Heat Treatments for Postharvest Pest Control: Theory and Practice

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8 Disinfestation of Stored Products and Associated Structures Using Heat

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8.1 Introduction

Background

The term 'stored products' is broad. It refers generally to non-perishable crops and their dry durable products. The crops include grains such as wheat, barley, maize, oats, rye, rice, millet and sorghum; pulses such as peas, beans and lentils; and oil seeds such as those from canola and sunflower. Dried fruits such as raisins, sultanas and currants are often included, as well as herbs and spices, but will not be considered in this chapter. For the purposes of this discussion, the emphasis will be on grains, grain products and associated storage structures, handling equipment, processing facilities and machinery.

Insect pests have been associated with stored products since the dawn of settled agriculture some 10,000 years ago. Grains, skins and fibres stored in quantity made opportunistic habitats for insect species living in leaf litter, animal nests and under the bark of trees, or feeding on seeds, general plant material, carrion and fungi (Hill, 2002; Rees, 2004).

The invention of the McCormick reaper in the 1830s and threshing machines shortly after spurred modern storage methods (Drache, 1976). The first grain elevator built in the USA at Buffalo, New York, in 1842, combined with the reliability of the steam engine, ended former restrictions in the capacity of grain handling. For example, in Chicago, Illinois, annual shipment of grain and flour increased from around 150,000 t (6 million bushels) per year in 1855 to 3.75 million t (150 million bushels) thirty years later (Reed, 1992). However, it must be remembered that the changes in storage and handling over the last

150 years in the industrialized world have had little impact on the traditional ways practised in many underdeveloped countries.

With the establishment of stored-product research and development at the beginning of the 20th century (Munro, 1966) have come the many strategies for protection and disinfestation that we see today against the plethora of insect pests that confront the grain and food industry. Total world production of cereals in 2002 was about 2030 million t, of which 14% was traded internationally, and about half of that was accounted for by wheat and wheat flour (FAO, 2003, 2004). In response to market influence in developed and exporting countries, the current status of stored-product insect management is in a period of transition from chemical methods to non-chemical methods, and hence there is great potential for using heat in stored products and associated structures.

Stored-product Insect Pests

The majority of stored-product insects come from only two of the roughly 26 orders of the Class Insecta (see Fig. 8.1): Coleoptera and Lepidoptera. On the other hand, predators and parasitoids of stored-product insects come from the orders Hemiptera, Hymenoptera and Diptera (Rees, 2004). Stored-product insects are often classified by whether they develop and feed inside or outside grain kernels, and thus are referred to as either internal developers or external developers.

Internal developers

As the most destructive of the stored-product insects, six species from two families of Coleoptera and one family of Lepidoptera are recognized as internal developers, sometimes referred to as primary invaders.

These include the grain borers (Family: Bostrichidae), such as the lesser grain borer, *Rhyzopertha dominica* (Fabricius), which is one of the most damaging insects, and the larger grain borer, *Prostephanus truncatus* (Horn), a major tropical pest of maize; the grain weevils (Family: Curculionidae), such as the rice weevil, *Sitophilus oryzae* (L.), maize weevil, *S. zeamais* Motschulsky and the granary weevil, *S. granarius* (L.); and, finally, the angoumois grain moth (Family: Gelechiidae), *Sitotroga cerealella* (Olivier), which today is less destructive than the other internal developers because infestations commonly start in the field and can be minimized by modern methods of harvesting (e.g. combines) and storage.

External developers

External developers are sometimes referred to as secondary invaders because they tend to infest broken materials and grain dust created by primary

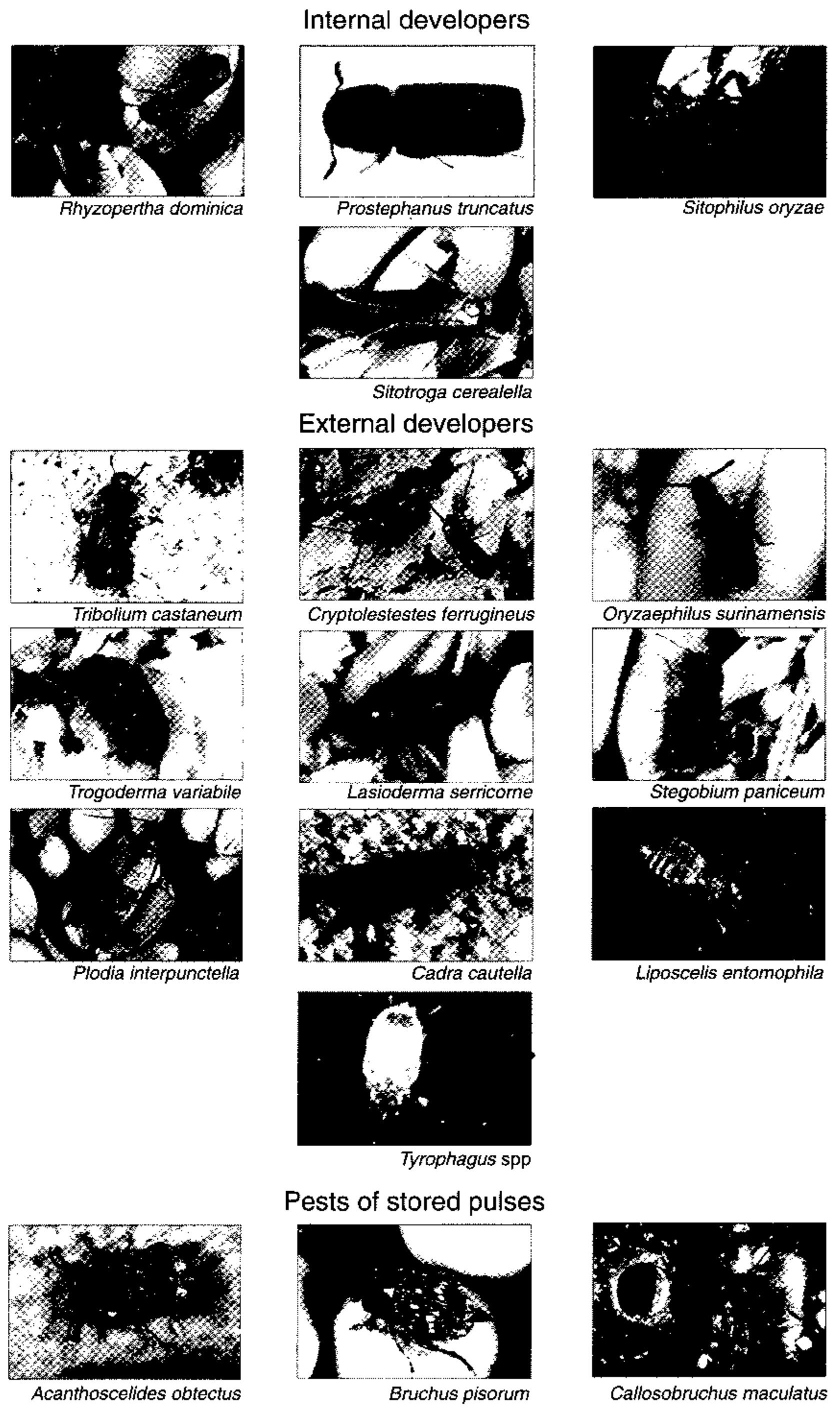


Fig. 8.1. Major insect pests of stored products, pulses and storage and processing structures (in order of reference in text; photography by J. Green, D. McClenaghan and N. Starick, CSIRO, Canberra, Australia).

invaders. They are found in grain but are more common in flour, meals and other processed foods. They have also been reported in storages, handling equipment and processing facilities. External developers represent six families of Coleoptera and one family of Lepidoptera.

The families include flour beetles (Family: Tenebrionidae), such as the red flour beetle, *Tribolium castaneum* (Herbst) and the confused flour beetle *T. confusum* Jacquelin du Val; and the grain beetles (Families: Laemophloeidae and Silvanidae), which are generally smaller and flatter than other externally developing stored-product Coleoptera. The most commonly found species of the family Laemophloeidae are the flat grain beetle, *Cryptolestestes pusillus* (Schönherr), and the rusty grain beetle, *C. ferrugineus* (Stephens). The most common silvanid is the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.).

Another important group are the grain-infesting dermestids (Family: Dermestidae), which generally refers to several species of *Trogoderma*. The warehouse beetle, *Trogoderma variabile* (Ballion) and the khapra beetle, *T. granarium* (Everts), are the best known. The larvae of these species can diapause for many months, making them particularly difficult to control. Of the Coleoptera, the anobiid beetles (Family: Anobiidae) are the last main group worth mentioning. These include the cigarette beetle, *Lasioderma serricorne* (F.) and the drugstore beetle, *Stegobium paniceum* (L.).

Several moth species (Family: Pyralidae) infest cereal grains and grain products. Probably the most important of these are the Indianmeal moth, *Plodia interpunctella* (Hübner), almond moth, *Cadra cautella* (Walker), tobacco moth, *Cadra cautella* (Hübner) and Mediterranean flour moth, *E. kuehniella* (Zeller). The larvae of these species leave a trail of silk behind them that can completely soil the surface of food products as they feed.

Finally, there are several pests that flourish under very humid conditions. Probably the most important in this group are several species of psocids (Order: Pscoptera e.g. *Liposcelis entomophila*) and mites (Class: Arachnida e.g. *Tyrophagus* spp.), which struggle to survive at relative humidities (RH) $<$ 60 and 75%, respectively.

Pests of stored pulses

Bruchids (Family: Bruchidae) specifically infest pulses as primary pests and do not attack cereal grains. Most commonly known members of this group are the bean weevil, *Acanthoscelides obtectus* (Say), various pea weevils (*Bruchus* spp.) such as *B. pisorum* (L.) and the cowpea weevil, *Callosobruchus maculatus* (F.). Members of this family lay their eggs on seed pods or exposed seeds. However, while other pests can continue to breed on dried seed in storage, *Bruchus* species are more important as a field pest and cannot reinfest once they emerge in storage.

Optimum conditions for population growth of most of the major pest species are between 28 and 33°C at 60–75% RH (see Table 8.1). However, several species grow well between 20 and 37°C and 25–80% RH. Adults at low

Table 8.1. Responses of stored-product insect pests to various temperature ranges (adapted from Fields, 1992).

Zone	Temperature range (°C)	Effect(s)
Lethal	> 62	Death in < 1 min
	50–62	Death in < 1 h
	45–50	Death in < 1 day
	35–42	Populations die out, mobile insects seek cooler environment
Suboptimal	35	Maximum temperature for reproduction
	32–35	Slow population increase
Optimal	25–32	Maximum rate of population increase
Suboptimal	13–25	Slow population increase
Lethal	5–13	Slowly lethal
	1–5	Movement ceases
	−10 to −5	Death in weeks, or months if acclimated
	−25 to −15	Death in < 1 h

suboptimum temperatures can live for many months; the minimum theoretical threshold for population growth being around 18°C.

An increase in the rate of egg-laying and a decrease in development time occur as temperatures increase, but populations often struggle to grow at 35°C unless humidity is high, and death in most species is practically inevitable at about 40°C. At optimum conditions, most species lay 100–400 eggs per female, and development time is between 20 and 40 days, which means that many species can more than double their population in about 1 month.

Stored-product insects are considered pests for a number of reasons. At high densities they can consume a considerable amount of food, which is an important problem in many developing countries where annual losses due to insects are estimated at 10–50% (USDA, 1965; Wolpert, 1967; Hall, 1970). At high densities, stored-product insects can cause heating of grain and encourage mould growth by initiating moisture migration and condensation (Longstaff, 1981). All of these processes can cause considerable losses and reduce the quality of finished products. Given the right conditions, insects can increase rapidly and cause extensive damage before they are detected.

Therefore, the threshold for stored-product insect management is very low or zero. For example, Canada and Australia stipulate that wheat at the point of export must be free of insects; Nigeria has similar restrictions with cocoa beans, as does South Africa with groundnuts (Snelson, 1987). According to Federal Grain Inspection Standards in the USA, stored wheat is considered infested if it has two or more live insects/kg.

Most Western countries have zero tolerance for insects in finished products such as flours or baked goods. Insect parts in processed food are also restricted. In the USA, wheat flour with 75 insect fragments/50 g of flour (Defect Action Level) cannot be commercially sold for human consumption (FDA, 1988). In some cases, buyers of grain and processed foods have the right to reject entire shipments based on the presence of insects or insect fragments. Buyers may also impose major penalties for insect infestation because of the cost of remediation and delay at port of entry (Snelson, 1987).

Management of Stored-product Insects

The development of relatively cheap and very effective chemical methods, which matured in the second half of the 20th century, led to chemicals being the method of choice for insect management. Two basic types of chemical insecticides are used on stored products, namely fumigants (Bond, 1984) and contact insecticides (Snelson, 1987).

Fumigants

Fumigants generally enter the insect through the respiratory system, and are toxic to all life stages. They are gaseous chemicals at ambient temperature and pressure, and can produce gas from a solid or liquid. They diffuse through air, permeate products and have little or no residual insecticidal effect (Bond, 1984; Harein and Davis, 1992).

Currently several fumigants are used against stored-product insects. For fumigation with phosphine (PH_3), solid metal phosphides are used in grain (aluminium phosphide) and warehouses (magnesium phosphide). Phosphine generators mix the metal phosphides with water to rapidly produce gaseous phosphine, which can be delivered to the site in cylinders and released directly into the commodity or structure. As phosphine is corrosive to copper and several other metals, it is not used extensively for the fumigation of structures. Methyl bromide (CH_3Br) is used extensively in cereal food-processing facilities for structural fumigation (flour mills, bakeries, pasta plants and breakfast cereal plants) and against quarantine pests, but is considered an ozone-depleting substance, so its production and use is now being phased out (Fields and White, 2002).

The resistance of insects to phosphine, and to a lesser extent to methyl bromide, is now an acute problem worldwide. For phosphine, this is in large part due to poor fumigation practices. Significant resistance was demonstrated even thirty years ago by Champ and Dyte (1976), who recorded phosphine resistance in 10% of 848 samples in over five stored-product insect species from 41% of 82 countries surveyed, and increased tolerance to methyl bromide in thirteen insect species in 5% of samples from 26% of countries.

Other fumigants include hydrogen cyanide, carbon disulphide, chloropicrin and ethyl formate. Sulphuryl fluoride has been used since the 1950s to control termites in the USA and Europe, and recently to manage insects in food-processing facilities (Drinkall *et al.*, 2002; Ducom *et al.*, 2002). Like sulphuryl fluoride, interest in hydrogen cyanide, carbon disulphide, and ethyl formate has been rekindled in recent years as alternatives to methyl bromide; carbonyl sulphide was patented in 1993 for this purpose (Banks *et al.*, 1993; Bengston and Strange, 1998).

Modified atmospheres, high carbon dioxide and high nitrogen (or low oxygen) have been used to a limited extent to disinfest grain or structures as alternatives to fumigation. In leaky structures, carbon dioxide is better than nitrogen, as concentrations of 35% are lethal to all life stages of stored-product insects. In contrast, nitrogen must reduce the level of oxygen to below 2%, requiring airtight storage to be cost-effective. Thus, the technology is hindered by the necessity for sealed storages and access to large amounts of cheap carbon dioxide or nitrogen. The use of modified atmospheres is discussed in detail by Banks and Annis (1990).

Contact insecticides

Contact insecticides, or protectants, generally enter the insect orally or across the cuticle. They are applied either to grain, floor–wall junctions, general surfaces or crevices in warehouses and food-processing facilities. Protectants are defined as insecticides that prevent infestations from becoming established in a commodity, but are less effective at managing a well-established infestation, and infested commodities and structures are often better treated by fumigation.

The most commonly used contact insecticides are: (i) organophosphates (malathion, dichlorvos, fenitrothion, pirimiphos-methyl, chlorpyrifos-methyl, chlorpyrifos-methyl with deltamethrin); (ii) pyrethroids (bioresmethrin, permethrin and deltamethrin); and (iii) synergized pyrethrins (Champ and Dyte, 1976; Snelson, 1987).

Because protectants vary in efficacy from species to species, they must be used judiciously. Moreover, as with fumigants, insect resistance is a major issue, which further adds to the complexity of application. Other less commonly used contact insecticides include diatomaceous earth (Ebeling, 1971; Desmarchelier and Dines, 1987; Paula *et al.*, 2002) and insect growth regulators such as methoprene and hydroprene (Strong and Diekman, 1973; Edwards *et al.*, 1987). Spinosad, an insecticide based on bacterial fermentation products (Spinosyns A and D), has been shown to be effective against stored-product insects in laboratory and field evaluations (Fang *et al.*, 2002a, b; Flinn *et al.*, 2004) and is registered in the USA as a grain protectant.

Physical disinfestation methods

Chemical methods of insect disinfestation face significant challenges. Methyl bromide is becoming more and more costly and is being phased out under the 1987 Montreal Protocol in both developed and developing countries. The use of phosphine is being increasingly regulated because of safety issues and insect resistance. Resistance to insecticides is widespread and chemical residues – owing to increased dosages – are becoming increasingly unacceptable to grain buyers and consumers. Not only do contracts with buyers now stipulate acceptable insect contamination and damage, but also which insecticides are acceptable and what constitutes the upper residue limit.

On the other hand, a physical method of grain protection and disinfestation would not carry these problems. One such method might be the use of mechanical methods such as impact (Bailey, 1962, 1969) or combinations of sieving, aspirating and blowing (Banks, 1987), which are used in food-processing facilities. One of the most widely researched physical methods, however, is the use of extreme temperatures for insect disinfestation in bulk-stored grain, associated structures and food-processing facilities.

Low temperatures are commonly used to manage stored-product insects. Few species can achieve a population increase < 18°C. *Sitophilus granarius* is one of the exceptions, as it can reproduce at temperatures down to 15°C. Between 1 and 5°C, depending upon acclimation and the species, stored-product insects are unable to move and reproduce. Temperatures < 0°C will kill insects; the lower the temperature, the faster the insects will succumb to cold injury (see Table 8.1).

There are a number of methods to reach these temperatures. Aeration of grain bulks with ambient air is used extensively immediately after harvest to cool the grain. The air, which is passed through the bulk at relatively low volume, has a minimal drying effect, but preserves grain quality by slowing population growth, minimizing moisture migration and preventing the build-up of hot spots (Darby, 1998). In conjunction with insecticides, aeration can delay the onset of resistance and reduce the amount of protectant used (Longstaff, 1984, 1986, 1988).

Aeration of grain with chilled or refrigerated air is also used (Fields, 1992; Burks *et al.*, 2000), and can be as cost-effective as phosphine fumigation. Low temperatures are sometimes used to manage insects within flour mills in temperate climates during cold winters, but this practice has fallen out of use because of the unpredictability of the low temperatures (–10°C) required, and the need to drain all water from the facility.

By contrast, the use of elevated temperatures has the major advantage of giving complete disinfestation while being comparatively rapid. Like the use of low temperatures, it is chemical-free, and insects are not as likely to develop resistance to it. Methods using heat have been developed that disinfest grain both at the on-farm and commercial storage levels, as well as storages, processing facilities and equipment. However, there are scientific, technical and economic issues still to overcome.

In this review of heat treatments to control stored-product insect pests, we cover the current thermal kinetic data for insect mortality, empirical methods used to obtain this information and common mathematical and statistical models designed to make treatment predictions as reliable as possible. We also examine the current status of heat treatment research and development, and include our outlook for thermal treatments of stored products and structures in terms of a solution to some of the problems confronting safe storage and disinfestation.

8.2 The Use of Heat for Insect Management

Heat Disinfestation of Stored Products

The concept of using thermal energy for the disinfestation of stored-product insects is not new. Traditional methods have made use of heat, particularly solar energy, for thousands of years. In China, heating grain in a thin layer on the ground to > 50°C and < 12% moisture content (MC) dates back 1500 years. The grain is then piled up to maintain that temperature for several hours before being stored in an insulated bin where the temperature drops to ambient over the following couple of months (Liu *et al.*, 1983). The first recorded occurrence of using heat to control stored-product insects was by Duhamel du Monceau and Tillet (1762) in western France. During a severe outbreak of the angoumois grain moth, *S. cerealella*, a temperature of 69°C was used to destroy caterpillars in grain spread out in ovens for 3 days.

The modern use of thermal energy has a history as long as other contemporary technologies for stored-product insect control. The first industrial-scale heat disinfesters were developed in Australia between 1915 and 1919 (Winterbottom, 1922). These early machines heated grain by conduction up to 60°C as the grain fell by gravity through a bank of steam-heated pipes. The units stood 6 m high and could treat 25 t (1,000 bushels)/h (see Fig. 8.2). Of the 12 such units built over this period, six processed over '10,000,000 bags of wheat' (816,000 t) (Winterbottom, 1922). However, as cheap chemical alternatives became more available, there was little interest in further pursuit of the use of thermal energy for grain disinfestation for the following 50 years or so.

With the impending phase-out of methyl bromide fumigation, there is now increasing urgency for an alternative rapid disinfestation system, particularly at point of export. While methyl bromide fumigation can be completed in < 2 days, current alternative fumigants require a minimum of 3 days, which is unacceptable to industry. By contrast, continuous flow heat treatment systems with a throughput up to 400 t/h are possible (Sutherland *et al.*, 1987), and there are also opportunities for farm-scale treatments.

Several factors must be addressed before thermal disinfestation of stored products becomes a significant part of current insect control practice. Most important is competitive cost, which is a combination of the lowest possible running and capital costs to challenge current chemical options, and includes issues such as throughput rate, thermodynamic design, energy costs, safety and versatility for a range of commodities. External forces, such as further deterioration in the efficacy of phosphine, may improve the cost balance in favour of heat disinfestation, but strategies for lowering cost must also be actively sought.

There is already considerable information on a range of laboratory-based methods of treatment, as well as some industrial-scale equipment. Our present understanding of the effects of thermal energy on insect mortality and grain quality will help improve the operation of current systems and the development of new ones.

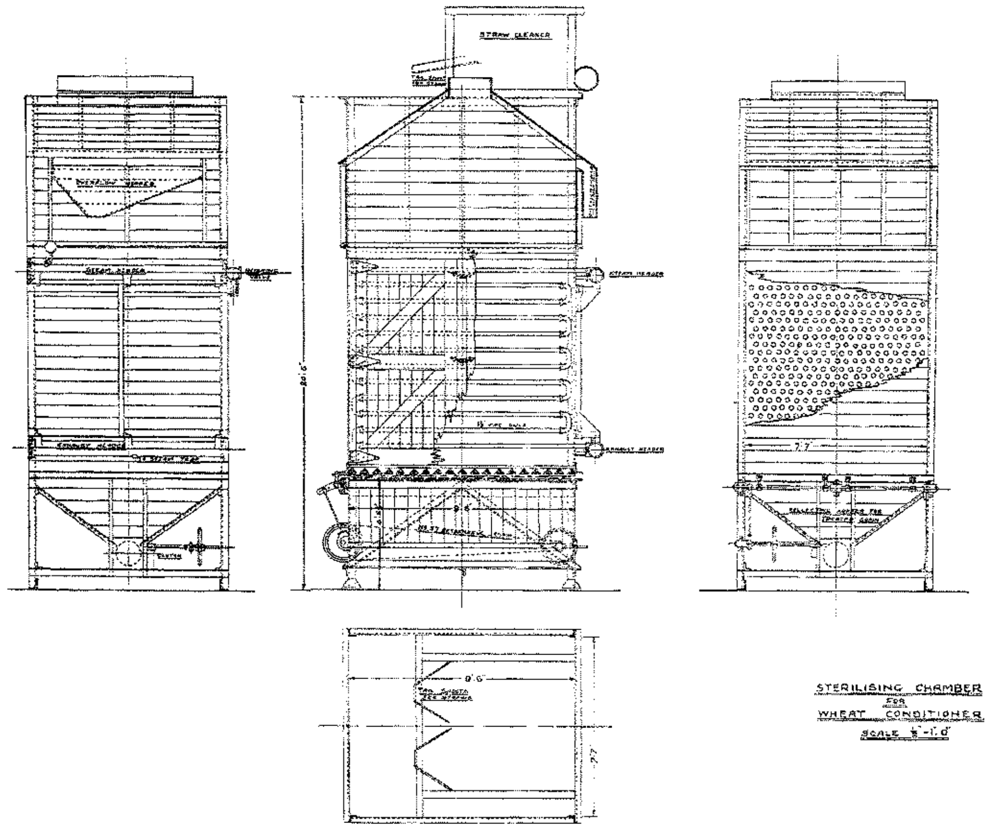


Plate No. 21.
Poole & Steel Wheat Heater.

Fig. 8.2. Poole and Steel wheat heater from Australia, *c.*1915 (from Winterbottom, 1922).

Heat Disinfestation of Structures

Heat disinfestation of structures is a simple concept involving raising the temperature of the whole or a portion of a facility to 50–60°C and maintaining these elevated temperatures for 24–36 h (Imholte and Imholte-Tauscher, 1999; Dowdy and Fields, 2002; Wright *et al.*, 2002; Dosland *et al.*, 2006). The minimum temperature for successful disinfestation is 50°C (Wright *et al.*, 2002; Mahroof *et al.*, 2003a, b; Roesli *et al.*, 2003); in portions of the facility where the temperature is $<$ 50°C insect survival can be expected.

Structural heat treatments can be performed using gas, electric or steam heaters. Depending on the size and nature of the structure, long periods of heating may be needed for penetration of wall voids and equipment to kill insects harbouring in them (Fig. 8.3).

As hot air stratifies vertically and horizontally within structures, the use of air movers or fans is essential to ensure uniform heating of all portions of a building. Structural heat treatments are labour-intensive because the facility

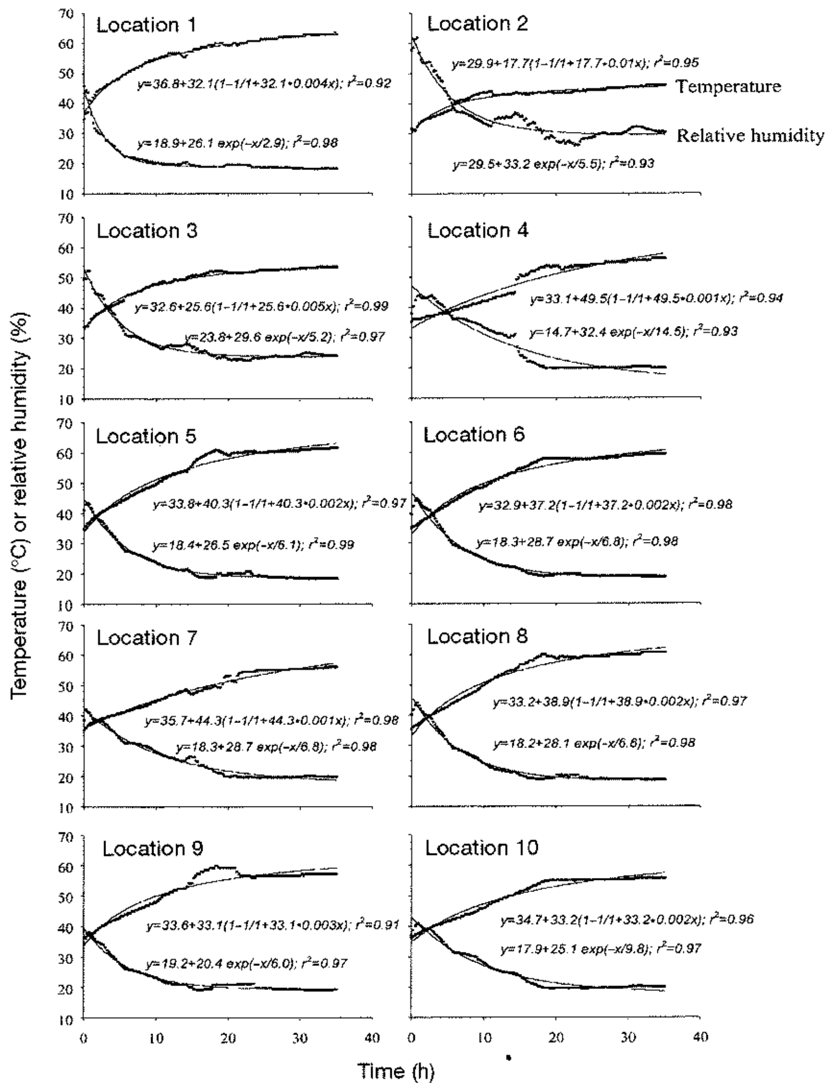


Fig. 8.3. Temperature and RH profiles at ten feed mill locations during heat treatment. Temperature and RH profiles were described by fitting two separate three-parameter nonlinear regression models to data. Each fitted line (solid line) was based on $n = 141$ temperature or RH observations. The adjusted r^2 values are presented in each graph (from Mahroof *et al.*, 2003a).

and equipment are slow absorbers of heat and need to be thoroughly cleaned. In addition, food, heat-susceptible materials and non-food materials (e.g. paper bags) should be removed from the facility because insects may seek refuge in these materials and escape treatment. Food products, if infested, should be removed and fumigated with phosphine before being returned to the structure after a heat treatment is finished. Good exclusion and sanitation practices are therefore essential for ensuring an effective heat treatment and prevention of reinfestation of structures.

In the USA and Canada, many flour mills used heat treatments as a pest management tool in the early 1900s (Dean, 1913), and in later years worker safety was often considered to be better with heat than with fumigants (Cotton, 1963). There exist anecdotal reports of adverse effects observed by millers, probably due to inadequate control of high temperatures, including warping of wood, stretching of line belts and degreasing of bearings (Imholte and Imholte-Tauscher, 1999).

Advances in building and equipment designs have greatly reduced many of the adverse effects of high temperatures on structures (Heaps, 1994; Imholte and Imholte-Tauscher, 1999; Wright *et al.*, 2002; Mahroof *et al.*, 2003a, b; Roesli *et al.*, 2003; Dosland *et al.*, 2006). The introduction of methyl bromide in the 1940s as a structural fumigant made the use of heat treatments almost obsolete. There is now a renewed interest in exploring heat treatments as alternatives to methyl bromide because of the impending phase-out of this fumigant (Makhijani and Gurney, 1995), although some critical uses of it (e.g. quarantine) may be retained for several years.

8.3 Effects of High Temperatures on Stored-product Insects

As temperature increases above the optimum of about 32°C for population growth, insect response goes through three stages (Fields, 1992; Dosland *et al.*, 2006). In the first stage (40–45°C), egg laying declines and ultimately halts, hatching and eclosion become difficult to complete, and with declining fecundity and shorter adult lifespan, the population starts to die out. In the second stage (45–55°C), individuals survive for several hours, experiencing severe water stress. High humidity (> 50% RH) can greatly extend survival in both of these stages. In the last stage, > 55°C, there is rapid mortality, where the entire population is dead in minutes to seconds. Disinfestation of structures and equipment generally makes use of temperatures associated with the second and third stages of mortality, while rapid disinfestation of bulk grain employs temperatures > 60°C (see Table 8.1).

The mortality of an insect stage at high temperatures is a function of temperature and exposure time. At any given temperature, mortality increases with an increase in exposure time and, at any given exposure time, mortality increases with an increase in temperature (Wright *et al.*, 2002; Mahroof *et al.*, 2003b; Boina and Subramanyam, 2004). High temperature causes a number of adverse biochemical changes in insects: lower ion concentrations (e.g. pH), inactivation of major glycolysis enzymes, disruption of plasma membranes and denatured proteins, nucleic acids, lipids and carbohydrates (Hochachka and Somero, 1984; Denlinger and Yocum, 1999; Neven, 2000).

High temperature can also have sublethal effects, such as reduced movement, fecundity and progeny survival. For example, the exposure of *T.*

castaneum pupae to high temperature prevented development to adults (Saxena *et al.*, 1992), or resulted in adults with separated elytra (A. Menon and Bh. Subramanyam, unpublished data, 2000), possibly due to chromosomal aberrations (Denlinger and Yocum, 1999). The growth and development of the mealworm, *Tenebrio molitor* (L.), and *T. confusum* and *E. kuehniella,* are also adversely affected by high temperature (Adler and Rassmann, 2000). *T. castaneum* exposed as pupae or adults had reduced fecundity, egg-to-adult survival and hence progeny production, even if only one of the mating pair had been exposed to heat (Mahroof *et al.*, 2005a).

8.4 Heat Tolerance in Stored-product Insects

Insect heat tolerance, or the ability to withstand high temperatures, is affected by, among other things, species, insect age, developmental stage and thermal acclimation (Dermott and Evans, 1978; Evans, 1981; Fields, 1992; Hallman and Denlinger, 1999). Insects exhibit physiological and biochemical adaptations to overcome injury caused by thermal stress (Evans, 1981), and are able to withstand some high temperatures because of induction or expression of heat shock proteins (HSPs), which protect cells – and consequently the organism – from heat stress by preventing aggregation or improper folding of proteins and resolubilizing and stabilizing proteins by targeting denatured proteins for degradation and removal (Currie and Tufts, 1997).

HSP 70s are constitutively present in all life stages of *T. castaneum*; however, the increased thermotolerance of young larvae (first-instars) is due to the relatively high levels of HSP 70s present when compared with the other stages. Time- and temperature-dependent expression of HSP 70 showed that the increased heat tolerance in young larvae lasted as long as 8 h at 40°C or 30 min at 46°C (Mahroof *et al.*, 2005b). Therefore, to kill young larvae of *T. castaneum*, heat treatments should target temperature and time combinations beyond those thresholds for heat tolerance.

Although insects are able to withstand high temperatures for brief periods of time, the temperatures used during structural heat treatments (50–60°C for 24–36 h), for example, kill even the most thermotolerant stages. Nevertheless, identifying species and stage-specific heat tolerance is important for determining the most heat-tolerant species of stored-product insects associated with structures and for identifying the most heat-tolerant stage of a species (e.g. flour beetles).

Using the minimum temperature–time combinations that ensure complete kill of the most heat-tolerant species or stage of a species will also ensure complete kill of the less heat-tolerant species or stages. To verify the effectiveness of structural heat treatments, cages or test arenas strategically placed within the heated structure and sampled at regular intervals of time should be used for the most heat-tolerant species and stages.

8.5 Survey of Current Thermal Kinetic Data: Empirical Methods and Common Models

Mortality Response Data

Fields (1992) conducted an extensive survey of the mortality data for stored-product insects exposed to moderate to high temperatures. The survey recorded data on 11 insect species, taking into consideration the following: (i) developmental stage; (ii) population strain; (iii) whether or not acclimation had occurred before treatment; (iv) heating method; and (v) RH. These factors were clearly shown to influence the magnitude of mortality responses to temperature over time.

Large data sets can often help in evaluating the influence that these factors have on mortality response. Some of these sets have been modelled to improve their predictive ability, such as:

- Developmental stages of *S. granarius* from 45 to 60°C at 13% grain moisture (Bruce *et al.*, 2004).
- Developmental stages of *T. castaneum* from 42 to 60°C at 22% RH (Mahroof *et al.*, 2003b).
- Developmental stages of *T. confusum* from 46 to 60°C at 22% RH (Boina and Subramanyam, 2004).
- Eggs of three species of psocids from 43 to 51°C at 70% RH (Beckett and Morton, 2003a).
- Developmental stages of *R. dominica* from 50 to 60°C at 12% grain moisture for four rates of heating (Beckett and Morton, 2003b).
- Large larvae of *T. variabile* from 50 to 56°C at 0% RH (Wright *et al.*, 2002).
- Developmental stages of *R. dominica* from 45 to 53°C and *S. oryzae* from 42 to 48°C at 9, 12 and 14% grain moisture for both species (Beckett *et al.*, 1998; Table 8.2).

Other data sets include:

- Adult *C. ferrugineus* from 45 to 50°C at 75% RH (Jian *et al.*, 2002).
- Developmental stages of *L. serricone* and *R. dominica* from 45 to 55°C at 14% grain moisture (Adler, 2002).
- Diapausing larvae of *E. elutella* from 40 to 45°C at 65% RH (Bell, 1983).

The great advantages that the continued acquisition of additional data ultimately bring are better targeted treatments based on good predictive models of mortality and the possibility that a better understanding of the processes at play brings new approaches to engineering solutions and treatment practices that are more cost-effective.

Table 8.2. LT 99s for a range of stored-product insect species predicted from several large data sets (Beckett *et al.*, 1998; Wright *et al.*, 2002; Beckett and Morton, 2003a, b; Mahroof *et al.*, 2003a; Bruce *et al.*, 2004; Boina and Subramanyam, 2004).

	Develop-ment stage	Moisture	Heating method	LT_{99} (in hours) Temperature (°C)																		
				42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
L. bostrichophila	e	70% rh	conductive		38.88	25.3	15.84	9.48	5.39	2.89	1.45	0.67	0.28									
L. decolor	e	70% rh	conductive		40.41	33.22	26.34	19.92	14.14	9.19	5.27	2.50	0.87									
L. paeta	e	70% rh	conductive				96.16	16.26	4.49	1.69	0.79	0.42	0.26									
R. dominica	5	12% mc	convective									6.84	3.45	1.75	0.90	0.46	0.24	0.12	0.07	0.03	0.02	0.01
	4	12% mc	convective									8.70	3.88	1.80	0.87	0.43	0.22	0.11	0.07	0.04	0.02	0.01
	3	12% mc	convective									14.29	5.96	2.61	1.20	0.58	0.29	0.15	0.08	0.04	0.03	0.01
	2	12% mc	convective									13.93	5.73	2.49	1.13	0.54	0.27	0.14	0.07	0.04	0.02	0.01
	1	12% mc	convective									15.71	6.18	2.58	1.14	0.53	0.26	0.13	0.07	0.04	0.02	0.01
	5	9% mc	conductive				49.09	31.03	19.37	11.95	7.27	4.36	2.58	1.50	0.86							
	4	9% mc	conductive				60.44	38.99	24.73	15.41	9.43	5.65	3.32	1.91	1.07							
	3	9% mc	conductive				55.05	37.99	25.65	16.91	10.85	6.77	4.09	2.39	1.34							
	2	9% mc	conductive				49.11	33.04	21.96	14.41	9.33	5.96	3.75	2.32	1.42							
	1	9% mc	conductive				41.59	29.62	20.74	14.26	9.61	6.34	4.09	2.57	1.57							
	5	12% mc	conductive •				52.24	33.60	21.37	13.43	8.34	5.11	3.09	1.85	1.09							
	4	12% mc	conductive				60.89	39.53	25.28	15.91	9.85	5.99	3.58	2.09	1.20							
	3	12% mc	conductive				70.8	48.91	33.10	21.92	14.17	8.92	5.46	3.24	1.85							
	2	12% mc	conductive				62.9	42.86	28.83	19.14	12.52	8.07	5.12	3.19	1.96							
	1	12% mc	conductive				46.93	34.05	24.3	17.04	11.72	7.89	5.20	3.34	2.09							
	5	14% mc	conductive				54.32	35.32	22.72	14.45	9.09	5.65	3.46	2.10	1.25							
	4	14% mc	conductive				61.15	39.84	25.60	16.20	10.10	6.19	3.73	2.21	1.28							
	3	14% mc	conductive				82.21	56.8	38.49	25.54	16.56	10.48	6.46	3.86	2.24							
	2	14% mc	conductive				76.09	52.38	35.58	23.83	15.73	10.22	6.53	4.10	2.52							
	1	14% mc	conductive				51.04	37.52	27.14	19.30	13.46	9.20	6.15	4.01	2.55							
S. granarius	ol/p	~13% mc	convective				78.53			2.33		0.51					0.06		0.01			< 0.01
			conductive				3.25			1.58		0.52					<0.01					

S. oryzae	a	12% mc	conductive	13.42	8.26	5.06	3.78	2.39	1.32	0.64											
	5	12% mc	conductive	20.50	12.55	7.61	4.58	2.73	1.61	0.94											
	4	12% mc	conductive	25.98	16.95	10.70	6.50	3.79	2.10	1.10											
	3	12% mc	conductive	26.31	18.95	13.09	8.59	5.30	3.03	1.57											
	2	12% mc	conductive	25.63	18.05	12.52	8.53	5.71	3.74	2.40											
	1	12% mc	conductive	14.23	10.69	7.72	5.31	3.45	2.08	1.14											
T. castaneum	a	22% rh	convective	70.58				8.29			0.93	0.84	0.75	0.68	0.61	0.55	0.49	0.44	0.40	0.36	0.32
	p	22% rh	convective	83.70				13.01			1.45	1.21	1.01	0.84	0.69	0.58	0.48	0.40	0.33	0.28	0.23
	ol	22% rh	convective	76.32				9.19			1.26	1.16	1.07	0.98	0.90	0.83	0.76	0.70	0.64	0.59	0.54
	yl	22% rh	convective	47.50				7.18			7.21	5.22	3.78	2.74	1.98	1.43	1.04	0.75	0.54	0.39	0.29
	e	22% rh	convective	21.22				10.60			1.76	1.42	1.14	0.92	0.74	0.59	0.48	0.38	0.31	0.25	0.20
T. confusum	a	22% rh	convective					3.56		2.56	1.20				0.96				0.57		0.25
	p	22% rh	convective					4.19		2.54	0.81				0.43				0.20		0.17
	ol	22% rh	convective					4.99		2.94	1.50				0.93				0.64		0.40
	yl	22% rh	convective					3.14		2.25	0.74				0.26				0.20		0.10
	e	22% rh	convective					3.48		1.95	0.69				0.27				0.20		0.11
T. variabile	ll	0% rh	convective								3.65	0.41	0.19	0.13	0.09	0.07	0.06	0.05	0.05	0.04	0.04

a: adult, p: pupal, ol: old larval, yl: young larval, ll: late larval, e: egg 1-5: arbitrary immature development stages from egg to pupa

Factors affecting insect mortality

Species

Several species of insects may be found concurrently in grain and associated structures. Knowing which of them is least susceptible to heat will help in targeting treatments against the species most difficult to kill: Closely related species, or species with similar life histories, vary greatly in heat tolerance. In Fig. 8.4, the treatment required for 99.9% mortality of the most heat-tolerant development stage of *R. dominica* is compared with that of *S. oryzae* and three species of Psocoptera (Beckett and Morton, 2003a).

The two beetle species, though of different genera, have similar behaviours because both are internal developers. Nevertheless, eight times more treatment is required for *R. dominica* to reach the same level of mortality as *S. oryzae* across the same range of temperatures. The psocid species, *Liposcelis bostrichophila*, *L. paeta* and *L. decolor*, are of the same genus; while they are

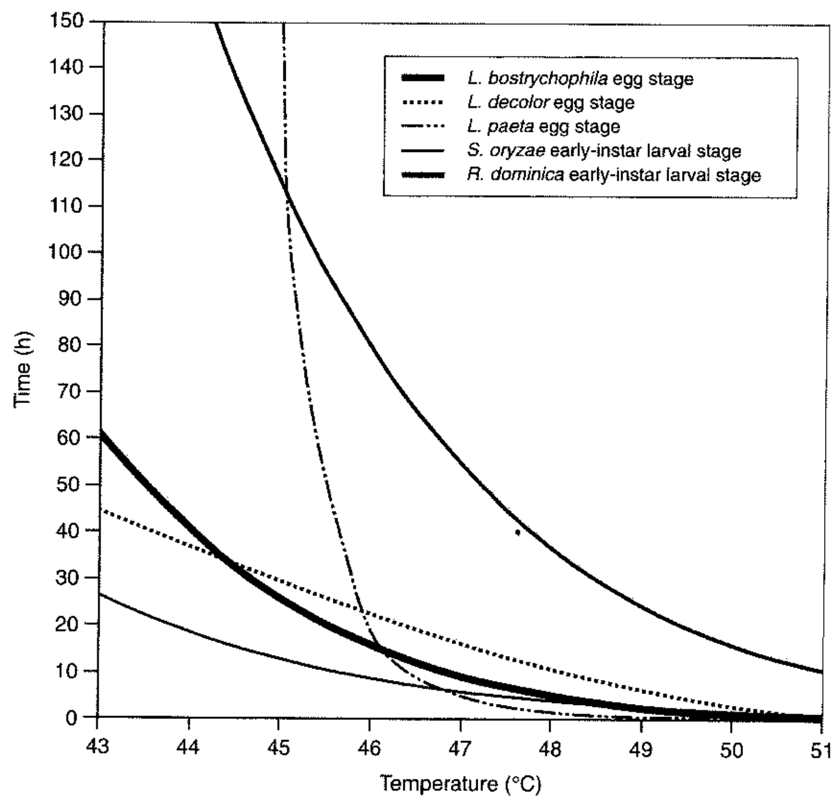


Fig. 8.4. A comparison of the times required to achieve $LT_{99.9}$ at a range of temperatures from 43 to 51°C for the most heat-tolerant stages of three species of Psocoptera, *Liposcelis bostrichophila, L. paeta* and *L. decolor*, and two species of Coleoptera, *Rhyzopertha dominica* and *Sitophilus oryzae*. RH was at 70% except for *S. oryzae*, where it was at 55% (from Beckett and Morton, 2003a).

far more susceptible than *R. dominica*, there is also considerable variation in heat-tolerance among them.

Liposcelis paeta, which survives at temperatures greater than most stored-product insects (Rees, 1998), is even more tolerant than *R. dominica* between 43 and 45°C. At 45°C, where times to mortality are still quite long, *R. dominica* takes roughly five times longer to kill than the most tolerant psocid. However, at 51°C, where times to mortality are short, it takes between nine and 36 times longer to kill than the psocids. *R. dominica* is thought to be the most heat-tolerant stored-product species (Dermott and Evans, 1978), and therefore is used as the reference point for maximum treatment conditions.

Roesli *et al.* (2003) gauged structural heat treatment effectiveness against insect species by examining insect numbers before and after heat treatment of a pilot feed mill, using commercial food-baited traps for several species of beetles and pheromone traps for *P. interpunctella*. The lack of or low numbers of captures of *L. serricorne* and *P. interpunctella* in commercial traps indicated that these species were extremely susceptible to elevated temperatures, while the effectiveness against *T. castaneum* did not last more than 4 weeks. Very limited data are currently available on possible reasons for reinfestation of insect species following an IPM intervention, including heat treatment. Understanding these reasons will help extend the duration of insect suppression obtained following a heat-treatment intervention.

Insect developmental stage

Several studies have shown that the heat tolerance of insects varies with developmental stage (Evans, 1981; Vardell and Tilton, 1981a; Fields, 1992). Beckett *et al.* (1998) quantified and compared variation between five arbitrary developmental stages of the internal developers *R. dominica* and *S. oryzae* over a range of temperatures. For example, in wheat at 14% MC, the time required to achieve 99.9% mortality of young larvae (the most heat-tolerant stage) of *R. dominica* required about 1.5 times more exposure than did old larvae and pupae of the same species at 45°C, and 2.5 times more exposure at 53°C. Because exposure time generally increases exponentially with a decrease in temperature, this finding indicates that the tolerant stage required about 45 h more treatment at 45°C and 2.5 h more at 53°C than did the susceptible stages.

This phenomenon is further illustrated by comparing the mortality responses of psocid eggs and adults (Beckett and Morton, 2003a). For example, at 47°C and 70% RH, the time required for 99.9% mortality of eggs of *L. bostrychophila* and *L. decolor* is 7.4 and 19.4 h, respectively, while that of adults is 1.7 and 3.3 h, respectively.

The relative heat tolerance among developmental stages can vary between closely related species (Mahroof *et al.*, 2003b; Boina and Subramanyam, 2004). Mahroof *et al.* (2003b) showed that young larvae (first-instars) of *T. castaneum* were generally more heat-tolerant at 50–58°C when compared with eggs, old larvae, pupae and adults, whereas Boina and Subramanyam (2004) found that the old larvae of *T. confusum* were more heat-tolerant than eggs, young larvae, pupae,and adults at 46–60°C.

Moisture

As mentioned above, environmental moisture at moderately high temperatures has a substantial impact on the chances of survival of stored-product insects. Environmental moisture refers to atmospheric water or, at the product level, the interstitial atmospheric moisture, which is chemically bound to the product and the moisture adsorbed by the product. Beckett *et al.* (1998) measured the impact of grain MC on the mortality response of *R. dominica* over a range of temperatures and found mortality to be less in grain at high MC than in grain at low MC at all temperatures from 45 to 53°C. For example, the increase in treatment time was 1.5 times greater for 99.9% mortality on 14%-moisture wheat when compared with 9%-moisture wheat. In other words, at 45°C the treatment takes 37 h longer for 99.9% mortality and, at 53°C, 1.7 h longer.

During heat treatment of structures, RH drops as temperature increases (Mahroof *et al.*, 2003a; Roesli *et al.*, 2003) and, at temperatures of 50°C and above, the RH during most of the heat treatment is around 20–25%. In unreplicated trials conducted during heat treatment of a flour mill (R. Roesli and Bh. Subramanyam, unpublished data, 2002), survival of *T. castaneum* adults occurred at higher humidities (> 60%), especially at temperatures < 50°C. However, at temperatures > 50°C, all adults were killed after 60 min of exposure irrespective of the humidity level. Temperatures for effective structural heat treatments should be ⩾ 50°C for at least 24 h or more. Hence, the importance of insect survival due to high humidity levels should not be an issue during structural heat treatments.

Rate of heating

According to Evans (1987) and Sutherland *et al.* (1989), the rate of heating to a target temperature influences the rate of insect mortality. Beckett and Morton (2003b) found that, under particular conditions, this effect can be sizeable. Using hot air at different temperatures to produce different heating rates, the time required for 99.9% mortality of *R. dominica* at grain temperatures of 50–60°C nearly halved as the air temperature was increased from 80 to 100°C. However, as the rate of heating was increased further, the rate of reduction in treatment time decreased rapidly (see Fig. 8.5). In this case, the rate of convective heat penetration and the degree of homogeneous mixing may have been limiting factors.

Mahroof *et al.* (2003a, b) and Roesli *et al.* (2003) found that the rate of heating different areas of structures varied during structural heat treatment, from as low as 0.3°C/h up to 14°C/h for different floors of a food-processing facility. The differences in heating rates are related to horizontal and vertical stratification of temperatures. More work is needed to determine whether heating rate is an important factor that influences insect mortality in heat treatments due to limited data available.

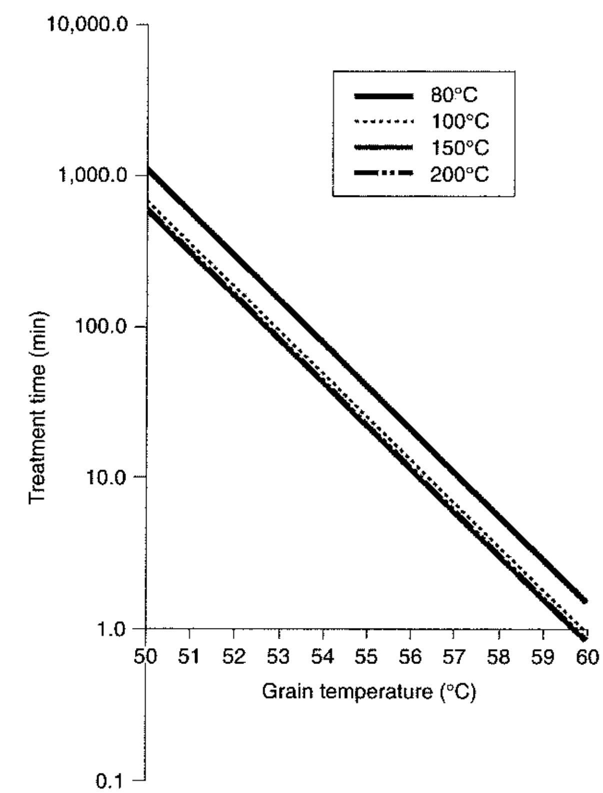


Fig. 8.5. The times required to achieve $LT_{99.9}$ at a range of rates of heating (80–200°C) based on air inlet temperature for a heat-sensitive immature stage of *Rhyzopertha dominica* (from Beckett and Morton, 2003b).

Empirical Methods

Obtaining temperature/mortality data

It is essential, when determining the heat tolerance of a species, that its developmental stages are considered individually, either specifically – which is possible with external developers – or arbitrarily, which is more practical with internal developers. Radiographic techniques can now be used to determine more accurately the age of stages developing within grain kernels (Sharifi and Mills, 1971). Heat should be generated and controlled with precision, and the temperatures measured in a way that is fast, reliable and accurate. The difference of one degree can have a substantial impact on the level of mortality. For example, for *R. dominica* at 14% moisture, the time difference for 99.9% mortality is 2.4 h between 52 and 53°C, 8.4 h between 49 and 50°C and 35.2 h between 45 and 46°C (Beckett *et al.*, 1998).

The method of heat generation is determined by the purpose of the study and the research objectives, be it commodity, storage facility, insect species, rate of heating, treatment temperature, microwave attenuation or infrared treatment. Various systems have been used to investigate rapid disinfestation of bulk grain: (i) fluid bed (Evans, 1981; Evans and Dermott, 1981; Vardell and Tilton, 1981b); (ii) spouted bed (Claflin *et al.*, 1986; Beckett and Morton, 2003b; Qaisrani and Beckett, 2003a); and (iii) pneumatic conveyor (Dzhorogyan, 1957; Fleurat-Lessard, 1980; Sutherland *et al.*, 1989) (see Figs 8.6a–e).

When considering heat dosage rates at moderate temperatures where treatment periods are protracted, controlled-environment cabinets or incubators are sufficient (Vardell and Tilton, 1981a). Beckett *et al.* (1998) combined the use of incubators with sealable containers to maintain constant MC However, the containers included preheated heat sinks to rapidly heat insect-infested grain to the target temperature. Another approach is to place insects confined in vials or bags into temperature-controlled oil baths (Thoroski *et al.*, 1985) or water baths (Bruce *et al.*, 2004).

Other systems rely on methods of heating such as electromagnetic energy in the form of micro- and radiowaves (Nelson and Whitney, 1960; Whitney *et al.*, 1961; Watters, 1976; Plarre *et al.*, 1997; Halverson *et al.*, 1998; Fig. 8.6f) and infrared radiation (Tilton and Schroeder, 1963). Yet another alternative is the high-temperature/short-time technique described by Mourier and Poulsen (2000), which uses equipment called a miroline toaster®, where hot air (150–750°C) is passed through a rotating drum. The grain, which is further heated by infrared radiation from the drum wall, is mixed as it passes through the drum (see Fig. 8.6g).

Another system uses a counter-flow heat exchange process, where grain is augered in the opposite direction to hot water in a surrounding jacket (Lapp *et al.*, 1986; Fig. 8.6h). Some of the technologies mentioned above are described in more detail later in this chapter. For heat treatment of structures, gas, electric or steam heaters can be used, which come with various heating capacities based on need. Equipment for structural treatments will also be described in more detail later.

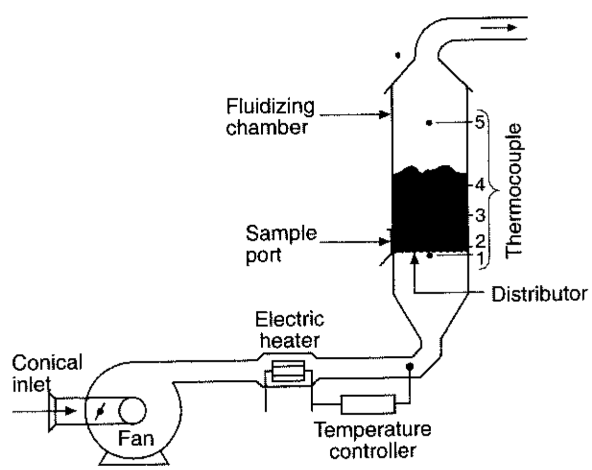


Fig. 8.6a. Batch-type experimental fluid bed (from Dermott and Evans, 1978).

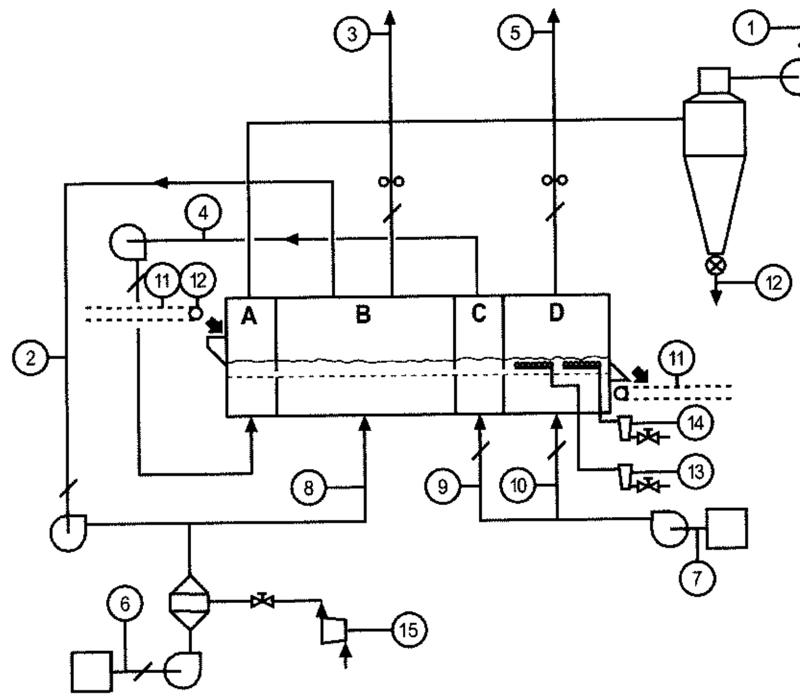


Fig. 8.6b. Continuous-flow fluid-bed process flow diagram (from Thorpe *et al.*, 1984). A, preheating and de-dusting; B, heating; C, cooling; D, evaporative cooling; 1, dust collection; 2, recirculated hot air; 3 and 5, exhaust gases; 4, heat recovery; 6, air intake for heating; 7, air intake for cooling; 8, hot air entry; 9 and 10, cool air entry; 11, grain conveyance; 12, grain inlet; 13 and 14, evaporative cooling system; and 15, LPG supply for burner.

Maintaining product quality and structural integrity

The maintenance of grain and stored-product quality, or the integrity of structures and equipment that experience a heat treatment, are of paramount importance. A heat treatment is not successful if these factors are compromised.

Ensuring product quality

Product quality is an issue when heat is used to disinfest grain, but not during the heat treatment of structures. In the latter case, all food products within structures should be removed to prevent insects from seeking refuge in these products and surviving the treatment. It is good practice to fumigate the removed products so that, if infested, they do not contribute to reinfestation of structures after the heat treatment.

Commodities that are heat-treated may respond in different ways. Wheat is generally considered fairly resilient, but this may not be true for other grains. Grain MC has also been shown to affect quality response to heat treatment

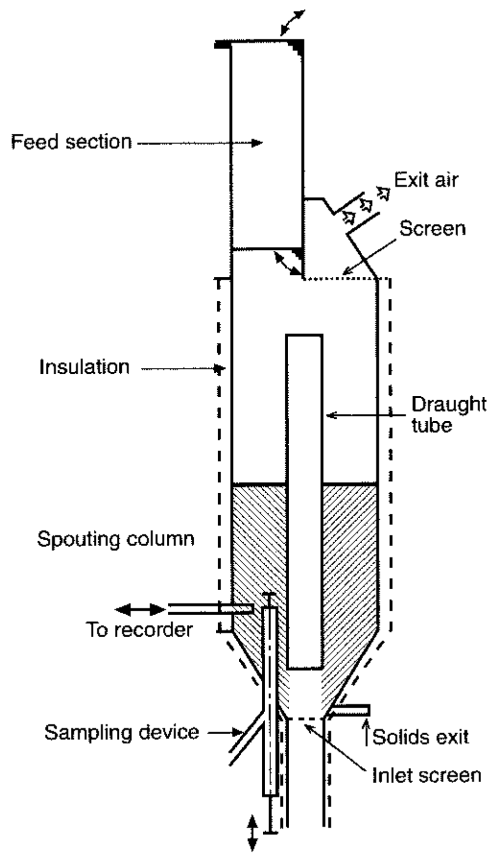


Fig. 8.6c. Batch-type experimental spouted bed (from Claflin *et al.*, 1986).

(Ghaly and Sutherland, 1984; Nellist and Bruce, 1987). An evaluation of germinative capacity provides a relatively quick initial measure of quality deterioration, but to identify any subtle modifications in grain composition, trials, such as dough and baking tests for wheat, micro-malting for malting barley and oil quality analysis for canola, are needed (Ghaly *et al.*, 1973; Dermott and Evans, 1978; Ghaly and Sutherland, 1984; Armitt and Way, 1990).

Dough and baking tests measure parameters such as flour yield, water absorption, dough development time, resistance to extension, extensibility, viscosity and bread volume. Micro-malting analysis measures parameters such as total extractable nutrient, wort colour, total nitrogen, soluble nitrogen, Kolbach index, wort viscosity, apparent attenuation limit, beta-glucan content, diastatic power and percentage malt yield (European Brewery Convention, 1998).

While germination or malt yield may not appear to be affected by heat treatment, other parameters may exist that could have a negative impact on

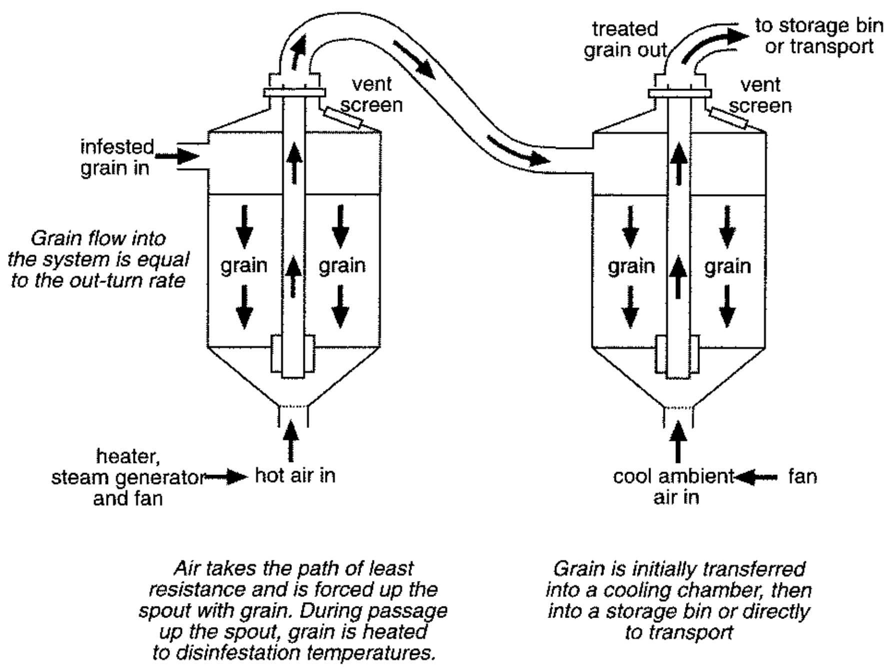


Fig. 8.6d. Continuous-flow spouted bed (adapted from Qaisrani and Beckett, 2003a).

brewing quality. Oil content analysis measures percentage oil, percentage free fatty acids, peroxide value, uric acid, glucosinolates, iodine value and percentage protein (Firestone, 1990). There may also be implications for quality maintenance under long-term storage.

Ensuring structural and equipment integrity

Data on the effects of heat treatments on structures are anecdotal; tests have not yet been developed or proposed to determine the effects on equipment and food-grade materials (gaskets, sifters, paints, lubricants, plastics, electronics, etc.) used in food-processing facilities. This is an area that requires further study.

During heat treatments of pilot flour and feed mills, no adverse effects were observed on the structures and no malfunction of the mill equipment was observed after multiple treatments (Mahroof *et al.*, 2003a; Roesli *et al.*, 2003). However, there have been sporadic reports of adverse effects such as overheating of certain areas due to improper air movement and temperature monitoring, and warping of metal or plastic following a heat treatment. Structural and equipment integrity can be ensured if proper planning and precautions are taken before, during and after a heat treatment (Dosland *et al.*, 2006).

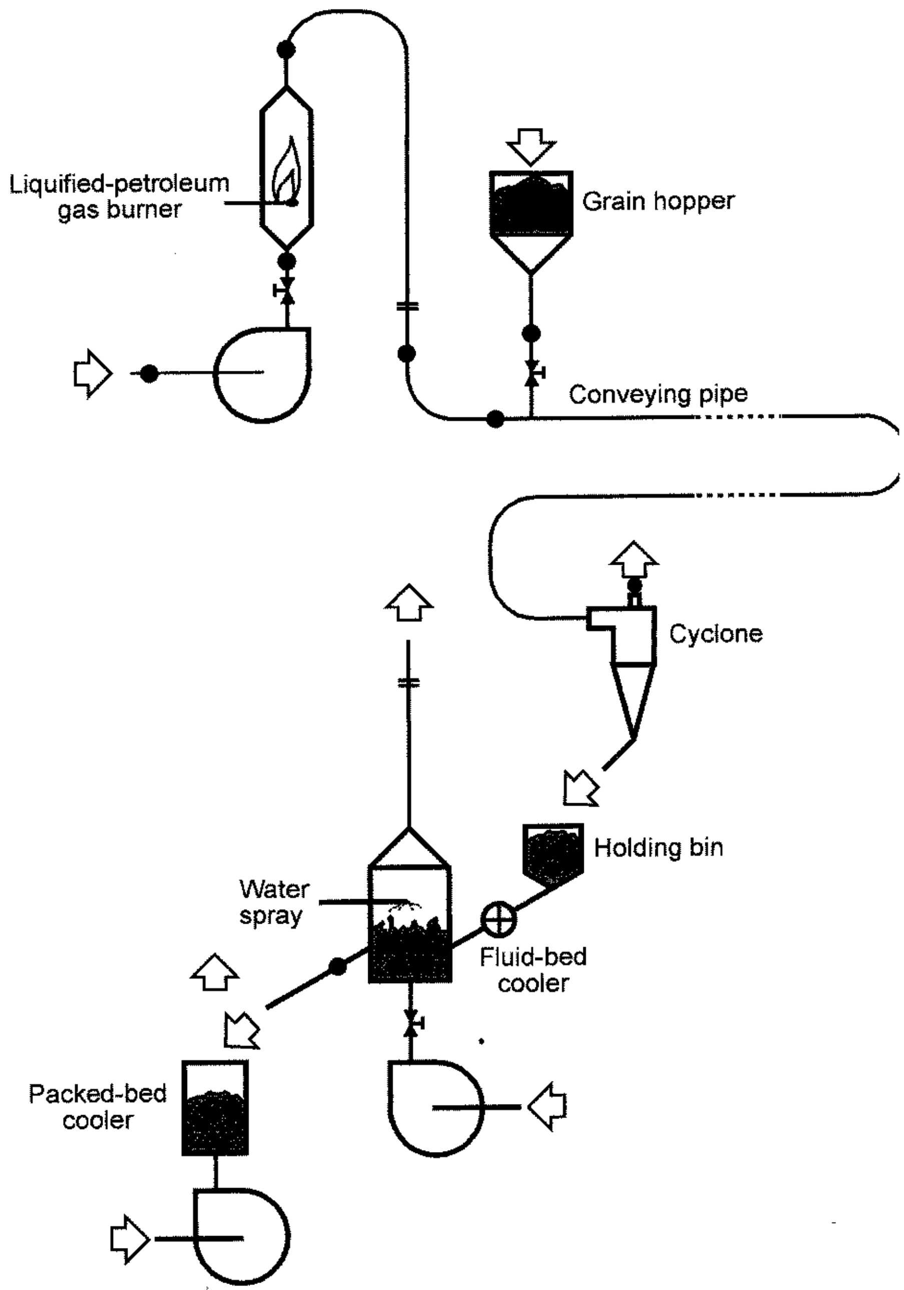


Fig. 8.6e. Pneumatic conveyor process flow diagram (from Sutherland *et al.*, 1989)

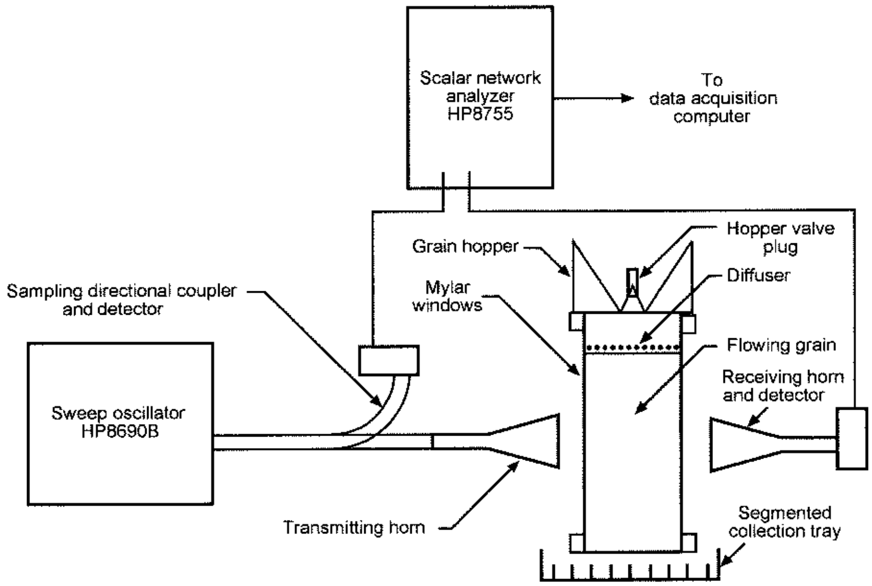


Fig. 8.6f. Microwave equipment for one-way path attenuation tests (from Halverson *et al.*, 1998).

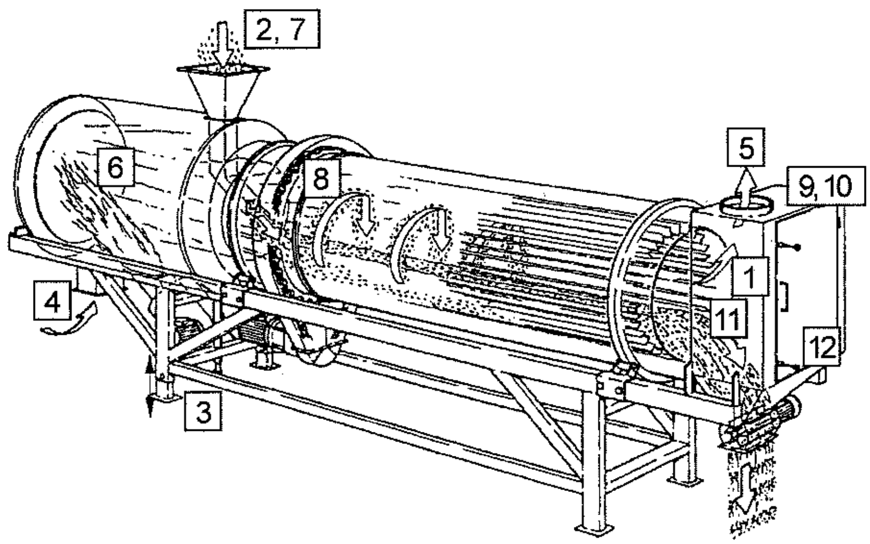


Fig. 8.6g. HTST Miroline toaster® (from Mourier and Poulsen, 2000). 1, air flow; 2, grain inlet; 3, drum inclination; 4, secondary air intake valve; 5, air outlet valve; 6, combustion air thermocouple; 7, material flow sensor; 8, drum rotation guard; 9, thermocouple for outlet air; 10, safety thermostat; 11, pressure guard; and 12, material overflow guard.

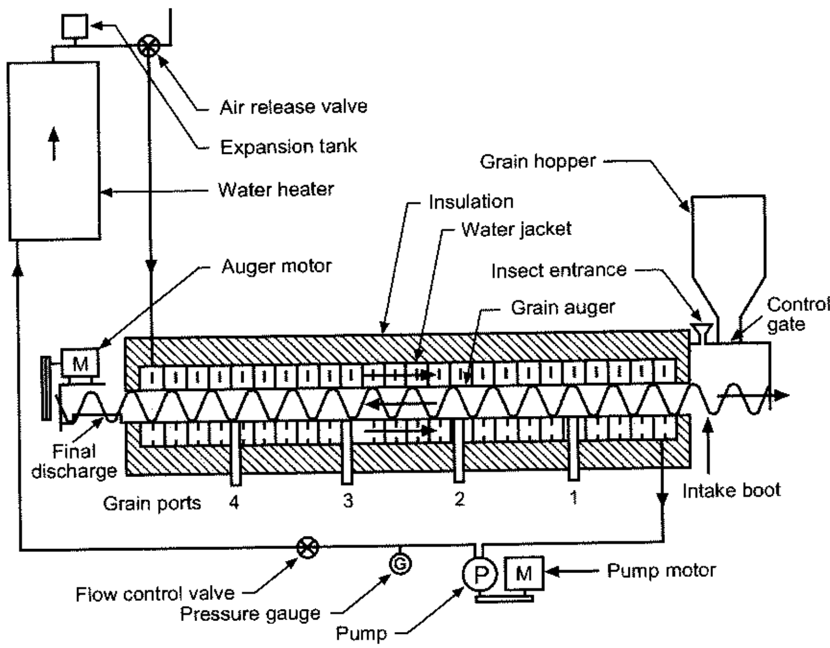


Fig. 8.6h. Counterflow heat exchanger (from Lapp *et al.*, 1986).

Simulation Models

Statistical transformations

Predictive models commonly rely on experimentation where mortality has been determined over a combination of temperatures (usually constant) and exposure times at a constant RH or grain MC. Obtaining sufficient data can be laborious, particularly when high levels of mortality are occurring, but such data are essential if meaningful predictions are to be made. Unfortunately, as mortality increases, the accuracy of predictions decreases and often a level of 99.0–99.9% mortality is considered a good compromise.

Predictions of 50% mortality are the most accurate and thus useful for comparative purposes. The estimation of 95% confidence limits is also useful for comparative purposes, but these expand as the level of mortality increases. They too should be considered with suspicion > 99% mortality, mainly because certainty about the scale of the statistical transformation being used decreases concomitantly.

Probit analysis is a satisfactory means of determining estimates and confidence limits of mortality, giving the linearized probit transformation of sigmoid distributions (Claflin *et al.*, 1986; Evans, 1987; Bruce *et al.*, 2004), which has been frequently used for evaluating lethal dosages of pesticides (Finney, 1971). A modified form of this analysis uses the inverse standard normal deviate (Wright *et al.*, 2002). Logit and complementary log–log transformations may at times fit the data better (Morgan, 1992), especially if mortality is being predicted as a function of temperature or time.

The difference between the three transformations is in the tails, or the first and last 10% of prediction. For heat treatments, interest rests in the upper tail because, the longer the tail, the longer the treatment time needed to kill the last of the population. A probit transformation gives the shortest upper tail, while those of logit and complementary log–log distributions are similar. However, this does not mean that the probit fit will automatically predict treatments for high mortality that are less than those from the other fits because, based on the distribution of the data, the whole curve can shift and the slope may change in an effort to obtain the overall best fit, including the tails.

Based on R^2 values, Beckett *et al.* (1998) found probits gave the best fits for *R. dominica* and *S. oryzae* over the conditions employed, while Beckett and Morton (2003a) found one or other of the other transformations gave better fits for three species of Psocoptera. Mahroof *et al.* (2003b) and Boina and Subramanyam (2004) preferred a complementary log–log transformation for estimating LT_{99} values for various life stages of *T. castaneum* and *T. confusum* exposed to several constant elevated temperatures.

Mortality models

Several models have been applied to temperature–mortality data. Tsuchiya and Kosaka (1943) found that, as temperature increased within the range 60–100°C, insect mortality was related to temperature via the hyperbola:

$$t_{x\%}\left(T - c\right) = \mathrm{K} \tag{8.1}$$

where c and K are constants, $t_{x\%}$ is the treatment time to a given percent mortality, and T is the treatment temperature. Under circumstances of rapid convective heating, the inlet air temperature can be related to treatment temperature and time for a given mortality (Dermott and Evans, 1978; Fig. 8.7), with the linear equivalent being more convenient:

$$1 / t_{x\%} = \mathrm{a} + \mathrm{b}T \tag{8.2}$$

where $t_{x\%}$ is the treatment time to a given per cent mortality, T is the treatment temperature and a and b are the intercept and coefficient of a linear regression equation, respectively.

Alternatively, Fleurat-Lessard (1985) used the following equation:

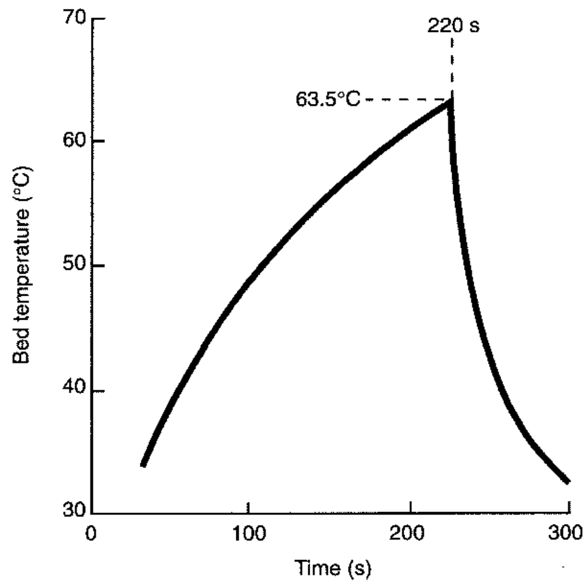
$$T_{max} - T = \mathrm{ab}^{t}x\% \tag{8.3}$$

where T_{max} is the inlet air temperature.

The Arrhenius equation, which describes the affect of temperature on the rate of chemical reactions, has been used to model mortality data from cold treatments (Brokerhof *et al.*, 1992; Banks and Fields, 1995). This model is described as:

$$1/t_{x\%} = \mathrm{A}c^{-b/T} \tag{8.4}$$

where A is a constant.



Batch heating and cooling of wheat to kill stages of *Rhyzopertha dominica.*

Air inlet temperature – 80°C

Air flow rate – 14.5 l/kg/s

Fig. 8.7. Heating and cooling curve for wheat exposed to 80°C for 220 s with an air flow of 14.5 l/kg/s at 1.6 m/s (from Dermott and Evans, 1978).

Mortality can also be modelled as a function of a temperature–time product that accrues above an arbitrary threshold temperature (Dermott and Evans, 1978; Banks and Fields, 1995; Wright *et al.*, 2002). This is similar to the concentration–time product concept used with fumigation and is described as:

$$t_{x\%}(T - T_0) = \mathrm{k} \qquad (8.5)$$

where $t_{x\%}$ is the treatment time for a given percentage mortality, T is the treatment temperature, T_0 is the threshold temperature and k is the accrued product constant. With this approach, changing temperature effects can be integrated and any statistical transformation can be used via:

$$\mathrm{y} = \mathrm{a} + \mathrm{bk} \qquad (8.6)$$

where y is the transformation corresponding to an observed mortality (Wright *et al.*, 2002). Wright *et al.* (2002) used this degree–minute approach for predicting the mortality of large larvae of *T. variabile* by obtaining time–mortality data at four constant temperatures between 50 and 56°C. The base temperature for accumulating degree–minutes, the intercept and slope of the linear regression of mortality (expressed as the inverse of the standard normal deviate) and the degree–minutes were different at each of the four temperatures. Despite these differences, Wright *et al.* (2002) pooled the data across 52, 54 and 56°C to describe the relationship between degree–minutes and mortality of *T. variabile* larvae. No statistical or biological basis was given for pooling the data across the three temperatures.

Subramanyam *et al.* (2003) developed a simple heat-accumulation model for predicting the mortality of first-instars of *T. castaneum* based on time–mortality data collected at six constant temperatures between 42 and 60°C (Mahroof *et al.*, 2003a). Independent data on first-instars, collected at the same constant temperatures, were used to validate the model. The base temperature for accumulating degree–minutes was 49.1°C and the model underestimated mortality by 25%, but explained about 70% of the variation in observed mortality of insects as a function of both temperature and time. These models need to be refined and validated under field conditions for predicting incremental mortality of insects at dynamically changing temperatures and times that occur during commodity or structural heat treatments.

Beckett *et al.* (1998) developed a model to cater for a range of grain temperatures and MC, and where control mortality is unknown, such as when immature stages are hidden within grain kernels or eggs are buried in substrate (Wadley's Problem). In this model, the expected survival of a given treatment is multiplied by the probability P, which is modelled by a linear predictor η on the scale of a given transformation (probit, logit, complementary log–log).

The confidence limits for the lethal time estimates (LTs) at a given percentage mortality (i.e. the time range in which one is confident that a treatment will give a certain level of mortality, say, 95% of the time) are obtained by a linear Taylor expansion of ln (LT). Thus, the model centres on the mid-point of the range of temperatures and grain MC, and a given LT is calculated as follows:

$$\mathrm{LT} = \exp((\eta - \beta_1 - \beta_3(T - T_{mid}) - (\beta_5 + \beta_6(T - T_{mid})) \\ (MC - MC_{mid}))/\beta_2 + \beta_4(T - T_{mid}) + \beta_7(MC - MC_{mid}))) \tag{8.7}$$

where β_1 is the intercept, β_2 is the time coefficient, β_3 is the temperature coefficient and β_4 is the product term of time and temperature interactions. If there is only one moisture parameter, the last three regression coefficients are removed and the equation is simplified as:

$$\mathrm{LT} = \exp((\eta - \beta_1 - \beta_3(T - T_{mid})) / \beta_2 + \beta_4(T - T_{mid})) \tag{8.8}$$

A novel model for predicting survival of heat-tolerant old or late-instar larvae of *T. confusum* during structural heat treatments was developed and validated at Kansas State University (Boina, 2004). The final model has the following form:

$$N_t = \frac{N_o}{10^{\left(\sum_0^t \frac{\Delta t}{D(T_t)}\right)}} \tag{8.9}$$

where N_t is the insect population after time t, N_0 is the initial insect population, Δt is the incremental exposure time (usually 1 min), $D(T_t)$ is the mean instantaneous value of D as a function of temperature and T_t is the time-dependent temperature profile. *D*-value, in microbiological applications, is the time required for one log reduction in population.

The model was developed for heat-tolerant *T. confusum* old larvae (Boina and Subramanyam, 2004) based on data at constant temperatures between 46 and 60°C, validated for the species in a structural heat treatment, and found to be satisfactory in describing insect survival at nine different heating rates. Figure 8.8 shows model predictions at two heating rates.

8.6 Current Status of Research and Development in Heat Disinfestation of Stored Products

Many approaches to heat disinfestation of stored products have been developed and advanced over the last 50 years, with technologies borrowed from a range of industries and governed by some combination of the physical principles of

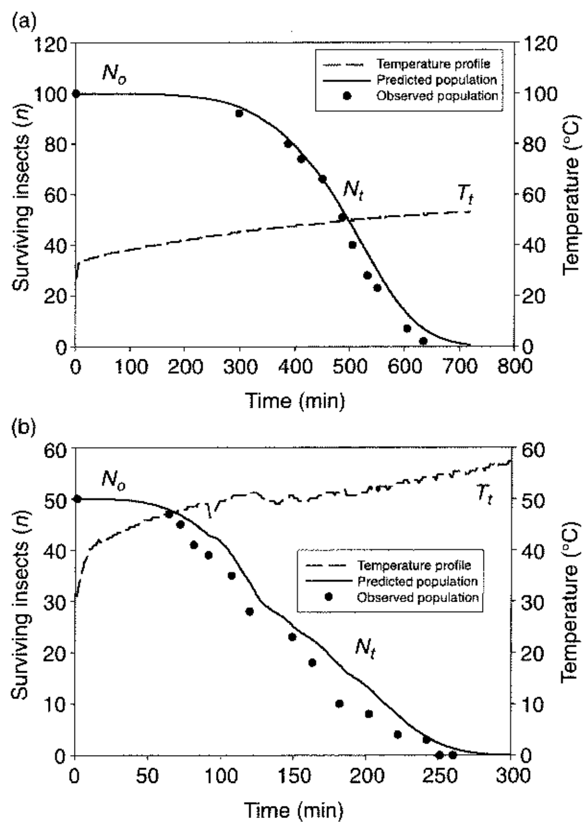


Fig. 8.8. Observed and predicted survival of *Tribolium confusum* old larvae during heat treatment at 2.44 °C/h (a) and 5.50 °C/h (b) at Kansas State University feed mill (from Boina, 2004).

mechanics, fluid dynamics, thermodynamics, heat and mass transfer and electromagnetic radiation. Several of these approaches are discussed below.

Convective Heating

Fluid bed

A fluid bed for the purpose of heat disinfestation is comprised of a column of grain supported by a perforated distributor plate. Air is passed through the distributor at a velocity sufficient to suspend, separate and mix the grain, which is called fluidization. Air at high temperatures can therefore be used, allowing rapid and uniform heat transfer and precise temperature treatment of the grain mass (see Fig. 8.6a, b). This technology serves both as an experimental tool to study heat dose mortality and a potential practical means of heat disinfestation (Dermott and Evans, 1978; Lim *et al.*, 1978; Fleurat-Lessard, 1980; Evans, 1981; Evans and Dermott, 1981; Vardell and Tilton, 1981a, b; Evans *et al.*, 1983).

The rapid disinfestation of large grain volumes requires a continuous flow process that depends on consideration of longitudinal dispersion of grain through a bed during treatment; hence, the residence time of the grain in the bed must be sufficient to achieve optimum disinfestation temperature (Evans *et al.*, 1983). The same principle is used to cool the grain, either with ambient air or air in combination with water spray for evaporative cooling. Relative to the other convective systems, cooling is considered easy and efficient.

There are several commercial prototypes, from a capacity of 10 t/h to the largest at 150 t/h. The latter was built and trialled in Victoria, Australia in the 1980s (Thorpe *et al.*, 1982, 1984; Evans *et al.*, 1984; Fig. 8.9). At full capacity, the plant achieved complete disinfestation of *R. dominica* in wheat at a air flow rate of 2.1 kg/s/m^2, an air inlet temperature of 230°C, a grain residence time of 2.2 min and a grain temperature of 70°C. Wheat quality as determined by dough and baking tests was unaffected.

At an initial grain temperature of 25°C, the energy requirement was 1.13 kWh of electricity and 26.6 kWh of gas/t. Heating efficiency was increased by recirculating hot air from the top of the bed back into the heating system, which caused blockage of the distributor plate with entrained husks, largely overcome by using a recirculating fan as a centrifugal separator and inserting a cyclone in the recirculating duct.

Plans for a 500 t/h plant were considered, dependent on how hot the inlet air could be before affecting grain quality. A hybrid bed consisting of multiple hexagonal apertures to overcome the likelihood of blockage resulted (Gray and Darby, 1996). Capital costs and the cheaper cost of fumigation have halted further developments for the time being.

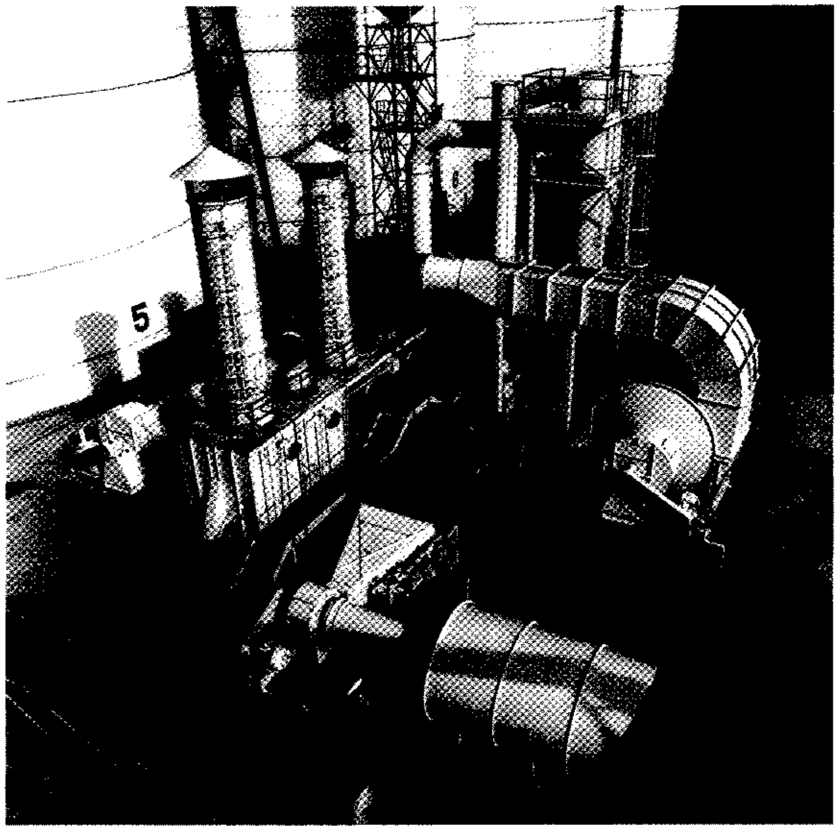


Fig. 8.9. Continuous-flow fluid bed heat disinfestation plant (150 t/h capacity) in Victoria, Australia.

Spouted bed

A spouted bed also uses hot air to lift, mix and heat grain. However, it differs from the fluid bed in that the air enters the column by passing at relatively high velocity through a nozzle at the bottom of a conical floor that causes the grain to 'spout' above it rather than 'fluidize' (see Fig. 8.6c, d). Thus, the grain moves in a more regular circular motion during heating, up the spout and down the annulus, rather than undergoing the bubbling motion of the fluid bed. The spouted bed also uses lower air velocity and operating pressures, and has better thermal economy (Mathur and Epstein, 1974).

Another advantage of the spouted bed is its ability to handle larger grains such as maize. It was initially developed in Canada for grain drying (Mathur and Gishler, 1955), but was subsequently investigated for its heat disinfestation potential (Claflin and Fane, 1981). Claflin *et al.* (1986) reported extensive trials with a 24 kg-capacity batch system, where the inclusion of a draught tube above the inlet nozzle gave more even heat treatment, which is essential for disinfestation.

The operating costs of the two systems are similar (Claflin *et al.*, 1986), and there is no inherent problem of air flow blockage by entrained debris. However, the difficulty with spouted beds is in scaling up to deal with large throughputs. This could partially be overcome by employing a multi-spouted system where a bed would have several cells, each up to a 1 m^2, with a throughput of 50–100 t/h operating in parallel and in series (Sutherland *et al.*, 1987). However, if total throughput requirements become too large (e.g. 400 t/h), the system becomes too complex for practical purposes.

In response to the commercial potential for farm-scale spouted bed use, a prototype continuous-flow system was constructed that can successfully operate at a rate of 8 t/h (see Fig. 8.10). The system consists of a heating and cooling chamber (0.75 × 0.75 × 1.5 m), each containing a draught tube to transport the grain out. Hot air at 220–250°C, heated via a LPG burner, enters the heating chamber at 0.25 m^3/s. Grain rises in the spout and passes up the draught tube into the cooling chamber, while being heated to just above 60°C. The same process is then repeated with ambient air in the cooling chamber. Cost of treatment in 2002 was about US$0.90/t (Qaisrani and Beckett, 2003a).

Pneumatic conveying

This means of convective heating takes advantage of a common method of handling, except that the air used to transport the grain is heated. Disinfestation by pneumatic conveying has been considered for some time (Dzhorogyan, 1957; Fleurat-Lessard, 1980), including as an alternative to fluid- and spouted-bed processes (Sutherland *et al.*, 1986, 1989).

This involved a detailed assessment of a system composed of a 30 m long × 50 mm diameter conveying pipe with air supplied by a centrifugal fan and

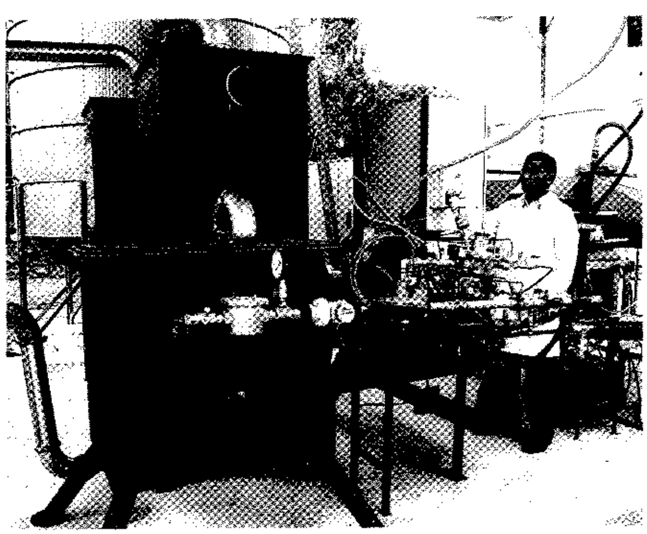


Fig. 8.10. Prototype of continuous-flow spouted bed heat disinfester (8 t/h capacity).

heated by an 80 MJ/h capacity liquefied petroleum gas burner giving air temperatures up to 320°C and a grain throughput capacity of up to 1 t/h (see Fig. 8.6e). Grain was fed into the conveying pipe via a venturi feeder and removed from the air at the end via a high-efficiency cyclone. The grain was then cooled by either a column cooler or fluid bed (Sutherland *et al.*, 1986).

The advantages of pneumatic conveying are: (i) grain heating is very rapid and not constrained by air velocity as it is with fluidization; (ii) there is no dispersion of grain residence time that gives uneven treatment; and (iii) chaff and dust remain with the grain. A grain-holding stage can also be included before cooling, which allows for lower grain treatment temperatures. The disadvantages are: (i) conveying time may be too quick for grain temperature to equilibrate; (ii) grain temperatures are harder to measure and control; (iii) thermal efficiency is poor without air recirculation; and (iv) cooling as a separate process is inefficient (Sutherland *et al.*, 1987). Because of the short particle residence times and containment of chaff and dust, pneumatic conveying is also not practical for either grain drying or grain cleaning, and it remains unconfirmed for large grain throughputs.

Computer simulations of the three convective systems show that the energy costs of the fluid and spouted beds are proportional to grain flow rate, but slightly lower for the spouted bed. If inlet air temperature is increased from 100 to 300°C, there is a clear cost advantage, but a further increase to 500°C does not overcome the extra capital cost involved. Although the energy costs of the pneumatic conveyor system are larger than those of the other systems and are not proportional to flow rate, they decrease as throughput increases. None the less, the pneumatic conveyor is thermally less efficient.

Grain dryers

Much of the data on grain viability and quality come from work on grain drying and storage (Ellis and Roberts, 1980; Nellist, 1981; Dickie *et al.*, 1990). Probit, or the inverse standard normal deviate can be applied equally well to measuring decline in seed viability as insect mortality. Several studies have also assessed the feasibility of using grain dryers for heat disinfestation, as such equipment is often readily available and would negate capital cost constraints.

Bruce *et al.* (2004) conducted detailed trials with a popular type of mixed-flow dryer in the UK, for which good drying simulation models exist. Qaisrani and Beckett (2003b, c) assessed the potential of using a commonly used cross-flow and radial-flow dryer in Australia. Results generally point to uneven heating and less-than-perfect mixing of grain. However, high levels of insect mortality can be achieved, and easily identifiable modifications to existing equipment could improve results considerably.

Conductive Heating

Developed and used at the beginning of the century (Winterbottom, 1922), the Poole and Steel wheat heater (see Fig. 8.2) was noteworthy not only because it marked the beginning of interest in thermal energy as an industrial disinfestation process, but also because it relied on conductive heating, which has the potential to be thermodynamically more efficient than convective heating in terms of thermal load, driving force and heat contact. Moreover, energy is not wasted moving and mixing the grain because it moves by gravity and, by falling over a series of steam-heated metal rods in alternating alignment, good mixing is ensured. Issues of dust generation, condensation and combustion may also be less problematic. While cooling was not included in the Poole and Steel rig, a similar process to heating could be envisioned using coolant-filled rods refrigerated by a heat pump.

Electromagnetic Energy

Micro- and radiowaves

The use of microwaves (MW) (Watters, 1976; Halverson *et al.*, 1997, 1998; Plarre *et al.*, 1997) and radiowaves (RF) (Nelson and Whitney, 1960; Whitney *et al.*, 1961; Nelson and Kantack, 1966) for heat disinfestation of grain has been extensively researched, mainly as a more efficient method of eradicating insect pests. Nelson (1973, 1987, 1996) evaluated the potential of this method of generating thermal energy as a treatment and reviewed the status of the technology.

Generally speaking, radiowaves range from very low frequency/long wavelength (10^4 Hertz/10^4 m) to extreme high frequency/short wavelength (10^{11} Hertz/10^{-3} m). However, the portion of the electromagnetic spectrum between 30 and 300 MHz with wavelengths from 10 to 1.0 m, respectively, defines the specific radio frequency (RF) range, while microwaves are around 10^{10} Hz/0.01 m.

Two kinds of physical processes describe how RF and MW energy is absorbed at the molecular level in the material: (i) heating of the material by ionic conductivity; and (ii) heating by dielectric polarization (where electric dipoles of molecules interact in an oscillating electric field). The main significant differences between RF and MW heating are power density and wavelength. Since the power density within the material is proportional to frequency, power densities for MW heating are considerably higher than those for RF. Depth of penetration is directly proportional to wavelength, and since RF wavelength is greater than MW, RF may be used to treat much thicker materials.

Any energy efficiency advantage from electromagnetic heating depends on the potential use of selective heating due to the significant dielectric difference between insects and grain, particularly between 10 and 40 MHz. At these conditions, the contaminating insects should experience lethal temperature before significant power is wasted heating the grain bulk. The dielectric properties of several stored-product species were presented by Nelson *et al.* (1998) and Nelson (2001), and wheat permittivity measurements by Kraszewski *et al.* (1996). The frequency dependence of the dielectric loss factor of bulk samples of adult *S. oryzae* and hard red winter wheat at 24°C and 10.6% MC is shown in Fig. 8.11 (Nelson, 1996).

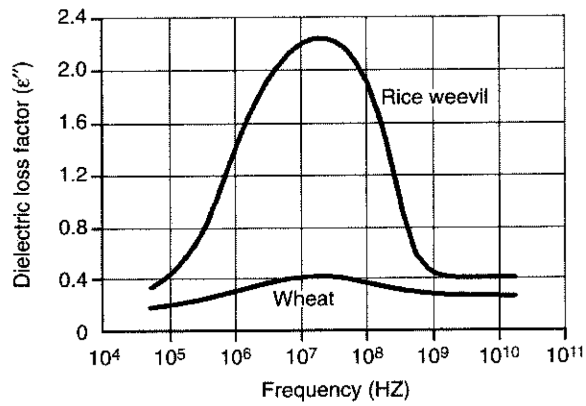


Fig. 8.11. Frequency dependence of the dielectric loss factor of bulk samples of the rice weevil, *Sitophilus oryzae*, and of hard red winter wheat at 24°C with 10.6% MC (from Nelson, 1996).

Nelson (1996) found no cost-saving advantage from the phenomenon because, once significant heat transfer to bulk grain begins in the RF heating process, selective heating cannot work to economic advantage and treatments ultimately generate bulk grain temperatures equivalent to other methods.

In comparison, Wang *et al.* (2001, 2002, 2003) had some success using RF to treat walnut pests. Not only can RF be used to rapidly heat walnut kernels to treatment temperatures that can then be maintained with hot air, but RF may also be an efficient method of drying after a common water bleaching process. Furthermore, clear differential heating was demonstrated using a surrogate gel material with similar dielectric properties to the codling moth (*Cydia pomonella* (L.)) pest. When placed inside the walnut and the kernel heated from 20 to 53°C at 27 MHz, the gel had a heating rate 1.4–1.7 times faster than the kernel, reaching temperatures 12.6–21.2°C higher than it. These results, along with no evidence of significant effects on quality, hold out promise that progress may also be made for grain disinfestation with RF.

Infrared radiation

Infrared radiation (non-ionizing radiation) is electromagnetic energy with wavelengths (0.075–1000 μm) longer than visible light (380–750 nm) and shorter than MW (0.1–100 cm; Penner, 1998). This energy is transferred to whatever material absorbs it, and the absorbed energy causes a measurable change in the material's temperature. This radiant 'heat energy transfer' depends on how readily the molecularly bonded atoms in the material convert the incident radiant energy into molecular vibrational energy that in turn raises the temperature of the absorbing material and its surroundings. Water readily absorbs mid-infrared radiant energy by the symmetric and asymmetric stretching of molecular bonds between oxygen and hydrogen atoms and by bending of the same bonds (Wehling, 1998). The wavelengths most associated with these absorption mechanisms fall between about 2.8 and 7.0 μm.

The unique nature of infrared radiation absorption by water has been used for rapid drying of cereal commodities, especially wheat (Bradbury *et al.*, 1960) and rice (Schroeder, 1960; Schroeder and Rosberg, 1960; Faulkner and Wratten, 1969). Blazer, in 1942, was the first person to suggest direct application of infrared irradiation to control stored-grain insects (Frost *et al.*, 1944). Because insects have a higher percentage of water (> 60) compared with grain, it is likely that they would absorb more infrared radiation than grain and heat up faster.

The selective rapid heating of insects as opposed to grain – presumably without loss of grain quality – makes the use of infrared radiation an appealing technology for stored-grain insect control. Frost *et al.* (1944) measured internal temperatures of four species of stored-grain insects exposed to various wavelengths, intensities and exposure time, and attributed their mortality to increased body temperature.

The use of intense infrared radiation was evaluated two to three decades ago in the USA for killing immature stages of stored-grain insects developing within kernels and adults (Tilton and Schroeder, 1963; Cogburn, 1967; Cogburn *et al.*, 1971; Kirkpatrick and Tilton, 1972; Kirkpatrick *et al.*, 1972; Kirkpatrick, 1973; Tilton *et al.*, 1983). In all these tests, infrared radiation sources used natural gas or propane combusted over ceramic panels in the presence of oxygen. These gas-fired radiation sources were of high intensity (3360 g-cal/s or 48,000 BTU/h), producing temperatures close to 926°C. The infrared radiation wavelength produced was 2.5 μm; small amounts of carbon dioxide and water vapour were also produced.

Kirkpatrick and Tilton (1972) exposed 100 adults of 12 stored-product insects in 150 g of soft red winter wheat (13.5% moisture) placed below the gas-fired heater in a single kernel thickness layer, 65 cm from the radiation source. From an initial temperature of 26°C, the grain attained a final temperature of 49°C in 20 s, 57°C in 32 s and 65.5°C in 40 s. A 40-s exposure was necessary to kill 99.6% of 12 species of adult stored-grain insects.

Control of immature stages developing within kernels requires higher temperatures than that required for killing exposed adults. Schroeder and Tilton (1961) reported complete control of *S. oryzae* and *R. dominica* stages developing inside kernels of rough rice at final grain temperatures averaging 56 and 68°C, respectively. The final temperature of rough rice (41–63°C) was inversely related to its distance from the heater (15.2–50.8 cm) and increased with an increase in exposure time at any given distance from the heater (Tilton and Schroeder, 1963).

The mortality of immature stages of *R. dominica*, *S. oryzae* and *S. cerealella*, based on emergence of adults from irradiated samples, varied between the species, and the treatments did not completely prevent adult emergence. The order of species susceptibility (high to low) was *S. oryzae*, *S. cerealella* and *R. dominica*. The authors extrapolated the adult emergence curves as a function of temperature and recommended a final grain temperature of 65–70°C for killing immatures of all three species. A final temperature of 59°C was attained after a 29-s exposure of soft red winter wheat at 65 cm distance from the infrared source. At this temperature, adult *R. dominica* mortality was 61% and adult emergence from immatures developing within kernels was 55% (Kirkpatrick *et al.*, 1972). A comparison of infrared and MW radiation against *S. oryzae* in soft red winter wheat revealed that infrared radiation was superior to MW in killing both adults and immatures developing within the kernels (Kirkpatrick *et al.*, 1972).

Potential for Heat Disinfestation of Stored Products

Opportunities to reduce costs may come from increasing the rate of heating and decreasing the treatment temperature (Beckett and Morton, 2003b; Fig. 8.12). However, decreased treatment temperature means an increase in treatment time, which has logistical and quality implications. It should be remembered that, for any given treatment time, the temperature required for most external developing species and *Sitophilus* spp. is relatively low compared with *R. dominica* (see Table 8.2).

So if this species is not present, the operating costs may be competitive and the capital cost recoverable. New developments in the application of electromagnetic energy may also lead to a reduction in treatment costs, and methods that rely more on conductive heat transfer could theoretically be promising. Another possible approach to cost-effective heat disinfestation is lower application temperatures, but in conjunction with an additional treatment such as an insect growth regulator.

8.7 Heat Disinfestation of Structures

The goal of a heat treatment is to control insects within a structure without damaging any product left in the equipment or the structure itself. Heat treatments are a well-established method of insect control in the food-processing industry, and the current practice is to warm the building up at 5°C/h to a target temperature of 50–57°C, hold this temperature for 24–36 h and, finally, cool the building at 5–10°C/h.

This intensity and duration of heat may seem excessive given that insects die in only a few minutes at 50°C (Fields, 1992; Strang, 1992; Table 8.1), but because the heat is generated from a few point sources, different parts of facilities heat up at radically different rates. For example, the metal surface of a roll stand will heat up rapidly, but a pile of flour inside a cinderblock wall will not. Therefore, the 24–36 h hold time at 50°C is needed to allow for the heat to reach all parts of the building (Dowdy, 1999; Fig. 8.13).

The two basic approaches to heat treatment are either heating the entire facility or only a section (e.g. a room with roll stands or sifters). There are several advantages in heating the entire facility, primarily that insects cannot escape to other, untreated parts of the building. Depending upon the design of the facility, if one section is not in production, the other areas also cannot

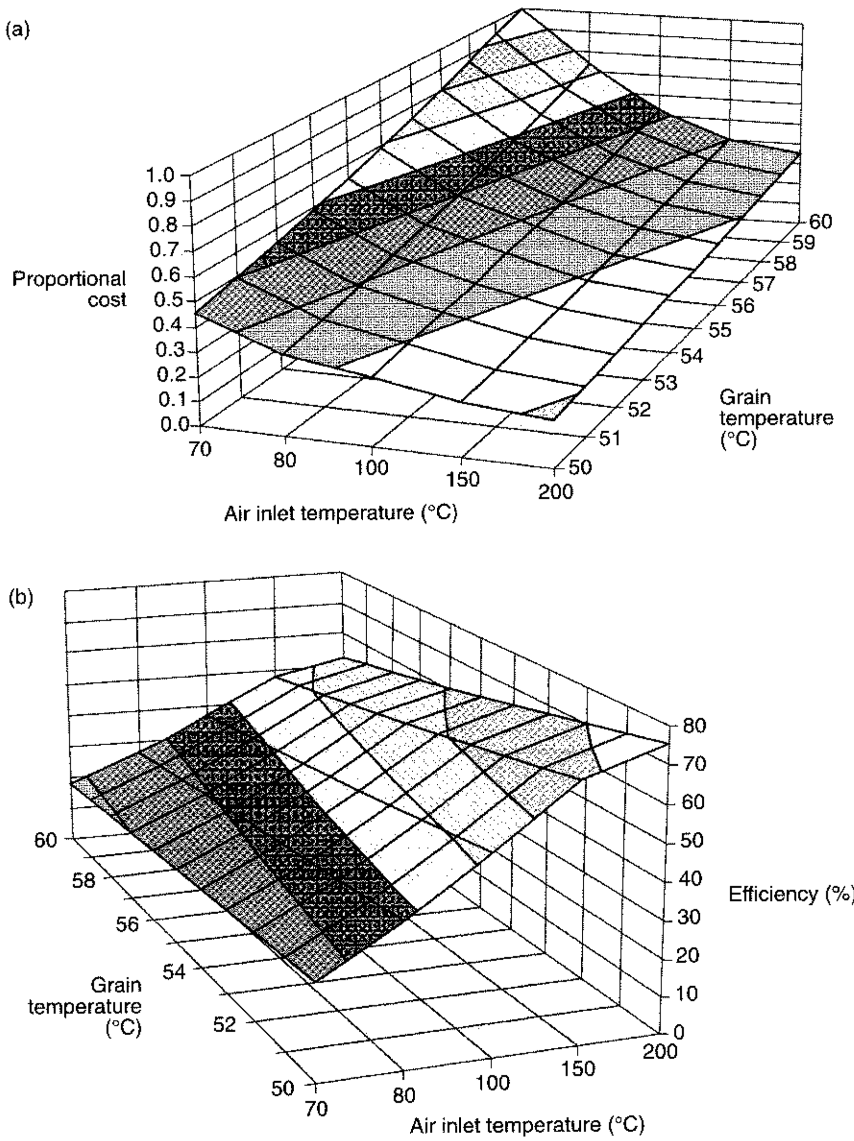


Fig. 8.12. The proportional cost (a) and relative efficiency (b) of heating bulk grain to a range of temperatures (50–60°C) using air inlet temperatures at 70–200°C.

function, so it is best to cover all parts of the facility at once to maximize production. It may also be more efficient for heating, as heat escaping from one area may move to another heated area. Finally, a whole-structure heat treatment is preferable because it is difficult to know all of the locations where insects are present.

Several food-processing companies choose to heat treat only part of their

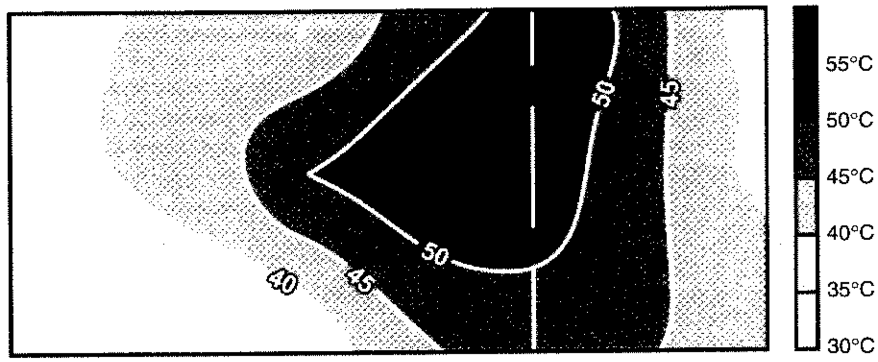


Fig. 8.13. Temperature gradients that develop during the heat treatment of a flour mill. The target temperature is 50–57°C for 24–36 h (from A.K. Dowdy, 1999, personal communication).

facilities at any one time (Heaps, 1996; Norstein, 1996), to reduce the number of heaters required and thus lower the capital cost for heat treatment. Some facilities are designed so that production can continue while the other sections of the facility are stopped for servicing. The size of the area of partial heat treatment may be as large as half of the facility, or part of a floor sectioned off with tarpaulins from floor to ceiling, or a single piece of equipment covered with a tarpaulin to contain the heat.

Unlike a fumigation, where the entire facility must be vacated, heat treatment of part of a facility does not force the rest of the facility to be vacated. Spot-heat treatment also allows for the rapid treatment of specific pieces of equipment, which can be heated and cooled more rapidly than entire structures, so that an individual machine need only be off-line for half a day (Norstein, 1996).

Equipment

Steam, gas or electrical heaters can be used for heat treatment. Steam is the least expensive form of heat. Some food-processing facilities (breakfast food, pasta, bakeries and pet food) use heat as part of their production. These facilities often use steam heat with boilers on-site. For facilities without boilers, portable boilers are available that provide sufficient heat for heat treatments. Steam heaters specifically built for heat treatments can be either fixed or portable (see Fig. 8.14a, b, c), but need pipes or hoses to carry the steam to the heater and return lines for the distillate (see Fig. 8.14a).

Gas- or propane-fired heaters are also popular (see Fig. 8.14b, c) and come in many sizes, usually placed on the outside of the building, forcing hot air inside (Norstein, 1996; Johnson and Danely, 2003) to maintain a positive pressure in the building, thereby carrying the hot air throughout the structure. This method requires more heat than heaters within the building. The most expensive form of heat is electric, so it is used only on a trial basis on a small-

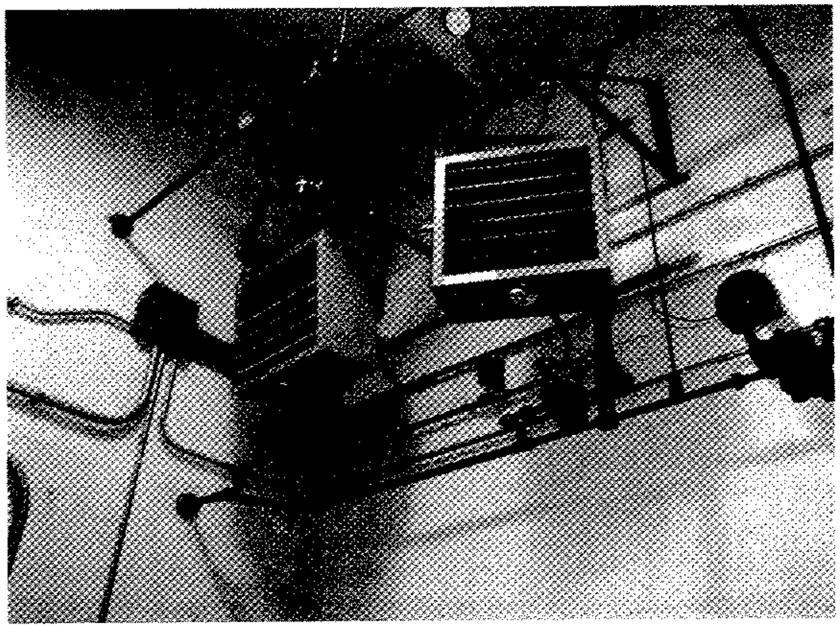


Fig. 8.14a. Fixed steam heater used in food-processing facilities.

Fig. 8.14b. Portable low-pressure steam heater used in food-processing facilities.

scale (i.e. not to heat treat entire structures; Imholte and Imholte-Tauscher, 1999).

Air circulation is almost as important as heating, but is often neglected in heat treatments (Dosland *et al.*, 2006). To distribute heat throughout an entire structure, eliminate cool spots (see Fig. 8.13) and avoid the potential for damage from overheating; good air circulation is essential. Swivel fans provide

Fig. 8.14c. Propane-fired heater used in food-processing facilities.

better circulation than fixed fans, but both must be able to operate at > 50°C for 36 h. Extra fans are usually installed, as some can be expected to fail during the treatment.

Just as measuring the concentration of methyl bromide is essential for a successful fumigation, so is measuring temperature key for a successful heat treatment. Temperatures should be recorded at least every hour or at shorter time intervals during the entire heat-up and cool-down. Some companies that regularly conduct heat treatments measure air temperatures with a hand-held thermometer at chest height once an hour in each corner of each room. Once all readings in a room attain 50°C, they maintain at least that temperature for 24 h. Fans on heaters may be shut off to prevent overheating. At the same time temperatures are taken, the facility is inspected for problems such as activated sprinkler systems, fan and heater operation, oil spills, etc.

Infrared thermometers allow for quick measurements of hard-to-reach surfaces. Care must be taken, as objects give different temperature readings due to different infrared emissivity even though they are at the same temperature. One way to prevent this is to place pieces of tape throughout the facility and take most readings off the tape, but note that this will yield only surface temperatures, whereas insects may be deep within the fabric of the building. Alternatively, thermocouple wires allow temperatures to be monitored deep in equipment, and can be run to the outside of the building to minimize worker exposure to heat.

Several small portable data loggers are available (Fields, 2005). Certain systems use RF to upload data to a central computer. Data loggers allow for continuous monitoring, but only a few allow for real-time data acquisition, which is needed to adjust the heat during treatment.

Many electronic thermometers may go out of calibration when held at the high temperatures typical in a heat treatment, and while glass thermometers are inexpensive and accurate, they are not allowed in food-processing facilities because of the risk of glass entering into the food stream.

Determining Heat Energy Requirements for Structural Treatments

It is important to determine the amount of heat energy required to raise the temperature of a building to provide lethal temperatures for disinfestation. An approximate estimation of the amount of heat energy required in British Thermal Units (BTU)/h is generally calculated by engineers working for the food-processing facility or by the companies that perform the heat treatment. One BTU is approximately equivalent to the following: 252 calories, 778 foot-pounds, 1055 joules, 108 kg-m or 0.0003 kW-h.

Estimating the amount of heat lost due to infiltration, steel components within a structure and exposed surfaces such as floors, walls, doors, windows and ceilings is the first step in determining heat energy requirements. A simple 'rule-of thumb' to determine whether or not enough heat energy is being used for heating a structure is that if the target temperature of 50°C is not attained within 6–8 h, it is safe to assume that additional heaters are needed.

Imholte and Imholte-Tauscher (1999) provided basic calculations to accomplish this task, which requires the measurement of surfaces in each room of a facility, estimating the weight of steel components and determining infiltration losses. Losses due to infiltration are generally estimated to be one to two complete air exchanges per hour with recirculating air. This number may be greater than two if outside air is heated and purged into a facility – for example, when using gas-fired heaters.

Knowledge of the type of construction material used for various surfaces is essential for arriving at a reasonable estimate of the heat energy required. These calculations help in determining if the current heating capacity is adequate or whether additional heating sources are needed to achieve the desired heat treatment temperature within the required heat treatment time of 24–36 h.

The Heat Treatment Calculator (HTC)

The Heat Treatment Calculator (HTC) is a software program recently developed at Kansas State University (Subramanyam, 2003) that calculates the amount of energy needed to heat a facility to the required temperature and maintain it for a given amount of time. Using this energy requirement, the HTC also calculates the amount of fuel needed for the heat treatment, which in turn provides a cost estimate. To calculate the energy requirements, the HTC uses the coefficients of heat transfer of the building materials used in the facility, the target temperatures and the dimensions of the facility (e.g. height, length and width of walls, windows, floors and roofs, etc.) to calculate the amount of heat dissipated through conduction, convection and radiation. The equations used for the various calculations are as follows:

Surfaces: (equation applied to walls, windows, doors, ceilings, and floors)

$$q_S = \Delta T \times Area \times \left(\frac{1}{\frac{x}{k}} \right) \tag{8.10}$$

$$q_S = \Delta T \times Area \times U \tag{8.11}$$

where ΔT is the temperature difference of the exposed wall, U is the heat transfer coefficient of the material, k is the thermal conductivity and x is the thickness.

Infiltration:

$$q_I = \Delta T \times 0.018 \times Volume \times aircirculations \tag{8.12}$$

Steel:

$$q_{St} = \Delta T \times 0.12 \times Steelweight \tag{8.13}$$

Hence, the total heat energy requirement is:

$$q_{Total} = \sum q_S + q_I + q_{St} \tag{8.14}$$

Fuel consumption:

$$Fuel = \left(\frac{q_{Total}}{q_{unit}} \right) \times efficiency \tag{8.15}$$

where q_{unit} is the amount of energy produced per unit of the fuel.

Using the current temperature profile and facility specifications, the HTC calculates the energy requirements for the given period and converts it to corresponding fuel requirements. The benefits and uses of the HTC include:

- Studying the variations of energy, fuel and cost with respect to changes in the heating requirements and weather conditions (outside and inside temperatures).
- Arriving at a price estimate of heat treatment under any given climatic conditions.
- Determining optimal conditions for cost-effective heat treatment without actually performing the heat treatment.
- Calculating the amount of heat lost due to various surfaces (floors, walls, doors, windows) and equipment, or any bottlenecks in the heat treatment. Areas where heat loss is severe can be better insulated using heat blankets and other heat-insulating materials.

To our knowledge, there is no published information on the costs associated with structural heat treatments, even though this technology is now becoming popular as a methyl bromide alternative. Increased use of this technology in the future, coupled with the use of empirical insect survival models, HTC and fuel costs may shed additional light on the actual cost/benefit relationships of heat treatment. Anecdotal reports from current users of this technology suggest that heat treatment is cost-competitive with existing structural fumigation treatments.

Common Problems

Although heat treatments are used extensively today in modern food-processing facilities, there are still several problems that may arise (Heaps, 1996; Imholte and Imholte-Tausher, 1999). Fortunately, many of the problems can be addressed with careful planning, but some will only be resolved after a company has gained experience in heat treatments.

Sprinkler heads should be rated for not lower than 95°C. Electronic equipment should be heat-tolerant, removed or jacketed and supplied with cool air. High temperature damages some plastics found in water lines, air hoses, brushes and brooms. Other items that may be damaged by heat include carbon dioxide fire extinguishers, adhesives and aerosol cans. Rubber conveyer belts should also be slackened to avoid damage.

One common problem with a first-time heat treatment is that not enough heat is supplied to a building to quickly obtain a target temperature of 50°C. Heating engineers should be consulted as to the amount of heat required. Heating during the hottest months will make it easier to obtain 50°C. The processing equipment within a facility often generates heat that is exhausted outside of the building. These exhaust systems may be able to be turned off before the heat treatment begins, allowing the buildup of heat in anticipation of the heat treatment.

Some areas of a building are difficult to heat, such as sub-floors, basements, outside walls and internal walls attached to non-heated sections of the building; extra heaters may be needed in these areas. Another problem is overheating; this can be prevented by good air circulation, monitoring temperatures during the heat treatment, judicious placement of heaters, moving portable heaters and/or shutting off heaters periodically.

Although heat treatments are safer than fumigations, some basic precautions should be taken to avoid workers experiencing heat stress (National Institute for Occupational Safety and Health, 1992). It is important to minimize the time spent inside a building during heat treatment. There should be at least two people entering a heated area at a time. Workers should drink plenty of fluids. People, who have medical problems such as a heart condition, are elderly or overweight may be more affected by heat stress.

Checklist for Heat Treatments

Checklists are a useful tool to make sure a heat treatment is conducted efficiently. The following is an abbreviated list taken from Dosland *et al.* (2006), Temp-Air, Division of Rupp Industries Inc. and Roo-Can International, Inc. Prior to heat treatment:

- Estimate the heat required in terms of heaters and fans.
- Set sprinkler heads to at least 95°C.
- Make sure there are enough electrical circuits and they can function at 60°C for 48 h.
- Remove heat-sensitive equipment, food products, additives, oils and glues.
- Close doors, seal intake and exhaust fans and place sand snakes at door jams.
- Thoroughly clean facility, open equipment and remove rubbish and product lines.
- Turn off power to electronic equipment, compressed, intake and exhaust air and loosen belts.
- Test temperature-monitoring equipment.
- Treat the non-heat-treated area adjacent to the heat-treated section with contact insecticide to prevent insect migration.
- Establish a worker safety plan, including a central area out of heat for rest, data sheets and emergency telephones.
- Place caged test insects in 'hard-to-heat' areas or in areas where insect problems are generally noticed.

During heat treatment:

- Set target temperatures at 50–57°C for 24–36 h with a heating rate of 5°C/h.
- Monitor temperature throughout the facility at least once per hour.
- Tour heat-treated areas once per hour to check for problems, adjust fans and heaters or lower temperatures if > 60°C.
- Note where there are accumulations of insects as a means of finding hidden infestations and target future control measures.

After heat treatment:

- Shut off all heaters, leave fans on, open doors and windows, cool down at a rate of 5–10°C/h.
- Return removed equipment and products.
- Collect test insects and remove data loggers and temperature wires.
- Write report summarizing problems, temperature data and caged insect survival.
- Discard first run of product, as it will contain high amounts of dead insects and insect parts.
- Perform required maintenance on heaters.

8.8 Conclusions

Many stored-product insects are associated with raw and processed cereal commodities and contribute to significant quantitative and qualitative losses.

Management of such species is a challenge, primarily because they are able to feed on a variety of food products and develop resistance to pesticides generally used to combat them. In addition, our limited ability to determine infestation sources and understand infestation patterns makes it even more difficult to understand the impact of our pest management methods. Most companies use integrated pest management to keep insects below economically damaging levels. There is a general shift in the grain and food industry from chemical to non-chemical methods.

One viable alternative to pesticides is the use of heat to disinfest grain and structures, which can be carried out with several methods. Heat disinfestation is relatively rapid and does not leave any insecticide residues but, like fumigants, grain or structures could become reinfested after treatment. Quick processing of disinfested grain or sanitation and exclusion practices in structures help minimize reinfestation.

The use of heat is gaining popularity in the grain and food industries. As chemical use is restricted or phased out due to government regulations and customer specifications, we predict there will be an increased adoption of heat for grain treatment and structural treatment. Heat is an environmentally friendly technology, and can be used in conjunction with other chemical (fumigants) and non-chemical (diatomaceous earth dusts) methods for insect management. However, this overview of technologies and methods used for grain and structural disinfestation includes several gaps in our knowledge and practice that need to be filled by additional research to make this technology more widely acceptable to the grain and food industries.

8.9 References

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