IMPACT, PHYSICAL REMOVAL AND EXCLUSION FOR INSECT CONTROL IN STORED PRODUCTS

H.J. Banks

CSIRO Division of Entomology, Canberra, Australia

Abstract

Many physical processes can be used to provide environments that adversely affect insect pests. Some on their own, e.g. heating, cooling, controlled atmospheres and ionising radiation, are capable of virtually eliminating an infestation in stored products. Systems based on these processes are available commercially. Other physical processes though not giving a very high level of mortality when used alone may be useful as part of an integrated control program. This paper reviews the potential of three neglected processes: impact, as both shock and disturbance, physical removal and physical exclusion for stored product pest control. Neither impact nor physical removal have been specifically used in systems for disinfestation of whole grains yet both can provide mortalities of > 99% in specific instances. Species and developmental stages differ in their response. Rhyzopertha dominica and pupae of Sitophilus species are notably sensitive to shock.

Impact, physical removal and physical exclusion all appear useful in combination with other methods, often remedying the particular weaknesses of such processes. The utility of combining two partially effective control measures is discussed. Physical exclusion is useful when protection is required subsequent to disinfestation, shock appears potentially compatible with phosphine treatments, while removal by aspiration combines well with use of cold. A list of compatible combinations is given.

1. Introduction

Physical control techniques, i.e. systems of insect control based on physical forces and barriers, have several attractive features. In particular they do not leave chemical residues in the commodity and they often rely only on locally produced materials and energy. Physical control techniques were once the main methods of pest control in stored grain but they have since been largely supplanted by chemical control systems, systems based on either protectants or fumigants.

Chemical control systems have several obvious advantages. Chemical protectants are effective in simple storage structures. They require simple apparatus for application and little training in their use. Their efficiency is almost independent of storage size and they are readily available. Although fumigants require well sealed storage

Proc 4th Int. Work Conf Stored-Product Protection, Tel Aviv, Israel, Sept 1986
[Eds E Donahaye and S Navarro], pp 165-184

systems and particular fumigants or situations may require some specialised machinery for application or distribution, such as with recirculation of methyl bromide, they are otherwise easy to use and usually highly effective.

Because of its convenience and efficacy chemical control will continue to be important to the protection of stored products in the foreseeable future. Nevertheless chemical control processes are under pressure from several aspects. The costs of the chemicals used are rising at a time when commodity prices are low. The development of resistance to currently used pesticides necessitates continual development of replacements. There is an increasing awareness and sensitivity to the occupational health and toxicological problems posed by use of insecticidal chemicals and there is a growing reluctance by markets and consumers to accept addition of chemicals to foodstuffs.

Over the last decade or so pressures on chemical control have provoked a renewal of interest in non-chemical means of insect control in stored products. There have also been moves to optimize chemical use and, importantly, a recognition that use of only a single measure may often be inappropriate (e.g. see Evans, in press). An integrated approach where two or more materials are applied together, utilizing the advantages of each, may be more economical and effective.

Several forms of physical control have now been developed to a stage where on their own, they can achieve virtually complete disinfestation of stored durable foodstuffs, though even these may benefit from use in combination with other methods. These include use of heat, cold, ionizing irradiation and modified atmospheres, discussed in detail elsewhere in this Conference. However, they have yet to make a significant impact on the use of chemical methods. There are several reasons for this including their cost, usually their capital not running cost, lack of marketing of the systems and a reluctance to change. Some physical forces show little promise as a basis for insect control (e.g. visible light (Rees, 1985), sound energy (Andrieu et al., 1977)). Some appear to have potential but usable processes have not been developed. Three promising, but neglected and little appreciated, forces are reviewed here. These are based on shock, physical removal and exclusion. The review is not intended to be comprehensive. It is intended to reawaken interest in these approaches to insect control, to remind us of their effects and work done on systems based on these forces and to highlight the scope for possible improvement and development. The topic can be considered broadly as 'mechanical control', a subcategory of 'physical control' of insects. In the forms currently developed, none of the forces are capable of routinely providing complete disinfestation of whole (i.e. unground or unmilled) commodities, yet each can, under certain circumstances, produce a substantial kill of pests or protection for a commodity. I hope to show that they could provide a useful part of an integrated approach.

To make it possible to assess whether the particular effects on insect pests of the three forces discussed here are such that they are valuable and to provide a basis from which to argue their use in an integrated system, it is necessary to consider under what circumstances the integrated use of two not very effective control measures can give as good a result as a single much more effective one.

2. Levels of control

Ideally a control measure should eliminate an insect population. This is not usually practical or economically feasible. Some survival is almost always likely in practice. The level of survival tolerable will depend on the situation. Two of the three forces considered here, impact and physical removal, are known not to provide a complete kill. However, they should not be dismissed as useless because of this. Systems based on either are potentially capable of giving a substantial degree of disinfestation and are thus possibly of use when combined with another method.

Before methods that give incomplete control can be discussed meaningfully it is necessary to set out the consequences of survival of part of a population. Figure 1 shows a simulation of the time a population of *Sitophilus oryzae* takes to recover to its pretreatment numbers after a treatment causing a given level of mortality. Two limiting situations are modelled: in one case the population structure is unchanged, while in the other a single tolerant development stage survives. It is assumed that there are no adverse effects on fecundity, longevity, sex ratio and other parameters that could reduce the rate of

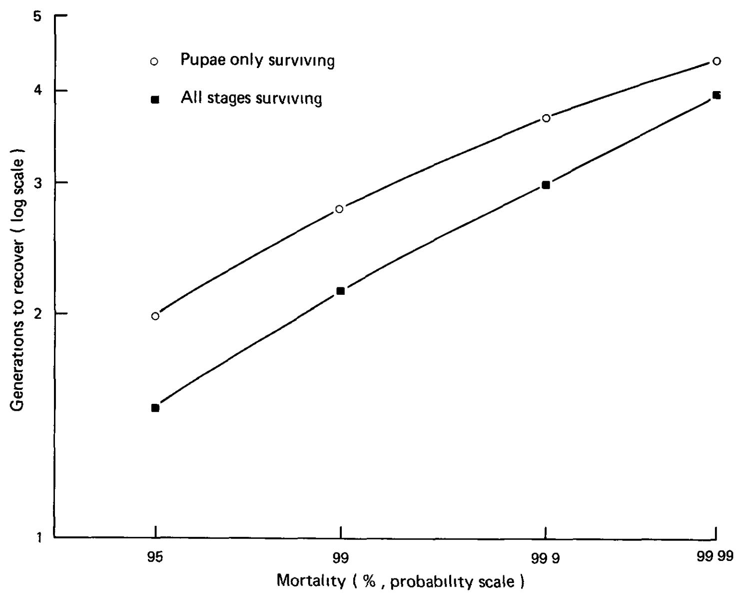

Fig. 1 Time for population recovery to original numbers after a control measure producing a particular mortality. Simulation for *Sitophilus oryzae*.

increase of the survivors and that the rate of increase is unaffected by low population density. The simulation is thus a conservative one, giving minimum times for population recovery for this species.

The effect will be qualitatively similar for other species. The few species of stored product pest with a greater production of adults per generation will recover slightly faster than S. oryzae from a particular level of kill. Others will recover more slowly.

It can be seen that, below about 99% mortality, the population of S. oryzae recovers to initial numbers in less than two generations when all developmental stages are equally affected and only slighly longer if just pupae survive. Thus, despite a substantial kill, a control measure giving this level of mortality is likely to be of little use on its own except under very brief storage periods or if population recovery is held back, such as by cold. However, it can also be shown that a combination of two indiscriminate 99% effective measures produces a high degree of kill (99.99%). In terms of the model used for Fig. 1, the population would have recovered in 2.1 generations if only one method had been applied but in 4.0 generations when both are applied. If only one developmental stage survives, the period to recovery can be longer. With only pupae surviving the recovery times are 2.8 for a single 99% effective measure and 4.5 for two such measures. If the two control measures have a different action, that is they affect different pests or stages, then an even better level of control can be expected. For instance, one measure may be active against adult insects while the other is active against immatures. The combination may then virtually eliminate an infestation despite the individual methods being relatively ineffective on their own.

For the purposes of discussion here it is taken that a > 99% effective indiscriminate measure is potentially useful. Furthermore with survival strongly biased to a particular developmental stage or species, a measure that produces > 99% mortality in a stable population may well have an application in stored product protection when integrated with a different and complementary method.

3.1 Mechanical control of insects - shock

Turning grain has been advocated in the past as a method of cooling grain and restricting insect infestation. Undoubtedly this practice does even out (Gay, 1941a; Muir et al., 1977) and, under certain circumstances, does reduce (Gay, 1941b) temperatures and moistures within a dry grain bulk, thereby generally making the conditions less favourable to insect development. However, there also appears to be a substantial detrimental effect directly on the insects from the mechanical forces involved in the turning (see below). Insects in grain appear to be susceptible even to minor disturbance or impact.

Mechanical shock and destruction of insects also form the basis of an elegant and highly effective machine known as the Entoleter. The machine consists essentially of a spinning disk equipped with a number of steel pegs towards the edge of the disk. The commodity to be treated is fed into the centre of the disk. It is then flung outwards by the disk's rotation, hitting the steel pegs and then the machine casing at high speed. The machine is widely used in flour mills and appears to be particularly suitable for disinfesting ground commodities during conveying. However, an Entoleter run at half its normal speed (i.e. at 1750 rpm) is said to be able to kill > 99% of free living insects in wheat without "serious breakage" of the grains (Cotton 1958). It thus appears capable of providing a useful degree of disinfestation in the robust whole grains, particularly after optimisation for this specific application.

There have been several basic and applied studies, described below, investigating the principles of insect control embodied in turning and the Entoleter. As yet this form of mechanical control has not been developed fully for controlling pest insects in whole grains. However, there is clear potential for this, probably integrated with another method, to give a system effective against all pests and developmental stages.

3.1.1 Laboratory Studies

The effect of impact on various stored product insect pests has been studied under laboratory conditions by Rodinov (1938), Bailey (1962, 1969), Joffe and Clarke (1963) and Loschiavo (1978).

Bailey (1962) developed an air gun that fired individual wheat grains at a solid target at a measured velocity. This was intended to mimic conditions in the Entoleter. The grains were infested with *Sitophilus granarius*. He found that the mortality of the internal stages was related to speed of impact (Table I) and that breakage of the grain under these conditions was related to moisture content (m.c.) with higher breakage at higher moistures. At 45.7 m s^{-1} breakage of whole infested grains was 9% at 10% m.c. (d.b.) and 19% at 12% m.c. At

TABLE I. Mortality of immature *S. granarius* in grains shot onto a target at various speeds. Mortality assessed by reduction in emergence compared with untreated grains. Approximately equal numbers of insects in each weekly cohort. Data of Bailey (1962).

Velocity m s^{-1}	Mortality
20.7	86
28.3	87
32.6	95
38.1	98.5
45.7	98.3

lower speeds the breakage was more acceptable, with only 2% breakage even at 14% m.c. at 20.7 m s^{-1}. At this speed of impact there was substantial survival of internal stages, apparently largely young larvae (aged 7-13 days, incubated at 23°C), but all adults were killed.

The effects of repeated disturbance have been studied by several workers. Infested grain was subjected to single or multiple impacts either by pouring onto a surface or dropping in a sack and the mortality assessed. Multiple impacts were found to be more effective than a single impact. Frequent disturbance throughout the development of S. granarius caused substantial mortality of immature stages, impacts equivalent even to very short free falls produced a significant effect (Fig. 2). Loschiavo (1978) noted substantial mortality of adult Sitophilus spp. and Cryptolestes ferrugineus repeatedly dropped in small wheat-filled sacks (Fig. 3). Rodinov (1938) noted a similar effect on S. granarius. All stages are affected by impact though not all to the same degree. Of the immature stages, pupae and prepupae are notably sensitive (S.

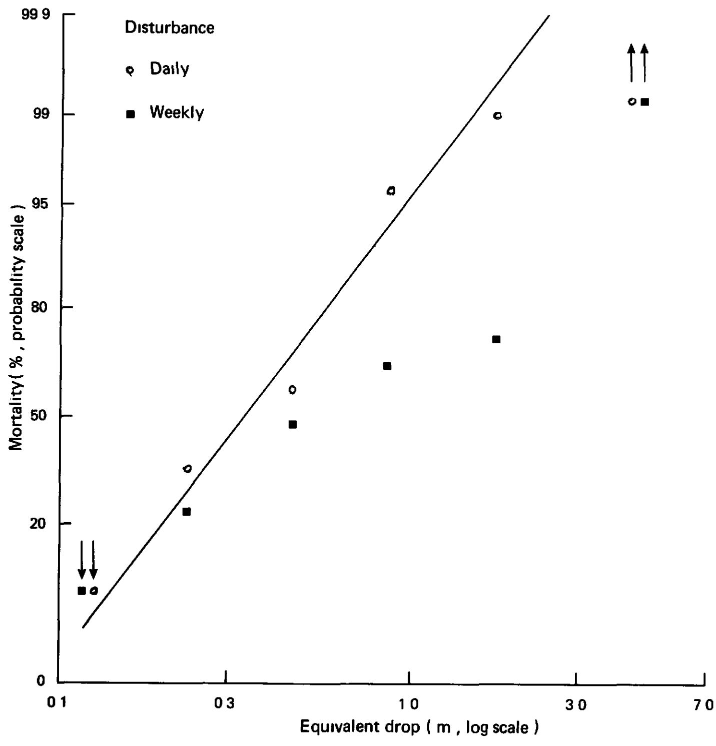

Fig. 2 Mortality of immature stages of S. granarius in cultures in grain projected against a steel block either twice daily or four times weekly given as a function of the equivalent free fall height. Data of Bailey (1969). Eyefitted line through daily data.

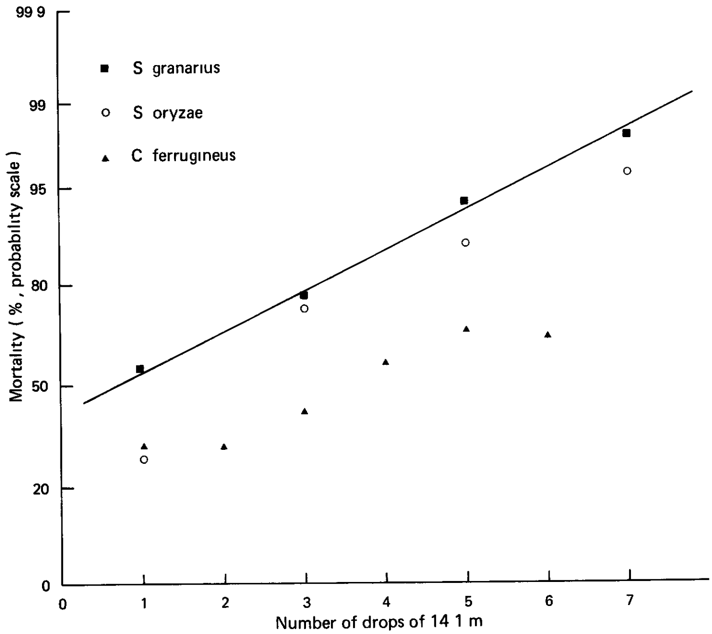

Fig. 3 Mortality of adult insects (three species) in wheat-filled sacks (400 g) dropped repeatedly on to a concrete floor from 14.1 m. Data of Loschiavo (1978). Eyefitted line through S. granarius response.

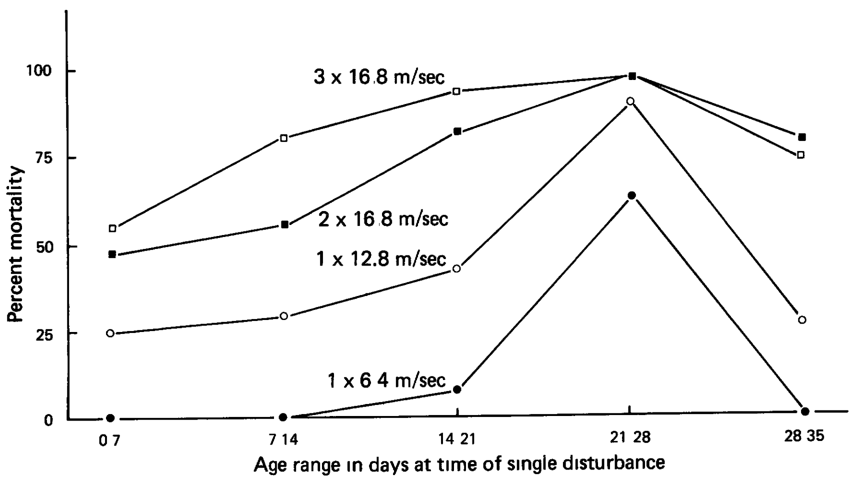

Fig. 4 Relative susceptibility of different age cohorts of S. granarius to a range of impacts applied once during development. Redrawn from Bailey (1969).

granarius, Bailey (1969); S. zeamais, Joffe and Clarke (1963)) but the effects are less selective with increasing vigour of the stress (Fig. 4).

Pouring wheat through a tube onto a metal surface was somewhat more effective in killing adult insects than onto a wheat surface. High mortality was obtained for C. ferrugineus (Fig. 5) but the effect on adult Tribolium castaneum and S. granarius was slight (36% and 4% mortality after seven drops of 14.1 m respectively). The small effect of pouring through a tube contrasts with the substantial effect noted when adult S. granarius is dropped in a sack. Immature C. ferrugineus and S. granarius were little affected by being poured down a tube in grain seven times (reduction in emergence 49% and 8% respectively) but substantial mortality was found with T. castaneum larvae (95%).

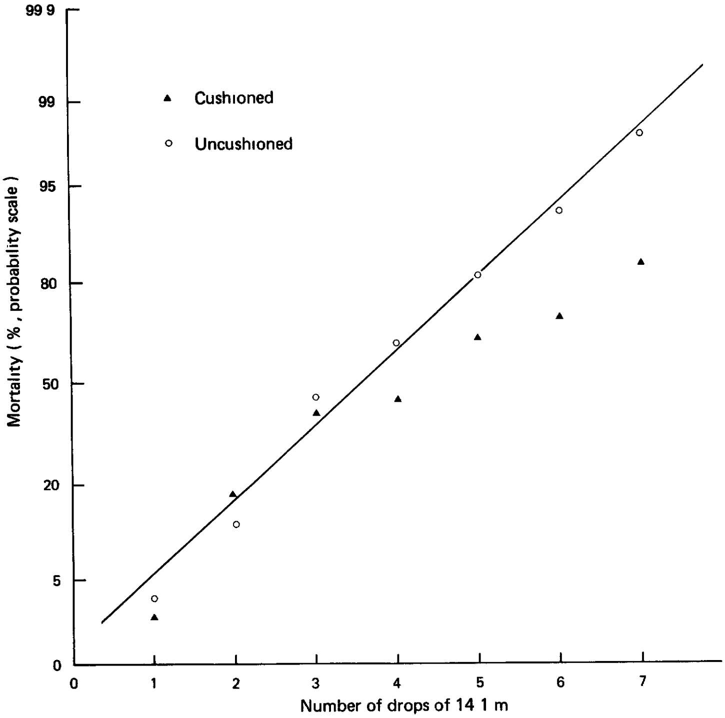

Fig. 5 Mortality of C. ferrugineus adults in grain poured repeatedly on to a metal surface ('uncushioned') or a metal surface covered with several centimetres of wheat ('cushioned'). Data of Loschiavo (1978). Eyefitted line through data for uncushioned surface.

It should be noted that, while impact does produce substantial insect mortality, mild centrifugal forces and rotation, often associated with impact in practice, apparantly do not. Bailey (1962) found no damage to adult S. granarius and R. dominica submitted to 10,000 g for 1 minute. Sullivan and McCauley (1960) observed 50% mortality of T. confusum adults only after 70 minutes at 20,000 g. These forces are much higher than can be expected in an Entoleter. Bailey (1969) observed that simple rotation of an insect culture, restrained to prevent grain movement, produced no detrimental effects. He concluded that the apparent adverse effect of rotation in insect cultures observed by Joffe and Clarke (1963) was caused by impact of the infested grain on the culture jars as they were inverted. Presumably the effect of tumbling observed by Loschiavo (1978) was also the effect of impact only and not of the rotation.

3.1.2 Field Studies

It is clear from the laboratory studies that insects are quite susceptible to mechanical shock and damage. This is borne out in practice by observations of the effects of grain turning and, in particular, pneumatic conveying.

The effect is sometimes observed, unplanned, during the course of trials of other insect control measures. Cogburn et al. (1972), investigating radiation disinfestation of grain observed substantial mortality of several pest species by grain transfer including pneumatic conveying (Table II). Similarly Kirkpatrick and Cagle (1978), studying disinfestation of wheat by infra-red heating, observed a similar effect but with slightly less effect on the immature stages (S. oryzae 94, 63%; R. dominica 100, 66%; C. ferrugineus 100, 77% kill of adults and immatures respectively). Green and Tyler (1966) had to modify their experiment, investigating the effect of an insecticide, because of a 95% mortality of test insects resulting from mechanical handling of the grain (a pneumatic conveyor, elevators and conveyors). Muir et al. (1977) noted a mortality of 80 and 60% of adults and larvae respectively of C. ferrugineus on transfer of grain (transfer system unspecified). Fleurat-Lessard (1980) noted 80% mortality of immature S. oryzae by pneumatic conveying and even pneumatic sampling systems may cause appreciable kill (Bryan and Elvidge, 1977).

TABLE II. Mortality produced by mechanical handling of infested grain from bin to bin involving a screw conveyor, a bucket elevator and two pneumatic conveying legs (data of Cogburn et al., 1972).

	Cryptolestes spp.	R. dominica	S. oryzae
Adult	99.6	99.3	99.1
Immatures	82	96	89

The effect of conveying may not be immediate. Rodinov (1938) noted 33% mortality of adult *S. granarius* one day after turning, rising to 92% after 12 days.

The most comprehensive studies on the effect of pneumatic conveying have been done by Bahr (1973, 1975) who investigated the effect of several systems and rates of transfer. He found no live *O. surinamensis* after pneumatic conveying at 25 t h^{-1} and screening from a ship load initially at 132 insects per kg (!). Transfer of severely infested rye at 37.5 t h^{-1} produced 99.8% and 96.4% mortality of all stages of *O. surinamensis* and *C. ferrugineus*. All free-living insects were eliminated, but some immature stages within the grain survived. In another trial high mortalities of several species were noted (Table III). There was an overall 99.7% kill of free-living stages, but substantial survival of internal stages of some species, notably *S. oryzae* (45% mortality only). Bahr (1975) also found that some immature *R. dominica* survive pneumatic conveying (92% mortality). As a result of his studies Bahr (1975) ranked various species of stored product pests in order of susceptibility to pneumatic conveying (Table IV).

TABLE III. Mortality of all stages of various pests in wheat pneumatically conveyed at 19 t h^{-1} (Bahr, 1973).

Species	Mortality (%)
Sitophilus oryzae	48
Oryzaephilus surinamensis	95
Cryptolestes ferrugineus	69
Ahasaverus advena	97
Typhaea stercorea	99.3

There is clearly scope for further studies on the effect of shock or impact on insect pests. In particular the parameters controlling the insecticidal effect of pneumatic conveying need investigating. With the unoptimised system already giving high mortality, often > 99%, there is an obvious need to determine if this can be improved upon to give an efficient system of disinfestation. The system will need to be effective at the very low insect infestation levels that can occur in good modern storage practice and to avoid causing economically unacceptable damage to the grain.

3.2 Mechanical control - physical removal

There are many processes that can physically remove insects from within or around a commodity. The virtues of some of these seem self-evident though they are seldom assessed quantitatively, e.g. vacuum

TABLE IV. Ranking of susceptibility of stored product pests to pneumatic conveying (Bahr, 1975).

Species	Susceptibility
S. granarius	Least susceptible
S. oryzae	
C. ferrugineus	
R. dominica	
T. castaneum	
O. surinamensis	Most susceptible

cleaning around bag stacks, sweeping up and removal of infested material and crawling insects. Those of others are less obvious. In many cases they have not been properly quantified nor have the processes been optimized.

There are several operations carried out during seed grading and cleaning that appear potentially capable of separating free living insect pests from the commodity and also separating infested and sound kernels. I believe that closer investigation of these methods could be rewarding, though not necessarily to provide an absolute control method. Generally most of a commodity bulk consists of undamaged and uninfested material. If it were possible to concentrate the infested material into a small fraction of the total, the scale and cost of treatment required for disinfestation would be reduced and clean commodity would not be treated unnecessarily.

Two particular systems have been investigated specifically to achieve such a concentration: one involves blowing air through a grain bulk to fluidize it, and the other separates grains into different weight and size classes using a 'grain spectrometer'. Both are aimed at separation of internally infested and sound grains, and are based on their different size to mass ratio. For instance, grains containing later developmental stages of S. granarius are substantially lighter than sound ones (Mathlein, 1971). The smaller the kernel the greater the proportionate loss (see Table V).

In the air separation technique, wheat was first graded to size by sieving, presumably a necessary preliminary in view of the observations in Table V. The various fractions were then fluidized with an air blast in a perspex tube. Baffles were fitted towards the top of the tube. These skimmed off grains reaching the top region. Using only one setting on the air blower, a concentration "by a factor of ten or better" of damaged and internally infested grains was claimed (Milner et al., 1953). There is no data available on the fate of free-living insects nor on the performance of such a device with very lightly infested grain.

TABLE V. Loss in weight of grains infested with some developmental stages of S. granarius (abstracted from Mathlein, 1971).

Grain	Kernel size (mg)	% weight loss 3rd instar larva	4th instar larva	pupa and prepupa
Wheat	54.2	5.8	18	20
	43.2	6.2	21	25
	31.8	8.2	28	35
Barley	56.8	-	21	24
	36.5	-	43	48

The 'grain spectrometer' (Fig. 6) provides another means of concentrating infested grain containing internal infestations. The device, originally described in 1859 (Booth, 1859), consists of a system that projects a thin stream of grain into the air at a defined velocity and a set of hoppers that catch the grains. Above a certain velocity a good separation of grains of different size-to-mass ratio is obtained, with the relatively light grains containing internal infestation falling out more quickly than sound ones. In the sole published example (Fig. 7), a sample of wheat containing 8.5% of infested kernels, presumably by Sitophilus spp., was fractionated. Wheat received in the hoppers furthest from the point of projection, comprising 49% of the total by weight, had approximately 1.5% of infested kernels. It was said that some of the lighter fractions gave further clean grain after reprocessing. No data was given on the effects of the spectrometer on free-living forms, on early developmental stages (infestation was assessed by x-ray) nor was there any attempt apparent at optimizing the machine's performance. Presumably an initial separation to size would have assisted.

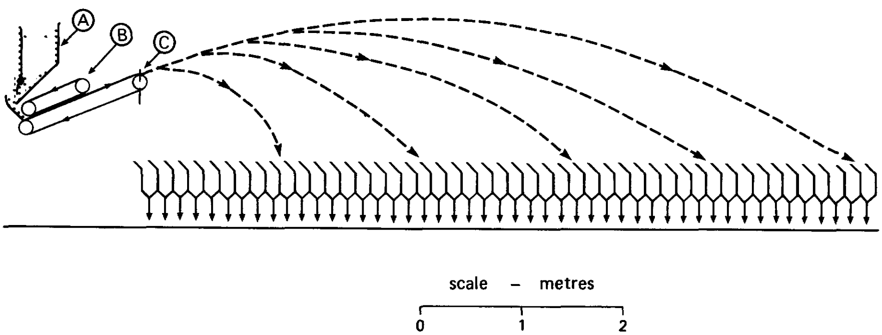

Fig. 6 The grain spectrometer. Grain is fed from hopper A in a thin stream between moving rollers B and C. The projected grain is collected in the hoppers. (Redrawn from Katz et al., 1954).

Sieving, though unfashionable as an insect control measure, also appears to give a useful concentration at least on some occasions. Mathlein (1971) carried out a detailed study on both laboratory and field scale and showed negligible long term insect control from sieving of infested wheat and barley unless the sieved and aspirated grain was subsequently cooled. A good control of infestation was then obtained. Payne et al. (1970) state 97-99% of insects infesting unshelled peanuts in their studies were removed by the initial screening and aspiration in a commercial plant, while "most" of the remaining insects were removed with low grade kernels sieved during grading after shelling. Under very heavy infestation some insect eggs and small larvae were carried into the top grade of peanuts, but not at "normal" levels. Presumably, the commercial sheller was not optimized for removal of insects, but nevertheless a better than 98% removal and kill was attained (Table VI).

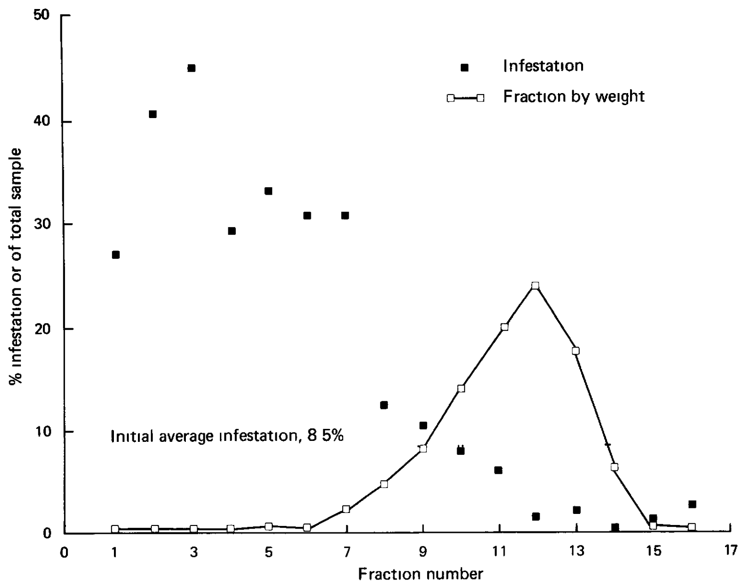

Fig. 7 Infestation level and proportion of total mass in fractions of a grain sample separated by the grain spectrometer. Data of Katz et al. (1954).

Simple aspiration does not appear to be capable of removing adult insects from grains. The air velocity needed to detach an adult insect from a rough surface vary with species but is of similar magnitude to that required to fluidize a bed of wheat (> 1 m s^{-1}). Armitage (1981) found Sitophilus granarius to be easier to remove from a gauze surface than O. surinamensis or T. castaneum but still only 50% were blown off with an air velocity through the gauze of 4 m s^{-1}. There remains the possibility that aspiration, perhaps coupled with fluidizing, may efficiently remove free living larvae since they may have legs unsuited for clinging (e.g. T. castaneum) or may be hirsute and thus easily caught up by air currents. Larvae of Trogoderma granarium for instance can be dispersed by wind (Howe, 1952) and would seem particularly suited to removal by aspiration.

TABLE VI. Insects removed by sieving and aspiration from peanuts passed through a commercial sheller (from data of Payne et al., 1970).

Infestation[a] (insects per kg)	% Removed[b] by Sieving	% Removed[b] by Aspiration	Residual infestation (insects per kg)
0.3	78	19	<0.001
0.1	94	4	<0.001
1.8	80	18	0.0064
5.2	81	14	0.10
132	52	41	2.56

a Live adults and immatures in top grade shelled peanuts (50-55% of total). Including insects emerging after incubation.

b No distinction made between live and dead insects. Percentages are thus of total numbers, live and dead, present.

3.3 Physical exclusion

Exclusion, the provision of a physical barrier to prevent insects invading a commodity, is a physical control analogue of use of a chemical protectant in chemical control. It is one of the few physical control processes providing long term protection of a stored product (cold is another). As a process it is difficult to quantify and there is very little published material to define its limits of effectiveness and what are truly the requirements for a set level of control, particularly for large scale storage.

There is no doubt that containers such as small sealed metal tins are insect-proof and are capable of maintaining commodities insect-free indefinitely. Such containers have been suggested for storage of small lots of grain (see Hyde et al., 1973). However, it is surprising that a substantial degree of insect exclusion is afforded even by partially sealed systems in view of the known ability of insects to detect food sources and the impossibility in practice of creating a totally leak-free storage. Most containers and structures used for storage of grain, even if efforts have been made to seal them, will have imperfections, some of which may be of the size that can admit adult insect pests or through which young larvae can crawl. Cline and Highland (1981) showed that adult stored product insect pests could penetrate a metal square mesh with apertures of > 10% larger than the body width (0.33 mm for Cryptolestes pusillus, < 0.7 mm for most common stored grain pests). Wohlgemuth (1979) found that young Plodia interpunctella can locate and pass through a 0.25 mm hole. Banks and Ripp (1984) give details of how to calculate the residual total area of holes and leaks in a storage sealed to a given pressure test level. At the current Australian standard for sealed storage (pressure decay half-life of 5 minutes for a full structure) this can be several square centimeters in a large storage, presumably including many holes of sizes large enough to admit insects. Furthermore it has been shown that several important species of stored product pest can locate leaks in storages (Barrer, 1983) and that Ephestia cautella will oviposit around holes emitting grain odour (Barrer and Jay, 1980).

Detailed statistics are required on the rate of reinfestation or failure of structures designed to exclude insects. There is some data on the overall performance of sealed systems in Australia (Banks and Ripp, 1984; Banks, 1986). However, it is not possible to separate the effects of insect exclusion from contributions to insect control by other factors, e.g. effect of structural sprays, effectiveness or lack thereof of control measures undertaken within the storage and absence of invading insects. Nevertheless, there have been no cases of reinfestation of grain bulks held in sealed storage in Western Australia in the Cooperative Bulk Handling system since the sealing program was started in 1981. This is despite storage of many months, pesticide-free, under conditions apparently favourable to insect development after a single fumigation with phosphine soon after intake (Banks and Ripp, 1984). In New South Wales infestation is sometimes noted in the bunker system after phosphine fumigation. Resurgence of the original insect infestation and reinfestation from external sources cannot be distinguished. The low apparent rate of reinfestation (see Table VII) is probably due, at least in part, to exclusion.

TABLE VII. Apparent reinfestation rate of PVC-covered bunkers managed by the Grain Handling Authority of NSW (D. Davis, personal communication).

Season	Number of bunkers	% reinfested (total)	% reinfested (current season's grain)
1983/84	117	6.8	6.8
1984/85	144	10.4	2.8
1985/86	134	12.7	2.2

The system of permanent sheeting used by BULOG, Indonesia to protect stacks of milled rice also apparently owes its success in part to insect exclusion. Stacks remain insect free for long periods after a single disinfestation by fumigation with CO_2 (data ia available for up to 16 months (Suharno et al., 1984; Suharno, 1986)) even under the heavy invasion pressure found in the humid tropics (Annis et al., 1984). Under exceptional invasion pressure by R. dominica and S. oryzae in the Philippines, PVC-sheeting left on disinfested stacks of rice may be penetrated (Sabio and Graver, in press). Sealed storage of grains under polyethylene or PVC sheet, either in bags or bulk, is widely used in China (Lu, 1984). A detailed assessment of the efficacy of the system is not available, but its continued use suggests that it is judged successful.

Insect exclusion is often used to protect commodities stored in small packs (e.g. 1 kg). Many stored product pests are incapable of penetrating intact films. These insects, known as 'invaders', e.g. T. castaneum, will infest such packs but they can only gain entry through imperfections in the seal. Others, 'penetrators', typified by R. dominica and Plodia interpunctella, can penetrate intact film though they attack areas of weakness such as seams for preference. There are numerous publications and reviews on the use of such films (Schmidt, 1980; Highland, 1978, 1981).

There have been remarkably few recent efforts to extend the principle of insect exclusion by packaging to larger grain bulks (50 kg and upwards). However, the 'Capatainer', a 1 m-cube pack of high density polyethylene, was used for storing cocoa beans in the Cameroons for up to 20 months (Challot and Vincent, 1977). No infestation was observed, despite favourable climatic conditions.

4. Integration with other methods

All three of the forces for insect control discussed above are inadequately researched, developed and quantified. With the machines available at present neither impact nor physical removal are totally effective against pests in whole grain without excessive grain damage. Nevertheless even in their present crude forms they have some features that may be useful as part of an integrated control strategy. The techniques currently used for control of insects in stored products are often limited in some way by particular species or stages of pest. If these limiting species or stages were removed then particular techniques would be more effective, less expensive or act more quickly. For instance, use of impact and phosphine fumigation are complementary. The tolerance of pupae of Sitophilus spp. determines the length of exposure required for phosphine fumigations. If pupae are not present the length of exposure can be significantly reduced (7 to 5 days at 25°C (Winks et al. (1980)). Impact is notably effective against Sitophilus pupae but less so against earlier immature stages. The latter are readily killed by phosphine. Mathlein (1971) demonstrated the successful combined used of sieving and aspiration, to remove cold-tolerant adult insects, and cooling to eliminate the much more cold-sensitive immature stages. Tilton and Brower (1985) suggested pneumatic conveying would reduce γ-irradiation doses required for control by eliminating the tolerant lepidopterous pests.

Table VIII summarises some apparently complementary combinations of impact and physical removal with other control measures.

TABLE VIII. Species or stage limiting particular insect control process and suggested complementary method for elimination of this tolerant target.

Method limited by target species or stage	Tolerant target	Complementary method effective against tolerant target
Cold disinfestation	Adult insect pests	Sieving and aspiration
Controlled atmosphere (low-oxygen) treatments	*Sitophilus* pupae	Percussion
Fenitrothion treatments	OP-resistant *O. surinamensis*	Percussion
Gamma irradiation	Lepidoptera	Percussion
Heat disinfestation	*Rhyzopertha dominica* late larvae	Percussion
High-CO_2 controlled atmospheres	*Trogoderma granarium* larvae	Sieving and aspiration and/or percussion
Methyl bromide fumigation	*Trogoderma granarium* larvae	Sieving and aspiration and/or percussion
Phosphine fumigation	*Sitophilus* pupae	Percussion

Packaging or physical exclusion is obviously complementary to any control processes that does not leave residual protection, e.g. heat disinfestation, fumigation or use of ionising radiation.

Whether it is reasonable to carry out the two complementary processes rather than use the single process will depend on the economic savings. However, until the systems are optimised it is not possible to give a reliable costing as most of the cost will be associated with undefined capital charges not running cost. Passive protection by exclusion effectively has no running costs though there may be maintenance charges. Both impact and sieving or segregation depend on mechanical energy and are unlikely to be intrinsically expensive compared with many other pest control methods, notably heating and cooling.

5. Conclusion

Impact, physical removal and exclusion all can provide a significant degree of insect control in stored products. In many instances, even at the present crude stage of development, impact and forms of physical removal can give > 99% mortality of particular species and developmental stages of stored product pest insects. In many instances exclusion appears a practical means of preventing insect invasion. It is to be hoped that these methods will soon receive the attention from researchers that they apparently deserve, so they can be refined to provide effective and useful aids to the protection of stored products.

Acknowledgements

I am grateful to Dr Barry Longstaff for carrying out the simulations on which Figure 1 is based.

References

Andrieu A.J., Fleurat-Lessard F. and Busnel R.G. (1977) Effect of high intensity sound waves on stored flour insect pests. Int. Cong. on Acoustics, Madrid, 1977, Paper J-11.

Annis P.C., Banks H.J. and Sukardi (1984) Insect control in stacks of bagged rice using CO_2 treatment and an experimental PVC-membrane enclosure. CSIRO Aust. Div. Entomol. Tech. Pap. No. 22, 38 pp.

Armitage D.M. (1981) Effect of high air velocities on adhesion to and behaviour on a perforated surface of arthropod pests of grain. Entomologists' Mon. Mag. 117, 59-61.

Bahr I. (1973) Untersuchungen über die Verminderung des Schädlingsbesatzes im Getreide durch pneumatische Förderung. Nachr. Pflanz. DDR 27, 232-237.

Bahr I. (1975) Über das Schadauftreten des Getreidekapuziners (Rhyzopertha dominica F.) und die Wirkung eines Saug-und Druckgeblases auf den Befall im Getreide. Nachr. Pflanz. DDR 29, 228-231.

Bailey S.W. (1962) The effects of percussion on insect pests of grain. J. econ. Entomol. 55, 301-304.

Bailey S.W. (1969) The effects of physical stress in the grain weevil Sitophilus granarius. J. stored Prod. Res. 5, 311-324.

Banks, H.J. (1986) Fumigation of flat bulks with phosphine. Proc. GASGA Technical Seminar on Fumigation Technology in Developing Countries, Slough, 1986. pp. 35-45.

Banks H.J. and Ripp B.E. (1984) Sealing of grain storages for use with fumigants and controlled atmospheres. Proc. 3rd Int. Working Conf. on Stored Product Entomol. Manhattan, 1983, 375-390.

Barrer P.M. (1983) A field demonstration of odour-based host-food finding behaviour in several species of stored grain insects. J. stored Prod. Res. 19, 105-110.

Barrer P.M. and Jay E.G. (1980) Laboratory observations on the ability of Ephestia cautella (Walker) (Lepidoptera: Phycitidae) to locate, and to oviposit in response to a source of grain odour. J. stored Prod. Res. 16, 1-7.

Booth J.L. (1859) Grain Separation. U.S. Patent No. 23153 (quoted by Katz et al., 1954).

Bryan J.M. and Elvidge J. (1977) Mortality of adult grain beetles in sample delivery systems used in terminal grain elevators. Can. Entomol. 109, 209-213.

Challot F. and Vincent J.-C. (1977) Stockage du cacao sous vide dans des conteneurs en polyethylene. Cafe Cacao The 21, 129-136.

Cline L.D. and Highland H.A. (1981) Minimum size of holes allowing passage of adults of stored-product Coleoptera. J. Ga Entomol. Soc. 16, 525-531.

Cogburn R.R., Tilton E.W. and Brower J.H. (1972) Bulk-grain gamma irradiation for control of insects infesting wheat. J. econ. Entomol. 65, 818-821.

Cotton R.T. (1958) Pests of stored grain and grain products. p. 156. (Burgess Publ. Co.: Minneapolis.)

Evans D.E. (in press) Stored products. In "Pest Management: A Synthesis". (Ed. T.H. Coaker.) (Academic Press: London.)

Fleurat-Lessard F. (1980) Lutte physique par l'air chand ou les hautes frequencies contre les insectes des grains et des produits cerealiers. Bull. Tech. d'Inf. Cer. Stockees 349, 345-352.

Gay F.J. (1941a) Temperature changes during the "turning" of bulk grain. J. Coun. Sci. Ind. Res. 14, 111-116.

Gay F.J. (1941b) A further study of temperature changes during the "turning" of bulk grain. J. Coun. Sci. Ind. Res. 14, 245-248.

Green A.A. and Tyler P.S. (1966) A field comparison of malathion, dichlorvos and fenitrothion for the control of Oryzaephilus surinamensis (L.) (Coleoptera: Silvanidae) infesting stored barley. J. stored Prod. Res. 1, 273-285.

Highland H.A. (1978) Insect resistance of food packages - a review. J. Food Process. Preserv. 2, 123-130.

Highland H.A. (1981) Resistant barriers for stored-product insects. In "CRC Handbook of Transportation and Marketing in Agriculture". (ed. E.E. Finney) Vol. 1, 41-46. (CRC Press: Boca Raton)

Howe R.W. (1952) Entomological problems of food storage in Northern Nigeria. Bull. ent. Res. 43, 111-144.

Hyde M.B., Baker A.A., Ross A.C. and Lopez C.O. (1973) Airtight grain storage. FAO Ag. Serv. Bull. 17, 1-71.

Joffe A. and Clarke B. (1963) The effect of physical disturbance or "turning" of stored maize on the development of insect infestations. II. Laboratory studies with Sitophilus oryzae (L.). S. Afr. J. Agric. Sci. 6, 65-84.

Katz R, Farrel E.P. and Milner M. (1954) The separation of grain by projection. Cereal Chem. 31, 316-325.

Kirkpatrick R.L. and Cagle A. (1978) Controlling insects in bulk wheat with infrared radiation. J. Kansas Ent. Soc. 51, 386-393.

Loschiavo S. (1978) Effect of disturbance of wheat on four species of stored product insects. J. econ. Entomol. 71, 888-893.

Lu Q. (1984) An overview of the present state of controlled atmosphere storage of grain in China. In 'Controlled Atmosphere and Fumigation in Grain Storages'. (eds Ripp B.E. et al.), pp. 15-29. (Elsevier: Amsterdam.)

Mathlein R. (1971) Mechanical cleaning of infested grain as a control method against some insect pests. Meddn St. VäxtstAnst 152, 209-227.

Milner M. Farrell E.P. and Katz R. (1953) Use of a simple blowing device to facilitate inspection of wheat for internal infestation. J. Ass. Off. Ag. Chemists 36, 1065-1070.

Muir W.E., Yacuik G. and Sinha R.N. (1977) Efects on temperature and insect and mite population of turning and transferring farm-stored wheat. Can. Agric. Engng 19, 25-28.

Payne J.A., Redlinger L.M. and Davidson J.I. (1970) Shelling plant studies with insect-infested peanuts. J. Amer. Peanut Res. & Education Assoc. 2, 103-108.

Rees D.P. (1985) Review of the response of stored product insects to light of various wavelengths, with particular reference to the design and use of light traps for population monitoring. Trop. Sci. 25, 197-213.

Rodinov, Z.S. (1938) The mechanism of movement of the granary weevil in a heap of grain. Zool. Zh. 17, 610-616.

Sabio G. and van Graver J. (in press) Solutions to some difficulties encountered in sealed stack storage in commodities in the Philippines. Proc. ASEAN 9th Tech. Seminar on Grain Post-Harvest Technol. Singapore, 1986.

Schmidt H.-U. (1980) Verpackung bzw. Packstoffe und Insekten, insbesondere Verratsschädlinge. Mitt. Biol. Bundesanstalt fur Land- und Forstwirtschaft. 195, 1-113.

Suharno P. (1986) Implementation of CO_2 fumigation technique for insect pest control in Bulog's warehouses. Proc. ASEAN 9th Tech. Seminar on Grain Post-Harvest Technol. Singapore, 1986 (in press).

Suharno P., Sukardi, Martono A., Shinta and Milunar (1984) Preservation of milled rice using carbon dioxide. In 'Health and Ecology in Grain Post-Harvest Technology. Proceedings of the 7th ASEAN Technical Seminar on Grain Post-Harvest Technology'. (Eds. Semple R.L. and Frio A.S.), pp. 385-393 (ASEAN Food Handling Bureau: Kuala Lumpur.)

Sullivan W.N. and McCauley T.R. (1960) Effect of acceleration force on insect mortality. J. econ Entomol. 53, 691-692.

Tilton E.W. and Brower J.H. (1985) Supplemented treatments for increasing the mortality of insects during irradiation of grain. Food Technol. 39, 75-79.

Winks R.G., Banks H.J., Williams P., Bengston M. and Greening H.G. (1980) Dosage recommendations for the fumigation of grain with phosphine. SCA Technical Rep. Series No. 8. 9pp.

Wohlgemuth R. (1979) Protection of stored foodstuffs against insect infestation by packaging. Chemy Ind. (London), 1979. 330-334.