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Use of zinc phosphide to overcome rodent infestations

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Abstract. Of the many rodenticides available for rodent management, few provide immediate control on a large scale while also offering a high level of safety to non-target predators and scavengers in the food chain. These are minimum requirements for the control of rodents in broadacre crops and in certain other agricultural situations. The need to meet the combined objectives of high potency and high safety has led to renewed interest in zinc phosphide (ZP) as a suitable active constituent of rodent baits.

ZP is generally well accepted by rodents, is relatively safe for secondary non-target species, and does not leave any significant residues in crops, soil, water or the atmosphere. MOUSEOFF® zinc phosphide mouse bait been used successfully to protect large areas of Australian crops from mouse infestation, first under emergency permit in 1997, and in all major mouse infestations subsequent to registration in 2000. More recently, research on related ZP technology has led to the use, under permit, of RATTOFF® to control rats in Queensland cane fields and hoop pine plantations. The research may be extended to the development of formulations and presentations of ZP bait that are suitable for rodent control in industrial situations including grain storages, warehouses, farm machinery areas, and perhaps for intensive animal and fodder storage facilities. Industry-sponsored extension and training programs have also commenced to improve knowledge about the new technology and to encourage a more proactive and less reactive management approach to rodent infestations in crops. The use of the new ZP technology will thus form a part of, rather than alternative to, integrated pest management (IPM) strategies for rodents.

Introduction

Rodents cause significant damage to a wide range of crops from planting to preharvest, and during postharvest storage and processing. Rodents can also transmit a variety of human and animal diseases via ectoparasites or via hair, bodily waste products and secretions (Brooks and Lavoie 1990; EPA 1998). In many countries, rodents are regarded as the most serious of all vertebrate pests and cause vast economic and social damage. While a number of effective anticoagulant rodenticides are available for the control of rodents in industrial and domestic situations, they are generally not suitable for the control of large-scale rodent infestations in crops, due primarily to their delayed mode of action and potential for accumulation in the food chain. A quick-acting ('acute') rodenticide is required for these situations.

Zinc phosphide (ZP) has been used as a rodenticide worldwide since the 1940s to control a variety of animals including rats, mice, squirrels, prairie dogs, voles and gophers (EPA 1998). This metal phosphide shares the same propensity to generate phosphine gas as magnesium and aluminium phosphide. However, it does not release phosphine gas as readily as aluminium phosphide and is thus more stable in storage and use. Whereas aluminium phosphide degrades in water, ZP requires the addition of weak acid to cause phosphine production (Chitty 1954). Since acidic conditions are found in the stomach of rodents, and these animals are unable to regurgitate, ZP has proven a suitable metal phosphide for incorporation into rodent baits.

ZP is commonly used around the world due to its relatively good safety record, low cost, and reasonably high efficacy against a range of target rodent species (Lam 1977; Sugihara et al. 1995). Unlike strychnine, ZP is used to control rodents in food-producing crops by many of Australia's trading partners. In Australia, ZP was introduced as an experimental rodent control option in 1997 and first registered in the MOUSEOFF® (Animal Control Technologies, Somerton, Victoria) product for mouse control in 2000.

MOUSEOFF® and RATTOFF®[2] products are whole grain-based baits, with 2.5% ZP. Dilution of the ZP with other bait material, including palatable oil attractants,

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[2] RATTOFF® is a registered trade mark and has patents pending.

reduces the handling hazards associated with the pure active ingredient, and the use of sterilised, seed-certified grain prevents the risk of weed spread or germination of the bait itself.

MOUSEOFF® has been highly effective in controlling mice in broadacre cereal and legume crops, with typical mouse control levels exceeding 95% within one night of application. The prototype RATTOFF® product, which is ZP bait packaged in edible, moisture-resistant sachets, has also proven effective under experimental and emergency-use situations to control rats in sugarcane and hoop pine plantations. In most circumstances, RATTOFF® has achieved >80% control within 4 days of a single application of just 1 kg of finished product (25 g active ingredient ZP) per hectare.

Environmental safety of ZP

ZP is not readily absorbed directly into plants via the root system or direct exposure to foliage. Experimental studies involving direct application of ZP to leaf axils have revealed only minor traces after deliberate application and entrapment in leaf axils at 100 times the required application rates. With typical application methods, only the occasional grain would be expected to lodge in plants, so there is negligible risk of crop contamination. Moreover, most mouse control is now achieved well before harvest with a modern focus on preventing development of plagues rather than on treating those that have already developed.

ZP residues do not accumulate in soil, since the chemical can slowly degrade in moist soil via a variety of pathways. Hydrolysis to liberate phosphine, and oxidation to harmless zinc phosphates or phosphites occurs with exposure to acids, from cation exchange, and from the gradual dissolution of carbon dioxide from the air to form weak carbonic acid in moisture or after rainfall (Hilton and Robison 1972). This degradation is gradual, but proceeds to completion. The small quantity of phosphine gas released into the atmosphere dissipates and degrades by reaction with free hydroxyl radicals under the action of sunlight. The half-life of phosphine gas in daylight is 5–28 hours (WHO 1988) and any phosphine that is not immediately dissipated in the atmosphere forms non-volatile phosphorus compounds on exposure to substrates (Hilton and Mee 1972).

Thus, ZP and its degradation products do not cause ground or surface water contamination and cannot give rise to long-term environmental accumulation. For these important reasons, ZP offers a suitable option for larger-scale rodent management situations.

Contrasting ZP with anticoagulant rodenticides

Mode of action

ZP is an acute, single-dose rodenticide. When ingested, ZP reacts immediately with stomach acids to produce small quantities of phosphine gas that are quickly absorbed into the bloodstream to adversely affect the lungs, liver, kidneys, heart and central nervous system (Guale et al. 1994). While liberation of phosphine is the primary method of toxicosis, there is some suggestion that intact ZP may also be absorbed into the liver to cause some toxic effects.

The acute oral toxicity (LD_{50}) for house mice (*Mus domesticus*) is 32–53 mg/kg body weight, for laboratory rats (*Rattus norvegicus*) is 27 mg/kg, and for black rats (*Rattus rattus*) is 21.3 mg/kg (Caughley et al. 1998). Death occurs within a few hours of ingestion, and there is no known antidote for ZP or phosphine poisoning.

At the standard dose rate of 25 g ZP/kg of bait, there is approximately 1 mg of ZP per grain of wheat bait, and a single grain is quickly lethal to a 20 g mouse. A 150 g adult rat requires around 3–5 grains, which represents less than 10% of the expected daily food intake of this species (Twigg et al. 2000). The currently accepted application rate of bait is 1 kg/ha and this provides about 2–3 grains/m^2. This low application rate represents the minimum limit of most spreading equipment, but is sufficient to significantly reduce mouse populations within the crop to less than 10% within a day of application. Each kilogram of MOUSEOFF® ZP bait has the theoretical potential to remove more than 20,000 mice, so even localised 'hot spots' are usually overcome by the 1 kg/ha application rate. A similar overall application rate is proposed for rat control, except that the bait is supplied in discrete 10 g degradable sachets to provide localisation of certain lethal doses to rats on first exposure. This approach is considered preferable to increasing the total rate of application of broadcast bait in order to minimise the risk of learned aversion following sub-lethal exposure.

The fast action of an acute poison such as ZP contrasts with the delayed action of anticoagulant poisons. Anticoagulants inhibit the liver enzyme that recycles (re-methylates) vitamin K. Once existing reserves of active vitamin K are depleted, blood-clotting systems fail, resulting in fatal internal haemorrhages (Buckle 1994). Because initial reserves of vitamin K and other clotting factors will maintain normal blood clotting until they are exhausted, there is seldom an immediate effect of the administration of anticoagulant poisons. Generally, reserves are available to maintain blood-clotting systems for several days or even weeks (depending on the activity of the animal), and during this time it is necessary to maintain inhibition of the vitamin K recycling enzyme to prevent replenishment of active vitamin K reserves. The clinical sequelae of anticoagulants are often delayed for several days (Palazoglu et al. 1998). This delayed action makes it difficult for rodents to associate the symptoms of the toxicosis to the ingestion of the bait, thus reducing the likelihood of learned aversion to bait and overcoming the natural bait neophobia of rats (Buckle 1994). However, the delay also means that the rodents can continue to accumulate poison and can also continue to damage crops or contaminate storages.

Since the main effect of anticoagulants is to prevent the activation of vitamin K, the parenteral administration of vitamin K provides a specific antidote that bypasses the effect of the toxin and restores blood-clotting mechanisms in cases of accidental poisoning (Mount et al. 1986).

While all anticoagulants operate via the same mechanism, they are divided into two major groups based on their persistence in the target animal. First-generation anticoagulants of the coumarin group (e.g. warfarin and coumatetralyl) and of the indole group (such as pindone) were developed in the 1940–1950s. They closely resemble the naturally occurring parent compounds, and exhibit biological half-lives of just a few days (Majerus et al. 1996). Because of the short half-life of the first-generation poisons, the vitamin K recycling enzyme is blocked for only a short interval and resumes normal activity as the poison is metabolised. Generally, the first-generation anticoagulants are not sufficiently persistent to cause death after a single exposure, unless very large single doses are administered (Mount et al. 1986). However, repeated administration of the poison over several days maintains the suppression of vitamin K recycling and causes death. Prolonged exposure is achieved by allowing continuous access to the bait, or repeated small exposures over several days, either by placement of large quantities of bait in protected bait stations, or repeated replenishment of bait stations with fresh bait over time (Buckle 1994).

After several years of application, resistance by rodents to the first-generation anticoagulant poisons was observed (Greaves et al. 1973; Meehan 1984), and this led to the development of more potent second-generation compounds.

Second-generation coumarin anticoagulants (e.g. brodifacoum, bromadiolone and flocoumafen) are the basis of most common modern rodenticides. These are first-generation compounds modified by the addition of side-chains to extend the biological half-life. These more persistent agents therefore usually produce lethal consequences from a single exposure (Eason et al. 1999). Second-generation anticoagulant baits are supplied in bait stations to control rats and mice in domestic and industrial situations where they have appropriately provided the cornerstone of effective rodent management for many years.

Non-target risks

With increased awareness regarding the untoward consequences of the use of chemicals in the environment, it is appropriate to contrast the differences in risk profile posed by the various, commonly used anticoagulant rodent baits compared to ZP rodent baits.

Despite the inconvenience and cost of repeated applications, first-generation anticoagulants are considered to pose a low risk of accumulation in the food chain (Mount et al. 1986) and at least one (coumatetralyl) is appropriately approved for limited use in crops and another (pindone) is approved for broadacre control of rabbits.

However, the occurrence of residues in carcasses and their accumulation up the food chain has been an emerging problem for long-acting (single-dose) second-generation anticoagulant baits (Young and DeLai 1997; Eason et al. 1999). Biological half-lives for second-generation anticoagulants often exceed weeks or even months, so these agents can block the vitamin K recycling process for extended periods after a single dose (Eason et al. 1999). Unfortunately, they are also slow to be cleared from the non-target scavenger or predator that receives a secondary dose after eating debilitated live rodents or carcasses containing poison residues (Rammell et al. 1984).

The potential for accumulation of long-acting anticoagulants is exacerbated if baits are applied for extended periods, since repeated exposure of scavengers over time can also result in poison accumulation to toxic levels. Because all anticoagulants have a delay phase while vitamin K reserves are depleted, the target rodent may continue to feed on bait during the latent period. This has the desirable effect of overcoming any natural bait neophobia or learned aversion, but also means that the target rodent has the opportunity to accumulate super-lethal quantities of long-acting poison before succumbing to the first exposure (Rammell et al. 1984; Mount et al. 1986). This ability to receive very large doses of poison can further increase the risks to any animal that scavenges such super-dosed carcasses. The potential for problems with large-scale use of second-generation anticoagulants has been demonstrated under experimental and field conditions (Godfrey 1985; Young and DeLai 1997; Eason et al. 1999). These risks of secondary poisoning with second-generation anticoagulants are magnified if they are used repeatedly on a large scale outside of bait stations in crops, especially if the crops are readily accessed by other animals.

Long-acting anticoagulant baits may therefore pose unacceptable risks if used on a large-scale for rodent control in broadacre crops, even though this practice does continue in some countries. In Australia, concerns about non-target impacts led to the voluntary withdrawal of a second-generation anticoagulant product from use in the sugarcane industry in 1998. The concerns were prompted by an observed decline in owls and other birds of prey in treated areas (Young and DeLai 1997), though it is recognised that not all of this decline may have been due to one specific chemical or product and may have involved other habitat disturbances over time.

As for any poisons, there may also be some risk of primary poisoning from the direct consumption of anticoagulant baits, particularly in the case of second-generation products that can kill after a single exposure. Generally, these risks are managed effectively by tailoring the palatability of the bait carrier to rodents, by supplying only small quantities of bait at stations, and by the use of effective bait stations that limit physical access of non-target animals to bait (Reidinger and Mason 1982; Rammell et al. 1984; Godfrey 1985). With appropriate precautions, these anticoagulant baits are therefore entirely appropriate for their traditional use in intensive industrial and domestic situations.

In contrast to the second-generation anticoagulants, ZP presents a low secondary risk profile due to its acute mode of action, rapid degradation in carcasses and lack of potential to bio-accumulate. ZP is not stored in muscle tissues or bones, and decomposes rapidly in the moist acidic gastro-intestinal tract of poisoned animals. Thus, there is little risk of accumulation or storage in the food chain and greatly reduced risk of true secondary poisoning (Savarie 1991; Johnson and Fagerstone 1994). Moreover, ZP causes emetic effects in those larger animals and birds capable of vomiting, so many mammals, birds and reptiles are able to eliminate ZP-laced foods via regurgitation (Hood 1972). This emetic effect is an advantage to many larger animals but disadvantages rodents, as they are not able to vomit.

However, while the secondary risks from ZP are very low, the primary risk is high since the poison is quick-acting and is similarly effective (on a specific bodyweight basis) on a wide range of species. As for any poison, this primary risk is magnified if large quantities of ZP bait are localised in areas that can be accessed by non-target animals, but lowered if the bait is applied at low rates per unit area, or if access to bait or baited areas is reduced by the use of bait stations and fencing. The use of appropriate baiting strategies, including low application rates, crop-only application, and unbaited buffer zones between crop and native vegetation, can also be employed to minimise non-target impacts. The black colour of the grains makes ZP bait generally unattractive to many birds, but this characteristic does not deter rodents (Schoof 1970).

The need for an acute rodenticide

In Australia, rats and mice have caused significant economic damage to crops including cereals, pulses, legumes, and sugarcane. In newly planted grain crops, just 500 mice/ha can eat 1 kg of grain, or 2% of a 50 kg/ha sowing per night. If unchecked, potential yields can drop by 10% per week in such infestations.

When an economically valuable crop or stored commodity is under threat by rapidly increasing populations of rodents, it is important that the rodenticide has the ability to provide an immediate reduction of damage. The advantage of using ZP compared to the anticoagulant rodenticide in this case is that the latter allows the rodents to continue to consume food, damage crops, and affect stored produce and infrastructure during the lag phase between initial exposure and effect.

Field trials using the capture–recapture method of population assessment have demonstrated the efficacy of MOUSEOFF® and RATTOFF® ZP products to control super-abundant populations of a range of rodent species in a variety of situations (Table 1).

MOUSEOFF® ZP bait is an S7 rodenticide and is registered in all states for supply via S7 licensed rural merchants and contractors for control of mice in a variety of broadacre crops. This has eliminated the need for local emergency manufacture of baits containing strychnine. MOUSEOFF® is applied by aerial or ground-based calibrated spreaders to ensure an even spread of 1 kg/ha.

In 2000, the experimental development of RATTOFF® bait sachets introduced a new option for rat management in Australian sugarcane, where two species of rat were responsible for damage to sugarcane valued at $20 million during the 1999/2000 season. Due to the tropical climate of northern Queensland, a more weather-resistant ZP bait presentation suitable for humid and wet tropical conditions was required. RATTOFF® consists of 10 g of inactivated whole-wheat grains coated with ZP and packaged into degradable and edible cellulose-membrane sachets. The cellulose membrane achieves short-term protection of the bait against moisture degradation but is readily opened by the rats to provide a localised lethal dose of bait. Sachets are placed at 10 m intervals within the crop, which is equivalent to 100 sachets/ha, or 1 kg bait/ha.

Industry-sponsored ZP extension materials

The introduction of ZP baits to Australia is a relatively new development in the fight against rodent infestations and will form an important part of an integrated approach

Table 1. Use of zinc phosphide to control large rodent infestations in Australian crops.

Rodent species	Formulation used[a]	Crop(s) treated
Mus domesticus (house mouse)	MOUSEOFF®	Wheat, sorghum, maize, canola
Rattus sordidus (canefield rat)	RATTOFF®	Sugarcane
Melomys burtoni (grassland melomys)	RATTOFF®	Sugarcane
Rattus affinity sordidus (Central Highlands plague rat)	MOUSEOFF®	Wheat, chick peas, cotton
Rattus tunneyi culmorum (pale field rat)	RATTOFF®	Hoop pine plantations
Rattus villosissimus (long-haired rat)	MOUSEOFF®	Cotton

[a] MOUSEOFF® is 2.5% zinc phosphide on inactivated wheat grain and is applied at 1 kg/ha. RATTOFF® is a similar grain formulation repackaged into discrete cellulose sachets (patent pending) that are more suitable for the control of rats in intensive crop situations in wet, tropical conditions.

to rodent management. In order to place these new technologies into context with other preventative and treatment options for rodent management, Animal Control Technologies, in conjunction with the broadacre grains industry and the sugar industry, has assisted in producing a series of extension activities. The aim of the extension projects is to improve understanding of mouse and rat problems, and of the various integrated management options to reduce the threats they pose to crops. The projects also provide additional information on the use of ZP to control residual and emerging mouse and rat populations within crops, and will attempt to overcome some of the misinformation that occurs when any new chemical is introduced to the rural marketplace.

For the cereals industry, the program is supported by the Grains Research and Development Corporation (GRDC). An initial outcome has been the establishment of a reference panel of experts to review the production of a 32-page 'farmer-friendly' booklet on best management practice for mice and technical information about ZP. The booklet will be distributed free to provide the latest available knowledge, and is the cornerstone of the extension package. The booklet was developed with inputs from Animal and Plant Control Boards & Commission in SA, Bureau of Rural Sciences, Department of Agriculture in WA, Department of Primary Industries in Victoria, Department of Natural Resources and Mines in Queensland, Agriculture in NSW, and inputs from private agronomists and rural land protection boards. The booklet will be supported by the development of a training video (that will also be available in modular DVD format) and a variety of fact sheets and advisory notes. Formal training seminars for agronomists, farm advisers and relevant local agency staff will be conducted in all major grain-growing areas during 2003 and 2004. The focus is a 'train-the-trainer' approach that should provide a firm base for the successful integration of ZP with other management options.

A similar approach has been taken regarding the development of advisory information to the sugar industry in a program coordinated by the Bureau of Sugar Experimental Stations (BSES), Cane Protection and Productivity Boards (CPPBs) and peak grower bodies such as Cane-Growers. During the first season of emergency use of RATTOFF® under permit, a series of more than 20 workshops were conducted at all major cane areas from Mackay to Mossman. These workshops, a 'Ratpack' advisory booklet prepared by industry, and RATTOFF® booklets provided up-to-date information that included emphasis on non-chemical farm practices to minimise the increases in rat abundance and also methods to monitor for rats (Smith et al. 2002). Technical information on the best-practice use of both RATTOFF® and the Bayer first-generation coumatetralyl product (Racumin) was provided to more than 2000 cane growers in one of the most extensive training programs yet seen in the industry.

In all the extension materials, significant emphasis is placed on the adoption of farm practices that reduce the risk of rodent infestation in the first place. For the cereals industry, this includes reducing available feed and shelter for mice and the adoption of strategies that reduce the amount of damage that mice can impose on the crop. Similarly, for the sugar industry, the use of rodenticides is only instructed after other methods to reduce the risk of rat infestations have failed to achieve the accepted level of control. Early use of chemical control measures is encouraged if objective monitoring of rodent numbers or crop damage indicate an emerging problem of economic importance. Thus, the use of rodenticides is being increasingly incorporated as part of, rather than a replacement for, integrated pest management (IPM) approaches, and the early intervention (based on monitoring) is more strategically proactive rather than reactive.

Ultimately, these approaches mean that the resort to chemical controls is based on an objective assessment of risk, and only necessary in exceptional seasons or in localised situations where other preventative measures have not been sufficiently successful.

This project demonstrates the effectiveness of collaborations and partnerships between the private sector, government and industry-related partners, and how these collaborations can achieve a nationwide increase in information dissemination regarding rodent pests, and the most effective solutions for their management and control.

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