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Crop Protection 19 (2000) 571–576

Crop Protection

www.elsevier.com/locate/cropro

Current status of non-residual control methods against stored product pests

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Abstract

There is an increasing dichotomy between the demands of the first world for quality food uncontaminated by insecticidal residues, and the desperate need of third-world populations to maintain and protect their harvested grain from the deprivations of insects, so as to maintain a minimum level of food security. Fumigation is widely regarded as a non-residual treatment and fumigation with phosphine will continue for the immediate future as the mainstay against insect infestation. However, to ensure its continued use, insect resistance to phosphine must be countered by more efficient application techniques. Already, available alternative control technologies such as hermetic storage and the use of controlled atmospheres using either nitrogen or carbon dioxide also rely heavily on well-sealed storage structures, that are rarely available in rigid silos, but easily obtainable with flexible plastic liners. Aeration systems to cool grain bulks and thereby prevent insect development, are being widely used even in warm climates but are only applicable for bulk grain. Other non-residual treatments such as mechanical impaction, irradiation, biological control or heating, are suitable for high-quality commodities or niche situations.

Keywords: Control; Non-residual; Stored-product pests

1. The food crisis

The recent polemics over food contamination in Europe have brought to the forefront the growing dangers of incidents of mass food poisoning. The potential for these dangers to materialize increases as production becomes progressively industrialized, and chain-store marketing strategies expand from local to national and global dimensions. As we enter the 21st century, public pressure is being increasingly brought to bear on legislators to close every loophole that might permit the contamination of food with toxic materials. Consequently, future prospects for adding the hitherto relied upon, effective but toxic insecticides to stored food products are bleak indeed, and the admixture of toxic residual insecticides is set to become a thing of the past. At the other end of the spectrum, the threats of malnutrition and hunger loom over millions of people in the developing world where most of the grain is grown and consumed and where the ravages of stored-product insects are the greatest. If we restrict the use of the insecticides that enable communities to control storage pests at the village level, we are obligated to provide socio-economically acceptable solutions that will ensure food security for all people. This will be our major challenge in the years to come.

2. Non-residual treatments — a clarification

By definition, non-residual control methods might preclude the use of fumigants, and even possibly controlled atmospheres, since neither are totally residue free. However, the generally perceived concept is that a gas penetrates and is sorbed into a food product, and then at the end of the exposure treatment it desorbes completely and can be removed by aeration. Therefore, since this overview includes those methods that are still being pursued as viable alternatives to the use of residual control procedures such as admixture with insecticides or inert dusts, the special case of the fumigants is included. Fumigation is still the most widely employed control method, even though the fate of both methyl bromide (MB), and more recently, phosphine are in the hands of the legislators (Banks, 1994). Although in most countries, food commodities fumigated with phosphine and

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0261-2194/00/$ - see front matter
PII: S0261-2194(00)00074-0

subsequently aerated are considered phosphine free with no regulations attached, the US Food Quality Protection Act (FPQA) which became law in the US in 1996 has set a tolerance for phosphine of 0.01 ppm in processed foodstuffs. This is well below the detection level available to most laboratories.

3. Hermetic storage — a long-term storage strategy

Historically, the search for non-chemical control treatments has been underway long before the development of synthetic insecticides. One technology has been literally lying under our feet since the dawn of civilization when farmers first began to store their grain in under-ground pits, perhaps to hide their stocks from thieves and pillagers, or perhaps because even then, they found that the grain stored better below ground than above it. That there is nothing new under the sun is evident from archaeological excavations of underground storage chambers in the middle east, such as the underground grain silo at Megiddo in Israel, built to provide food for King Solomon's war-horses, and from modern day traditional underground storage pits in the horn of Africa, in the plains of northern India, or in Argentina.

In hermetic storage the metabolic activities of insects and micro-flora act as bio-generators, that alter the oxygen (O_2) and carbon dioxide (CO_2) composition of the intergranular atmosphere so that insect development is arrested (Oxley and Hyde, 1955; Oxley and Wickenden, 1963; Bailey, 1965; Hyde and Burrell, 1969). It must be stressed that to kill all insects by hermetic storage takes a long time and complete kill may never be achieved if a dynamic equilibrium is reached between the rates of oxygen ingress into the grain bulk and the rates of oxygen depletion by insect respiration. Therefore, this is a long-term storage strategy where minimal damage rather than zero survival is the objective.

3.1. Underground versus above-ground storage

The advantages of traditional underground storage such as the low O_2 content in the subsoil and rock, and insulation from diurnal and seasonal temperature fluctuations may be off-set by disadvantages such as risks of moisture ingress, and loading/unloading problems that pose a limitation to their commercial suitability. It was therefore a logical step to develop above-ground hermetically sealed storage structures. Both metal and concrete silos have been constructed in the past with the objective of obtaining a sufficiently high-seal and impermeability to gases as to enable storage under hermetic conditions. Unfortunately this apparently simple transition from underground to above-ground hermetic storage has been fraught with problems and failure.

In metal silos the strong absorption of heat through the walls of the silo during daytime, and the rapid cooling at night invokes the establishment of temperature gradients and convection currents that result in moisture migration and grain wetting. This cannot easily be resolved because of the impossibility of aerating the grain when the silo is hermetically sealed. The alternating day and night temperatures also create pressure differences. As a result, air movement through leaks in the seal are accelerated by the pressure difference across the barrier so that even using a pressure relief valve, sufficiently low O_2 and high CO_2 concentrations are difficult to obtain.

For concrete silos, sealing is a greater problem though the use of water-based acrylics, solvent-based PVC and polyurethane foam application to bridge gaps has been developed and applied particularly in Western Australia (Delmenico, 1993). In new silos there is also the problem that the build-up of CO_2 concentrations within the silo is retarded because the gas is strongly sorbed into the concrete.

3.2. Flexible plastic liners for hermetic storage

In short, except for drum storage at the village level, where no headspace is permitted, above-ground rigid structures provide little future for hermetic storage. Instead, the thrust has been towards the development of flexible plastic liners that envelope the grain and seal it from the outside air. For bagged grain, the stack forms the storage structure that is covered by an under-liner and an over-liner which are zipped together with a continuous tongue-and-groove zipper. These structures are portable, relatively cheap and suitable for use in developing countries at village level. For bulk grain, particularly for long-term storage of large grain reserves, bunkers in which the grain is loaded onto an under-liner that is sealed to an over-liner, contained within the limits of surrounding ramps, provide a cheap and effective solution. The use of plastics whether for indoor or outdoor sealed storage has been the result of the technological strides taken by the plastics industry that can now provide suitable materials which were not available a few decades ago.

4. Fumigation in the context of sealed storage

This emphasis on improved sealing runs in accordance with modern good fumigation practice. Of the two remaining fumigants available for use on food, the days of MB are numbered except for quarantine and pre-shipment purposes. At present, the years 2005 and 2015 are the scheduled final phase-out dates for developed and developing countries, respectively (UNEP, 1995). Therefore, a prime objective must be to maintain the effectiveness of phosphine as our remaining fumigant for as long as its use is permitted.

Much inadvertent damage has been done to the efficacy of phosphine since its introduction as a pesticide in the early 1930s. For many years the convenient, cheap and relatively safe application method by means of pellets has made this the most favored disinfestation treatment especially for bagged grain in the tropics. The very nature of the slow release of the gas gave the impression that a sufficiently high concentration could be maintained during the exposure period, and that a tightly sealed structure was not necessary. Nothing could have been further from the truth. Throughout the world, insects surviving from partially successful fumigations have gradually developed populations with high levels of resistance to phosphine (Zettler, 1997) especially in developing countries, and even to an extent where fumigation failures have been reported (Tyler et al., 1983).

Many studies on the sensitivities of insects to phosphine have shown that insects react differently to this gas than to other fumigants. In most cases the egg and pupal stages are much more tolerant than the larval and adult stages. Therefore two different approaches were proposed by Winks (1987) to achieve successful control:

(i) to apply a high dose that will maintain a concentration sufficient to kill all stages including the least susceptible one. This approach relies upon a good seal of the fumigation enclosure.

(ii) to retain a lower fumigant concentration long enough for eggs to hatch and pupae to turn into adults, and then to maintain that fumigant concentration for long enough to kill the insects at their more susceptible stages.

(i) *High dose, no maintenance, high seal.* Recommended fumigation times have been progressively extended over the years from 3 to 5 to 7 days, mainly due to the rising resistance phenomenon, and it is important that high concentrations remain throughout the exposure period. Minimum recommended concentrations by Friendship et al. (1986) were 0.2 mg/l (ca 150 ppm) for 5 days, while those recommended by van Graver and Annis (1994) were 100 ppm (0.14 mg/l) for 7 days. Trials by Taylor and Harris (1994) demonstrated the difference between typical fumigations of poorly sealed stacks, and fumigation of well-sealed stacks and revealed that with care, lethal concentrations can be maintained.

Because there are limitations in the extent to which phosphine will penetrate bulk grain, the concept of recirculating the gas through the bulk has been termed "closed loop fumigation" (CLF) and is being commercially applied in the US (Noyes and Kenkel, 1994). For batteries of bins or concrete silos, manifolded phosphine recirculation systems (MPR) have been designed (Noyes et al., 1997).

(ii) *Low dose, low maintenance, low-seal.* This approach accepts the reality that most existing silos are poorly sealed and that sealing is expensive. The concept of SIROFLO® as developed by Winks (1993) is a pressurized distribution system whereby a continuous low volume stream of phosphine from a cylinder source or on-site generator, is metered into an air supply introduced into the bottom of a silo. The system is designed to counter the factors that give rise to gas loss through leaks, and pockets of low concentration in conventional fumigations, and particularly to overcome the temperature induced chimney effect. The dosage requires a 35 ppm concentration for 14 days, or 20 ppm for a 4 weeks exposure, and this results in a low cost treatment with phosphine levels of less than 0.3 ppm in the work space (Winks and Russell, 1997). The method is being widely applied in Australian silos and is being adopted in other countries, while a manifolded system for silo complexes (SIROCIRC®) has also been developed.

Old fumigants and new fumigants. Some old fumigants that have lost their Codex Alimentarius approval are being re-examined, though at best they may be considered for the fumigation of non-food commodities or for special situations. Also, some new fumigants are under investigation though the costs of international evaluation will make their registration tedious and very expensive. One fumigant worthy of special mention is methylphosphine which has been shown to be more effective against phosphine resistant strains of four stored-product insects than against their corresponding susceptible strains (Chaudhry et al., 1997). This potential for alternating the use of fumigants to reduce the phosphine resistance problem is an exciting challenge.

5. Controlled atmospheres (CAs)

The CA technology for insect control is an alternative that has been thoroughly developed and is already filling niche markets, such as treatment of organic commodities. However, as long as phosphine is cheaply available without regulatory limitations on its use, CAs will continue to play a background role. Again, the pre-condition for successful CA treatment is a tight hermetic seal. Sealing techniques (Andrews et al., 1994), and methods of verifying the seal (Navarro, 1999) are well developed, as are the application procedures (Navarro and Donahaye, 1990; Annis and van S. Graver 1991). CAs lethal to insects can be obtained using nitrogen (N_2), provided that a hypoxic atmosphere of 1% or less O_2 can be maintained, whereas when flushing with CO_2 is chosen, the insects are placed under the stress of both hypercarbia and hypoxia (Calderon and Navarro, 1980).

5.1. Generation and sources of CA

To obtain the high concentrations of CO_2 or N_2 required to kill the insects, large quantities of gas are required. Of the many methods available, the major ones in use are listed here. For CO_2 the usual source is from tanker delivered liquified CO_2 for large structures, or from cylinders for smaller ones. Vaporisers are also required. A high initial CO_2, concentration must be obtained inside the storage container and concentrations are then monitored over time to assure that the set criteria are met. Jay and D'Orazio (1984) stipulated a 5–6 day exposure at 60% CO_2, (above 27°C), whereas more recent insect susceptibility studies that take into account the least susceptible common stored-product species, have led to regimes of 10 days above 50% or 15 days above 35% CO_2 for ambient temperatures above 20°C. For N_2 treatments, on-site generation is preferable using 'pressure-swing adsorption' (PSA) systems or high pressure semi-permeable membrane systems that can generate N_2 at a purity of 99.9% at high output flow-rates, with the advantage that costs of such installations have decreased. Liquid N_2 has also been used recently in Australia (Cassells et al., 1994). A third CA supply source that has been extensively investigated is by the use of exothermic gas generators that produce low O_2 concentrations and some CO_2 by combustion of hydrocarbon fuel.

5.2. *Application methods*

The *single-shot* technique is the simplest application method and the one that is most widely applied both in bins and in flexible plastic enclosures. One method suitable for small structures, such as stack storage in plastic liners, is to apply the CO_2 rapidly in liquid form; the gas then displaces the air above it by lift-out with minimum mixing at the interface. Clearly with this method the problem of pressure build-up must be taken into account, especially if the structure is rigid. For application in the gaseous phase, existing aeration systems and recirculation systems are used to achieve uniform concentrations. For N_2 the single-shot procedure is hardly feasible since an O_2 composition of close to, or less than 1% must be maintained for prolonged periods in order to produce complete kill (Annis and Dowsett, 1993).

The *flushing and maintenance* procedures were developed to overcome the problems of concentration decay due to incomplete seal, or air ingress through pressure relief valves. Ideally the target concentration is maintained by one or more sensors with upper and lower set-points that trigger a solenoid valve to activate or cut-off the maintenance gas flow.

5.3. *Future developments*

In short, the CA treatments are fully developed and waiting in the wings. Their future use depends much upon the price of on-site CO_2 and N_2, and incentives to seal leaky structures. With certain commodities they can provide the added benefit of maintaining quality by retarding oxidative processes. At present, they provide an alternative to phosphine but not to MB since they require long exposures. However, the stimulus to develop quick-action treatments to replace MB has led to interesting aspects of CA treatments. When CO_2 is applied under pressure (at about 25 bar), rapid disinfestation can be obtained. This technology is already available but requires high-pressure chambers and therefore is only suitable for relatively small quantities of high-value commodities (Fleurat-Lessard et al., 1996). The possibilities of accelerating insect kill by combining high CO_2 or low O_2 concentrations with elevated temperatures were investigated by Jay (1986), Soderstrom et al. (1992) and Donahaye et al. (1996). Ongoing studies of this nature may well lead to alternatives to MB where rapid kill is required.

6. Aeration and cooling

Aeration involves the use of forced ventilation as opposed to the natural convection ventilation of grain bulks. Manipulation of the temperature in the stored-grain ecosystem has long been applied for the suppression and control of insect populations, and will continue to do so. Ideally, this complex technology requires an inter-disciplinary cooperation between engineers, entomologists, phytopathologists, food technologists and plant physiologists. In practice, aeration procedures have been developed piecemeal to suit very different climatic conditions and storage situations throughout the world. Fortunately, this wealth of information will soon be brought together in the first comprehensive text book and working manual on this subject (Navarro and Noyes, 2000).

Of the many purposes for using aeration, the most important one is to cool the grain to control insect infestations. A rule of thumb is that if the grain can be cooled below 20°C, insect development is significantly slowed and at 10°C it is arrested. This is true for the major storage pests originating from warm climates, whose optimum temperatures for development range between 25 and 35°C. The engineering technology for aeration has been progressively developed since the 1950s, initially for cooling grain in temperate climates to control moisture migration and mould development in the US corn-belt (Hukill, 1953; Shedd, 1953; Holman, 1960). In the mid-1960s aeration was used in Mediterranean and sub-tropical climates, where it was shown that grain can be cooled and will stay cool provided there are reasonably cool winters (Elder, 1969; Navarro et al., 1969). The use of refrigerated air or "chilled" aeration to cool grain-bulks was investigated in the 1970s both in Israel and Australia, the technological success being offset by the high-cost of energy consumption. However, refrigerated aeration has been adopted in several tropical countries and is currently being re-evaluated in the US for high value bulk commodities as the number of alternative control options continues to diminish (Maier, 1994).

Aeration technologies are being widely applied and have tremendous potential for integration into the non chemical approach to grain storage protection. Unfortunately, they are not suitable for the cooling of bagged grain, and consequently they are not available to many of the grain storage situations in developing countries.

7. Other insect control technologies

Included here are four insect control concepts with "niche" applications, though probably their full potential has yet to be realized:

Thermal disinfestation: For bulk storage installations, rapid disinfestation can be obtained by fluidized-bed heating of grain (56–72°C) during translocation in a moving stream. This technology, developed largely in Australia holds promise but has yet to be widely applied. Heating of flour mills to 50°C is a well-known disinfestation practice but is not widely applied.

Irradiation: A succinct overview (Bell, 1996) of the history of the three types of ionizing radiation that have been evaluated against stored product insects, also explains the relative failure of this technology to gain a foothold in commercial practice. And so, the bottom, but perhaps not the last line to be written, is that insects can be controlled at doses lower than those causing damage to the commodity. However, they survive for several weeks at these doses, and there are no routine inspection tests that can ascertain whether the surviving insects are sterile. This means that there are no approved irradiation quarantine treatments to date. This is compounded by the current resistance of consumers to irradiated food, and the costs and logistics of carrying out the treatments.

Impaction: The Entoliter has long been the standard equipment in the flour industry. The lethal effect is based on the centrifugal force of spinning discs that impact the flour and free-living insects against the outer steel casing of the apparatus. Other studies have been carried out to show that impact during the movement of flowing grain as with pneumatic conveyers and high-speed kernel-to-kernel impact of grain from downspouts causes substantial kill, but insects inside the kernels are less affected. Impaction has potential as an additional control factor in "integrated pest management" (IPM) or "integrated commodity management" (IPC) strategies, but for grain its value only lies in situations where the crops are being handled in bulk.

Biological control: The potential to control or suppress pest populations using parasites or predators cannot be denied though their future probably lies in integration with other non-chemical preventative and control methods. Under natural conditions these enemies of stored-product insects often become abundant in the commodity only after the pest population has reached the levels that have already caused serious damage (Haines, 1984). Furthermore, the inundative artificial addition of insects to the food commodity environment has negative repercussions that render this approach more suitable for non-food products or raw-products which can be cleaned before use, and for warehouse-space treatments where the eggs of phyticine moths for example present an exposed target for parasitization. Much remains to be learned on the population dynamics of natural enemies, in order to develop simulation models that will enable optimization of release strategies to reduce population growth of pest species. In practice, this approach has not yet been commercialized except for the special case of mass release of the beetle predator *Teretrius nigrescens* against the larger grain borer *Prostephanus truncatus* in Togo (Markham et al., 1994). It is regrettable that so little funding is allotted to ecological studies on host–parasite and predator relationships. Without such knowledge the practical implementation of biological control in stored products remains a dream of the future.

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