" (that is, the margin of control) when using a recommended dose of pesticide 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 beetle *(O. surinamensis)* even when high levels of resistance were present, whereas control of grain weevils with malathion could be so marginal that slight resistance would cause control failures.

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

At the time of the FAO Survey, all the field strains tested were susceptible to malathion. In 1974, sampling from 151 inland sites (farms, provender mills and warehouses) revealed only one resistant population.

In subsequent years until 1979, MAFF made strenuous and successful efforts to prevent malathion-resistant *O. surinamensis* from becoming established on UK farms. The threat came from importation of resistant strains from overseas (notably Asia) in animal feed ingredients which, in the course of trade distribution, would spread resistant insects to the farms, via wholesalers and feed compounders.

MAFF Inspectors intercepted imported cargoes infested with *O. surinamensis* and eliminated such resistant strains as were found. After 1979, however, the increasing containerisation of cargoes (delivery direct to site), together with reduction in the manpower and budget of the Inspectorate, and an upsurge in the need for inspection and certification of export barley, curtailed the surveillance of imports. We now accept that malathion-resistant *O. surinamensis* were established on UK farms by 1980.

During the 1980s a move away from use of gamma-HCH, malathion and fenitrothion began, in favour of the more persistent organophosphorus compounds such as pirimiphos-methyl and chlorpyrifos-methyl. This occurred for a variety of commercial reasons, including the end of patent protection of malathion and of increasingly widespread resistance to it. Currently, pirimiphos-methyl is by far the most widely used compound for stored product pest control, with chlorpyrifos methyl increasing, and a decline in use of fenitrothion and malathion.

In the 1984-5 sampling of farms where MAFF advice had been sought by farmers, some 30% (of 95) strains tested were resistant to malathion and 30% (of 54) to pirimiphos-methyl. Furthermore, 92% (of 37) strains tested were resistant to chlorpyrifos-methyl, while 6% (of 31) strains tested were resistant to fenitrothion.

Six of those farms found to have OP-resistant *O. surinamensis* in 1984-5 still had resistant populations present a year later. At one of these farms a treatment carefully applied at the recommended dose by skilled personnel failed to eradicate the resistant population. In this breakdown of control measures, the proportion of resistant individuals in the population had increased after the pesticide treatment. Taken together with the increasing incidence of insecticide-resistant *O. surinamensis* on UK farms, this warns of the growing risk of treatment failure.

Ten percent of strains of mites *(Acarus & Tyrophagus* spp.) collected from 372 farm grain stores in England in 1987 (Prickett, personal communication) were found to be resistant to pirimiphos-methyl.

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 other countries including the UK 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.

Problems with resistance can only effectively be negated by decreasing the widespread use of pesticide admixture, though 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 and 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 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 reduce the selection pressure for resistance. Treatment of the grain would also be required to guard against the few insects likely to survive the fabric treatment, but this could employ minimum dosage rates.

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

3. Physical control methods. Pesticide-resistant insects may be less hardy than susceptibles, and more vulnerable to cooling.

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, problems of resistance are best solved in the longer term by placing greater emphasis on safe storage and control of pests by non-chemical methods. To this end, manipulation of the physical environment of the grain store and of the stored commodity offers the greatest potential.

iv. Other Techniques

a. Microwaves

Radio frequency energy such as microwaves can be used to raise the temperature of a wide range of products. This has many potential uses but its use for the disinfestation of foodstuffs is particularly attractive and has been the subject of much research. Nelson (1973) reviewed the technical aspects of microwave heating to disinfest food and suggested that the effectiveness of the method might depend on being able to treat selectively the pests rather than the substrate. He further suggested that improvements could come from adjusting the frequency of the radiation used to maximise the heating effects for any specific pest.

Several workers have assessed the technique under practical conditions with varying degrees of success. Kirkpatrick (1974) found that cowpea weevils, *Callosobruchus maculatus* (F.), infesting peas were not controlled by temperatures which seriously reduced germination. He also reported that the same temperature produced by infrared radiation was more effective against insects. Hurlock *et al*. (1979) were able to control several species of stored product insects infesting wheat. However, they were less successful when the insects were infesting cocoa where exposure to the dose that killed all insects in wheat allowed 2% of those infesting cocoa to survive. These workers also supplemented the microwave heating with hot air to extend the period at elevated temperature which improved the effectiveness of the technique.

The use of microwaves to disinfest food clearly has a number of advantages, particularly with food for human consumption. The treatment leaves no residues and lends itself to commercial requirements for an "instant kill" method that can be applied during a production process. However, there are a number of disadvantages that must be overcome before the technique can be used in practice. For example, few workers have reported consistently obtaining 100% kill by microwave heating for a wide range of insects, yet in the processed food industry, no survival of pests can be tolerated. The need for complete kill is made more difficult by likely restrictions on maximum temperatures because of flavour changes in the product. The possibility of exploiting selective heating of the pests rather than the substrate seems impractical. In the UK the use of microwaves is strictly controlled and only two frequencies, 896 and 2540 MHz, are permitted for heating. Neither of these frequencies are close to the likely optima for heating insects (Nelson, 1973). In any case, the small size of insects must limit the amount of microwave energy that they absorb in relation to the substrates. Their large surface area to volume ratio is also likely to allow them to dissipate heat readily.

Before microwave heating can be used as a commercial tool to disinfest foodstuffs some careful development work is needed to ensure that the method will give complete kill of all stages of all likely pests under practical conditions.

Wilkin and Nelson (1986) showed that microwave heating could be exploited to disinfest walnuts on a commercial scale, the process being well suited to a continuous flow on a production line. However, the problems of temperature variation and unequal cooling mean that the process is more likely to be satisfactory if the nuts are heated in a thin layer rather than in boxes. The temperature/time combinations (60°C for 15 minutes) needed to ensure all pests were killed did not seem to affect the flavour of the nuts.

Costs have been indicated as a reason why development of the technique has been slow. Initial installation costs would be expensive (£250,000 for a plant treating 10 tons/hour); however running costs per tonne would probably equate with those of fumigation: putting it at the expensive end of pest control technology.

Other methods of thermal disinfestation, involving heating the grain to 55-65°C for periods of minutes or seconds have involved the use of fluidised beds (Evans *et al.*, 1983), spouted beds (Claflin *et al.*, 1983), pneumatic conveying (Fleurat-Lessard, 1980) and partial vacuum with microwave or infrared heating (Tilton and Vardell, 1983). All the above would be relatively expensive to install and operate.

b. <u>Ionizing radiation</u>

The technique of beta- and gamma- irradiation as a means of disinfesting stored products is proven and the technology for bulk grain irradiation at the necessary dosage in commercial-scale facilities has been available since the 1960s (Tilton, 1974). However the high capital cost of the necessary plant and the strong lobby in the UK and some other countries against any extension of nuclear power facilities, has prevented any further up take or development of the technique. Wilkin (1986) quotes an estimate of the cost of irradiation treatment for a 500,000 tonne annual throughput at about £7 per tonne. This would be compared to (say) £1 per tonne for fumigation or for modified atmosphere storage (smaller bulks).

6. RECENT ADVANCES IN THE CONTROL OF BIODETERIORATION AND FUTURE RESEARCH NEEDS.

This review has, so far, highlighted a number of areas where there are shortcomings in the current data or practices, and where developments are already occurring or about to occur. These are considered in this Chapter in the order that they appear in earlier Chapters.

Chapter 2 - Grain storage practices

The lack of information on the changes that have occurred in the UK cereal industry over the past 10 or 15 years is both surprising and regrettable. This makes it extremely difficult to evaluate thoroughly the effects of any changes in storage practice on infestation and other aspects of cereal quality. This lack of data is almost certainly a reflection of the once prevalent attitude that there was no such thing as a UK cereals industry, merely various individuals who interact as little as possible. This approach may have been tolerable in the 1970's but is unacceptable for the world's fifth or sixth-largest cereal exporter.

The lack of any form of national planning is also very evident, with many developments being at the behest of individuals or in response to outside pressures such as those applied by the EEC. This contrasts sharply with all other major cereal producers. Perhaps the advent of British Cereal Exports will effect a change in attitude.

The lack of co-ordination across the cereal industry is also reflected in the compartmentisation of problems. Thus manufacturers of drying equipment do not consider the consequences of putting warm grain into store and the companies promoting pesticides may not inform their customers of the benefits of physical control measures. There would appear to be great benefit in setting up some liaison links across the industry to try to encourage multi-disciplinary approaches to dealing with infestation and other problems that affect farmers, commercial store-keepers, grain traders and end users. The Home-Grown Cereals Authority Committee controlling the distribution of R&D funds collected by the levy on cereals, would seem to be in a favourable position to influence departments.

Research on storage in the UK seems to have largely kept abreast of needs. However, important lessons can be learnt by studying work carried out overseas. Countries such as Australia and the USA expend large R&D budgets on developing methods to avoid biodeterioration in stored cereals. While much of their work is aimed at solving specific problems associated with their own climatic or storage conditions, some of their projects have direct application to the UK. Fact-finding visits and regular scientific exchanges would be far more cost-effective than duplicating research programmes.

Dissemination of information

Farmers and storekeepers obtain information on new developments and advice on problem-solving by a variety of routes. ADAS would appear to be the largest, best informed and best-supported source of information. Information is dispensed via its front line advisers, who are supported by a selection of leaflets and back-up services. ADAS also provides training courses for farmers (in conjunction with the ATB) and commercial storekeepers as well as mounting exhibits at shows. However, ADAS has undergone a radical change over the last 2 years with the introduction of the policy of charging for advice. The same quality of service is available but it must now be paid for by farmers and storekeepers. The charging policy has, perforce, restricted supplies of free leaflets and the amount of data that are provided at shows or displays. The effects of this policy on the dissemination of the results of R&D are not yet clear.

ADAS covers England and Wales but has no direct involvement with Scotland. A limited information service is provided by DAFS Infestation Control Branch at Edinburgh and some of the Scottish Agricultural Colleges. Both these sources rely on the ADAS Slough Laboratory for R&D support.

The principal alternative source of information on storage problems stems from the suppliers of agricultural chemicals and pesticide companies. Some of these employ well qualified staff who can provide a high level of advice, but all must be at risk of bias because of vested interests. Only a limited amount of R&D is carried out on storage problems by pesticide companies because the small scale of the storage market for using pesticides can justify only a small budget.

There are also a small number of agricultural consultants who provide advice on grain storage.

Information from ADAS advisers shows that virtually all serious problems involving the biodeterioration of stored grain could have been avoided if better use had been made of existing data or the store keeper had had a better understanding of the principles of safe storage. Clearly there is still a need to improve the education and practical knowledge of everyone involved in the storage of grain.

Chapter 3 - Factors affecting Biodeterioration

Almost all factors that govern the deterioration of cereals during storage are well researched and there is a wealth of published information. However, there have been relatively few studies on the interaction of the various organisms or the effects of minor changes in the physical conditions. Current research in this area seems interesting and could help to explain some practical situations where expected problems have not materialised.

Chapter 3 mentions the need for early detection of low numbers of insect and mite pests. Correct identification of the pest is a prerequisite for effective communication. More training in identification and greater use of identification services such as those provided by ADAS are necessary to avoid wasteful treatments being applied against harmless species and to ensure that the control strategy is relevant for the species present. Reliable early warning of pests and monitoring of their numbers by the development of efficient techniques can be used as the basis of store management systems. Integrated use of pest detection with temperature and moisture monitoring and aeration can prevent problems developing and reduce the use of pesticides to a minimum (Pinniger *el al.*, (1986). However, different detection systems are needed for finding pests in food stores, warehouses, bulk cereals and cereals in transit.

Bait bags containing wheat, groundnuts and carobs were developed at Slough for use in empty warehouses and stores; the combination of attractive foodstuffs and refuges within the trap add up to a very successful monitoring tool. Over 60 different species of warehouse and food store pests have been found in bait bags placed in a wide variety of environments. Corrugated card traps with a central pitfall area containing cereal oil are useful in places where, because of their food content, bait bags cannot be used. They are not as efficient as bait bags and there is a need for a more efficient trap which is acceptable to the food industry (Pinniger, in press 1988). Moth traps incorporating pheromone lures have been used by the food industry for many years. When properly integrated with a cleaning/control programme, regular trap recording can enable dramatic reduction of infestation in flour mills, warehouses and food processing plants.

Detection of insect pests of bulk grain by use of pitfall and probe traps has been shown to be at least ten times as effective as conventional sampling methods (Cogan & Wakefield, 1988). These two trap types have now been adopted by IBAP for detecting insects in grain bulks, but there is still room for improvement.

One practical consequence of improving detection and trapping of pests, is that of needing to interpret the findings in a meaningful way. If pests are easy to find, then damage has probably occurred already, but the status of different pests varies widely. At low levels of infestation the acceptance of insects or mites present depends on the species, the commodity at risk and the environment. One booklouse (psocid) in a flour mill warehouse may not cause concern, whereas a single live weevil detected in a 20-tonne lorry-load of grain arriving for Intervention will be enough to have the load rejected. Temperature and humidity of the environment are also crucial in deciding the significance of a trap catch.

Detection of pests in bulk cereals in transit is still undertaken by using either spear or vacuum sampling devices, to collect samples and manual examination of the debris removed by sieving, all of which is labour-intensive, haphazard and largely ineffective. There is a need for a wholly mechanical method which can estimate infestation within seconds and so minimise the delay to waiting transport. Preliminary studies have demonstrated the ability of nuclear magnetic resonance spectroscopy (NMR) to detect grain weevils developing within wheat kernels (Chambers *et al.*, 1984), and it is possible that existing instruments now commercially available at reasonable cost can be adapted for this purpose. Another physical method, based on near infrared reflectance (NIR) has been found capable of detecting flour mites in animal feed (Wilkin *et al.*, 1986). Both these instrumental methods show considerable potential for the monitoring of conveyor-belt or lorry-load situations and are worthy of further research and development.

The lack of information on the distribution and frequency of occurrence of pests in UK grain must be regarded as a serious gap in our knowledge. Hopefully, the recently completed ADAS Slough Laboratory Information Gathering Exercise will help to redress the balance, at least as far as farm stored grain is concerned. It is vital that such exercises are repeated on a regular basis if changes in pest status, types of problem, patterns of resistance and the overall quality of grain are to be monitored. If the current level of cereal exports is to continue or increase then such data become vital to national marketing efforts.

One area where current R&D seems lacking is the importance of microbial spoilage in grain. Gross problems, when fungi develop to a point where grain becomes very hot and bound together in a solid mass, are obvious. However the importance, or even the frequency of occurrence, of less-visible mould growth is poorly researched.

An analysis of the parameters that have to be satisfied before infestation can develop shows that, in nearly every case, adjustment of the physical conditions would prevent any deterioration. Storing grain at 14% moisture or less and cooling it to 5°C, achievable with current technology, would prevent all losses, eliminate most pests and rule out the need for most pesticides. This approach would, of course, extract an economic penalty that many traders and producers claim would be unsustainable. However, when Intervention became the means of market support it also introduced lower levels for moisture than was previously the case (first 15% and then 14.5% as opposed to 16%). This did not prevent many millions of tonnes being sold into Intervention and did help the Intervention Board for Agricultural Produce store the grain safely without loss of quality for up to 3 years. One reason that the IBAP conditions for moisture were accepted was that the Board paid a bonus for lower moisture contents. If this practice was widely adopted it would give enormous potential for reducing the occurrence of mites and mould as well as the economic benefit of reducing haulage costs by restricting the amount of water being transported. The price of grain could be set on a dry-weight basis and adjusted according to the moisture content of a particular load.

A method of reducing the temperature of grain during storage has been available for many years and is now widely used. The principles of its operation are well understood, yet the majority of users do not extract the full potential benefits from the system. There is a widespread misconception that cooling grain with ambient air may also dampen it if aeration is carried out at high relative humidities. Also many users seem to stop aeration when temperatures are 15°C or, at best, 10°C, whereas it would cost very little more to continue to reduce temperatures to 5°C or even lower. The availability of a simple automatic control system for aeration fans would greatly assist in reducing pest problems in UK grain.

The type or variety of cereal is not considered to be of great importance in affecting the chances of infestation. However, this aspect may be worthy of some R&D since changes in variety could influence the equilibrium relative humidity of a cereal as well as its susceptibility to attack by pests. It is not inconceivable that resistance to pest attack could be bred into cereals and experimental work with maize already shows promise.

Chapter 4 - Losses

The lack of information on the economic cost of biodeterioration in grain in the UK could be construed as a serious gap in basic knowledge. Certainly it makes cost-benefit analysis of R&D and control measures somewhat problematical. However, the UK is not alone in lacking such information. Indeed it is difficult to find accurate cost figures for losses in stored grain for any developed country. Even in Australia where much economic analysis is carried out, the basic assumption is made that failure to control insects will result in a catastrophic loss of export sales. The main thrust of their work is aimed at assessing the relative cost of various control options and determining the most effective point of application for a control strategy.

It would, with commercial co-operation, be possible to collect data relating to the costs of biodeterioration in stored grain in this country. However, the project would have to run for several years before a worthwhile picture could be assembled. The data would allow proper assessment of the value of control measures applied by farmers and storekeepers, as well as providing cost-benefit analysis of resources put into research. Such a project would be costly in terms of manpower and a limited investigation, in which selected areas were targeted for investigation could be a better alternative.

Chapter 5 - Prevention and Control

It is much easier to sum up the new developments and future research needs for this Chapter. However, actually controlling the implementation of new developments or, for that matter, the use of existing technology, is much more difficult. A whole range of economic and commercial factors frequently influence more control over the grain industry than scientific data. Central government policy (and more importantly EEC policy) may also apply constraints or actively encourage the implementation of new developments. For example, new developments in the laboratory with pesticides are totally dependent on the manufacturer's willingness to market the product. The vigour with which any pesticide is marketed will have a profound effect on its rate of use, sometimes overriding research results showing shortcomings in its performance. The overall profitability of the industry, at least in part controlled by the UK and European legislatures, has a major influence on the uptake of new ideas. These constraints need to be kept firmly in view when considering the likely use of new developments and the value of research and development.

Physical control:-

The advantages of cooling and drying grain are well researched and understood but they are not used to maximum advantage because of commercial and application restrictions. Cooling in particular has great potential and future research needs to concentrate on finding the quickest, simplest and cheapest method of fan control during cooling and to investigate the survival of free-roaming insects in cold bins. An integrated control method should be developed that employs aeration together with fabric and surface pesticide treatments, to ensure total and reliable control with minimal pesticide use. Work should also focus on the survival criteria for different species and strains of insect and mites: we need knowledge of pest increase at near-minimum temperatures. While much information exists on insect biology under optimal laboratory conditions, few researchers have had the patience to extend the work to grain stores under seasonal conditions.

Other practical operating difficulties may also need investigation.

Low-temperature drying systems currently offer the most economical way of drying grain. They are widely used and apparently work well in many cases. However, mycological data suggests that the use of such systems allows substantial fungal growth to occur before drying is completed. Mite infestations are known to be an inevitable consequence of low-temperature drying and prophylactic treatments with an acaricide are frequently used to avoid these problems. Future assessments of slow drying systems must include biological input. More research is needed to determine the extent of fungal growth more accurately and then to assess its practical significance. A better co-ordination between the mechanical and physical aspects of these driers with the biological consequences of certain drying strategies, would offer the opportunity to improve their performance.

High-temperature driers are highly developed but their manufacturers seem to pay scant regard to the consequences of delivering grain at elevated temperatures. Liaison between manufacturers and biologists would allow more exchange of information and this could assist in the improved design and use of machinery.

Modification of the storage atmosphere is not used as a method of preserving grain in the UK, although it is used in the storage of fruit and vegetables. Much research has been carried out world-wide and the technique has definite practical potential. The method could not be applied to all stored grain in the foreseeable future as major modifications would be needed to most of the stores currently in use. However, it could have immediate value for certain types of grain; malting barley and milling wheat for example. It could also offer a very effective way of storing or disinfesting "organically grown" grain without the use of pesticides and at least some current storage structures could be converted to modified atmosphere storage at small cost.

Work at Slough on the lethal aspects of various atmospheric gas mixtures incorporating carbon dioxide has so far concentrated on the gas ratios produced by purging with bulk carbon dioxide or by the use of catalytic converters and thermal generators, i.e. low-oxygen exhaust gas. Bell and Wilkin (1985) took the opportunity to participate with the United States Department of Agriculture in field trials on controlled atmosphere storage using burner gas generated by an exothermic burner. Their preliminary assessment suggests that the on-site burner gas generator, if its initial high cost is discounted, provides a cheaper purging gas than bulk carbon dioxide. In either case, the operating costs compare favourably with current techniques involving contact insecticides or fumigants.

The use of controlled atmospheres for control of infestation has long been seen as a desirable alternative to chemical methods of control, offering a pesticide-free, environmentally 'clean' method of treatment. However, doubts about their efficacy, particularly at lower temperatures, and about the costs entailed in upgrading facilities to the required standard of gas retention, have generated resistance to their adoption as a control strategy for bulk stored commodities such as grain. The concept behind such an attitude has been that the only practical method of treatment is to dose a structure and leave it, relying upon an adequate seal to retain the applied atmosphere. More recently emphasis has been placed on atmosphere maintenance by a continual or repeated recharging of the structure with gas (i.e. "topping-up") and recent research has pinpointed various systems for the production of gas that are worth evaluating from an economic point of view. The prospects for efficacy against pests at low temperatures are greatly extended when treatment is linked with grain drying or grain cooling. In the former situation grain temperatures may be high, and much shorter exposures are required for both oxygen-deficient and high-CO_2 atmospheres. In the latter situation the lowered temperatures prevent breeding and development of most pest species but the cooled commodities are left with a static population of adults.

The ultimate constraint on the adoption of controlled atmosphere storage in the UK is currently, and will remain, the availability of a suitable gas generator or supplies of bulk carbon dioxide at a realistic price. This aspect should not be overlooked when allocating future R&D resources and predicting the likely uptake of the technique.

Developments in the detection and monitoring of infestation in grain have already begun to be applied, particularly by commercial storekeepers. These developments are of practical importance as they allow insects to be detected long before any damage is caused. However, much work is needed to interpret correctly these results from trapping under practical conditions. Failure to do this will result in the creation of "problems" from infestations that otherwise would have gone undetected and an increase in the use of chemical control measures. The possibilities of developing better methods of detecting insects in incoming stocks of grain could also have far-reaching consequences as they would help to reduce the need to rely on prophylactic applications of pesticide because of the shortcomings of current methods.

Other physical control methods such as heating (using microwaves or hot air), cooling by refrigeration or the mechanical destruction or separation of pests seem to have either limited potential to replace existing methods or to be totally dependent for their adoption on changes in marketing standards.

Chemical control:

Recommendations about reducing the use of pesticides have been made regularly for the last 10 years but these seem to have had little impact in the field of grain storage. In fact there are considerable data to indicate that pesticide usage has grown substantially over the period. This increased use has come about because contact pesticides have proved cheap and effective. Reduced usage will only result if more cost-effective control measures are developed or if pesticides can be used in a more effective way at lower doses. This latter route offers the greatest immediate potential. Therefore, although some areas of pesticide usage may be superseded, this is unlikely to have a major effect on practical control measures within the next 5 or 10 years. It is essential that R&D resources continue to be applied to improving pesticide usage and to developing new methods. In particular current R&D aimed at reducing the amount of pesticide used without detracting from the efficacy of treatments and integrating pesticide usage with other control techniques, must continue to attract a high degree of support.

In addition, new problems continue to appear that threaten existing control strategies. For example with admixture, field investigations have shown that treatments by farmers or commercial storekeepers rarely achieve the intended dose. Some explanations for this are beginning to emerge from work on formulations but much more data are needed.

Changes in pest status of some insects associated with stored grain have also occurred and there are no data on the effectiveness of pesticides against a number of species. The widespread use of the techniques has also increased the frequency with which residues are detected in grain and various grain products. Levels are below CODEX Maximum Residue Levels but the frequency of occurrence of residues has increased many times (Wilkin and Fishwick, 1981). Finally, resistant strains of many species of stored product insects and mites are now widely distributed but the impact of these strains on current control recommendations is unknown.

New pesticides, even new chemical groups, continue to be developed. Research at Slough on the potential usefulness of such developments for controlling stored product pests will continue. The Laboratory's R&D programme provides the only unbiased and independent assessment of stored product pesticides that is available to users or to regulatory bodies such as the Advisory Committee on Pesticides.

Fumigation is often the technique of last resort and the limitations likely to be placed on the method by the restriction of available chemicals should not be taken lightly. Chemicals suitable for use as fumigants are few in number and have been depleted by the discovery that most, besides being acute poisons, have potential to produce chronic toxic effects in mammals. In recent years ethylene dibromide and ethylene oxides have been taken out of use on foodstuffs and ethylene dichloride may not be available after 1989 when a UK derogation on an EEC directive expires. Work at Slough has until recently, concentrated on evaluating possible replacements for the liquid fumigant mixture of carbon tetrachloride and ethylene dichloride, and some alternative mixtures have been developed (Bell and Rowlands, 1983). Unfortunately no commercial concern has agreed to seek approval of the new mixtures although sufficient data are available to support registration of a 20% methyl bromide 80% methyl chloroform mixture.

On the grounds of increased safety and efficacy MAFF can identify many situations where the new mixture would be the chosen recommendation for control. If ethylene dichloride is withdrawn, the only known alternative is phosphine which cannot cover all the needs. Hence there is an urgent need for the new mixture to become available for use, although at present it is difficult to see what further pressure can be applied to bring this about. In 1989 there may be no effective control measure to recommend in some situations. This will create problems for the export market as many importing states will have a 'nil tolerance' of insects.

In the past two or three years there has been a renewed focus on phosphine as the only remaining fumigant in world-wide use that is not threatened on health grounds. Studies have been conducted on the behaviour of the gas as an insect poison, its possible repellent or attractant effects at various concentration levels and its powers of distribution in bulk stores. Methods of application to bulk grain using the commercially available phosphine releasing formulations and experimental phosphine-carbon dioxide mixtures in cylinders, have been examined. Work has also been carried out on the incidence of resistance among stored product pests in the UK (Bell, 1986).

Novel compounds:

Perhaps the most exciting potential for pest control is offered by the insect growth regulators (IGRs), a group which includes compounds that disrupt cuticle formation and affect the endocrine systems. It is the latter that we shall consider here, particularly the insect hormone analogues and anti-hormones. They have striking advantages over conventional pesticides in being of low toxicity to mammals and exhibiting a high degree of biological activity and specificity (Edwards, 1983).

Briefly, the hormones act by interfering with insect development at crucial stages. In the case of the synthetic juvenile hormones they are applied at the final larval stage, producing developmental abnormalities that culminate in a pupal-adult intermediate destined to die at pupation or emergence. The timing and dosing can be critical, however, since the natural function of the hormone is to maintain the larval state. Overdosing in the early larval stages can produce extra moults and in some cases "permanent" or outsize larvae (ie feeders) not a desirable situation for grain storage!

Since identification of the chemical structures of the insect juvenile hormones, a number of analogues (mimics) have been synthesised and, in fact, commercial juvenile hormone analogues (JHAs) have been available for some 13 years now. Despite this, they have only slowly come into use, and then mainly in the public health sphere. Initial problems with stability and formulation, high cost and varying degrees of effectiveness, especially against stored product insects (notably a poor performance against *Sitophilus spp*), all hindered the advancement of JHAs as grain protectants.

Moreover, a strain of *Tribolium castaneum* resistant to a wide range of conventional pesticides is also less sensitive to a number of JHAs. This has highlighted the importance of testing the effectiveness of any new compound, whatever its mode of action, against insecticide-resistant strains.

Recently a number of new compounds with hormonomimetic effects on insects have been discovered. One of these, fenoxycarb or ethyl N-2-(4-phenoxyphenoxy) ethyl carbamate has low mammalian toxicity (16,500 mg/kg rat, acute oral LD_{50}) and has shown potential as a grain protectant, exhibiting high JH-activity against both susceptible and insecticide-resistant strains of *Sitophilus* spp. (Edwards and Short, 1984), as well as a wide range of susceptible and resistant strains of other storage insects. Once again some degree of tolerance to fenoxycarb was found in the multiple-resistant strain of *T. castaneum* however (Thind and Edwards, 1986).

An older commercial compound, hydroprene, shows potential for the control of both stored product pests and cockroaches in flour mills, warehouses and food manufacturing plants.

However, there remain some obvious practical drawbacks with JHAs. Generally they do not kill adults and their lethal effect is delayed, making control a prolonged business with no immediate observable effects. Moreover, JHAs exert their effect at the late larval stage, by which time any damage to the grain has been done! So, in recent years, interest has focussed on the so-called "anti-hormones" which, if they can prevent the synthesis or reception of the natural juvenile hormones, might disrupt the development of insects in the early larval stage, and also affect such hormone-regulated processes as diapause and reproduction.

7. SUMMARY OF RECOMMENDATIONS FOR FURTHER ACTION AND RESEARCH

1. There is a lack of information, both general and specific, on the storage practices used by the cereal industry. Ways should be sought to obtain more information in the future, perhaps via regular information gathering exercises.

2. Liaison links should be set up between producers and users of storage equipment and biological researchers. Co-operative R&D projects between the groups should be encouraged.
3. Information and research results from other grain producing countries should be collected, assessed and, where appropriate, utilised.
4. The quality of the basic training and information available to farmers and storekeepers should be examined and improved as necessary, with particular attention given to channels of communication.
5. A programme of economic analysis should be set up to evaluate the cost-benefits of various methods of pest control and storage research.
6. The biological consequences of low-temperature drying should be studied and the results linked to work on improving the design and management of systems.
7. The advantages of making full use of low-volume grain cooling should be more widely publicised.
8. Work on the development of improved methods of detecting pests in the grain should continue with particular emphasis on grain in transit. The results of the work should be integrated with control strategies to avoid creating new problems or triggering additional treatments.
9. Efforts should be made to stimulate commercial interest in developing and marketing controlled atmosphere generators and bulk supplies of carbon dioxide. Future research should be related to commercial interest.
10. Improved methods of pesticide use and application should be developed which will reduce the amount of active ingredient needed. Efforts should also be made to integrate pesticide use with physical control methods.
11. Research should continue on the development of grain protectants based on insect growth regulators.
12. Changes in levels of resistance to pesticides in the major pests should be monitored and strategies developed to mitigate the effects of resistance.
13. The limitations of phosphine fumigations in bulk grain should be assessed and improved methods of application developed.

Acknowledgements

The authors would like to thank the following who read the drafts and made helpful and pertinent comment and corrections: Dr K Mclean, Mr D Armitage, Dr D Halstead, Dr J Chambers and Mr K P Thomas, as well as acknowledging the important contributions made by the Slough Library and Typing Pool.

REFERENCES

ADAMS, J.M. (1977). A review of the literature concerning losses in stored cereals and pulses published since 1964. Trop. Sci., **19**, 1-28.

AITKEN, A.D. (1975). Insect Travellers, Volume 1, Coleoptera. A survey of the beetles recorded from imported cargoes by the Insect Inspectorate of the MAFF, with a special analysis for the years 1957-69. Tech. Bul. MAFF. No. 31, HMSO, London.

ANON (1970). Bakers Asthma. Br. med. J. April., **4**, 37.

ANON (1983). The United Kingdom Cereals Market - The Next Five Years. Min. Ag. Fish and Fd. 1983. Whitehall Place London.

ARMITAGE, D.M. (1980). The effect of aeration on the development of mite populations in rapeseed. J. Stored prod. Res., **16**, 93-102.

ARMITAGE, D.M. (1986). Pest control by cooling and ambient air drying. Int. biodet., **22**, (Suppl), 13-20.

ARMITAGE, D.M., BURRELL, N.J. and LLEWELLIN, B.E. (1982). Changes in fungal and mite populations in grain during prolonged drying and subsequent storage. Proc. 3rd Int. Drying Symp., **2**, 193-201.

ARMITAGE, D.M., DAY, P.G. & LEWIS, G.J. (1983). The effect of three species of mites unpon fungal growth on wheat. Bull. ent. Res., **73**, 233-237.

ARMITAGE, D.M. & GEORGE, C.L. (1986). The effect of three species of mites upon fungal growth on wheat. Exp. & appl. Acarol., **2**, 111-124.

ARMITAGE, D.M. & LLEWELLIN, B.E. (1987). The survival of *Oryzaephilus surinamensis* (L) and *Sitophilus granarius* (L) in aerated bins of wheat during British Winters. Bull. Ent. Res., **77**, In press.

ARMSTRONG, M.T. (1961) Survey of infestations of *Oryzaephilus surinamensis* on farms 1959-60. Tech. circ. MAFF, Infest. Control, no. 26.

BANKS, H.J. (1984). Current methods and potential systems for production of controlled atmospheres for grain storage. Proc. Int. Symp. Controlled Atmospheres and fumigations in Grain Storages, Perth, Australia, 1983. 523-542.

BARSON, G. (1983). The effect of temperature and humidity on the toxicity of three organophosphorus insecticides to adult *Oryzaephilus surinamensis*. Pestic. Sci., **14**, 145-152.

BELL, C.H. (1986). Factors governing the toxicity of phosphine to insects. Proc. GASGA Seminar, Slough, England, 78-87.

BELL, C.H. & ROWLANDS, D.G. (1983). The future for liquid fumigants. Proc. 6th Pest Contr. Conf., Cambridge, Paper **19**, 10pp.

BELL, C.H. & WILKIN, D.R. (1985). Report on a visit to investigate the use of exotherimically generated atmospheres for controlling pests in stored cereals, USA, 5 June - 23 July 1985. ADAS internal report, Slough, England.

BURRELL, N.J. (1970). Low volume aeration. Key points to note. Power Fmg., **45**, 15.

BURRELL, N.J. (1974). Aeration. In, Christensen, C. (Edit): "Storage of Cereal Grains & their Products", 2nd ed, 1974, 454-454-486.

BURRELL, N.J., ARMITAGE, D.M. & HILL, S.T. (1978). The effect of cooling damp barley before airtight storage. J. Stored Prod. Res., **14**, 53-59.

BUTTERWICK, M.W. and ANSELL, D.J. (1972). The economics of bulk centralised grain storage in Great Britain. Rept: Br. Assn. Grain, Seed, Feed, agric. Merchants Ltd, and HGCA.

CHAMBERS, J., McKEVITT, N.I. & STUBBS, M.R. (1984). Nuclear Magnetic resonance spectroscopy for studying the development and detection of the grain weevil, *Sitophilus granarius*, within wheat kernels. Bull. ent. Res., **74**, 707-724.

CHAMP, B.R. (1986). Occurrence of resistance to pesticides in grain storage pests. Proc. ACIAR/ASEAN Seminar, Pesticide and humid tropical grain storage systems. Manila, 1985, 229-255.

CHRISTENSEN, C.M. (Edit) (1982). Storage of cereal grains and their products. AACC Inc. St. Paul Minnesota, USA, 544pp.

CHRISTENSEN, C.M. & KAUFMANN, H.H. (1969). Grain Storage: The role of fungi in quality loss. Univ. Minnesota Press, 153pp.

CLAFLIN, J.K., EVANS, D.E., FANE, A.G. & HILL, R.J. (1983). Thermal disinfestation of wheat in a spouted bed. Proc. 3rd Wk. Conf. Stored Prod. Ent., Manhattan, Kansas, 531-537.

COGAN, P.M. & WAKEFIELD, M. (1988). Further developments in traps used to detect low-level infestations of beetle pests in stored grain. BPCP Monograph No 37.

COOPER, T. (1973). Take the danger out of dust. Br. Fmr. Stkbrdr., **2**, 37.

CUNNINGTON, A.M. (1976). The effect of physical conditions on the development and increase of some important storage mites. Ann. appl. Biol., **82**, 175-178.

EDWARDS, J.P. (1983). Novel methods of pest control. Proc. 6th Pest. Contr. Conf., Cambridge, Paper **6**, 8pp.

EDWARDS, J.P. & SHORT, J.E. (1984). Evaluation of three compounds with insect juvenile hormone activity as grain protectants against insecticide-susceptible and resistant strains of *Sitophilus* species. J. stored Prod. Res., **20**, 11-15.

EVANS, D.F. (1983). The influence of relative humidity and thermal acclimatisation on the survival of adult grain beetles in cooled grain. J. stored Prod. Res., **19**, 173-180.

EVANS, D.E., THORP, G.R. & SUTHERLAND, J.W. (1983). Large-scale evaluation of fluidised-bed heating as a means of disinfesting grain. Proc. 3rd Wk. Conf. Stored Prod. Ent., Manhattan, Kansas, 523-530.

FLEURAT LESSARD, F. (1980). Investigation of the sanitary conditions on the development and increase of some important storage mites. Ann. appl. Biol., **82**, 175-178.

FLEURAT LESSARD, F. (1980a). Lutte physique par l'air chaud on les hautes frequentes contre les insects des grains et des produit cereales. Bull. Tech. Inf. des. Stock., **349**, 345-352.

FLEURAT LESSARD, F. (1986). Controlled atmosphere fumigation for insect control. Proc. GASGA Seminar, Slough 1986, 164-172.

FREEMAN, J.A. (1969). The importance of the control of insects in home-grown grain. Chemy Ind., 1401-1404.

FREEMAN, J.A. (1973). Problems of infestation by insects and mites of cereals stored in Western Europe. Ann. Technol. Agric., **22**, 509-530.

GARTHWAITE, D.G., CHAPMAN, P.J. and COLE, D.B. (1988). Pesticide Usage Survey Report no 63. Commercial grain stores, 1985/6. MAFF, 23pp.

GRIFFITHS, D.A., PRESTON, H. & NILES, E.V. (1973). Inter-relations between mites and fungi. Pest Infest. Res. 1970, **93**, HMSO, London.

GRIFFITHS, D.A., WILKIN, D.R. & SOUTHGATE, B.J. (1977). A survey of mites in bulk grain stored on farms in England and Wales; second phase: 1974-5. Dupl. Rept. Slough Laboratory. 6pp.

HGCA (1986). Cereal Statisitics 1986, Home-Grown Cereals Authority, London.

HGCA Research Report. Moisture content of cereal grains. Wilkin, D.R. and Stenning, B. (In preparation).

HGCA Research Report. Control of pests in stored cereals. Rowlands, D.G., Pinniger, D.B. and Wilkin, D.R. (In preparation).

HOWE, R.W. (1965). A summary of optimal and minimal conditions for population increase of some stored products insects. J. Stored Prod. Res., **1**, 177-184.

HURLOCK, E.T. (1965). Some observations on the loss in weight caused by *Sitophilus granarius* to wheat under constant experimental conditions. J. stored Prod. Res., **1**, (2), 193-195.

HURLOCK, E.T., LLEWELLIN, B.J. & STABLES, L.M. (1979). Microwaves can kill insect pests. Food Manufacture, **54**, 37-38.

HURLOCK, E.T. and JEFFERIES, M.G. (1980). A survey of insects and mites occurring in grain stores on farms in the United Kingdom during 1976-7. MAFF Rept. Slough Laboratory, 13pp.

HUSTED, S.R., MILLS, R.B. FOLTZ, V.D. & CUMRINE, M.H. (1969). Transmission of Salmonella monteride from contaminated to clean wheat by the rice weevil. J. econ. Ent., **62**, 1489-1491.

HYDE, M.B. & BURRELL, N.J. (1969). Control of infestation in stored grain by airtight storage or by cooling. Proc. 5th Br. Insect. Fungic. Conf., 1969, 412-419.

JACOB, T.A. (in press, 1988). The effect of temperature and humidity on the developmental period and mortality of *Typhaea stercorea* (L) J. Stored. Prod. Res.

JOHNSTON, J.H. (1983). Public Policy, Pest Management and Stored Grain Insects. Thesis - School of Economic and Financial Studies, Macquarie University North Ryde, NSW, Australia.

KIRKPATRICK, R.L. (1974). The use of infrared and microwave radiation for the control of stored products insects. Proc. 1st Work. Conf. stored Prod. Ent., Savannah, Georgia, 431-437.

KREYGER, J. (1972). Drying and storing grains, seeds and pulses in temperate climates. IBVL Publication No 205, 333pp.

McLEAN, K.A. (1980). Drying and storing combinable crops. Farming Press Ltd. 281pp.

MILLS, R.B. (1972). Host-plant resistance applied to stored-product insects. Proc. N. cent. Brch. Ent. Soc. Am. 1972, **27**, 106-107.

MILLS, K.A. & COGAN, P.M. (1982). Report on Second European Congress of Entomology and visits to various scientific institutes. ADAS Slough Laboratory Report. 1982.

NELSON, S.O. (1973). Insect control studies with microwaves and other radio-frequency energy. Bull. ent. Soc. Amer., **19**, 157-163.

PAPWORTH, D.S. and TAYLOR, J.K. (1975). Pesticide use in commercial grain stores. J. Flour Animal Feed Milling., **157**, 34-37.

PAYNE, J., WILKIN, D.R. & MEDLAR, B. (1979). Report of a study tour of French and West German Intervention stores and three research stations. ADAS Slough Laboratory. 1979.

PHILLIPS, J.K. & BURKHOLDER, W.F. (1984). Health hazards of insects and mites in food. In: Insect Pest Management for Food storage and Processing, edit: Baur, F.J., St. Paul's, Minn. AACC. 279-290.

PINNIGER, D.B., CHAMBERS, J. & COGAN, P.M. (1986). New approaches to the detection of pests in grain. Int. Biodet., **22**, (supplement), 7-12.

PINNIGER, D.B. (1988). The prevention through improved detection of insect pests in storage. Int. Biodet., In Press.

PIXTON, S.W. (1980). Changes of quality in wheat during 18 years storage. In: Controlled Atmosphere Storage of Grain, Int. Symp. 12-15 May 1980, Castelgandalfo (Rome), ed: J. Shejbal 301-310.

PRICKETT, A.J. (1987). Maintaining insecticide susceptibility in stored grain pests. Proc. 4th Int. work Conf. Stored-Product Protection, Tel Aviv, Sept 1986, 406-417.

SOLOMON, M.E. (1966). Tyroglyphid mites in stored products. Nature and amount of damage to wheat. Ann. appl. Biol., **33**, 280-289.

SOLOMON, M.E., HILL, S.T., CUNNINGTON, A.M. & AYERST, G. (1964). Storage fungi antagonistic to the flour mite (*Acarus siro* L). J. appl. Ecol., **1**, 119-125.

STOREY, C.C. (1979). Inert atmospheres for control of insects in stored cereals. Natur. Gr., 134-138.

TAYLOR, J.K. (1978). Pesticide Usage Survey Report (Food storage). Commercial grain stores. 1977-8. MAFF. HMSO London.

TAYLOR, J.K. and LLOYD, G.M. (1978). Pesticide Usage Survey Report, 50. Farm grain stores. 1983/4. MAFF. HMSO London.

THIND, B.B. & EDWARDS, J.P. (1986). Laboratory evaluation of the juvenile hormone analogue fenoxycarb against some insecticide-susceptible and resistant stored product beetles. J. stored Prod. Res., **22**, 235-241.

THOMAS, K.P. & CLASPER, S. (1986). The toxicity of four organophosphorus pesticides to *Ahasverus advena* (Watl) (Col : Silvanidae) and *Typhaea stercorea* (L.) (Col : Mycetophagidae) Int Pest Control **28**, 102-3.

THOMAS, K.P., PINNIGER, D.B. and WILKIN D.R. (1987). An assessment of chlorpyrifos-methyl, etrimfos, fenitrothion and pirimiphos-methyl as grain protectants. Pestic. Sci., **21**, 57-72.

TIGAR, B.J. & PINNIGER, D.B. (1988). An assessment of methacrifos as a grain protectant and its efficacy against *Oryzaephilus surinamensis*, *Tribolium castaneum*, *Sitophilus granarius*, *Sitophilus oryzae*, *Acarus siro*, *Glycyphagus destructor* and *Tyrophagus longior*. Pestic. Sci., In Press.

TILLEY, H. (1976). Automating the grain store. Big Fm. Mgr., May 1976, 38-40.

TILTON, E.W. (1974). Achievements and limitations of ionizing radiation for stored-product pest control. Proc. 1st Wk. Conf. Stored prod. Ent., Savannah, Georgia, 354-361.

TILTON, E.W. & VARDELL, H.H. (1983). Combinations of partial vacuum with microwave or infrared heating of grain for insect control. Proc. 3rd Wk. Conf. stored Prod. Ent., Manhattan, Kansas, 8-547.

WHITE, N.D.G. & SINHA, R.N. (1981). Energy budget for *Oryzaephilus surinamensis* (Coleoptra : Cucyidae) feeding on rolled oats. Environmental Ent. **10**, (3), 320-326.

WILKIN, D.R. (1975). The effects of mechanical handling and the admixture of acaricides on mites in farm-stored barley. J. stored Prod. Res., 1975, **11**, 87-95.

WILKIN, D.R. (1984). Mite infestation in English grain. Agritrade Feb. 1989, **24**.

WILKIN, D.R. (1985). Pest damage in stored grain. Chemy Ind. (3), 71-75.

WILKIN, D.R. (1986). FAO/IAEA Study Tour on Irradiation of grain, Holland, 1986. MAFF Report, 4pp. ADAS Slough Laboratory.

WILKIN, D.R., CRUICKSHANK, S.L. & DYTE, C.E. (1983). Pesticides used on grain in commercial grain stores. Int. Pest. Control, **25**, 82-85.

WILKIN, D.R., COWE, I.A. THIND, B.B., McNICOL, J.W. & CUTHERBERTSON, D.C. (1986). The detection and measurement of mite infestation in animal feed using near infrared reflectance. J. Agr. Sci., (Cambridge), **107**, 439-448.

WILKIN, D.R. & FISHWICK, F.B. (1981). Residues of organophosphorus pesticides in wholemeal flour and bread produced from treated wheat. Proc 1981 Brit. Crop. protect. Conf. Brighton, 183-188.

WILKIN, D.R. and HURLOCK, E.T. (1986). Stored grain pests and their management. Spoilage and Mycotoxins of cereals and other stored products. Ed. B. Flannigan. Int. Biodet. Supp. 1986, **22**, 1-6.

WILKIN, D.R. & NELSON, G. (1986). Control of insects in confectionery walnuts using microwaves. BCPC Monograph No. **37**, 247-254.

WILKIN, D.R. and THIND, B.B. (1984). Stored product mites detection and loss assessment in animal feeds. Proc. 3rd Int. Wk. Conf. Stored Prod. Ent., Manhattan Kansas, 1983, pp 608-620.

WILKIN, D.R. & THOMAS, K.P. (1970). Treatment of grain with propionic acid. Pest. Infest. Res., 1969, 32-33. HMSO, London.

WILKIN, D.R. & WILSON, P.E. (1983). Mite-free grain. MAFF CL26, 5pp. ADAS Slough Laboratory.

WILSON, P. (1985). Insect infestation and pesticide usage in East Anglian farm grain stores. Int. Pest Control, **25**, 116-8.

WOODROFFE, G.E. (1962). The status of the foreign grain beetle *Ahasverus advena* (W) as a pest of stored products. Bull. Ent. Res., **53**, 537-540.

ZDARKOVA, E. & RESKA, M. (1976). Weight loss of groundnuts (*Arachis hypogaea L.)* from infestation by mites *Acarus siro*. (L.) and *Tyrophagus putrescentiae* (Shrank). J. stored Prod. Res., **12**, 101-104.

NOTE

A computer printout of a large number of references used in the compilation of this review is available on request from the authors. A charge to cover the expense of reproducing this document will be made by prior agreement with the Agricultural Development and Advisory Service.