A brief history of the entomological problems of wheat storage in Australia

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Abstract

Australia has achieved a high standard of freedom from insects in its grain exports. However, this was not always the case and serious insect problems were a feature of grain stored in, and exported from, Australia in previous years. Particular problems were experienced during the First and Second World Wars when it became necessary to store grain for much longer periods than normal because of difficulties with shipping. During the First World War, when grain was exclusively stored in bags, the industry experienced devastating losses caused by mice and weevils. This, and the period after the Second World War, provoked a period of intensive research and development during which a number of processes were investigated.

In the years following the Second World War markets began to demand higher standards of freedom from insects in grain shipments. This was achieved by a combination of fumigation, legislation and the introduction of insecticides as grain protectants. More recently there has been a change in attitudes towards pesticide residues in food. This has had a substantial impact on storage strategies and control methods used within these strategies in Australia.

Introduction

Australia currently enjoys a reputation for exporting grain that has one of the highest levels of freedom from insects of any country in the world. Moreover, it has maintained this standard for more than 25 years. However, this has not always been the situation. It is not widely remembered nowadays, that Australia was the scene for what was described as 'the greatest battle man has had to fight against stored grain pests anywhere and at any time' (Ratcliffe et al. 1940). Aspects of that dramatic battle were recorded by Winterbottom (1922), in what is one of the great accounts of research and development in grain storage. Unfortunately original copies of this classic publication are scarce, and it is little known overseas[1].

It is almost certain that many of the insect pests associated with stored grain were introduced into Australia with the arrival of the First Fleet in 1788 (Waterhouse 1973). Evidence for this is adduced indirectly from contemporary descriptions of infestation in ships provisions (Waterhouse 1973). Also, it is known that all the ships of the fleet were old and thus very likely to carry residual infestations of stored products insects in their stores and hatches. Thus it is very probable that supplies including rice, wheat, barley and Indian corn obtained at Cape Town in 1787, became heavily infested en route to Australia. Likewise, the grain imported during the early years of settlement from various sources, including the Cape Colony and India (Clark 1962), would have been infested in a similar manner. More recent introductions of pests, such as *Trogoderma variabile* and *Reesa vespulae*, are better documented (Anonymous 1978; Banks 1990; Hartley and Greening 1983).

It is interesting to note that this has not been a one way traffic. Mackie and Carter (1937), in California, report that *Rhyzopertha dominica*, the lesser grain borer, was apparently introduced into the United States from Australia during the First World War (WWI).

Grain production in Australia commenced in the first year of settlement, when 8 acres of wheat and barley were harvested at Farm Cove, Sydney (Simmonds 1989). Little is recorded of the problems caused by insect infestation in grain stored during the first 100 years. However, there can be no doubt that the early settlers tasted the added 'flavour' of insect fragments and pheromones in their daily bread and probably simply accepted the fact that, if grain was stored for any length of time, it became infested.

In New South Wales (NSW) agricultural production in general was limited while settlement was restricted to the coastal strip. This changed completely in 1813, when the mountain barrier to the West was crossed; so providing access to vast new spaces for agricultural development. By the mid-19th century 32% of the arable land in NSW was under cultivation, 37% in Tasmania, 14% in South Australia (S.A.), and in very good years the colony even exported cereal crops. Nevertheless, disease and drought seriously affected harvests, and ways of increasing the yield of cereal crops had yet to be discovered. By the end of the 19th century wheat production had risen from about 10 million bushels (ca 286,000 t) to about 27 million bushels (ca 770,000 t) which can be attributed to new strains of seed, mechanisation, and fertilisers (Lacour-Gayet 1976).

The expansion of wheat growing into the hotter drier western regions of NSW, was made possible by William Farrer (working at Lambrigg close to Canberra), who selected drought resistant, early maturing wheats that had good milling and baking qualities, while in S.A., Custance also selected for early maturity and drought tolerance (Simmonds 1989).

Australian involvement in the development of mechanised grain harvesting is no longer well remembered. The extensive exploitation of the wheat growing areas in the 1850s was made possible, in part, by the invention in Australia in 1843, of the Ridley stripper — the world's first machine for stripping heads of wheat from the stalk. This was followed in 1885 by the development of the McKay harvester, and later, by the Sunshine header harvester (Callaghan and Millington 1956). This was a turning point for the industry, because it increased greatly the rate at which the crop was harvested.

All this wheat was handled and stored in bags (initially 4 bushels weighing 240–250 lbs, later reduced to 3 bushels), which were cumbersome and labour intensive.

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[1] Copies of a facsimile edition of this publication are available for purchase from: The Librarian, Stored Grain Research Laboratory, GPO Box 1700, Canberra ACT 2601, Australia.

The Bag Handling Era

Bagged grain was stored in roofed sheds or outdoor stacks at receiving sidings, or at the port of shipment. These stacks were built on timber dunnage and when complete, they were covered by a galvanised iron roof laid onto the top of the stack to protect them from rain. The sides were protected from the weather by means of hessian curtains or left unprotected. Under normal conditions grain was seldom stored for more than 6 months, and the system worked satisfactorily (Callaghan and Millington 1956).

At the outbreak of WWI, Australia's grain production was approximately 2 Mt/year, all stored and handled in bags. The 1916–17 and 1917–18 seasons yielded bumper wheat harvests, bigger than any prior to 1915–16, which was also a record harvest (Winterbottom 1922). Before the War, it had been policy to export all surplus marketable grain as rapidly as possible, because there was virtually no provision for long-term storage. Thus, combined with the wartime disruption in shipping, this unprecedented accumulation of stocks led to prolonged storage, and served to highlight the weaknesses of the system. The losses incurred during this period were described as 'perhaps the most catastrophic in history' (Wilson 1953).

Early in 1917, the situation was exacerbated by a plague of mice that attacked the bag-stacks. Within 3–4 weeks, hundreds of stacks collapsed as a consequence of their ravages. Soon, thereafter, the stacks were 'attacked' by a plague of weevils *Sitophilus (Calandra) oryzae*. Insects built up to numbers that are difficult, for most of us today, to imagine. Winterbottom (1922) gives a graphic account of the situation. He reports at one of the worst affected sites, Wallaroo (S.A.) where more than 4.5 million bags of grain were stored, that up to 1 ton of weevils/day were collected and destroyed. He also estimated that 40 tons of wheat were being lost daily at this site alone! The weevil was not the only insect involved; the records showing that a full spectrum of both primary and secondary species was found infesting the grain.

Various methods of protecting the bag-stacks were devised. A number of processes were applied to control the infestation. These included, physical exclusion and sealing, self-gassing (Ratcliffe et al. 1940) or use of controlled atmospheres and poisonous gases, physical shock, heat treatment and sterilisation, mechanical cleaning, dust treatments, underground storage, and hygiene practices. Winterbottom (1922) details the research undertaken to apply these processes. The experiments with poison gases, including hydrogen cyanide and carbon bisulphide failed, but when one considers the difficulty associated with making a bag-stack gastight at that time, this is not surprising. The ability to implement these processes effectively in those days was limited. However, after the War, it was acknowledged that the wheat could not be shipped if it was infested and it is illuminating to note that, approximately 1.7 Mt of grain were cleaned and sterilised, in one year, as part of a concerted program to cope with the weevil problem.

It is remarkable, looking back 70 years later, that these processes used by Winterbottom are again receiving research attention in Australia, as we seek to replace chemical insect control methods because of market aversion, pest resistance, industrial and environmental concerns, and cost.

In an interesting commentary on contemporary general knowledge, Winterbottom records that 'there were numbers of men ... connected with the wheat trade all their lives, who stated straight out that ... every grain of wheat carries a weevil germ'. Spontaneous generation of life! Hygiene was a key component of infestation prevention, but against such a background it is hard to believe great efforts were made to implement it.

With the outbreak of the Second World War (WWII) there was again a cessation of regular shipping, and the occurrence of carryover storage from a bumper harvest and changes in the grain storage situation. Even though the majority of grain was still stored in bags, construction of bulk storage facilities had commenced (see below) and the problems confronting the industry were more varied than they had been during WWI. Grain was now stored in bags, silos, terminal elevators, and bulk storages of various types.

Wilson (1953) describes the problems encountered during this period. Two factors facilitating the wider introduction of the best available measures for safe storage of grain influenced decisions taken during this time. Firstly, centralised control of the industry was now possible through the Australian Wheat Board (AWB), that had been established in 1939 to control storage and marketing of wheat. Secondly, the Economic Entomology Division of the Council for Scientific and Industrial Research (CSIR) was given the responsibility for advising the AWB on problems of insect infestation. They provided research workers to analyse the problems, and prepare solutions for the difficulties that might be encountered during a period of prolonged storage.

Initially considerable attention was given to bag storage, with the objective of preventing insect outbreaks similar to those that occurred during WWI. Old storage sites were avoided and new depots established and made as pest proof as possible. Particular attention was paid to excluding mice, which had played a major role in the last War.

Storage depots were sited in the driest, coolest possible locations (Ratcliffe et al. 1940). At these sites, care was taken to ensure freedom from pests and check that wheat was free from infestation before it was accepted into storage. Stacks were built according to specifications laid down by the AWB (Anonymous, Undated a) and were protected by mouse-proof barriers, side walls and covered by roofs of galvanised iron sheets.

It was intended that wheat should only remain for a brief period at the receival sidings before being moved to these depots. However, due to logistic problems this was not always possible and some long-term storage occurred at the receival sidings where bag-stacks could not be protected so carefully. In spite of this, a repeat of the problems encountered during WWI did not occur and many millions of bushels of wheat were held for periods of 3–4 years with negligible losses.

One of the factors contributing to this 'success', was the ability to satisfactorily fumigate the bottom layers of bags of the bag-stacks, where weevil infestations had been observed to commence (Ratcliffe et al. 1940; Wilson and Gay 1946). This depended on preventing the escape of fumigant (carbon bisulphide and methyl bromide), from the bottom of the stacks by making the sides of the enclosures surrounding them gastight. Together with preventive hygiene measures, this simple method of stack fumigation continued to be used for successful long-term storage of bagged grain after WWII (Wilson 1953).

The bulks of grain stored in various structures presented new problems. Those in horizontal depots were observed to become infested by the lesser grain borer, along the outer periphery of the grain mass (Wilson 1953) in the form of hotspots and it was thought that they might prove to be difficult to control. However, it was found that the grain in these storages could be protected against infestation by surface applications of mineral dusts (Gay et al. 1947; Gay 1947). The dusts were unable to control established infestations of *R. dominica* which were treated by local (spot) applications of liquid fumigants. This regime of dust treatment and fumigation was applied to 16 million bushels of wheat in Victoria (Wilson 1946) and proved to be effective and economical, allowing wheat to be stored for up to three years and finally exported 'in first class condition' (Wilson 1953).[2]

The recently constructed (vertical) silos had not been intended for long-term storage of grain. This strategy had not been given consideration and the necessity for holding wheat in country silos, for a year or more, now presented a serious risk of infestation. Virtually all the silos, then constructed in Australia, had open topped bins and were unsuitable for fumigation. Trials were undertaken to discover whether effective fumigations could be carried out (Fitzgerald et al. 1941), but it appears that grain turning (Gay 1941a,b; Hodgson 1961) was widely used in silos to break up hot spots, reduce grain temperature and minimise the effects of condensation. Robertson and Milthorpe (1948) observed that turning would have two effects on the insect population: it would spread the insects through the grain mass and would, in winter, kill a large percentage of free-living larvae.

As result of the success of these efforts during WWII it was decided that the AWB should remain the sole marketing authority for wheat, and growers were obliged to deliver all their wheat to the Board, with the exception of that for feed and seed requirements.

The war years in Australia witnessed the start of serious coordinated scientific research into the problems of grain storage, and its practical application by the industry. This was to lead shortly, thereafter, to a change in the accepted standards for grain quality and freedom from infestation. The standards prevailing at the end of WWII were vastly different from those we now expect, since the introduction of the 'nil tolerance' for insects. Until the early 1960s, insects were an accepted component of stored grain. The only issue was whether, or not, insect numbers had reached levels that were 'visible' or levels at which significant losses, heating or mould development could occur.

[2]This interest in grain protectant properties of dusts has since been further pursued by Desmarchelier (1987).

The Advent of Bulk Handling

As late as 1907–08 three quarters of the NSW harvest was shipped in sailing vessels, which were only capable of carrying bagged wheat. However, by 1911–12 sailing vessels had almost been completely replaced by steamers, which eventually allowed grain to be shipped in bulk (Callaghan and Millington 1956).[3]

The first two states in Australia to adopt bulk handling were NSW and Western Australia (W.A.), each state adopting an entirely different approach to the matter. The turning point, in favour of bulk storage, was the heavy losses sustained by bag-stacks during WWI described above. The industry's complete dependence on a secure supply of grain bags had been clearly demonstrated (Callaghan and Millington 1956) and this fact, together with their cost[4], must have played an important role in emphasising the need for an alternative means of storage. However, bulk handling had been under consideration in both states for some time before WWI. Indeed, in NSW it had been proposed as early as 1890[5] (Callaghan and Millington 1956) before finally in 1917, a Royal Commission found in favour of bulk storage (Marvell 1988).

In NSW immediate steps were taken to initiate construction of country elevators at selected centres connected by rail to Sydney. Country construction commenced in 1917, and in Sydney in 1918. The first silo was completed in 1918 at Peak Hill, and the first bulk shipment of wheat from the Sydney terminal was made on 1 April 1921, when about 4000 t of wheat was loaded onto a steamer bound for the United Kingdom.

Silo construction was disrupted by WWII (when, in NSW, half the crop was still handled and stored in bags). Thereafter,

[3] In a retrospect, Kelly (1987) noted that 45,676 t of barley loaded in bulk, into a ship in one day in March 1980, would have taken 1.5 months to load had it been bagged.

[4]The cost of buying bags for the harvest in W.A. during the 1930–31 season was $1,744,000 (or 14% of the total return from the crop), while the cost of handling and merchandising was three times the sum spent two years earlier (Anon, Undated b).

[5] In W.A. bulk handling was first considered in 1913 (Anon, Undated b).

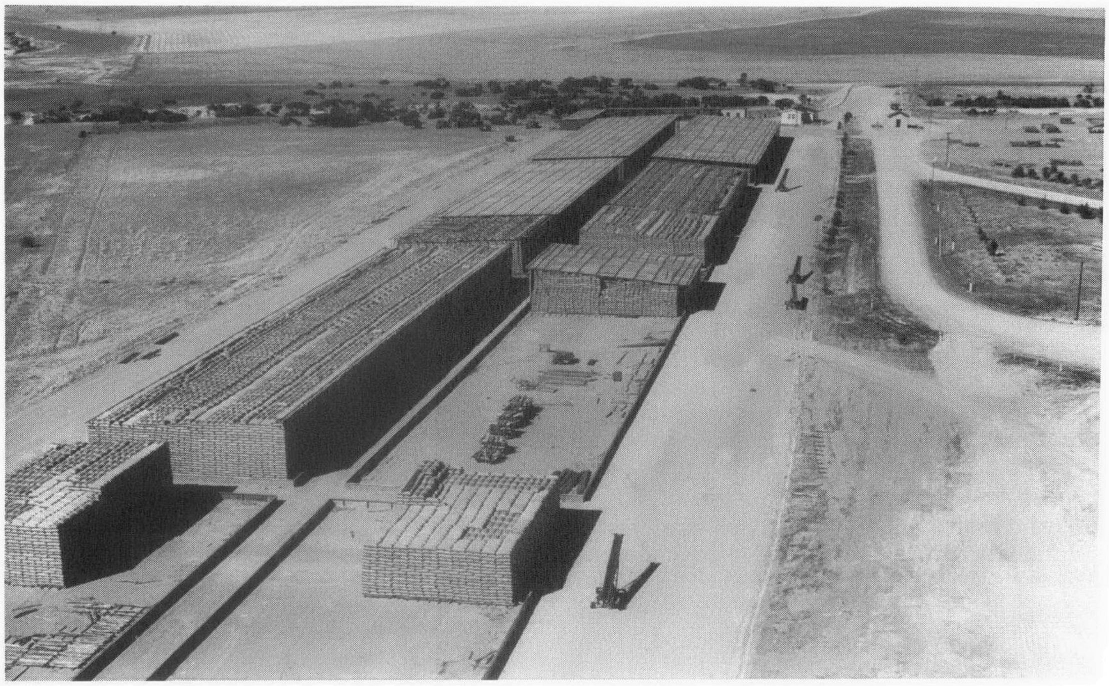

Fig. 1. Some of the last bag-stacks in South Australia during the 1960s.

nationwide, construction of bulk storages continued at a fairly rapid rate. However, the system in NSW was slow to win farmers' approval and in consequence its expansion was not rapid (Callaghan and Millington 1956). Trading in bagged wheat continued into the 1960s with S.A. being the last State to handle bagged grain (Fig. 1). This was not because S.A. was slower to change[6] but because it was the State from which exports were made to countries without bulk receival facilities.

In NSW the 1960s saw an upsurge of wheat production that exceeded storage capacity and the state bulk handling authority (BHA) was forced to build a number of emergency storages—horizontal sheds without fixed handling equipment. Bulk storage capacity was more than doubled between 1960 and 1970, increasing from 2 M to 5 Mt. The latest development in NSW has been the construction of Australia's newest port terminal at Port Kembla, which was commissioned in 1989. It has a capacity of 260000 t in 30 gastight vertical steel bins, all equipped with recirculatory fumigation facilities. It is served by one rail receival hopper with an inloading rate of 3600 t/hour, with road receivals possible at up to 600 t/hour. The shiploading rate, along 2 shiploaders, is 5000 t/hour.

One of the greatest problems encountered by the Australian grain industry has always been that of fluctuating harvests. The increasing capital costs of providing permanent storage capacity lead to the use of more temporary bulk storages. For some time 'A' frames had been used for this purpose (Fig. 2). These were built on cleared sites and consisted of two rows of timber 'A' frames, to which were attached galvanised iron sheets to form retaining walls. The ground in between was covered with bituminised (Kraft) paper and filled with grain up to its angle of repose. The bulk was roofed over with corrugated iron sheeting attached to 'purlins' and 'rafters' laid on the grain surface. While they provided a simple solution to the need for temporary storage of bumper harvests, and kept most of the rain out, they suffered from a number of problems. It was very difficult to protect grain stored in them from insects and rodents, and they were almost impossible to fumigate effectively when infestations were discovered.

As early as 1962 the NSW BHA collaborated with CSIRO in trials involving underground storage[7] of wheat at Cunningar in a structure based on the Argentinian designed airtight underground storages.[8] Further trials using plastic lined pits were undertaken in 1975–76 at Narrabri (Champ and McCabe 1984).[9] An above-ground, earth covered system of bunker storage evolved from this and was extensively used in Victoria during the late 1970s (Banks et al. in press). The NSW BHA modified these and developed the plastic sheeted bunker system of storage (Plate xx) together with its associated handling equipment (Barker 1992; Connell et al. 1992). The development of a technique that allowed these bunkers to be effectively fumigated was crucial to their success (Banks and Sticka 1981). They have proven so successful that presently, in NSW, bunkers provide about half of the total storage capacity. The concept has been adopted, in various forms in Australia by all other state BHAs, and 'exported' to several countries overseas including Brazil, India, Iran, Pakistan, and the USA.

In W.A., bulk storage commenced with experiments in 1931 (Anonymous, Undated b). The basic design selected was derived from the horizontal bag storage sheds (Anonymous, Undated b; Callaghan and Millington 1956). These were served by a locally designed system of mobile grain handling equipment. These sheds, constructed of timber and galvanised iron sheets, continued to be used until the early 1960s. A program of modernisation was then implemented based on horizontal storage sheds, vertical storages (silos) having been found to be too expensive for a once-a-year operation (Anonymous, Undated b). However, more recently such vertical storages were integrated with the horizontal system to facilitate more efficient and rapid grain segregation.

Grain Protection and Pest Control

Most grain in Australia is harvested at the beginning of summer, when ambient conditions are hot and dry, so that warm dry grain (< 12% moisture content w.b.) at 30°C or greater, may be harvested and taken into storage then held throughout the hot summer months of the year. It retains much of this heat in bulk storage, where in the absence of forced aeration, it is only slowly influenced by falling ambient temperatures during autumn and winter, unlike grain grown in the Northern hemisphere. This places Australian grain at risk of infestation for much longer periods than that grown in North America and Europe; a fundamental difference that makes grain protection in Australia a difficult proposition.

In 1948 the AWB became the only licensed marketer of Australian wheat, which had the effect of focussing and coordinating the industry. This, in the future, was to have a profound effect on the industry, particularly in the area of pest control. As owners and sole exporters of wheat from Australia, the AWB recognised the increasing importance of freedom from insect infestation as a marketing factor in the late 1950s and early 1960s. It also provided the means by which choice of pesticides, rates of application and compliance with health and safety issues could be, and were, achieved rationally, quickly and effectively.

When insect infestations were detected these were treated by fumigation. During WWII it had been demonstrated that fumigants could be used effectively to disinfest grain. It is significant, during this period, that methyl bromide became available and was used in the central storage system by the BHAs. During the 1950s facilities were erected at Pinkenba, Queensland (Qld), designed specifically for recirculatory fumigation with methyl bromide.

Dawn of a New Era — The 'Nil Tolerance'

Up until the late 1950s the principal market for Australian wheat was the United Kingdom (U.K.). It was not uncommon for reports of infestation to be received from the British authorities. These reports, received by the Australian Department of Primary Industry, were referred to the relevant BHA for an explanation. That explanation, together with an assurance that efforts would be made to prevent a recurrence, were conveyed the U.K. Ministry of Agriculture, Fisheries and Food, and there the matter ended until the next incidence of infestation was reported. The importers invoked no penalties thus there was no specific incentive for improving the situation.

Up till the early 1960s maintenance of grain quality relied heavily on turning as a means of equalising temperature and it

[6]Bulk handling commenced in SA during the 1955–56 season (Kelly 1987).

[7]Underground grain silos were observed on a farm in NSW during the 1850s (Mossman and Banister 1974). This form of storage is still used on farms in NSW using plastic lined pits (McCabe and Champ 1981).

[8]The research leading to the development of this form of storage referred to studies, undertaken during WWI in Australia (Spafford, 1939), which 'yielded conclusive proof of the advantages of grain storage in hermetically sealed underground depositaries' (Anon. 1949).

[9]These trials, of 10 and 15 years duration, provide records of what may, possibly, be the longest scientific observations of hermetic storage (Banks, McCabe, Champ and Bailey, unpublished data).

Fig. 2. (Top) 'A' frame temporary storage being emptied—note A frames and roof on grain bulk. (Bottom) 'A' frame temporary storage being emptied showing sections of roofing and side walls removed.

almost certainly had a considerable effect in controlling insects. In 1954 Australia was one of the first countries to adopt large-scale use of phosphine in bulk grain (Winks and Bailey 1965) and the situation improved considerably. It remains the principal fumigant in use to this day.

Around 1958 Australia entered into a contract to sell wheat to the People's Republic of China (PRC). The Chinese authorities insisted that all shipments should be accompanied by a phytosanitary certificate, in the form adopted by the Eastern block countries, which stated that the grain had been inspected and was 'free on shipment from evidence of injurious diseases and from live insects/pests'. The Australian grain industry soon became aware firstly, of the difficulties associated with meeting this requirement and secondly, of a different attitude towards this issue compared with that of the U.K. market. The Chinese, when they found insects, notified the AWB and reserved the right to claim for the cost of disinfestation within 30 days. When, shortly thereafter, grain sales to the USSR commenced, similar standards were imposed.

In 1965, the AWB received claims on about 1 million t of wheat that cost the industry about £1 000 000 — a sizeable sum in those days.

Following the early difficulties meeting the Chinese requirements, the Department of Primary Industry promulgated the Exports (Grain) Regulations which prohibited the export of grain from Australia unless it was found to be free from insect pests. These regulations were introduced in 1963. However, had the full measure of this legislation immediately been implemented, not a single grain of wheat would have been exported from Australia without enormous costs. Most of the terminals were simply not equipped to disinfest large quantities of infested grain. In addition, the Exports (Grain) Regulations also required that ships loading grain exported from Australia had to be free of insects and other residues that could contaminate a grain cargo. It was clear from the response of the shipping industry that the standards imposed on ships loading grain in Australia were much more stringent than any standards imposed previously.

Fortuitously, shortly before the Exports (Grain) Regulations were introduced, malathion was introduced during the 1960–61 harvest when 250000 bushels were treated in NSW (Hodgson 1961). By about 1963–64 something like 80% of the grain shipped from Australia was treated with malathion. However, most of the treatments were applied as grain was received into terminals, and although the pesticide killed many adults present in the grain, immature stages continued to emerge during the voyage to China where they were detected on arrival. Clearly, the logical time for treatment was when the grain was received into country storages. The change to country receival points was rapidly made and so commenced the 'golden age of malathion.' Previously, control measures were applied only when infestations were detected. Now, by contrast, malathion could be applied to 'clean' grain as a *preventive* treatment and provide protection from insect infestation for up to nine months. It brought about a new concept in grain storage and opened the way for a new concept — that of grain protection!

Within the next year or so, Australia's outturn performance improved dramatically and complaints diminished to no more than a handful per year. It became possible to meet the demands for a 'nil tolerance' for living insects in our export markets. Where infestations were detected at export terminals, usually as a result of uneven application of the protectant or depleted malathion levels, grain would be retreated with malathion and held for a period before shipment or in some terminals, fumigated with methyl bromide or phosphine and, in W.A. with hydrogen cyanide (Winks and Bailey 1965).

Prior to the advent of malathion, the most prevalent pests in Australian wheat were *Tribolium castaneum* and *Sitophilus oryzae*. After the introduction of malathion this changed dramatically since these two species were very susceptible to this chemical and *Rhyzopertha dominica* became the dominant pest; a position it has held throughout the protectant era. Predictions had been made as early as 1964–65 about the possibility of the development of resistance.[10] Resistance to malathion was first detected in 1968 in *T. castaneum*, in peanuts, followed a year or two later by resistance in *S. oryzae* in the wheat industry. In 1972, resistance appeared in *R. dominica*, the lesser grain borer. This species was the most tolerant of the beetles to malathion and resistance in this species was a serious blow to the continued effectiveness of this material.

Dichlorvos was introduced as early as 1970–1971 in some areas and later elsewhere (1975 in S.A.), as the effectiveness of malathion deteriorated. In response to this problem, the wheat industry, in 1971, formulated an integrated pest control plan (Anonymous 1987). It advocated, inter alia, that the industry should in the long-term, minimise its dependence on chemical protection and move towards more extensive utilisation of fumigants, controlled atmospheres and manipulation of grain temperatures. However, it was recognised that a short-term solution was required: a grain protectant chemical to replace malathion. For this purpose the AWB, in 1973, established the Working Party on Grain Protectants[11] to consider replacements for malathion, and sponsor research and field trials on the various alternative chemicals that were

[10] This, and the difficulties experienced meeting the demands of our new markets, led the AWB to establish the Pest Control Research Advisory Committee, to investigate Australia's ability to meet the likely ongoing technical requirements of the industry. This committee also led to the establishment of the CSIRO Stored Grain Research Laboratory.

[11] Recently renamed the AWB Working Party on Grain Protection, this name change reflects the changing quality demands of our overseas and domestic markets.

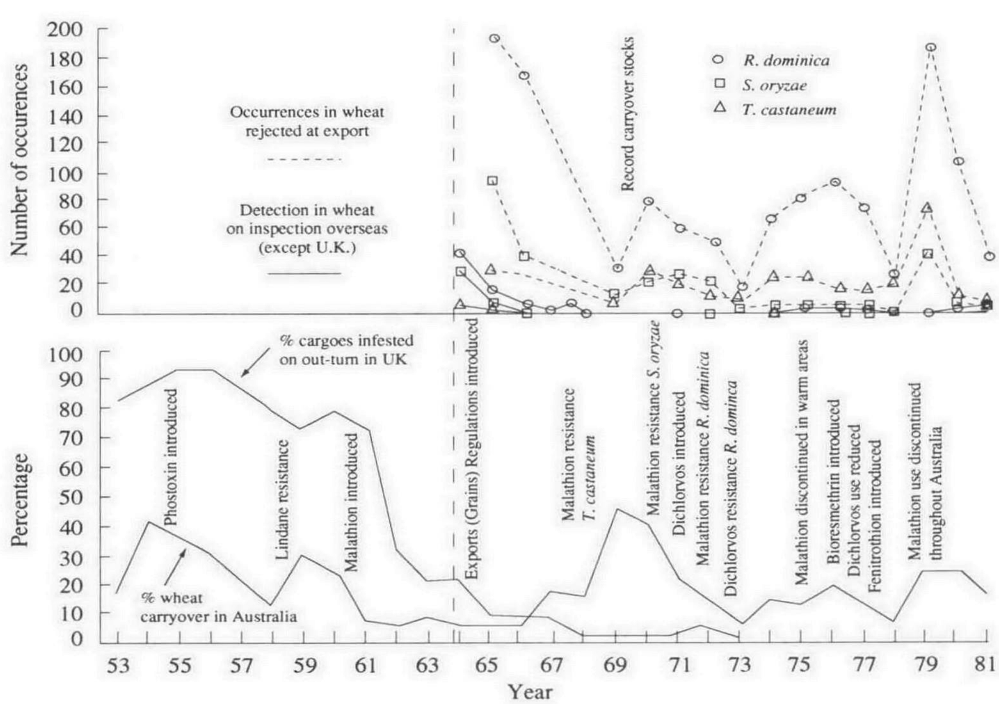

Fig. 3. Out-turn performance of Australian wheat shipped to the United Kingdom with associated records of introduction of key grain protectants and fumigants (Champ and Winks 1982).

selected (Bengston 1988; Snelson 1987). The first of these was the mixture of fenitrothion and bioresmethrin that became available in time to be used on the 1976–77 harvest (Ardley and Desmarchelier 1978; Bengston et al. 1975). This latter combination has served the industry well for over 15 years. The research coordinated by the Working Party in the succeeding years, has proven to be of great practical benefit to the grain industry. It has provided alternative protectants, that are both efficacious and acceptable to international markets (Bengston 1988; Desmarchelier et al. 1987).

Australia probably derived more benefit from malathion as a grain protectant than any other country. However, it is ironical that its success made it more difficult to implement alternative pest control methods. Its effectiveness encouraged construction of numbers of inexpensive horizontal stores, that were built with little or no provision for alternative insect control measures. Measures such as fumigation or aeration proved to be very difficult to apply in some of these structures (CSIRO, (1987)).

Aeration

Prior to the advent of malathion, grain aeration was the principal method of grain protection in NSW, Victoria and S.A.. Research by the CSIRO Divisions of Mechanical Engineering and Entomology (Bailey 1968; Moran 1991; Sutherland 1966; Sutherland 1968) had shown that there was a role for aeration in grain storage in Australia, and machinery was designed to produce the required air flow through grain bulks of various sizes, so that temperatures in them, were lowered and evened. In NSW, the BHA commenced fitting aeration facilities to horizontal sheds from about 1965 (W.L. Cooper, pers. comm.) and utilised aeration for long-term storage of most grain wherever possible, even during the 'malathion era'.

When aeration was used in conjunction with grain protectants, it was shown that there were significant advantages. Protectant decay was reduced and rendered more uniform by the lowered and more even grain temperatures achieved by aeration. This allowed reduced application rates to be used which, in turn, led to lower residue levels (Desmarchelier et al. 1979).

Aeration technology provided the means for the NSW rice industry, established in the 1920s, to convert from bag to bulk storage. The industry has developed, built and operates storage and drying systems that are economic, practical and produce a high quality rice product that is chemical-free. It now handles an average annual harvest of about 1 Mt and continues to improve its storage and drying technology.

Grain aeration, today, plays an important role in the integrated commodity management strategies implemented by the Australian grain industry to preserve grain quality. For example, in NSW alone, there are some 120 storages with a total capacity of 2.25 Mt capable of being aerated (W.L. Cooper, pers. comm.), and aeration continues to be used for grain protection in S.A. and Victoria.

The Move Away From Grain Protectants

During the last decade, issues concerning residues of grain protectants have featured prominently in the quality demands of some of our overseas markets, which set levels that were difficult to meet. In addition, Australian flour millers set lower residue limits to ensure that all grain fractions complied with the Codex maximum residue levels (MRLs) in both domestic and overseas markets for their value added products. Thus it became increasingly apparent that the grain industry would have to look for alternatives to grain protectants and apply methods that would be essentially residue-free.

Although fumigants had been used throughout the protectant era in an attempt to disinfest grain, they were used incorrectly in structures that were clearly not gastight. Nevertheless, phosphine was the fumigant of choice in situations where protectants were not used—particularly those requiring low-residue or 'residue-free' grain. In the early 1970s the Stored Grain Research Laboratory developed specifications for sealing storages to a standard suitable for effective implementation of gas technologies (Banks and Annis 1980). This standard was adopted in W.A., where a program of sealing to these specifications commenced in the early 1980s (Ripp et al. 1984). This enabled grain, in that State, to be fumigated with phosphine effectively and cheaply. W.A. was thus able to meet the increasing demands for low or, residue-free, grain during the late 1980s with little difficulty and, presently, no grain protectants are used by the state BHA.

Other States were not so fortunate since they had sealed few of their storages and the move to reduce the use of grain protectants during the 1980s posed significant problems for them. However, as equally fortuitous as the malathion trials of 1960–61 were when the Exports (Grain) regulations were introduced, so too were the 1986 trials of a new method of application for phosphine in leaky storages (Winks 1989). This new flow-through method of application (SIROFLO) was rapidly developed from trial stage to commercial application and enabled the industry in the Eastern states to meet the increasing demand for low-residue or residue-free grain (Winks 1993). However, a major source of 'residue-free' grain in these states was, until recently, from bunkers that were fumigated with phosphine.

The Future

From its small beginnings in 1788, the Australian grain industry has experienced considerable expansion, not only in the quantity of grain, but also in the range of grains, legumes and oilseeds that it now handles. However, possibly the greatest change that has occurred in recent years has been 'deregulation'. In 1986 the Australian government instituted a Royal Commission into Grain Storage and Transport, which in 1988 recommended that domestic marketing, storage and transport of grain should be deregulated and all restrictions and sole rights removed (Anonymous 1988). Perhaps the major long-term impact of deregulation will be on pest control so that standards of insect freedom and quality will be market driven rather than determined by government regulation. However, the standards that we have achieved in terms of insect control in our grain, have become and will remain, an intrinsic characteristic of our industry.

To maintain this reputation, the program of research, development and implementation that has provided the industry with new pest control techniques will need to be continued. This will be driven by the need to respond to changing market requirements. Concerns over the use of additives in foodstuffs are likely to continue. This anxiety will tend to move the focus of grain protection away from grain protectants.

Phosphine is likely to dominate the methods used for grain protection, at least in the foreseeable period. Nevertheless, there are a number of other methods that are in use, or available for use. Some of the possible alternatives include, controlled atmosphere storage using either carbon dioxide or low oxygen atmospheres (Annis 1990; Cassells et al., these proceedings), different fumigants, or heat disinfestation. Aeration may be relevant in this context. There is substantial unused aeration capacity in the storage system that could be utilised effectively, given suitable optimisation and development of insect and operational control strategies. Further adoption of Dryacide® may play an important role in this respect.

Although methyl bromide has been available for many years as an alternative fumigant, its continued use is threatened (Banks, these proceedings). Other technologies to replace methyl bromide are actively being pursued. At present, heat disinfestation is the only fully developed and acceptable alternative that will match treatment rates at export terminals. Carbonyl sulphide may prove to be a suitable replacement for methyl bromide in many of its uses. Initial tests have shown it to be effective against beetles, moths, mites, psocids and fungi, *and tests on wheat, paddy and barley have shown that it leaves no detectable residues* (Desmarchelier, these proceedings). However, a great deal of work remains to be done before this chemical can be put forward for registration and brought into commercial use.

Old fumigants such as hydrogen cyanide, carbon disulphide, ethyl formate and sulphuryl fluoride are being re-evaluated. Although found to be inferior to methyl bromide and phosphine, when they were originally examined, they are now being re-examined in the light of improved application methods that have been developed recently.

Grain protectants are still being used by the industry and will continue to be used for some time although their use is currently declining. The synthetic pyrethroid, deltamethrin (along with several others) (Arthur 1994), and insect growth regulators (Bengston 1987; Elek, these proceedings) show considerable promise in this regard.

Overall, there is little doubt that insects will continue to pose a major problem for grain stored in Australia. However, the methods currently available and those being researched should provide the basis to maintain the current high standards of insect freedom and quality well into the next century.

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