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INSECTS AND WHEAT IN AUSTRALIA

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In the early days of agriculture in Australia rusts, not insects, were the greatest menace to the production of grain to feed the infant colonies. William Farrer, in whose memory this Oration was founded, sought not only to improve the quality of wheat and its adaptability to drier environments, but also - with others such as Joseph Bancroft in Queensland and, later, W.L. Waterhouse in New South Wales - to wed quality to rust resistance. They had very substantial success, and, as so often happens, reduction of the primary hazard brought others progressively into prominence. It is with some of these that I shall be concerned, and particularly with the pests of stored grain which present an ever increasing problem as human populations grow and urbanization spreads.

1. Early history

It is probable that the insects now associated with grains only came to primitive man's attention some 10,000 years ago when he first began to cultivate plants and to store their seeds. Most of the insects of grain stores are seldom if ever seen nowadays far from human habitation, nor far from stored grain or other products. However, these same insects must, of necessity, have existed earlier in very small numbers in the field, doubtless attacking individual grains and occasional aggregations when these happened to occur. That is, unless the evolutionarily short time of 10,000 years has been sufficient for quite a number of species to become very closely adapted to the stored products environment. There is, of course, no way of telling whether they were pre-adapted to this new environment or whether they evolved rapidly to exploit it.

Ancient Egyptian drawings clearly depict methods of grain storage and, indeed, specimens of grain weevils (*Sitophilus*) and flour beetles (*Tribolium*) have been found in grain or flour residues from the tombs of various Pharoah's dating back to 3,000 BC (Solomon, 1965). Possibly the earliest written record is from the Old Testament book of Haggai (Chapter 2, verse 16): "when one came to a heap of 20 measures, there were but 10". A 50% loss of stored grain was evidently not uncommon in those days and probably still occurs locally in some tropical areas.

It is almost certain that many of the more important stored product insects accompanied the first fleet to Australia in 1788 travelling in flour, grain, ships biscuits and other stores; they have been continuously present here ever since, although their numbers and genetic diversity have been added to on many subsequent occasions.

Joseph Banks wrote in his journal on the Endeavour in 1769 on his way to Australia "Our *bread* indeed is but indifferent, occasiond by the quantity of Vermin that are in it, I have often seen hundreds nay thousands shaken out of a single bisket. We in the Cabbin have however any easy remedy for this by baking it in an oven, not too hot, which makes them all walk off, but this cannot be allowd to the private people who must find the taste of these animals very disagreeable, as they every one taste as strong as mustard or rather spirits of hartshorn. They are of 5 kinds, 3 *Tenebrios*, 1 *Ptinus* and the *Phalangium cancroides*;...".

2. Insects and Wheat Production

Before continuing this story let us look briefly at wheat production. It is fortunate that, although Australia has all the major cosmopolitan pests of *stored* grain, she does not have any of the principal insect pests that attack the *growing* crop in the northern hemisphere and only one of the important insect-transmitted virus diseases. Pests such as the hessian fly, various midges, the wheat bulb fly, the cereal leaf beetle, various wireworms, and the Senn pest, to mention a few, are absent. We do have, it is true, some non-specific native pests that can cause serious damage to wheat and to many other crops. These include locusts and grasshoppers, armyworms, pasture webworms and cutworms (especially the larvae of the Bogong moth *Agrotis infusa* (Boisd)).

The larvae of the armyworm *Pseudaletia convecta* (Walk.) plagued the hungry early settlers of New South Wales, time and again threatening their precious wheat crops. There are many references in early issues of the Sydney Gazette, such as the letter by 'Observer' of 1 November 1822 which, referring to 'bladeless stalks of wheat', says in part "though numbers [of these caterpillars] were seen feeding on the leaves of the wheat in the day time, yet they appeared in little account when compared with the myriads which issued forth under clods and rubbish, as night set in, and fed on the wheat until day-light..... The devouring ravages of these caterpillars was so great that every sufferer was anxiously looking for rain to destroy them: and, when the wished-for rain came, what was the disappointment, that, in lieu of destroying them, it seemed to have opened the hitherto sun-parched ground, and added millions of young ones...". This same armyworm is common in the Sydney district to this day.

Rather than dealing further with insect pests of the growing crop, I wish now to introduce quite another aspect in which insects and other biological control agents investigated by my colleagues have commenced to play a beneficial role in the very same environment.

3. Skeleton weed

Skeleton weed (*Chondrilla juncea* L.) is an extremely serious weed of cultivation and particularly of wheat fields in south-eastern Australia. This perennial Composite is believed to have been introduced to the Wagga area in the early years of this century in the packing of grape vines from southern Europe (Judd and Carn, 1935). Its roots penetrate many feet into the soil and, if broken into pieces by cultivation, each piece is capable of producing a new plant.

In autumn a flat rosette of leaves is formed which grows in size until early summer when the rosette leaves die not long after producing one or more tough green photosynthesising stems, bearing many yellow flowers. After flowering and seeding profusely the wiry stems die in autumn and regeneration of a new rosette subsequently occurs at the base of the dead flowering shoot. In wheat fields the early growth of the plant rapidly depletes the surrounding soil of available nitrogen and moisture, thereby suppressing nearby wheat plants; much later, the wiry, skeleton-like stems interfere seriously with harvesting machinery. Although certain weed-killers (e.g. Picloram) applied in spring suppress the plant by killing the rosette and also its tap-root down to one or two feet, the plant often regenerates subsequently from lower levels in the soil. The cost of this treatment is, however, near or beyond the economic limit in many areas and there are serious residue problems. Competition with other plants in a pasture fallow effectively reduces the density of skeleton weed plants, but their density rises again rapidly from seedlings and, more importantly, from broken pieces of root when the wheat phase of the rotation is resumed. The yield of fields that become heavily infested with skeleton weed can be reduced from 30 bushels per acre to 15 or less and reduced yields due to skeleton weed have been estimated to result in losses of $30 million or so a year.

Many strains of skeleton weed occur naturally in the Middle East and Mediterranean areas. Although skeleton weed is very widely distributed there, it is hardly ever regarded as a weed and is a relatively uncommon plant, occurring mainly in disturbed situations where there is little competition from other plants. Differences in cultural practices undoubtedly help to suppress it in Europe and the Middle East. However, it is also heavily attacked by a range of organisms, none of which were present in Australia when our investigations commenced in 1966. The organisms studied in our programme include a gall midge (*Cystiphora schmidtii* Rubs.), two aphids (*Chondrillobium blattnyi* Pint., *Uroleucon chondrillae* Nev.), two root-attacking caterpillars (*Oporopsamma wertheimsteini* Rbl, *Bradyrrhoa* *gilveolella* Tr.), a root-attacking beetle (*Sphenoptera foveola* Gebl), a root-attacking coccid (*Neomargarodes chondrillae* Arch), an eriophyid mite (*Aceria chondrillae* Can.) and several fungi. Most destructive of the fungi was the widespread rust, *Puccinia chondrillina* Bubak and Syd., although two powdery mildews (*Leveillula taurica* Arnaud form *chondrillae* (Jacz) and *Erysiphe cichoracearum* D.C.) also caused extensive damage when conditions were suitable.

Puccinia chondrillina is a macrocyclic, autoecious rust that has only been recorded on the genus *Chondrilla*. This rust occurs on *Chondrilla* from the cold continental climate of southern Siberia to the hot Mediterranean climates of Portugal and North Africa. In many situations it kills young *Chondrilla* seedlings, and severely damages and greatly reduces seeding by older plants, which sometimes are unable to produce new rosettes from their roots (Hasan and Wapshere, 1973).

Extensive testing of *Puccinia chondrillina* against the plant species (some 50 in all) of substantial agricultural importance to Australia demonstrated that it was entirely specific to *Chondrilla* and was quite unable to develop on other closely related Cichoriaceae (Hasan, 1972). So specific was it that the first strain tested which originated from France did not attack any of the three forms of skeleton weed that occur in Australia. Eventually a strain of the rust originating in Vieste in southern Italy was found to be highly pathogenic to our most common narrow-leaved variety and the full plant specificity tests were carried out on the Vieste strain. Absence of attack on any other plants, combined with the knowledge that this rust occurred on skeleton weed in eastern United States of America without causing any damage to other plants, formed the basis for approval by the Australian Plant Quarantine authorities for it to be introduced to Australia.

Spores of the rust were flown to Canberra early in 1971 and mass reared for release, constituting the first example in the world, since the establishment of effective quarantine controls, of the deliberate introduction and release into a new country of a plant pathogen for weed control (Cullen *et al.*, 1973).

After two generations of the rust had been cultured in quarantine on potted skeleton weed plants in order to ensure that there were no undesirable fellow travellers, uredospores were removed for mass breeding and subsequent field establishment. Liberations were made over the period from June to December 1971, first of all in Canberra, and later at Wagga and Tamworth in New South Wales, at Parilla, Karoondah and Waikerie in South Australia and Mildura, Hopetown, Walpeup and Numurkah in Victoria.

On 10th June 1971 *C. juncea* plants infected with *P. chondrillina* were transplanted into a dense natural growth of skeleton weed at Wagga. After one rust generation (10 to 30 days depending upon the temperature), spores were found on plants 1 metre distant, and subsequent observations indicated that, by the fifth rust generation, they had become established at least 24 km distant. This initial spread seems to have been on a scale only slightly less than recorded for wheat rust epidemics (Lambert, 1929, Schmitt *et al.*, 1959). Weather conditions in New South Wales during the period December 1971 to February 1972 were moist and very suitable for fungal infection. Foci at least 80 km, 160 km and 320 km away from Wagga were probably initiated at the 8th, 10th and 11th rust generations respectively. To the east these overlapped infestations spreading from Canberra, and to the north those from Tamworth. By late March 1972 some or many infected plants could be found in virtually every stand of *C. juncea* examined in NSW (Cullen *et al.*, 1973). Winds were predominantly easterly during the summer, but there were also suitable northerly and south-westerly air movements.

In the southern and western region of *C. juncea* distribution the drier summer resulted in a slower spread but, after autumn rains, the distribution became general there also and all skeleton weed areas in south-eastern and southern Australia were known to be colonised at latest by December 1972. The warm dry summer of 1972/73 resulted in very extensive damage to the stems of skeleton weed plants over vast areas, in many cases killing stems back to ground level prior to flowering. As to be expected, regrowth has occurred in many instances, for it will require successive episodes of this sort to kill a deep rooted weed with substantial underground reserves. So dramatic was the destruction in some areas that the question has been asked whether the barer-than-usual ground might be subject to soil erosion! Only the common narrow-leaved variety has been attacked and it may be desirable later to consider the testing and importation of rust strains capable of attacking the other two strains of the weed.

This vast epidemic spread of the rust has been documented more thoroughly than that of most plant diseases and, on this scale, is unique in being both deliberate and beneficial. It is of significant historic interest that the first liberation was made in Canberra barely 13 miles from Lambrigg where Farrer did so much of his work and that the first major spread should have been from Wagga which, some 60 years earlier, was the epicentre of dispersal of skeleton weed in Australia. Even more striking perhaps is that, in the very wheatfields where William Farrer's principal adversary had been the wheat rust *Puccinia graminis* form *tritici*, another *Puccinia* species should be so dramatically harnessed to man's benefit.

Five other organisms have so far been demonstrated in extensive tests in Europe to be specific to skeleton weed. They are the gall fly, *Cystiphora*; the bud mite, *Aceria*; the root moth, *Bradyrrhoa*; the aphid *Chondrillobium*; and the mildew fungus *Erysiphe cichoracearum* (Wapshere and colleagues, unpublished). The first three have been approved by Quarantine authorities for introduction and the gall fly and the bud mite were imported in 1971 and have now become established.

The gall fly is known to have spread in two seasons up to 16 km from one of its centres of liberation in South Australia, and there and elsewhere has caused die-back of stems and considerable reduction in seeding.

It attacks all three forms of skeleton weed, but its success on the common narrow-leaved form has been limited somewhat by the simultaneous heavy attack on this form by the rust.

The bud mite converts both flowering and shoot buds into a twisted mass of tiny leaves resulting in stunted growth and prevention of flowering. The mite is spreading steadily and appears to attack the common form of skeleton weed much more effectively than the other two varieties.

4. Wheat Storage and Transport

The climates throughout the wheat growing areas of Australia are generally very favourable to insect infestation of stored grain. In this respect, our problems are more comparable with those of tropical areas of the world than with those of the other major grain-exporting countries which all lie in the cool temperate belt. Wheat is harvested in Australia at high air temperatures, often of the order of 30°C and above; it retains this heat remarkably well in bulk storage, and much of it is exported into a northern hemisphere summer where warm conditions are again encountered, so that for long periods temperatures are favourable for insect development. By contrast, wheat grown in the northern hemisphere is generally harvested at lower temperatures and, in any case, is often exported during winter into other winter-bound northern hemisphere countries. Australia thus faces more difficult problems in maintaining freedom from insect attack than do the majority of other main wheat producers.

Australian wheat averages 10% moisture content, a figure which is suboptimal for insect development. When wheat was sold overseas by weight in the windjammer days it is said that an astute sea-captain could increase his profits by opening the hatches from time to time to allow the moist sea air to be taken up by the wheat and, if greedy, he might even turn the ship's hoses into the hold and sell the added weight of water as wheat! If, indeed, this did occur the higher moisture content would certainly improve conditions for insect attack. Moreover, the addition might well go undetected in northern markets which are accustomed to a moisture content closer to 13% in northern hemisphere wheat.

World War I (1914-18)

During World War I, unprecedentedly large stocks of bagged wheat accumulated in Australia. These were not only attacked very extensively by grain pests but also severely damaged by a mouse plague, so that enormous losses were sustained. The methods of control then available were very limited by present day standards. First and foremost the importance of thorough and systematic cleaning up of grain stores at all locations from farms to shipping ports was clearly recognised and emphasised, although seldom attained. Dry wheat was recognised to be more resistant than moister wheat and, so far as possible, only dry wheat was taken into store. No chemical protection of infested grain was available and experiments at that time with cyanide and carbon bisulphide fumigation proved unpromising. Infested grain was sieved, winnowed and heat sterilized and large quantities were dealt with in this way. Surprisingly, the potential was recognised of asphyxiating grain insects by sealing grain in airtight containers or by pumping carbon dioxide into less-well-sealed containers, but the end of the war came before any practical use was made of this approach (Winterbottom, 1922).

World War II (1939-1945)

Twenty years later, World War II again created problems of long-term wheat storage. Although bag storage was still used to some extent there had, meanwhile, been a progressive development of the capacity to hold wheat in bulk storages of various types and sizes, ranging up to structures 1/3 mile long with a capacity of 10 million bushels. The Australian Wheat Board was set up in 1939, shortly after the war commenced, to control the storage and marketing of wheat, thereby facilitating the wider introduction of the best available measures for safe keeping of the grain. At this time also, the CSIR Division of Economic Entomology was given the responsibility of advising the Board on problems of insect infestation.

Where bags were to be stored for any length of time, covered depots were established at key points in the driest and coolest locations possible, consistent with transport requirements. Pains were taken to avoid old storage sites that harboured infestation, to maintain new sites free from pests, to render them mouse-proof, to check that the wheat was free from infestation before it was admitted to the depot and to send off quickly for utilization bags showing signs of infestation (Wilson, 1952). It was found that insects most frequently occurred first in the layer of bags at the base of a stack and gradually spread up the outside walls, these being the regions where there tended to be a moisture build-up, wheat being a hygroscopic material. The interior of the stack and its upper part, where the moisture content stayed low, remained comparatively free from insects. Investigation showed that heavy fumigants like carbon bisulphide or methyl bromide applied to the upper surface rapidly reached the bottom of a stack. When these fumigants were prevented from escaping through the sides by airtight enclosure of the stack walls, highly satisfactory insect kills were obtained and millions of bushels of wheat were eventually treated in this way (Wilson & Gay, 1946). Once established, this method permitted the long term storage of bagged wheat without fear of heavy loss.

Quite different problems were posed by the vast mounds of wheat held in bulk depots. Under these circumstances insect damage seldom occurs except to the periphery of the wheat mass and, if the remainder should be infested when loaded, it rapidly reaches combinations of temperature and moisture content lethal to the insects. Metabolic heat produced by the insects dissipates very slowly through wheat so that, in infested wheat in the interior of a bulk, local hot spots develop where the rising temperature forces any mobile insects to cooler surroundings, thus dispersing the infestation. Hot spots link up in this way until, in the extreme case, all the bulk is about 42°C, except for the periphery where heat can be lost to the atmosphere. Here a temperature gradient is established in which the various species of insects can generally find a zone very suitable for their reproduction. Although this happens to a lesser extent than in bag stacks, surface wheat will often increase in moisture content by taking up moisture from the air and also by the movement of moisture to it from the hotter inner layers of the wheat mound. The moisture content of the inner wheat thus becomes even less satisfactory for insect development than at intake.

Investigation showed that surface infestations on mounds of bulk wheat could be treated relatively effectively by direct application of certain liquid fumigants to the region of any 'hotspots'. Carbon bisulphide, or ethylene dichloride mixed with carbon tetrachloride, gave excellent control of most species. A barrier against reinfestation was also established by applying a layer of finely-ground mineral dust, generally magnesite, upon the wheat surface and this method was also used to protect the bulk when it was first established (Gay, 1947).

<u>The period 1946 to 1968</u>

As a result of the success of the war-time Wheat Board it was decided that the Board should remain as the sole marketing authority for wheat, both domestically and overseas, and for flour overseas. Wheat growers are obliged to deliver all of their wheat to the Board or its agents, except for any they retain for seed or stock feeding purposes. Wheat is almost entirely handled by one bulk Handling Authority in each State on behalf of the Australian Wheat Board and is exported through a total of 18 ports. This centralised organization has greatly aided, indeed made possible, the attainment by Australia of the extremely high standards now demanded by importing countries. Many countries now insist that each consignment of wheat be accompanied by an international phytosanitary certificate stating, *inter alia*, that it contains no living insects.

Over the years the storage of bagged wheat has steadily diminished and now all is held in bulk. In Western Australia the wheat is held in horizontal storages in the country areas, vertical silos being restricted to the 4 shipping ports. In the other States a variety of horizontal and vertical silos are used both in country areas and at the ports.

Except for ceasing to use inert dusts, primarily because they increased friction and hence interfered with the flow characteristics of grain essential for the available grain handling machinery, grain protection changed little for a decade after World War II. The introduction of phosphine as a fumigant in 1956 resulted in some reduction in infestation in overseas shipments, but the really spectacular development was brought about in 1960 by the introduction of malathion which soon became the basis of all protection in Australia. Malathion was not only a new material, but it ushered in a new concept. Previously control was essentially the treatment of known infestations: by contrast, malathion was used as a preventive treatment, and was eventually applied to all of the wheat crop, giving protection for 9 months or so. Generally, 12 p.p.m. malathion was added to grain on intake into bulk storage, with the intention that no more than the international tolerance of 8 p.p.m. should remain when the grain reached the market place either here or abroad. Since even 4 p.p.m. malathion maintained grain completely free from all insect pests that occurred in Australia, infestations seldom developed and our standards soon rose to meet the nil tolerance of living insects that had for some time been demanded by a number of importing countries. Indeed the situation was so improved by 1963 that the Commonwealth Government was able to introduce legislation prohibiting the export of wheat infested with insects and giving it powers to ensure the cleanliness of holds of ships calling for Australian wheat.

When problems were occasionally encountered in bulk storage in Australia, fumigation was resorted to especially at shipping terminals. This was because the application of a supplementary malathion treatment required the grain to be turned during application and in any case did not kill larvae within the wheat grains. Thus, adults continued to emerge into the lethal surroundings for a further 3 to 4 weeks, by which time the grain might have reached its overseas destination. Where quick clean up was necessary, fumigation with methyl bromide for 24 hours, followed by 24 hours ventilation permitted the necessary phytosanitary certificate to be issued. Alternatively, exposure to phosphine (generated from aluminium phosphide tablets) or to hydrogen cyanide (generated from calcium cyanide powder) killed all insects, but required a considerably longer period (up to a week) to produce mortality.

Another method for reducing the potential damage by insects has been the introduction over the past decade or so of grain aeration on a steadily increasing scale, firstly into South Australia, then into Victoria and New South Wales.

This approach has been extensively used in North America (Holman, 1960) and consists of forcing naturally occuring cool air through the grain mass so as to lower the temperature to a level at which little or no insect damage occurs. Information was collected in Australia on the temperatures necessary to suppress reproduction in each species (a temperature of 15^{o}C is desirable, although 18^{o}C greatly lowers the reproductive rate : Howe, 1965). Studies were made over the wheat belt of the number of hours each month that the temperature was low enough for aeration to be effective (Bailey, 1968) and machinery designed to produce the required flow of air through grain bulks of various sizes (Sutherland, 1966). A special control device was designed by the

CSIRO Divison of Mechanical Engineering to switch on aeration machinery at combinations of outside air temperature and humidity that would cool the grain but not increase its moisture content (Griffiths, 1967). This method is proving to be a valuable aid in avoiding serious insect damage and has already been introduced into a substantial number of bulk storages. It must be emphasised, however, that infestations already present are not eliminated so that, if the wheat is to be exported, supplementary chemical treatment is required. Where fumigants are employed their distribution within the grain mass is aided by the aeration machinery (Storey, 1971). On the other hand the lower temperature of the grain mass means that higher fumigant concentrations and/or longer exposure times must be employed.

For the treatment of infestations in grain residues around farm or other storages, either lindane or malathion was found to provide excellent control. However, although lindane was both cheap and effective, it could not be recommended for application to grain for human consumption or stock feed.

The period 1969 to the present

I might perhaps be pardoned for saying, at this stage, that an important recent development has been the establishment, with the generous assistance of the Australian Wheat Board, of a Stored Grain Research Laboratory in the CSIRO Divison of Entomology. I have no doubt that this laboratory will contribute many new and important advances in the next few years.

However, to return to my narrative, it is now recognised to be virtually inevitable that, where almost total reliance is placed on the use of an insecticide for the control of a major pest, resistance to that insecticide will sooner or later emerge. This is simply the common evolutionary mechanism whereby intense selection in favour of individuals capable of surviving a single major mortality factor results in the population of the species concerned eventually becoming capable of resisting or avoiding the action of the mortality factor. It should have come as no surprise, therefore, when a population of the rust-red flour beetle *Tribolium castaneum* (Herbst) resistant to malathion was discovered in Queensland in April 1968 (Champ and Campbell-Brown, 1970). In fact, resistant strains of this species had been known for some time from Nigeria and from southern United States (Parkin, 1965; Speirs *et al.*, 1967) and resistant insects were soon found to be moving in international shipping, since they were intercepted in the holds of a number of ships visiting Australia in 1969 (Champ and Campbell-Brown, 1970). It was found, moreover, that there were two types of malathion resistance, one of which is specific for malathion, whereas the other confers cross resistance to a number of other compounds (Dyte and Rowlands, 1968). In particular, some of the Australian strains were resistant to lindane (Champ and Campbell-Brown, 1970). The international tolerance of 8 p.p.m. malathion precluded any significant increase in dose rate and, in any case, such a procedure is known from experience with other pests to result in the development of even higher levels of resistance. The Queensland discovery of resistant flour beetles stimulated a detailed and extensive survey for malathion resistance in all of the major stored grain insects in Australia. Australian scientists subsequently collaborated with FAO during 1972 and 1973 in a world survey of resistance in grain pests.

The Australian survey has shown that strains of all of our major grain pests are resistant to malathion in at least one mainland State (and generally in all five States) and that some of the strains are also resistant to lindane. The highest resistance levels (up to 500 fold) have been recorded from terminal storages, whereas samples from country storages still show a comparatively high proportion of susceptible strains.

The FAO survey has demonstrated that strains of all of the major stored grain insects are malathion-resistant in many parts of the world. All of the resistances known in Australia occur in at least some other countries also, but there are some resistances (for example, those to the fumigants methyl bromide and phosphine) that have not so far been detected in Australia.

Where infestations are discovered in malathion-treated wheat the current options are to fumigate (e.g. with methly bromide, as in Queensland) or to use an alternative insecticide, such as dichlorvos, which is applied at a concentration of 6 p.p.m. although it is effective as low as 2 p.p.m. Six p.p.m. has been used since 1972 in New South Wales and, to begin with, gave excellent control, but already strains of two grain pests are able to survive this dosage. Fenitrothion, which is not yet cleared internationally for addition to grain to be eaten, appears to be a comparatively safe material, and is used for treatment both of storage structures and of grain residues. Fenitrothion and synergised pyrethrins (which are comparatively expensive) appear to be the only available alternative insecticides that are known to be effective and that appear to be safe enough. It is disappointing to have to add, however, that low level resistance to these two materials is known in other parts of the world, so the outlook is indeed grim in a world that demands both complete absence of live insects in grain and no more than exceedingly minute pesticide residues which, moreover, are only approved after many years of international discussions.

One approach that received a good deal of attention in a number of countries during the previous decade was the possibility of using radiation to disinfest grain. This involves treating grain in motion with ionizing radiation either to kill any insects present, or at least to sterilise them. For this purpose it is possible to use either gamma radiation (from a Cobalt ^{60} source) or various machines for producing accelerated electrons. Immediate kill requires 300,000 to 500,000 rads, kill within a few days about 100,000 rads and sterilisation, but without greatly accelerated mortality, up to 25,000 rads depending upon the species (Tilton, 1966). By comparison, man is killed by about 500 rads - one fiftieth of this does. At a dosage of 25,000 rads the cost under optimal conditions is rather greater than the most expensive fumigation treatments. Wheat treated with a dose of gamma radiation up to 50,000 rads is officially acceptable for human consumption in USA and in some other, but not all, countries. Such treatment leaves no chemical residues, although it does produce minor changes in some constituents, especially at higher doses. So far the method is not used commercially by any country and one is tempted to ask why this is so. There are 3 principal reasons.

(a) because of its high capital cost, irradiation can only be used in terminal silos where large and continuous movement of grain occurs whereas, to meet current international standards, insect control must start as soon as the grain is harvested and be maintained continuously thereafter. As best then irradiation can only be a supplement to chemical or other controls and is not a complete alternative.

(b) fumigation is the most costly of present day control measures. It provides, at best, only short term insurance against reinvasion because it leaves little or no protective residue. However, unlike radiation, fumigation can be used almost anywhere and it need be employed only when it is required. On the other hand a $Cobalt^{60}$ source continues its breakdown irrespective of whether or not is is being used and hence some expenditure is involved continuously. With a four-fold fluctuation in the Australian wheat crop, such has occurred during recent years, any $Cobalt^{60}$ facility would either be inadequate to meet peak demand or excessively expensive when the crop is at a minimum.

(c) the sterilising dosage of 25,000 rads, which costs more than fumigation, is unlike fumigation in that it permits insects to survive for several weeks after treatment. Since the treatment at port terminals is most likely to occur within a day or two of departure it is probable that living insects would still be present on arrival of the grain at its destination. There is, as yet, no rapid method available whereby port inspectors can determine whether or not the insects are sterile and, in any case phytosanitary certificates certifying freedom from all living insects are, as mentioned earlier, mandatory for many importing countries.

5. Insects and Wheat Products

To round off the picture it is desirable to deal briefly with insect pests of wheat products. When wheat is converted into flour and bran it ceases to become suitable for the various highly-damaging, grain-boring beetles, although it becomes even more satisfactory for flour beetles and certain moths. It is an interesting sidelight that, if flour is converted to spaghetti the dense consistency of the latter once again makes it satisfactory for the grain-boring species.

Little trouble is nowadays experienced with retail packs of flour, cake mixes or baked products, such as biscuits, since these are insect-free when packaged and are protected from infestation by the wrappings.

The most important measure for flour mills is rigorous hygiene. Infested residues may be treated as described earlier for stored grain. Flour itself may be disinfested extremely effectively by means of a physical method, the use of a machine known as the entoleter (Cotton and Frankenfeld, 1942). Flour is fed onto the centre of a fast-spinning disc carrying rows of peripheral pegs so spaced that all particles hit several pegs forcibly as they are flung out by centrifugal action. The disc speed is such that any insects present are smashed and killed.

6. The Future

It appears that, at least in the short term, the future for the protection of stored grain will be beset with many problems. Although it is probable that malathion will continue, for several years yet, to give valuable protection, particularly for farm use and as a pre-storage treatment, it would be realistic to conclude that its days as the mainstay for control of grain insects are numbered. It is possible that, for a period, dichlorvos may replace it, but here again the resistance already emerging in some species suggests that, at best, it may only provide a breathing spell of a further year or two. Any alternatives must be effective against all the resistant strains of the dozen or so major stored product beetles and the half dozen important moth species and it is indeed fortunate that resistant strains of all these species from around the world have been assembled in the FAO survey. These strains will be invaluable in any screening for alternative compounds. Even if effective new materials are discovered the procedures for establishing an acceptable level for insecticide residues in the grain through the International Codex Alimentarious Commission are exceedingly slow and, at present, occupy more than 7 years, so there is no chance of an acceptable chemical grain protectant appearing virtually overnight.

The fumigants, methyl bromide and phosphine, will undoubtedly play a very important role in the next few years but, here too, the appearance of resistant strains in overseas storages indicates that it would be unwise to rely on them for more than the next few years. Hydrogen cyanide and ethylene dibromide may prove useful additional fumigants.

In these circumstances, a brief consideration is desirable of some other possible approaches to control, and particularly physical methods that do not rely upon the use of toxicants. Grain pests constitute the only major pest group whose effective control by physical means appears to be feasible.

(1) The value of grain aeration has already been stressed for cooler climates. The CSIRO Division of Mechanical Engineering is now

investigating the use of refrigerated air for regions where overnight air temperatures remain too high to permit adequate cooling. The use of refrigerated air is certainly feasible, but its adoption will depend upon whether or not is is possible to carry out both insulation and refrigeration economically. Insulation may also prove to be advantageous in cooler climates to enable the temperature of the surface of the grain to be maintained at lower temperatures.

(2) An alternative approach, that merits careful consideration, is the use of aeration machinery to propagate through the grain mass successive heat fronts in such a way that all insects will be killed. This approach is under consideration.

(3) A quite different method that, at first sight, appears to be the direct converse of aeration is airtight storage. As I mentioned earlier, it was suggested nearly 60 years ago during World War 1. In its simpletest form it is based on the principle that the metabolism of insects in infested grain, sealed in a container, before long lowers the oxygen tension to a lethal level. With perfect sealing only about one part of wheat in 7,000 is consumed before lethal conditions are produced. To bring about 100% mortality of all stages requires an increase of carbon dioxide to 40% or a decrease of oxygen to 2.0% (Bailey, 1955, 1956, 1957, 1965, Denmead and Bailey, 1966) and it is the depletion of oxygen that occurs first. Australian experiments have shown that it is extremely difficult to construct concrete silos that are impervious to carbon dioxide and water vapour, particularly as external pressure and temperature changes promote an air pumping action. Flexible pressure-equalisation bags have been proposed to overcome this problem. Alternatives to complete sealing are to replace the air continuously by a gas that will not support life. It is possible to do this, for example (a) by removing the oxygen from air

by burning it to carbon dioxide using propane gas; (b) by purging the air by blowing in nitrogen derived from liquid nitrogen; or (c) by using carbon dioxide in 60% admixture with air, which kills more rapidly but is more expensive than the other methods. Since the time required for mortality under these conditions is temperature dependent this method may have its greatest application in the hotter climates where aeration is least appropriate. At the moment it is probable that the only storages that can be sealed effectively are certain welded steel silos such as occur in parts of South Australia, Victoria and Queensland. Individual bins have a capacity of up to 250,000 bushels.

Airtight storage is employed on a massive scale only in Argentina where it is principally used for maize. This is generally harvested with a high (15 to 16%) moisture content. The satisfactory protection obtained may be due to the fact that, even in only moderately well sealed storages, the very high respiration rate of the moist grain and of any associated fungi and microorganisms maintains an oxygen tension low enough to be lethal to insects.

(4) Another physical method that merits further investigation is the use of mechanical shock. The entoleter, already described, is highly effective for flour, but the forces required to kill the younger stages of grain beetles that live inside individual wheat grains are great enough to damage 2 or 3% of the grains and this has so far been regarded as an unacceptable level of damage. However, modifications of the method merit re-examination both from the point of view of their effectiveness and of the economics involved. It has, for example, been found that if very much smaller forces, more comparable with those sustained during turning of grain, are applied either daily or every few days they are effective in preventing the development of immature stages.

Unfortunately multiple treatments on the same day seem to be less effective than the same total number of treatments applied on successive days (Bailey, 1969).

Turning of large bulks of infested grain several times a week would be costly and in any case would not be possible without having adequate storage available to permit one bin at a time to be emptied. The cause of death following 'mild' disturbance is not yet understood, but if its mechanism can be discovered it may prove possible to devise simpler means to produce lethal effects.

(5) The requirements, not only of some of the physical methods but also for the most effective use of fumigants, draws attention clearly to the fact that the majority of the major storage structures in Australia have been built with far too little attention to the special design features that would facilitate these methods and considerable improvement in this respect is long overdue.

(6) It is both fashionable, and sometimes valuable, to construct, with the aid of a computer, a numerical model of any complex system that man wishes to manipulate for his benefit and one of my colleagues has recently embarked on such a project. It is highly important to the useful application of any model to know *inter alia* what the possibilities are for modifying the nature of the input and output of the model.

At present the input, the grain presented for storage, more frequently than not contains insects. This is because few wheat farms are completely without infested grain and transport containers may harbour infestations. If it became possible to ensure that only clean grain came into the larger commercial depots there is no doubt that the grain pest problems in Australia would be greatly diminished. Grain handling machinery undoubtedly requires redesign in order to enable far readier access for thorough cleansing. Furthermore, infestations could undoubtedly be reduced significantly if farmers adopted, perhaps with additional advice, the best available means of ensuring that their farms and especially their storage areas were free from insects. Insecticides might occasionally be required to supplement strict hygiene. Cross infestation from produce other than wheat would need close attention. It is heartening to note that all States have recently agreed to take concerted action to reduce the incidence of infestations in grain on the farm and in the smaller storages.

(7) As for the output from the system, no importing country would wish to have landed on its shores wheat that presented it with an inbuilt control problem. However, if grain irradiation procedures were sufficiently reliable to guarantee that only sterilised insects were present, it is perhaps not impossible for standards to be modified and to lift the embargo on living, sterile insects providing it could be certified that the grain had received the necessary radiation treatment.

To recapitulate, I advocate the following blueprint for the future:-

1. The establishment of greatly improved hygiene on farms and expecially in farm machinery.

2. The disinfestation of all transport used in handling grain.

3. The construction of storages designed to exclude insects and to facilitate fumigation and especially control measures that place minimal reliance on pesticides.

4. The development and, wherever possible, adoption of physical means of control (ambient air, cooled air, inert atmospheres, mechanical shock, radiation).

5. The use of protectant insecticides and fumigants only where other methods fail to produce entirely satisfactory results.

I am confident that, with vigorous attention to such measures, it will prove possible to meet the serious challenge that faces us.

TABLE I

THE PRINCIPAL PESTS OF STORED WHEAT AND FLOUR IN AUSTRALIA

Beetles

Oryzaephilus surinamensis (L.)	saw-tooth grain beetle
Rhyzopertha dominica (F.)	lesser grain borer
Sitophilus granarius (L.)	granary weevil
Sitophilus oryzae (L.)	rice weevil
Tribolium castaneum (Herbst)	rust-red flour beetle
Tribolium confusum Jac. du Val.	confused flour beetle

Moths

Ephestia cautella (Walk.)	tropical warehouse moth
Plodia interpunctella (Hübn.)	Indian meal moth

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