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Integrating fumigation and aeration

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Abstract. In Australia, fumigation and aeration are mainstays for stored grain pest control and quality maintenance. Most grain produced in Australia will be either fumigated or aerated during storage and handling. Currently, fumigation involves the use of phosphine and methyl bromide, but both of these fumigants are under threat, phosphine due to occupational health and safety, and environmental, concerns and increased resistance, and methyl bromide due to environmental protection legislation. In response, several new fumigants are being developed, and fumigants with registration on other commodities are being investigated for use on grain. However, registration is expensive and companies are unwilling to pursue it. Furthermore, these alternative fumigants have different performance characteristics and will not compete with phosphine in terms of cost of material or ease of application. The use of aeration is growing, with non-chemical insect suppression as one benefit. An integrated fumigation and aeration system is increasingly being sought by the market but equipment that implements both technologies effectively is not available at present. This is partly due to the divergence between the technical requirements for grain conditioning of these technologies. Fumigation performs well with warm grain in sealed storages, while non-drying aeration cools grain and does not require a sealed storage. Nevertheless, fumigation and aeration can be integrated in a manner that will maximise the insect control benefits available from both technologies while still providing the grain quality benefits of aeration. Technology that will handle the fumigation performance characteristics of existing and potential fumigants, and the grain temperature conditioning traits of aeration, can extend the life of phosphine and set up appropriate infrastructure for alternatives.

Introduction

Grain infestation is a universal problem of grain storage in Australia due to a temperate climate that favours insect proliferation. Australia's main export competitors have less of a problem, due to their cooler climates. The current mainstays for pest control are the use of chemicals as fumigants or protectants. Over 80% of Australia's grain is fumigated with phosphine, while approximately 25% of grain in the eastern states is treated with protectants. Phosphine and methyl bromide are the most common fumigants used, but both are under threat.

Australia's industry is heavily capitalised for use of fumigants, especially phosphine. The major threats to phosphine use in Australia are occupational health, safety and environmental (OHS&E) risks and insect resistance. OHS&E issues include: exposure of workers and/or the surrounding community during fumigation treatments; accidental releases due to equipment failures; transport and disposal of the various fumigant formulations; and build-up of fumigants in enclosures as a result of grain 'desorption'. Investigating this issue, Meaklim (1998) concluded that the main threats to continued phosphine availability were accidents and use by untrained people. Several recent industrial incidents with 'leaky' packaging of solid phosphine formulations, pressure regulator failures (explosions) with bottled phosphine, and the practice of growers 'bombing' silos or truck loads support these findings.

In Australia, phosphine resistance has been steadily increasing over the past 20 years, and commercially significant or 'strong' levels have been identified (Collins et al. 2003). Strong resistance refers to a 50 to 100-fold increase in dose required to achieve 'end point' mortality levels equivalent to those in susceptible strains (Champ 1985; Bengston et al. 1998). Such resistance is likely to result in conventional fumigations failing, although strong resistance occurs at lower phosphine concentrations of less than 100 ppm (Annis and Dowsett 2000: Collins et al. 2000, 2001). Initially, strong resistance to phosphine in primary pests of cereals was identified in various countries in Asia: Bangladesh (Dyte et al. 1983; Taylor and Halliday 1986); India (Rajendran and Narasimhan 1994); China (Ren et al. 1994; Liang 1990); Philippines (Sayaboc and Gibe 1997; Bengston et al. 1998). This was generally attributed to under-dosing of parts of the grain bulk during repeated fumigations (Champ 1985; Bengston et al. 1998). Collins et al. (2003) summarised numerous works on the progressive development of weak phosphine resistance in cereal pests in Australia since 1982, demonstrating that, in 2002, over 50% of insect strains had weak resistance. Most significantly, strong resistance has recently been

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found occasionally in Queensland (Collins et al. 2001) and NSW (Wallbank and Farrell 2000) and is of comparable strength to the resistance seen in overseas strains (Collins et al. 2000).

Poor fumigations are common throughout Australia, and the trend of increasing phosphine resistance will continue. For phosphine to remain effective, greater use of increased doses and better application techniques will be required. Increased doses can be implemented by higher concentrations and or longer exposure times, noting that application protocols are controlled legally via the product labels. This process has already begun. The protocol for Siroflo® and other 'low dose' procedures in Australia has been recommended to double (from 0.5 to 0.1 mg/L) for Queensland and NSW (Bengston and Strange 1998). Provisional recommendations for increasing 'label rates' for phosphine have been submitted to the National Pesticides and Veterinary Medicines Authority (APVMA) to address strongly resistant *Rhyzopertha dominica* (Collins et al. 2000). Eventually, phosphine is expected to become ineffective due to resistance.

The continued effectiveness and availability of phosphine will depend on appropriate fumigation and OHS&E practices being adopted across the industry; but this is very uncertain. Resistance-management technology and approaches will need to be more readily available and the impetus for their use well established. The fact that higher concentration dosing (>150 ppm) is as effective against all insects irrespective of resistance status is a particular opportunity, as increasing the concentration of phosphine is usually cheaper than extending dosing times when costs of appropriate sealing are taken into account. Costs will increase with increased phosphine quantities, more advanced application techniques, better sealing and greater use of sealed stores, requirements for further training, and stricter monitoring and regulation.

Methyl bromide use in Australia is not as geographically widespread as phosphine use. Its is routinely used for grain disinfestation before shipping at a number of ports on the eastern seaboard. Methyl bromide is not used more widely because of its substantially higher cost per tonne treated, the need for fan-forced reticulation equipment, and stricter OHS&E requirements than for phosphine. After January 2005, methyl bromide use will be allowed only under the Quarantine Pre-Shipment exemption (QPS) of the *Montreal Protocol on Substances that Deplete the Ozone Layer* (UNEP 1987). Its use under the QPS exemption will be scrutinised more closely by Environment Australia in the near future, as total methyl bromide QPS use has increased in Australia in recent years (Mackie, these proceedings).

Over the next few seasons, current methyl bromide practices on grain should continue under the QPS exemption, as alternatives with competitive disinfestation rates at comparable cost are lacking. In the longer term, government approved protocols will become standard practice, and scrubbing or recycling methyl bromide from silo purges are likely to become mandatory. If full containment technologies are cost competitive, methyl bromide could be an option for phosphine resistance 'breaking' at non-port locations. But there is no doubt that all costs associated with methyl bromide use will steadily increase, leading to it becoming uneconomic.

The impending loss of phosphine and methyl bromide has been well recognised for many years and various new fumigants have been investigated, but none offer the performance characteristics of phosphine or methyl bromide. Carbonyl sulfide (COS) has been developed and patented (Banks and Desmarchelier 1993), but odours can be an issue (Fields and White 2002). However, as fumigants are toxic to humans, registration for food use is required. This is protracted and costly relative to the market size, such that most companies will not pursue registration. Progress on commercialisation of COS is reported by Wright (these proceedings) Alternative fumigants registered for other commodities are being evaluated for grain use. At present, ethyl formate shows the most potential (Muthu et al. 1984; Annis 2000), but fan-forced distribution is required to overcome its rapid sorption by grain. The commercial product Eranol® (Orica) is registered in Australia for use on dried fruit. BOC is currently developing VAPORMATE®, a formulation of ethyl formate in CO_2. Neither is registered yet for use on grains. Because they cost more than phosphine, they will probably be used as a phosphine-resistance break option.

Apart from fumigation, residual chemical protectants are used for disinfestation, but markets prefer cereals free from the chemical residues that result (McMullen 2000; Sidley 2000). Furthermore, insect resistance to 'contemporary' protectants is widespread, such that there is no single protectant that will control all species (Collins 1998). It is now necessary to use 'cocktails' of protectants matched to the suite of resistant insect species thought to be present in the grain mass (Champ 1985; Collins 1998; Wallbank et al. 2000). For some chemicals, companies are withdrawing commercial support of the product label registration because of the small market. Cross-resistance between fumigants and protectants has not been detected (Champ 1985; Bengston et al, 1998), and this has enabled their occasional use to disinfest grain after phosphine fumigation has failed (Wallbank and Farrell 2000).

Non-chemical grain disinfestation and insect control options have been pursued for over 50 years. The 'likely' options for Australia are: suppressing insects by aeration-cooling or in-line cooling systems; disinfestation by heating the grain (thermal disinfestation); and possibly mechanical disinfestation. Aeration is the only established option, but cooling does not disinfest grain, rather it suppresses insect population growth. Furthermore, dedicated 'insect control' aeration cooling systems are not available at present for all Australian storage scenarios. Several thermal disinfestation options are technically developed, but commercial systems are not used due to high costs and fears of grain quality loss. In-line cooling and mechanical disinfestation options have not been developed.

Aeration can be used for non-chemical insect suppression and is a mainstream grain quality preservation option. Technically, fumigation and aeration technologies can be integrated in a manner to maximise the insect control benefits available from both while still providing the grain quality benefits of aeration. Although stores equipped with independent fumigation and aeration capacity exist, an integrated, forced fumigation and aeration technology has not been developed. Initially, such technology will need to improve phosphine fumigation and offer the capacity to fumigate with likely alternative fumigants such as ethyl formate or possibly methyl bromide should phosphine resistance be encountered.

In this paper, we consider the engineering and biological aspects of fumigation and aeration, and how these two processes can be integrated into a broadly applicable system. The fumigation issues are discussed with respect to four fumigants that are deemed to have the most potential as bulk grain disinfestation options from the technical and commercial perspectives outlined: phosphine (PH_3), methyl bromide (CH_3Br), ethyl formate (EF) and carbonyl sulfide (COS).

Fumigation issues

Fundamentally, successful fumigation requires exposing all the insects present within a store to a given toxic gas for a sufficient time for all to be killed. The disinfestation achieved is dependent on four, time-dependent factors:

- insect mortality
- fumigant 'sorption' by grain
- fumigant distribution and dispensing
- store leakage.

The rate at which insect mortality is achieved is dependent on insect, fumigant and grain factors. For the fumigants phosphine (PH_3) (Annis 2001), methyl bromide (CH_3Br) (Munro 1969), ethyl formate (EF) (Wright et la. 2002) and carbonyl sulfide (COS) (Weller and Morton 2001), increasing the fumigant concentration reduces the time needed to achieve complete mortality of the major stored-product pests in whole grain. Concentration, grain temperature and fumigant resistance have an interrelated effect on mortality rate. For susceptible strains of key pests, rates have been found to be greater at 30°C than at 20°C for phosphine (Collins et al. 2001) and COS (Weller 1999). However, phosphine-resistant *Rhyzopertha dominica* (F.) survives doses of phosphine below 100 ppm more readily at 30°C (Collins et al. 2001).

When an air–fumigant gas mixture contacts grain, gaseous fumigant is often lost to the grain via 'sorption' (Banks 1986). Each of the fumigants considered here displays this phenomenon: phosphine (Berck 1968; Dumas 1980), methyl bromide (Winteringham and Harrison 1946; Berck and Solomon 1962), ethyl formate (Reuss and Annis 2003) and carbonyl sulfide (Weller 2003). The sorption rate depends on a variety of fumigant and grain parameters. For fumigants like ethyl formate and methyl bromide, the rate of sorption is so high that fan-forced application systems are mandatory to move the fumigant throughout the grain before it is lost to sorption. For phosphine and carbonyl sulfide, sorption is significant only in particular commodities

Fumigants can be distributed throughout a store passively via natural convection and diffusion, or fan forced. Passive distribution is feasible with phosphine and carbonyl sulfide, but, as noted above, not with ethyl formate or methyl bromide due to sorption phenomena. Passive distribution with phosphine is a common procedure, but can require over 10 days before all the grain mass is experiencing insecticidal phosphine doses, especially in summer or with large stores (Banks and Annis 1984; Boland 1984; Williams et al. 1996). In the few studies completed, passive distribution of carbonyl sulfide was acceptable in smaller stores, but may require forced distribution in larger stores (Ren et al. 2002). Forced or active fumigation systems distribute fumigants according to design and can provide various options to maximise performance: positive or negative pressure; continuous or multiple doses; recirculation or flow-through. A small, 1 litre per second per tonne aeration system, will change the store volume gas 2–5 times in an hour, depending on system details.

The store leakage 'rate' refers to fumigant–air mixture loss that occurs through leaks in the store fabric or boundary. Physically, stores need to be able to 'leak' in a controlled manner to maintain store integrity amid climatic pressure and temperature variations. Otherwise, the store needs to be sealed adequately to maintain the required fumigant concentration for sufficient time according to the dosing schedule, which may not be continuous. It has been clearly demonstrated that fumigants cannot be distributed passively in an unsealed store (Banks and Annis 1984), and continuous low-flow, low-concentration phosphine systems have not always disinfested grain bulks in open-top stores (Bengston and Strange 1998; Wallbank and Farrell 2000). At the same time, passive fumigations have been shown to work in stores that fail pressure tests (Newman, Daglish and Wallbank, these proceedings) illustrating the influence of environment factors. The key issue has proven to be to what extent a store should be sealed to be effective in all scenarios. In summary, fumigations fail if leakage rates, either locally or overall, lead to a grain zone being diluted of fumigant, resulting in inadequate exposure of insects to fumigant. The frequency and extent of dilution by various climate events and their likelihood is the determining issue.

Aeration issues

A conventional use of aeration is to cool the grain, and this has been promoted in Australia to be effective in controlling insect populations at grain temperatures of less than 20°C (McLaughlin and Andrews 1994; Johnson et al.

1999). This view is presumably based on several excellent laboratory studies where the population growth of major pests was measured as a function of temperature (Evans 1977, 1987a; White 1987; Beckett and Evans 1994). Of note are the results of the work of Evans (1987a,b) in which no population growth was measured at 9–13°C with fully cold acclimatised Australian strains of major pests. However, many workers have found live and active insects present in industry scale stores where grain temperatures were reduced to less than 10°C (Burgess and Burrell 1964; Elder and Ghaly 1984; Maier et al. 1996; Fields and White 1997; Flinn et al. 1997; Fleming and Armitage 2003; Jian et al. 2003). So insect control based on cooling has considerable uncertainty, and the differences between precise laboratory work and industry stores needs to be appreciated in practical insect control approaches.

Infestation levels of industry are traded against a 'nil tolerance' level, either direct or 'implied'. Nil tolerance requires that grain is 'free from live insects' according to specific sampling procedures that vary depending whether trade is international (AQIS 1999) or domestic (Anon. 1994). This standard is high and a key part of Australia's marketing approach. In either case, the success of an insect control process includes the chance of detecting any live insects in a load, in conjunction with how many insects are present. As cooling to 10–20°C does not kill insects, insect control with aeration is dependent on insect numbers never being above a detectable level. This means that aeration is an imperfect insect control option that will not work under all infestation pressures.

Aeration changes the temperature of the 'core' of the grain bulk. It has much less influence on the outer 150–200 mm, the thermal peripheral layer that surrounds the core grain. The temperature of the peripheral layer is influenced by other heat-transfer factors: exposure to direct sun or night sky; weather events such as wind, rain and frost; and store construction materials, such as metal, concrete and PVC. Peripheral layers establish because of the good insulation properties of bulk grain, which prevent changes in temperature at the periphery from penetrating into the bulk that is conditioned by aeration. So insect control in the peripheral layers via temperature management is not generally achievable with aeration. Temperature cycling in the peripheral layers may not favour prolific insect population growth, but the research and development to quantify this has not been done.

The capacity of aeration to cool the grain is dependent on the weather. The final grain temperature achieved is a function of the inlet air conditions used and the moisture content of the grain. Naturally occurring air conditions vary according to climate, location across Australia, time of the year, and time of day. Controllers are used to select appropriate cooling air amid these factors. With a dedicated insect cooling aeration system that involves specific sizing and control, aeration-cooling can achieve insect suppressing temperatures under just about all Australian conditions, including in the inland wheat belts of WA and SA in summer. However, dedicated insect-control cooling systems are not traded at present. General cooling systems are available which will work quite well when and where the weather conditions experienced are favourable.

Integrating fumigation with aeration

An integrated aeration–fumigation system is envisaged as a sealed store fitted with recirculation ductwork from the headspace to the fan. An automatic, combination 'valve' apparatus for forced recirculation, thermosiphoning or venting would be fitted to the ductwork near the fan. The valve device would accommodate pressure relief, one-way flow, a condensation trap and seal-testing capabilities. Connections for a possible scrubber (to remove fumigant from air) could also be included, depending on the application. A controller and weather station would automatically manage the various fumigation and aeration operations and their sequencing. Figure 1 is a diagram of the basic concept.

Such an integrated aeration–fumigation system would enable grain temperature manipulation and fumigant administration to be implemented in a synergistic manner, not possible with current approaches. Aeration equipment is generally used to cool grain, but can warm grain to optimum fumigation conditions of 26–34°C just as effectively in non-winter conditions. Grain receival temperatures vary widely, depending on harvest conditions, and range from below 20°C to above 35°C, frequently reducing fumigation performance substantially. Each of these fumigants will perform faster, and thus more reliably, at optimal temperatures.

If grain is disinfested by fumigation, then cooled to insect-suppression temperatures, cooling-based suppression becomes a dependable control option and resistance management strategy. The procedure reduces the need for repeat fumigations thus preventing selection of resistance. However, purpose-built control for grain temperatures specific for fumigation and insect suppression is required as part of an integrated technology.

The recirculatory aeration system enables each fumigant to be administered optimally, ensuring that gas will be distributed throughout the store rapidly and using dosing methods to suit the fumigant. In particular, relatively high concentrations can be rapidly and evenly distributed throughout warmed grain, maximising disinfestation speed and reducing the influences of the less-than-perfect sealing that predominates in industry. Furthermore, automatic control enables distribution at optimal times to overcome detrimental climatic conditions. Thus, the gas distribution and local climate factors that contribute to disinfestation failures in existing systems are addressed with the integrated technology.

If the technical issues can be addressed cost effectively, an integrated aeration–fumigation technology can be expected to be an effective and sustainable solution for industry. It will prolong the life of phosphine by enabling more effective treatment, improved safety, and faster disinfestation with complete efficacy and resistance management. Also, it will provide a means to administer resistance-break alternative fumigants such as ethyl formate or methyl bromide within the same store. It provides the basis for implementing any new fumigant(s), remembering that the likely options will not perform well in all stores with passive distribution methods. Dedicated insect-suppression cooling strategies can also be implemented, noting that present aeration systems are designed and controlled for a non-specific cooling strategy, and results are dependent on the weather experienced.

Benefit–cost aspects of integrated aeration–fumigation technology

The benefit of developing an integrated aeration–fumigation technology would be assessed by comparing the costs of the integrated system envisaged with those of the current un-integrated or 'independent' systems, or a straight aeration system. Current 'independent' aeration and fumigation arrangements involve a sealed silo for passive (natural convection) phosphine fumigation with an aeration system fitted. In most cases, the fumigation step involves sealing all the aeration inlets, vents, etc. and introducing phosphine via a solid formulation. Aeration is operated independently, with all the inlets, vents, etc. opened. In many cases a controller is not used. A straight aeration system designed for insect control would be bigger and have dedicated control. An integrated system would consist of a sealed store fitted with a combined aeration and fumigation reticulation system in which the fumigation and aeration steps are handled automatically (see Figure 1).

The benefits of the integrated system over the independent system or straight aeration can be summarised as follows:

- effective fumigation in the range of sealed storages typical of industry
- more rapid complete fumigation (not partially fumigated leaving eggs etc.)
- fumigation at any initial grain temperature and moisture
- improved predictability and reliability, no routine repeat fumigations
- capacity for use in the aeration then the fumigation mode
- the system will accommodate new (registered) fumigants
- aeration–fumigation provides greater disinfestation capacity than straight aeration.

Several of these benefits could be captured now, using phosphine, such as the ability to disinfest grain more rapidly and reliably in typical sealed silos for all grain conditions. The monetary benefit depends on the storage and handling business involved. Other benefits are more strategic and refer to the broader industry. For example, capacity to administer a routine resistance-break strategy with automatically sequenced phosphine fumigation and cooling. Alternatively, resistance-break options of rapid acting fumigants such as ethyl formate can be applied to infested grain. In the future, potential fumigants such as COS could be applied with such technology if needed.

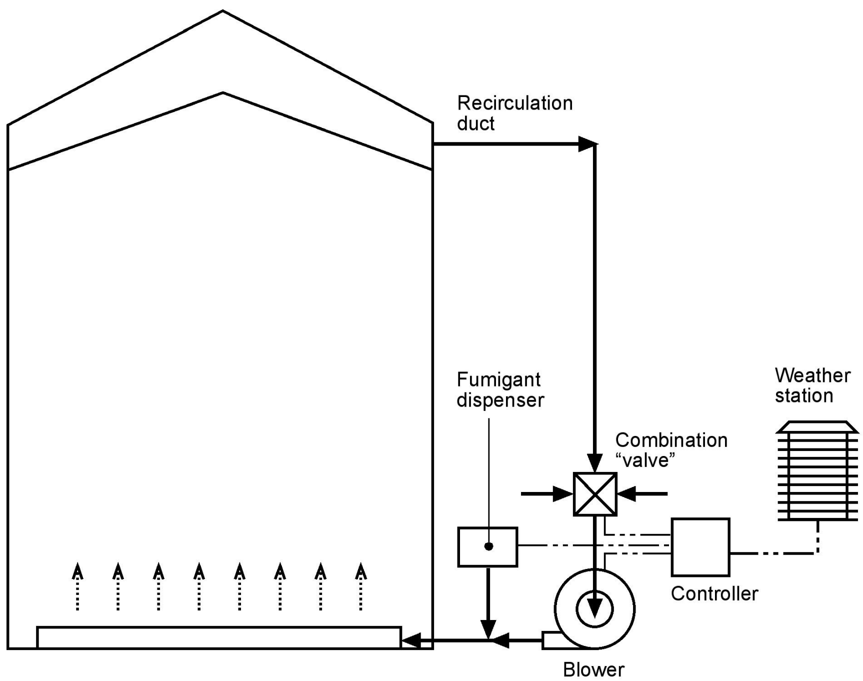

Figure 1. Concept of an integrated forced fumigation and aeration system.

Assessing the costs of an integrated system over the existing options relates primarily to the capital costs of the reticulated fumigation system. Operating costs will be comparable. The capital costs will cover the reticulation ductwork, automatic valve and a controller. The purchase costs of an integrated system would be analogous to the purchase of aeration controllers with current aeration equipment. They are perceived as expensive relative to the benefits provided until mishaps occur or a more professional storage management approach is sought. The costs of a specific fumigant-dispensing apparatus to suit alternative fumigants or fitting scrubbers are separate issues as these would be required only where phosphine resistance was regularly encountered.

A key influence in the relatively small Australian agricultural sector is being able to develop flexible and broadly applicable technologies. An integrated aeration–fumigation solution that addresses all farm production scenarios, all fumigants, all grain conditions and all store types, would enable suppliers to manufacture sufficient equipment numbers for the business to be commercially viable. Purchasers are more attracted to equipment that will address the entire spectrum of insect control and grain quality protection issues for the foreseeable future. Achieving these criteria will, in turn, create a technically and commercially sustainable solution.

Conclusion

An integrated aeration–fumigation technology could provide immediate practical and strategic benefits to the Australian grain industry. The main gains are from improved disinfestation performance due to the enhanced grain temperature manipulation and timely gas distribution enabled by the aeration equipment. Developing an integrated technology will require the further development of forced fumigation and aeration technologies. Aeration and fumigation systems that are un-integrated are traded at present, but do not offer rapid disinfestation for all grain, infestation pressures and fumigant scenarios. In reality, good fumigation practice will not be universal in the industry and solutions that accommodate this circumstance will be needed. In particular, phosphine will need to be applied effectively within a domestic environment where infestation pressure from resistant insects is increasing. An integrated technology will contribute to Australia's existing fumigation infrastructure, prolonging the cost-effective, safe and environmentally responsible use of phosphine. A further benefit will be the capacity to routinely implement a sustainable resistance strategy based on combined fumigation and cooling.

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