INSECT MANAGEMENT for Food Storage and Processing

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Edited by
Jerry W. Heaps
General Mills, Inc., Minneapolis, Minnesota

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Chapter 10

Temperature Modification for Insect Control

Ole Dosland, Quality Centered Consulting Services, Kansas City, Missouri
Bhadriraju Subramanyam, Kansas State University, Manhattan, Kansas
Ken Sheppard, Pepsico Beverages and Foods, Chicago, Illinois (Retired)
Rizana Mahroof, Kansas State University, Manhattan, Kansas

Integrated pest management (IPM) is an effective and environmentally sensitive approach to pest management that relies on a combination of common-sense practices. IPM programs use current, comprehensive information on the life cycles of pests and their interaction with the environment. This information, in combination with available pest-control methods, is used to manage pest damage by the most economical means, with the least possible hazard to people, property, and the environment. IPM programs take advantage of all pest-management options possible, including, but not limited to, the judicious use of pesticides (e.g., using pesticides only when needed). IPM is basically an effective management approach that integrates numerous tactics into a logical program that provides long-term solutions to pest problems. One of these tactics is physical pest management, which includes utilization of heat, cold, humidity, and air movement. These methods are utilized to destroy pest populations outright or to manipulate the pest environment, making it unsuitable for pest entry, dispersal, reproduction, or survival. This approach is becoming extremely important in today's world of pest management, because of increased emphasis on nonpesticidal or low-risk methods for managing pests. This chapter discusses temperature modification, especially the use of high temperatures, for managing stored-product insects in structures, empty bins, and processing equipment.

The use of temperature modification for insect management is an effective and environmentally sensitive approach. Creating temperature extremes provides effective physical control because responses of stored-product insects vary with temperature (Table 1).

Unlike most insect pests, stored-product insect pests live in an environment largely manipulated by humans. Therefore, temperature manipulation of their habitat can slow the increase in populations or can be used to eliminate populations (Howe, 1965; Fields, 1992). A basic concept for managing stored-product insects is to create an environment outside their optimum zone for survival and reproduction. Insects are unable to tolerate sustained temperatures outside the zone of 23.9–32.2°C (75–90°F). Lower temperatures, usually those below 15.6°C (60°F), prevent population growth of stored-product insects by affecting mobility and survival and suppressing reproduction. It is also important to bear in mind that cool temperatures extend the shelf life of food products. So why don't we see more foodstuffs shipped and stored at cool temperatures? As we continue to lose traditional pest-control tools, we will see the wisdom of this pest-management tactic and will likely see more temperature-controlled shipments (reefer trailers) and use of cool storage in the future.

The key is to *not* allow an insect to acclimate to lower temperatures, which would happen if it were exposed to a slow drop in temperature. Most temperature reduction for insect control should be *quick*. A "rule of thumb" for insect management by freezing is to maintain a temperature in the insect's microhabitat of 0–10°F (–12.2 to –17.8°C) for a minimum of 7–10 days. For example, maintaining insect-susceptible products such as birdseed, dry pet food, and flour in environments maintained at less than 4°C (39.2°F) discourages infestations of stored-product insects.

The use of higher temperature (heat treatments) as a nonchemical alternative to fumigation has been a feasible treatment for stored-product insect control in various food-processing facilities for many years. Attempts made in the early 1900s encouraged some food-processing companies to use this technique for several years. However, the use of heat by the food-processing industry was not sustained, due to concerns about damage to equipment and structures from inadequate control of high temperatures. The advent of fumigants, especially methyl bromide, was readily embraced by the food industry as an alternative to heat treatments. Consequently, since the early 1940s, methyl bromide has been the most popular and economical fumigant for use in the food industry. Now there is renewed interest in exploring heat treatments as an alternative to methyl bro-

TABLE 1
Responses of Stored-Product Insects to Temperature[a]

Zone	Temperature (°F)	Temperature (°C)	Insect Response
Lethal	120–140	48.9–60.0	Death in minutes
	110–115	43.3–46.1	Death in hours
Suboptimum	95–100	35.0–37.8	Development stops
Optimum	75–90	23.9–32.2	Maximum development
Suboptimum	65–70	18.3–21.1	Development slows
	55–60	12.8–15.6	Development stops
Lethal	35–45	1.7–7.2	Death in weeks
	–5 to 10	–20.6 to –12.2	Death in days
	–20 to –10	–28.8 to –23.3	Death in minutes

[a] Adapted from Fields (1992).

mide, which is to be phased out in the United States and Europe by 2005 due to its adverse effects on the stratospheric ozone levels (Makhijani and Gurney, 1995). (It is probable that certain critical uses of methyl bromide may be retained beyond 2005 in the affected countries.)

Presently, with advances in building and equipment designs, there is renewed interest in utilizing high temperatures for stored-product insect management in food-processing facilities (Heaps, 1994; Imholte and Imholte-Tauscher, 1999; Wright et al, 2002; Mahroof et al, 2003a,b; Roesli et al, 2003). Heat treatment is becoming very popular in flour mills and food-processing facilities in North America, Europe, and Australia. However, the degree and duration of insect suppression obtained by heat treatments is influenced by various factors, including good exclusion and sanitation practices.

BACKGROUND AND HISTORY OF HEAT TREATMENTS

The use of heated air has long been recognized as one of the most practical and effective methods for destroying insect life, particularly stored-products insects. According to Goodwin (1922), heat was used for the general heat treatment of a flour mill in this country as early as 1901 by a miller who designed his mill for heating after he made the observation that flour-infesting insects were killed by the heat in the vicinity of steam pipes leading to a corn dryer. However, it remained for Dean (1911) to investigate the effectiveness of heat in flour mills on a scientific basis and to call attention to its practicality. As a result of investigative tests conducted during 1910–1913, Dean developed a method that was so successful that mills in many parts of the country adopted it. This method was thoroughly tested by workers in the Bureau of Entomology of the U.S. Department of Agriculture and by various state entomologists and was found to be highly effective, inexpensive, and free from hazards to the workers. The fact that heat treatments were safe for workers appealed to many millers (Cotton, 1963).

Pepper and Strand (1935) wrote that superheating was superior to either fumigation or freezing, two of the most popular methods for insect control in Montana flour mills. This method, by which the insects are killed by raising the temperatures to about 48.9–54.4°C (120–130°F), has been known and used in other parts of the country for many years. Recent improvements in unit heaters now give it several very important advantages. The new method of heating mills by means of unit heaters has made heat treatments easy because it requires no elaborate piping system and the heat can be evenly distributed in the space being treated. Pepper and Strand (1935) emphasized the importance of measuring temperatures at floor level rather than above the floor, because temperatures above the floor tend to be several degrees higher than floor temperatures. Therefore, ensuring that temperatures at floor level are 48.9–54.4°C (120–130°F) is critical for killing insects crawling on the floor. Pepper and Strand (1935) also reported that, by keeping the air in circulation, it is possible, without using excessive heat, to raise the floor-surface temperatures high enough to kill all species of stored-product insects. One way to circulate heated air within the facility is to use fans or air movers that are strategically placed, based on recording temperatures in several locations. Fans or air movers should be used to redirect heat from an area that is being overheated (temperatures >57.2°C or >135°F) to an area that is being underheated (<50°C or <122°F).

Besides heat treatment of facilities, heat is also used to manage several other pests in both perishable and dry durable food products. High-temperature treatments are used to disinfest dried fruits and nuts (Johnson et al, 1992), perishable commodities (fruits) (Jang, 1991; Hansen and Sharp, 1998; Neven, 1998a; Wang et al, 2002), and grains (Dermott and Evans, 1978; Evans, 1986; Beckett et al, 1998; Mourier and Poulsen, 2000; Beckett and Morton, 2003). Hallman and Denlinger (1999) described how heat treatments (including solarization, electric heating, and steam heating) are being studied as replacements for methyl bromide fumigation for planting beds, containers, and wood.

Facility heat treatments are distinctly different from heat treatment of fresh fruits, nuts, or grains. In facility heat treatments, heaters are used to slowly heat the ambient air. A long treatment period is necessary for the heat to penetrate wall voids and equipment to kill insects harboring there. A typical heat treatment of a processing facility consists of heating the building to a target temperature of 50–60°C (122–140°F) and maintaining these high temperatures for 24–36 hr (Dosland, 1995; Mahroof et al, 2003a,b; Roesli et al, 2003). In heat treatments of fresh commodities nuts, dried fruits, or grains, high temperatures of 60–85°C (140–185°F) are used for short time periods (in minutes). Typical heating rates during heat treatment of perishable commodities, nuts, dried fruits, and grains range from 1 to 15 degrees C/min, whereas during facility heat treatments, heating rates are generally around 2–5 degrees C/hr. However, in both cases, the products or the facility is allowed to cool to ambient temperature, which may take several hours. It is important during heat treatments of products to ensure that the quality is not affected. Similarly, in the case of facility heat treatments, it is important to ensure that there is no damage to the equipment, uninfested materials stored within the facility, or the structure.

EFFECTS OF HEAT ON INSECTS

Lethality in insects at high temperatures depends on both the temperature and time of exposure (Evans and Dermott, 1981; Fields, 1992; Denlinger and Yocum, 1999; Dosland, 1999; Mahroof et al, 2003b). Temperature and exposure time to achieve a certain percentage of insect kill are inversely related: the higher the temperature, the shorter the exposure time needed to kill insects. Denlinger and Yocum (1999) gave a possible explanation for the variation in onset of mortality at moderate to high temperatures. An insect is capable of surviving a series of nonlethal lesions when it is exposed to moderate temperatures, but after certain point, the lesions accumulate to a critical level a cause death. At high temperatures, lethal lesions develop more quickly so that the healing processes that counter the lesions at less-severe temperatures are rendered inoperative.

High temperatures increase the body temperature of insects. The wax of the insect cuticle is sensitive to temperature changes. At high temperatures, the wax becomes more fluid, allowing loss of water. This affects the insect's water balance, leading to death by desiccation as well (Hepburn, 1985). Levins (1969) showed that body size is a decisive factor for vulnerability to desiccation; often, smaller insects are killed more quickly by high temperature than larger insects, because of their larger surface-area-to-volume ratio. Since most stored-product insects are small (2–3 mm long), they are more vulnerable to death by desiccation.

The metabolic rate of insects is totally dependent upon environmental temperature. The overall metabolic rate of an insect is often related to respiration rate. Neven (1998b) showed that respiration increases in response to increasing temperatures up to a critical upper limit. After this point, respiration decreases. Death occurs soon after respiration rates begin to drop, even if the insect is returned to the normal temperature.

An array of abnormalities is caused at the cellular level in insects exposed to high temperatures. Such exposure commonly results in a decrease in hemolymph pH and ion concentrations, denaturation of proteins and nucleic acids by destabilizing weak interactions such as Vander Waals or ionic bonds, inactivation of major glycolysis enzymes, denaturation of lipids and carbohydrates, and disruption of the plasma membrane (Hochachka and Somero, 1984; Denlinger and Yocum, 1999; Neven, 2000). We would normally assume that high temperatures elicit more rapid responses to immediately kill the exposed insects. This is usually the case, but not always. Based on temperature-time relationships, we know that some insects may survive high temperatures; however, in such insects, developmental or reproductive defects may be present.

Changes in temperature can affect the central nervous system and ultimately the activity of the insect's endocrine (hormone-producing) system. Changes in the endocrine system influence insect growth and development (Neven, 2000). High temperatures can also result in chromosomal aberrations, leading to developmental aberrations known as phenocopies, which resemble mutations (Denlinger and Yocum, 1999). A variety of phenocopies were reported in the fruitfly, *Drosophila melanogaster* Meigen; examples are bithorax phenocopy in the embryo (Hallman and Denlinger, 1999), aberrant adult bristle shapes and colors (Milkman, 1962), and deformation in wing shape or venation (Mitchell and Lipps, 1978).

Work by Denlinger et al (1991) on flesh flies, *Sarcophaga crassipalpis* Macquart, showed that a 2-hr exposure to 50°C (122°F) killed all pupae or pharate (newly emerged) adults. At 45°C (113°F), exposed pupae survived to complete pharate adult development, but they died without escaping from the puparium. When *S. crassipalpis* pupae were exposed to a temperature of 45°C for 80 min, the muscular system appeared to be more vulnerable to injury than the nervous system (Yocum et al, 1994). In the red flour beetle, *Tribolium castaneum* (Herbst), exposure of pupae to 45°C (113°F) for 24–72 hr at any age inhibited development and consequent adult formation (Saxena et al, 1992). Adler and Rassmann (2000) have reported that, during a structural treatment in a flour mill when the temperature did not exceed 50°C (122°F), the mealworm, *Tenebrio molitor* (L.), the confused flour beetle, *Tribolium confusum* (Jacquelin du Val), and the Mediterranean flour moth, *Ephestia kuehniella* (Zeller), survived the treatment, but further growth and development were prolonged and severely affected. More recently, A. Menon and R. Mahroof (*unpublished data*) observed that, when pupae of *T. castaneum* were exposed to 50°C for 60 min, the surviving pupae emerged into adults that had deformed wings.

The process of courting, mating, and reproduction can occur only over a certain range of temperatures (Girish, 1965). Increasing the temperature above the insect's optimum zone by a few degrees disrupted spermiogenesis or resulted in defective sperm production. High temperatures interfere with the ability of the sperm to separate out due to ensheathment by a common plasma membrane (Saxena et al, 1992). Oosthuizen (1935) reported that temperatures might affect egg production first by affecting the mechanism of egg production directly and then by altering the rate of egg formation in the ovary. Destruction of matured egg cells, primary and secondary oocytes, or other injuries in ovarian tubules may affect the mechanism of egg production. Neven (2000) reported that high temperatures could affect the endocrine system and prevent maturation of germ cells, perhaps inhibiting the deposition of vitellin (egg yolk protein) in the eggs.

Some remarkable instances show reproductive defects in insects exposed to high temperatures. *S. crassipalpis* pupae exposed to 45°C (113°F) for 60 min emerged successfully from the puparium; the adults survived quite well but often failed to reproduce. In *S. crassipalpis,* males were more susceptible to this form of injury than females. Although they copulate normally, the males fail to inseminate the females (Denlinger and Yocum, 1999). Several species of *Aedes* (mosquito) larvae reared at 30°C (86°F) developed into normal adults, but when the temperature was elevated to 33°C (91.4°F) during the last half of the fourth instars, males with female-type antennae, palpi, and oral stylets resulted, and such males do not swarm, copulate, or produce sperm (Anderson and Horsfall, 1963). Girish (1965) reported that the Khapra beetle, *Trogoderma granarium* Everts, could breed even at 40°C (104°F) in grain containing a high moisture content, but the rate of development of its larvae was reduced considerably. Saxena et al (1992) observed that, in *Tribolium granarium*, adults exposed to 40°C (104°F) for 48 and 72 hr were totally incapable of propagating a new generation. Even with a 24-hr treatment at this temperature, one-day-old pupae were more susceptible to induction of sterility than those older than a day (Saxena et al, 1992). No progeny were produced by adults of the lesser grain borer, *Rhyzopertha dominica* (F.), exposed for one week to 42 and 44°C (107.6 and 111.2°F) at 40, 50, and 60% RH (Vardell and Tilton, 1981). Lale and Vidal (2003) reported that the female cowpea weevil, *Callosobruchus maculatus* (F.), and the female pulse beetle, *Callosobruchus subinnotatus* (Pic.), laid significantly fewer eggs when they were exposed to 50°C for 1 hr compared with females exposed to 40°C (104°F) for 1 hr. More recently, Mahroof et al (2005a) have shown that, when pupae and adults of *T. castaneum* were exposed to 50°C

(122°F) for 39 and 60 min, respectively, the surviving adults showed a significant reduction in oviposition, egg-to-adult survival rate, and progeny production.

It is important to recognize that the rate of death of insects at high temperatures (either constant or dynamically changing during heat treatments) varies among species (Fields and White, 2002) and within species among different life stages (Mahroof et al, 2003b). The rate of heating also has an impact on how quickly insects succumb to high temperatures.

Heat Tolerance in Insects

The major challenge of a successful heat treatment is to target and kill the most heat-tolerant stage of an insect. Insect heat tolerance, or the ability to withstand high temperatures, depends on many factors, including intraspecific variation in heat tolerance, the age structure of the population exposed, previous thermal acclimation or temperature history of exposed insects, genetic adaptation, and rapid heat hardening (Dermott and Evans, 1978; Evans, 1981; Hallman and Denlinger, 1999). Insects possess physiological and biochemical adaptations that help prevent the injury caused by thermal stress (Evans, 1981). In certain cases, insects may use the harmful effects of the temperature for their own benefit. For instance, insects infected with viruses, bacteria, protozoa, and fungi frequently seek high temperature to rid themselves of infection (Heinrich, 1993). High temperatures are also used to escape predation (Wehner et al, 1992). Increased heat tolerance in insects is sometimes acquired through selection, which may not be directly associated with temperature (Denlinger and Yocum, 1999). A strain of *T. castaneum*, selected for resistance to malathion, exhibited increased tolerance to heat stress but not to cold, desiccation, or starvation (Shukla et al, 1989). Tolerance to both heat and cold has been reported in many other stored-product insects (Burks et al, 2000).

At the cellular level, high-temperature survival is enhanced by the synthesis of heat-shock proteins (HSPs) (Bendena et al, 1991; Currie and Tufts, 1997; Denlinger and Yocum, 1999; Lewis et al, 1999; Lakhotia et al, 2002; Qin et al, 2003). In response to a sudden increase in temperature, the normal pattern of protein synthesis is halted and a new set of proteins, the HSPs, are expressed (Lepock et al, 1987). The fact that different tissues within the same organism may synthesize different stress proteins, and may have different temperature thresholds for expression, could lead to differences in heat tolerance at the tissue level (Joplin et al, 1990). At the organism level, the least-heat-tolerant tissue will obviously be the weakest link in survival at high temperatures.

A range of environmental stresses, including heat (Currie and Tufts, 1997), cold (Goto and Kimura, 1998), desiccation (Tammariello et al, 1999), and anoxia (Myrmel et al, 1994), has been reported to induce HSPs in various organisms. Generally, these proteins are thought to provide the cell with protection by preventing aggregation or improper folding of proteins. In addition, they are involved in resolubilizing and stabilizing proteins by targeting denatured proteins for degradation and removal, thereby ensuring the survival of the organism under stressful conditions that promote cell damage and death (Currie and Tufts, 1997). In addition to being induced by stress, these proteins have essential functions under normal growth conditions and are classified as part of a larger family of molecular chaperones (Hartl, 1996). There are several families of HSPs, largely classified by molecular weight (Lewis et al, 1999). HSP 70 is one of the most highly conserved HSPs, with the greatest specific activity, and thus may be easy to detect (Currie and Tufts, 1997). An increase in the total specific activity of HSP 70 within a biological system can be used as a nonspecific indicator of stress, and in some circumstances, the overexpression, or lack thereof, of HSP 70 can be used as a biomarker for monitoring environmental changes (Lewis et al, 1999).

When *T. castaneum* life stages were exposed to six different elevated temperatures, the first instars (larvae hatching from eggs) were the most heat-tolerant stage (Mahroof et al, 2003b). Further study suggested that increased heat tolerance in first instars could be due to increased expression of HSP 70 at higher temperatures. Time- and temperature-dependent expression of HSP 70 showed that the increased heat tolerance in first instars lasted as long as 8 hr at 40°C or 30 min at 46°C (115°F). Thus, to kill first instars of *T. castaneum*, heat treatments should target temperature and time combinations beyond the threshold for heat tolerance (Mahroof et al, 2005b).

CALCULATING HEAT ENERGY REQUIREMENTS

The effectiveness of a heat treatment with respect to the lethal temperatures attained is determined to large extent by how much heat energy is required. Determining heat energy requirements is critical in order to account for heat losses due to exposed surfaces such as floors, walls, doors, windows, and ceilings; losses due to infiltration; and losses due to steel components within the structure. Engineers in a company can make heat-loss calculations. The heat energy required is calculated in terms of British thermal units (BTUs). One BTU is equal to the amount of heat required to raise the temperature of 1 lb of water at its maximum density (which occurs at a temperature of 39.1°F) by one degree F. One BTU is approximately equivalent to the following: 251.9 cal; 778.26 ft-lb; 1,055 J; 107.5 kg-m; and 0.0002928 kW-hr. A pound (0.454 kg) of good coal, when burned, should yield 14,000–15,000 BTU; 1 lb of gasoline or other fuel oil provides approximately 19,000 BTU.

Imholte and Imholte-Tauscher (1999) give simple step-by-step instructions for determining heat energy requirements. However, the calculations require measuring the surfaces in each room of a facility, estimating the weight of steel components, and determining infiltration losses. Infiltration losses are generally estimated to be one to two complete air exchanges per hour if air is recirculated. This number may be greater than two if outside air is heated and purged into a facility, for example, using gas-fired heater Knowledge of the type of construction material used f surfaces is essential for arriving at a reasonable estimate of the heat energy required. These calculations help in determining whether 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 hr. In-house engineers or companies that provide the heaters or do the heat treatment should be consulted to obtain a general idea of how much heat energy is required.

At Kansas State University, a software program, Heat Treatment Calculator, was developed by one of the authors of this chapter (B. Subramanyam) to calculate heat-energy requirements. The user-friendly program can estimate heat losses by room and floor, and it prompts the user to enter all values necessary for determining heat energy requirements. The heat transfer coefficients for various building materials have been entered into a database. The user can enter a new value for materials not included in the database. The costs associated with heat treatments using different fuels can also be estimated using the Heat Treatment Calculator. The program enables users to estimate the heat energy required by altering the starting or desired temperature. The program also helps determine the heat energy required for different building materials. This information may be valuable if one is interested in constructing a facility designed with heat treatments in mind.

DELIVERY OF HEAT TREATMENTS

Planning

Identifying Problematic Areas Within the Facility

It is important to realize that no two heat treatments are exactly alike. However, the goal of any heat treatment is to deliver air at a temperature of at least 51.6°C (125°F) to the insect pest one is trying to kill. Therefore, identifying areas of insect infestation within a facility is critical. Insects require food, water, and shelter to survive, and many areas in a food plant provide this triangle of life. One must know where the problematic areas are and design the delivery of the hot air into those areas. In some cases, heat treatments may reveal a source of infestation, because the heat tends to flush insects from their hiding places.

Poor sanitary design results in accumulation of food materials, especially within pieces of machinery. These are the places where insects typically hide and survive. A problematic area seems to be a common wall separating dry cleaning areas from wet cleaning areas or separating areas with different levels of cleaning standards. In the ideal world of good sanitation design, there would be a solid wall free of any windows or voids. Insect problems within structures can be limited by good maintenance and a high level of seal integrity. Heat is effective in treating insects harboring in these areas, provided the hot air (at ≥50°C/122°F) is delivered there. Measurement of temperatures in these areas is therefore critical for the success of a heat treatment. Killing insects, especially those hiding in small amounts of food materials, requires some time. Depending upon the amount of hot air available, a rule of thumb is that the time required for structural heat treatments ranges between 24 and 36 hr. Rather than heat-treat a large area, it is economical and beneficial to heat-treat only the area where infestation is present.

Common insect shelter zones inside food-processing plants may be within bins and equipment, a result of poor sanitation design and/or seal inadequacy. A common area seems to be the dry-ingredient bins and the augers or spouts used for unloading the ingredients. Other problematic equipment areas are supports and unaccessible equipment. Heat is very effective in treating these insect-harboring areas. Depending upon the amount of hot air available, a time rule of thumb for equipment-related heat treatments is 8–16 hr (Dosland, 1995).

Sources of Heat

Many options can be considered when selecting a heat source. Heat can be from electricity, gas, or steam; it can be internal, external (rented), or a combination of these sources. Each heat energy source has it own advantages and limitations, and the selection of the energy source is generally based on need and availability. Engineering experts should be consulted to help determine the optimum approach for a particular need.

Air Movement

An overlooked component in most heat treatments is air movement. A number of air circulators and fans are necessary to get the hot air to the insect and provide an efficient, economical, and uniform distribution of heat while minimizing damage to structures and equipment. It is important to identity air movement within the heating zone(s), such as a one-way positive-pressure slow exhaust approach, a horizontal or vertical "swirl" return-air approach, or a combination approach. It is important to give thorough consideration to air movement, especially for the small rooms, considering equipment blockage or leakage, window and door frames, air exhausts and intakes, and other hard-to-reach infested areas.

Remember the 3 "Bs" for air-circulation considerations.

Be Flexible

- Air circulators that swivel are better than fixed.
- Use large units (i.e., 91.4-cm [36-in.] air circulators) for larger spaces.
- Use small units (i.e., 50.8-cm [20-in.] box fans) for smaller spaces.

Be Windy

- Too many air movers are better than too few. Plan for 10–25% not working during the treatment.
- Use built-in existing air movers.
- Plan to supplement, if needed, with portable units.
- Create a breeze that is noticeable on the skin.
- Protect sensitive equipment with dedicated units in the cool zone.

Be Thorough

- The first few hours will be very busy, with monitoring and adjusting of air movement, based on temperature measurements.
- Learn from previous heat-treatment experiences.
- Maintain an accurate map of heaters and air movers.
- Develop a detailed report for future heat treatments.

Assembling a Heat-Treatment Team

"Planning, preparation, and practice prevent pitiful performance" is a saying applicable to heat treatments. If you are conducting a heat treatment for the first time (or for the second, third, or fourth time), you should put together a

TABLE 2
Checklist for Heat Treatments

Prior to Heat Treatment

☐ 1. Appoint site heat-up planning team (include engineering). Elect a team leader to coordinate the effort.
☐ 2. Identify specific areas to be heated and make site plan. Determine local heat/air sources.
☐ 3. Identify heat-sensitive structures and supports, including roofs. If protection or engineering assurances cannot be developed, then do not conduct a heat treatment because of possible damage to structures.
☐ 4. Identify heat-sensitive equipment within the facility. Develop measures for protecting this equipment.
☐ 5. Identify sealing materials needed inside and outside the heat zone to exclude pest harborage.
☐ 6. Identify air movement plan, circulation equipment, fan placement, and type and number of fans needed. Identify energy source(s) and extension cords to spread out the amp load for air movement.
☐ 7. Establish fire protection plan. Check with insurance carrier for coverage on any damage to structures or equipment.
☐ 8. Repair damaged doors, windows, or other openings that would allow heat to escape. Eliminate major drafts from unheated areas.
☐ 9. Notify corporate safety, engineering, and regional personnel of intent to conduct heat-up.
☐ 10. Notify local (city and county) fire and police departments of intent to conduct heat-up.
☐ 11. Notify contractors or other persons who may be using the facility so their equipment, materials, and supplies can be removed.
☐ 12. Use 100–150 μm thick (4–6 mil) polyethylene sheets to seal off exhaust fans, dust collectors, or air make-up systems that exhaust to the outside.
☐ 13. Remove heat-sensitive products or raw materials from the heated area. Examples are vitamins, shortenings, and some packaging materials. Most products are not conducive to the high temperatures used during heat treatments.
☐ 14. Empty paper bags and bagged or bulk raw or processed products should be placed in a reefer trailer and fumigated with phosphine to kill residual infestations.
☐ 15. Remove pressurized containers and cylinders from the heated area. Label fire extinguishers with proper location for emergency "near-by use" during heat treatments.
☐ 16. Where possible, remove electronic equipment; any that cannot be removed must be unplugged. Where computer programs are involved, backup copies should be made. A simple experiment run at a Kansas State University heat workshop has shown no adverse effects on computers after they have been subjected to a typical heat treatment.
☐ 17. Empty all trash, waste, and product containers. Set containers upside down in the heated area.
☐ 18. Check sprinkler system and head sensitivity for 141°C (286°F). If less sensitive, replace heads. An option is to drain the sprinkler system and post fireguards during the inactivation period. Check system for tripped heads and refill slowly before activation.
☐ 19. Older sodium or mercury vapor lights should be turned off during heat treatment. Check with engineering staff or the supplier regarding heat tolerance of these lights. Identify alternative lighting plan to minimize plant power usage.
☐ 20. Check bearing and belt types, and loosen where necessary.
☐ 21. Check lubricant type and reservoirs, and provide for expansion due to heating.
☐ 22. Identify plastic-type materials, including PVC piping and Tygon tubes, and monitor these for possible heat damage. Also check pneumatic-line plastic connectors for any adverse heat-related effects.
☐ 23. Double check temperature limitations on all solid-state equipment such as any electronic controllers, small computers, or photo eyes. The best source for this information is the equipment suppliers. Sensitive equipment can be protected by providing it a cool zone during the heat treatment itself. Develop floor-by-floor and area-by-area specific checklist for planned preparation activity of the sensitive equipment within the heat-treatment zones.
☐ 24. Take precautions about magnets that could lose their activity as a result of exposure to high temperatures. Contact the manufacturers for temperatures beyond which the magnets lose their desired properties.
☐ 25. Remove loose rubber gaskets and sensitive caulking and replace them with heat-resistant materials.
☐ 26. Establish an employee safety plan that includes warning signs, buddy system (people working in teams of two), clothing, drinking/eating, heat stress first aid (ambient room), first aid kit, emergency phone numbers, employee heat tolerances (based on physicals), and cool vests.
☐ 27. Identify and provide appropriate personal protective equipment (PPE), such as bump caps with cloth lining and cloth gloves. It is advisable to wear light, loose-fitting clothing.
☐ 28. Note any metal that should not contact the skin directly, such as metal buttons, glasses, or brass, as these are good conductors of temperature.
☐ 29. Establish temperature-monitoring plan, including key locations to be monitored manually or with any remote temperature-measuring devices, and frequency for recording temperatures. Calibrate all monitoring tools with reference to a standard mercury thermometer.
☐ 30. Identify all areas adjacent to heated areas. Spray surfaces, especially floor-wall junctions and doorways, with a wettable powder/microencapsulated residual insecticide to preclude insect migration to unheated areas. A Tempo 20WP or Demand CS products are examples of some products that can be used at the present time
☐ 31. Determine numerous locations on the plant layout for placement of insect test cages. The cages should have an insect species that is problematic within the specific facility, and temperatures should be measured near the test cages. It is also important to use the most heat-tolerant stage of the insect species in the cages. If information on heat tolerance of a species is unknown, then expose eggs, young larvae, old larvae, pupae, and adults of the insect species separately in test cages.
☐ 32. Do a thorough job of sanitation, especially within pieces of accessible equipment. After cleaning, close the equipment. Heat penetrates open equipment only 20 min faster than unopened equipment, and the 20-min time savings is small relative to the 24–36 hr heat-treatment period.
☐ 33. Identify the person responsible to turn off plant power, if necessary.

During Heat Treatment

☐ 1. Before heaters are turned on, walk through the facility with the "heat-treatment team" to determine whether the facility is ready for the treatment. Determine whether the level of sanitation is adequate and ensure that all critical items have been removed from the facility.
☐ 2. Measure and examine temperatures from as many locations as possible within the facility to identify cool as well as overheating areas. Areas with temperatures exceeding 60°C (140°F) should be lowered within the target zone immediately.
☐ 3. Elevate temperatures outside and around the infested area and move elevated temperatures inward toward the infestation to kill insects and prevents them from escaping the treated area.
☐ 4. If the heat treatment is provided by a private company as a service, that company can be responsible for the operation of the rental power and/or heating equipment and assisting with temperature and humidity monitoring. Facility maintenance personnel should monitor specific structures and heat-sensitive equipment, in addition to providing oversight during heat treatment.
☐ 5. Numerous 60- to 90-cm air circulators should be used for distribution of heat within the facility. Box fans can be used for small areas.

(Continued on next page)

TABLE 2 (*continued*)

During Heat Treatment (*continued*)

☐ 6. Monitor and record temperatures and humidity at predetermined locations, initially every hour, and every two hours after temperatures have reached 50°C (122°F). Check areas near insect cages on a regular basis. Remember that insects exposed to sudden heat shock appear dead but may come back to life if they are removed from the heated area. Insect test cages with adults removed during heat treatment should be kept at room conditions for 24 hr before insect mortality is assessed. All other stages should be reared to adulthood for mortality assessments.

☐ 7. Designate an office as a "heat-treatment command center" with phone, first aid kit, temperature log sheets, fluids (water or other hydrating beverages), and emergency phone numbers.

After Heat Treatment

☐ 1. Discontinue heating after the desired exposure time and temperature are achieved. Keep air movers running during and after shutting down the heaters.

☐ 2. Uncover roof/wall vents, air intakes, and other openings for exhausting hot air. Open screened windows.

☐ 3. Turn on plant power when temperature cools down to approximately or below 43°C (109.4°F).

☐ 4. Recover insect test cages and temperature-sensing equipment or charts. Record insect mortality.

☐ 5. Where survival occurs in insect test cages, treat that area with a residual insecticide.

☐ 6. Start the exhaust fans in heated areas. Monitor temperatures during the cool-down period.

☐ 7. Replace fire extinguishers at proper locations and return plant to normal fire protection standards. If sprinkler system was drained, check each sprinkler head before activation. Refill slowly.

☐ 8. Start removing portable power or heater equipment and begin reassembly of plant equipment, to get ready for normal operation.

☐ 9. Remove all sealing equipment and complete post-treatment cleanup. "Flush" the initial material out for about 10–20 min of the process and dispose of it as trash. A high degree of insect fragments may exist inside the processing equipment in this initial flush. Check the flushed material and record information on the types and numbers of insects present.

☐ 10. The "heat-treatment team" should review treatment activity and effectiveness and list suggestions to improve a future application.

☐ 11. Prepare post-heat-treatment report. This report should be detailed and serve as baseline information for future heat treatments.

TABLE 3
Symptoms of Heatstroke

Early: Muscle Cramps Phase (caused by loss of salt from heavy sweating)	**Later: Heat Exhaustion Phase (caused by dehydration)**
Dizziness	Fainting
Fatigue	Cool, moist skin
Muscle cramps	Dilated pupils
Nausea	Headache
Profuse sweating	Pale skin
Thirst	Irrational behavior
Weakness	Nausea and vomiting
Lightheadedness	Unconsciousness

team to help with the planning. This team should consist, at minimum, of sanitarians/hygienists, pest management professionals, engineering/maintenance personnel, plant/general manager, and the appropriate corporate support personnel in addition to an experienced heat-treatment advisor. Planning and preparation begin months before a heat treatment. One should consider practicing heat-treatment of a small area of a facility before scaling up to the whole facility to gain a better understanding of the nuances involved in conducting a heat treatment. It is important to realize that every heat treatment is a learning experience. The efficiency with which the treatment is done will improve with subsequent heat treatments. Table 2 provides a checklist to help teams identify the numerous areas of preparation necessary in order to conduct an effective, efficacious, and economical heat treatment.

Safety Considerations During Heat Treatments

Exposure to sustained heat can cause health-related problems. Heatstroke, a serious health problem, causes shock, brain damage, and eventually death. A typical scenario involves short exposures (10–20 min, depending upon an individual's heat tolerance) to 50–60°C (122–140°F). Working in teams of two can be improved if both members understand heat stress signs and symptoms. Typical problems encountered are body rashes and muscle cramping. Heatstroke must be avoided, as it is a life-threatening condition in which the body's heat regulation shuts down. Symptoms can be classified into early and prolonged exposure phases, as noted in Table 3.

A few other safety items to become aware of during a heat treatment are burns from hot surfaces and impaired grip strength due to sweat. Some basic protective gear is essential for preventing heat-related injuries. Workers should wear cotton gloves, cotton-lined bump hats, and loose-fitting cotton clothing. The use of remote thermometers to measure temperatures reduces the time workers spend in heated areas during a heat treatment. Some general safety tips to consider are listed below. Some pertain to the planning team:

- Limit exposure to the hot environment.
- Rotate workers.
- Establish designated "cool areas."
- Provide personal protective equipment.
- Have thermal protective vests on site.
- Make sure medical assistance is available.
- Provide worker training, including heat awareness.

Some pertain to the workers during heat treatments:

- Wear loose-fitting clothing.
- Work in teams of two.
- Observe each other and other workers for any signs of heat stress.
- Rest frequently.
- Drink enough fluids, especially water.
- Avoid overheating if you are taking drugs that impair heat regulation, or if you are obese or elderly.
- Be alert to dust exposure.
- Be alert to chemical exposure such as volatiles (solvents in pesticides).

Monitoring Heat Treatments

Monitoring heat treatments consists primarily of paying attention to three areas: temperature/time relationships, insect mortality, and anything unusual.

Time and Temperature

Temperature/time monitoring is critical to the success of a heat treatment. Achieving a lethal temperature for a desired time simply does the job. One needs to know when the job is done and when it has been done right. Remote temperature monitoring throughout the heated area and inside walls, bins, equipment, and other known insect-harboring areas is the best overall approach. Remote temperature-measurement systems are based on radio frequencies, with the temperature reading being sent to a receiver connected to a computer. Several devices that provide time-stamped data, like the HOBO data loggers (Onset Computer Corporation, Bourne, MA), must be launched and read by the computer. Infrared thermometers that measure surface temperatures give an instantaneous reading, but the batteries of the unit are affected by heat. It is important to understand not only the accuracy of the temperature-measuring devices (calibrate using a standard temperature device such as a mercury thermometer), but also how temperatures can affect their performance.

Despite advances in temperature-sensing systems, it is essential to measure temperatures manually using an infrared thermometer to better understand the heat distribution within your facility, to take corrective actions and prevent under- or overheating, and to take note of any usual heat-related effects on structures or equipment. Measuring air temperature is not an effective means of monitoring heat treatments. It is good to know the output temperature of the heater and the ambient air temperature. However, the critical temperature is that obtained in the zone where the insects occur.

Specific locations for monitoring temperatures must be identified in advance. Temperature should be measured in as many locations as possible to determine that the area being heated is well within the 50–60°C (122–140°F) range. Contour maps showing temperature distributions can be generated, especially if temperature data are collected from different locations and the locations are identified by *x* and *y* coordinates (Akdoğan et al, 2004). Also, contour maps can be generated to show how long temperatures above 50°C (122°F) were maintained in different locations of the facility.

Insect Mortality

Assessing insect mortality is a practical method to ensure heat-treatment efficacy. If a picture is worth a thousand words, then dead insects found, generally on the floor, in the heated area may be worth a million. The types and numbers of insects within the facility should be monitored by using traps or taking product samples weekly for several weeks before the heat treatment and continued weekly for several months after the treatment. Information on insect numbers in traps and product samples indicates the degree of suppression obtained immediately after the treatment and the duration of the effectiveness of the treatment.

In addition, insects that are serious pests should be placed in test cages to monitor heat-treatment effectiveness. If a select species is used, it is important to expose all life stages to ensure that the heat treatment was effective against these stages. To determine the time for 100% insect mortality, insects in test cages can be sampled 0, 3, 6, 12, and 24 hr after a heat treatment. Adult insects should be held at room conditions for at least 24 hr before mortality is assessed to account for any exposed adults that have recovered. Immature stages should be reared on food until the adult stage to assess mortality.

The Unusual

Monitoring for the unusual is necessary to minimize structural, equipment, or other problems. Observing the unusual may consist of looking for sprinkler-head releases, flickering lights, sagging plastic tubing, lubricant leaks, pressurized-container releases, and cracks in structures. With good preparation and controlled heat-up and cool-down, these conditions likely will not be noted. However, if they do occur, because temperatures in certain areas exceeded 60°C (140°F), further damage can be minimized with timely corrective action. Other unusual things to look for are inoperative air movers, fans, temperature-monitoring devices, and/or heaters. Usually several air movers and fans will stop operating and must be replaced to prevent cool zones within the heated area. Heat-treatment monitoring for the unusual requires most of the effort early, until temperatures have stabilized and are uniform.

Post-Heat-Treatment Activity

Once lethal temperatures are attained, it is time to stop the heat treatment. The sequence of events after stopping the treatment consists of a cool-down, removal of heat-treatment equipment, cleaning, preparing equipment and the facility to be ready for operation, and development of a report on the heat treatment. The cool-down phase involves keeping air moving while sequencing the shutdown of the heat source, opening filtered doors and windows, and starting exhaust fans. The monitoring activity should continue until the facility cools to the ambient temperature. Note that air temperatures decrease faster than the temperatures of surfaces, such as walls, ceilings, floors, and equipment. To avoid adverse effects on structures and equipment, the cool-down process should be slow (a drop of 2–3 degrees C/hr). Once the temperature falls below 38°C (100°F), the heat-treatment equipment can be removed along with necessary personal protective equipment.

Post-heat-treatment cleaning and inspection are necessary steps before the process is put back into operation. Note the importance of deep cleaning, as insects may have escaped the hot air by running deep inside the equipment. Since dried insects can create an extensive number of insect fragments, the system should be flushed.

A post-heat-treatment meeting of all involved parties should be held within a couple of days to develop a comprehensive heat-treatment report. The finished report should consist of the plan (who did what, when, where, and how); the preparation checklist, with possible revisions; a map showing locations of heaters, air movers, fans, temperature-monitoring locations, and insect traps; the results (data on time-dependent temperature and relative humidity profiles, insect survival in test cages, unusual observations or problems encountered); and the costs. This final report will provide a valuable reference for the next heat treatment.

HEAT-TREATMENT CASE STUDIES

Study 1. An In-House Heat Treatment of a Malting Facility

Confining heat to a specific zone while the rest of the facility remains in operation, with maintenance, renovation, construction, and/or cleaning activities, makes heat a viable option for many facilities. At a large malting operation in the upper central United States, an opportunity arose to confine heat to a specific inaccessible zone while the rest of the facility remained in operation with maintenance, construction, and deep-cleaning activities.

The decision to conduct a heat treatment was made in early August 2001. The spider beetle, *Gibbium aequinoctiale* (Boieldieu), was found along inside walls, which were made of brick and inaccessible for cleaning. Thorough inspections had determined the likely insect source to be within these walls, so the feasibility of conducting a heat treatment for these spider beetles was investigated. A laboratory experiment determined that the adult beetles were completely killed at 48.9°C (120°F) after 30 min of exposure. The malting operation had significant heat available, with excellent air velocity and uniform distribution. The facility was to be shut down for an entire week to schedule major preventive maintenance and deep-cleaning activities. Although this facility had not done a heat treatment for insect control, personnel were familiar with the concept and knowledgeable about using heat. The goal was to create an environment of 48.9–60°C (120–140°F) for 16–24 hr in a targeted area measuring 17,055 m^3 (602,640 ft^3). An action plan was developed and put into motion.

Preparation and Operation

Building sealing and cleaning. Basically the area was sealed (de-drafted) around entry doors to restrict cool air from entering the treated area. Cleaning activities were designed to remove all grain and minimize grain-related debris such as chaff. Floors were swept and junctions of the brick walls and the floor were cleaned by vacuum.

Application of a residual insecticide. At temperatures around 40°C (104°F), insects tend to move rapidly toward cooler areas. Research has shown that the wettable powder of a pyrethroid, cyfluthrin (Tempo), might be the material best suited for these high temperatures (Arthur and Dowdy, 2003). Cyfluthrin was applied in a pin stream to wall-floor junctions and to cracks and crevices soon after the cleaning activities were finished.

Power and heating equipment. The facility provided all power and heat. Three boilers provided heat to each kiln, with a start-up heat sequence in which the east and west kilns were first, followed 30 min later by the center kiln. Nine boilers with a total capacity of around 45 million BTU were used for this entire heat-up. A delivery temperature of 60–62.8°C (140–145°F) was selected.

Air-circulation equipment. A total of 50 air movers and fans were used to direct the hot air to the insect source. Three high-volume industrial air circulators were positioned in the middle of each kiln's vertical heat entry. One high-volume duct was added to target hot air down into the walkway. A pedestal air circulator was positioned in the corner of each kiln to direct hot air directly toward the entry door. A combination of 12 smaller air movers and box fans were positioned to direct air along the walkway and other walls. More than 25 extension cords and power-distributor boxes were utilized to provide electrical power to the air-circulation equipment from 10 local outlets.

Temperature monitoring. Thermocouples were positioned in 23 upper-wall locations near the ceiling throughout the three kilns. At each location, temperatures were measured at 1-min intervals by means of thermocouples inserted 15.2 cm (6 in.) into the wall. For ease of monitoring, the data receiver was positioned in a nearby hallway. A digital probe was used to measure temperatures about 15.2 cm (6 in.) into 42 lower-wall locations near the floor. Three sets of measurements were obtained by paired workers (using the buddy system) during the early, middle, and end phases of the heat treatment. A Raytek Raynger MX4 high-performance infrared thermometer was used at the same 42 lower locations for surface-temperature measurements, along with the 23 upper-thermocouple locations. Thirteen sets of surface-temperature measurements were obtained. Two HOBO data loggers were positioned within the kilns near two corners to measure atmospheric conditions and were programmed to measure temperatures at 1-min intervals. A total of 36,971 temperature measurements were obtained.

Temperatures attained during the heat treatment. The ambient daytime temperature before the heat treatment was around 23.9°C (75°F), and the nighttime temperature was 15.6°C (60°F). The target temperature of 48.9°C (120°F) was reached within 2 hr. Temperatures stayed within 48.9–62.8°C (120–145°F) for about 24 hr. The 60–62.8°C (140–145°F) delivery temperature, with a strong, uniform air movement, was impressive. The air-circulation plan was effective, so the plan was sustained while workers searched for any cool zones that needed airflow modifications. The floor temperature reached 51.7–54.4°C (125–130°F), which indicated excellent temperature penetration into the concrete. The maximum temperature recorded by a HOBO data logger in the west kiln (on the floor in the southeast corner) was 62.8°C (145°F), and the relative humidity was 7.2%. The maximum temperature recorded by another HOBO data logger in the center kiln (on the floor in the southwest corner, on the opposite side of the wall from the previous data logger) was 64.2°C (147.6°F). The relative humidity recorded at this site was also 7.2%. Although it was tempting to shorten the holding time, experience from past heat treatments indicated that it takes a long time to raise the cores of concrete walls to 48.9–60°C (120–140°F). The cool-down phase went more quickly than planned and took about 4 hr.

Relative humidity monitoring. A digital thermohygrometer was used to verify atmospheric temperature and relative humidity. Relative humidity started around 65% and avaraged ~10% before the start of the facility cool-down phase.

Test-insect monitoring. A total of 600 adults of the confused flour beetle (*T. confusum*) (60 cages with 10 insects each) were used to monitor the efficacy of the heat treatment. Forty-two Bug–Chek cages (LSB Products, Manhattan, KS) were positioned throughout the heated area near the same 42 lower temperature-monitoring locations. Twelve cages were used in a grain-chaff heat-penetration experiment, with six additional cages held in an ambient area to serve as a "control." All insects exposed to heat treatment were held at room conditions for seven days before mortality was assessed.

Results

Observed insect mortality. About 98% of the control insects were alive. All of the 420 confused flour beetles positioned throughout the heated area were dead. A few survivors were found in cages located near an entry door. All spider beetles found on the floor near the walls were dead.

Effect of heat on structures and equipment. There were no structural or equipment problems following the heat treatment. All air circulators performed satisfactorily. A series of the smaller air movers stopped operating close to 60°C (140° F), and 10% of the 50.8-cm (20-in.) box fans also stopped working during the heat treatment.

Costs. The total cost to conduct this heat treatment was around $20,000; about 25% of this was the heat energy cost. Around 25% of the heat-treatment expenses would likely not be incurred again in the future. Examples of such expenditures are drilling 65 holes for probes, hole plugs, extension cords/boxes, air circulators, and fans. A methyl bromide fumigation of the same 17,055 m^3 (602,640 ft^3) of space (assuming that such a treatment was even possible, given the extreme difficulty of sealing the floors and ceilings) might cost more than $40,000. This heat treatment, therefore, was an economical and environmentally sound approach for managing spider beetles or confused flour beetles within wall voids.

Study 2. Heat Treatment of the Kansas State University Pilot Feed Mill

Experiment I

The pilot feed mill in the Department of Grain Science and Industry at Kansas State University, Manhattan, KS, was built during 1951–1953. The mill is used for teaching, research, holding short courses and workshops, and developing feed formulations for private industry. The feed mill has six vertical sections: a basement, first, second, third, and fourth floors, and a roof. The first floor is attached to an extrusion room and a warehouse; dimensions of this floor are approximately 24 × 21 × 4 m. The dimensions of second, third, and fourth floors are each 17 × 12 × 4 m. Metal bar grating separates the first three floors, and metal plates separate the third and fourth floors.

The mill produces cattle, swine, poultry, and experimental rat feed in mash and pellet forms. The types of grain used in the mill, in descending order of importance, are maize, sorghum, wheat, and barley. Additional ingredients such as soybean meal, meat and bone meal, or fishmeal also are used from time to time. All raw ingredients, feed additives, and minerals are stored in bins or a warehouse for several weeks to months.

The feed mill was heated during August 4–6, 1999, using natural-gas heaters from Temp-Air (Rupp Industries, Inc., Burnsville, MN). Three THP-550 heaters, each producing 550,000 BTU/hr (138,050 kcal/hr), and one THP-1400 heater producing 1,400,000 BTU/hr (352,794 kcal/hr) were used for heating the mill. Heaters were placed outside the mill, and the heat generated by the units was discharged into the mill through 50.8-cm-diameter nylon ducts with circular openings (about 10 cm in diameter). Ducts from the THP-550 heaters (one duct per unit) were placed in the basement and in the first floor. Both the ducts from the THP-1400 heater were placed in the first floor. To facilitate heat distribution, Bayley fans (Rupp Industries, Inc.), each with a 1.5-hp motor, a fan-blade diameter of 0.78 m, and an airflow rate of 391 cm^3/min, were placed in the first, second, and third floors (two fans per floor).

Two 7.6-cm^2 metal plates were placed 1–1.5 m above the floor level in different, and widely separated, locations within each floor. Surface temperatures were measured at hourly intervals throughout the heat treatment by reflecting the light from an infrared thermometer (gun) (model 4TP78, Raytek, Santa Cruz, CA) off the metal plates. The accuracy of temperature measurements with this instrument is ± 0.25% for temperatures $\leq$600°C. Temperatures outside the mill and heater discharge temperatures throughout the heat treatment were also recorded.

Before the heat treatment, floors and all accessible equipment were thoroughly cleaned. Bulk or bagged ingredients and finished feed products were loaded into a trailer and fumigated with phosphine by a commercial applicator. No pest-control treatments of any kind were made after heat treatment, but sanitation was performed as needed.

Temperature profiles during heat treatment. The gas-heater discharge temperatures during heat treatment ranged from 62.8 to 112.8°C (≈145–235°F). Temperatures outside the feed mill during heat treatment ranged from 22.2 to 31.1°C (72–88°F). Temperatures among the four mill floors at the start of heat treatment were 28.3–30.6°C (83–87°F) (Table 4) The target temperature of 50°C (122°F) was reached quickly (1.5 hr) in the first floor of the mill and slowly (8 hr) in the fourth floor of the mill (Table 4). The hourly rate of increase from the ambient to the threshold temperature varied among mill floors (2.6–13.7°C/hr). Temperatures in all four mill floors were above 50°C (122°F) for 28–34.5 hr. The maximum temperatures recorded were 9–25°C above the threshold temperature.

Insect bioassays. Life stages of the red flour beetle (*T. castaneum*) and confused flour beetle (*T. confusum*) were introduced into separate plastic dishes 4.5 cm^2 × 1.5 cm high, each containing 10 mL of whole-wheat flour admixed with 5% brewer's yeast (w/w). The stages included 10 eggs, 10 younger instars (six-day-old larvae, weighing 0.12 mg), 10 pupae (26-day-old), and 10 adults (two-week-old). Ten unsexed adults of mixed ages of the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.); rusty grain beetle, *Cryptolestes ferrugineus* (Stephens); lesser grain borer; rice weevil, *Sitophilus oryzae* (L.); and 10 third instars of the Indianmeal moth, *Plodia interpunctella* (Hübner), were placed in separate dishes containing 10 mL of whole-wheat flour plus brewer's yeast, or hard red winter wheat kernels of 12% moisture (only for *R. dominica* and *S. oryzae*). All dishes were placed on metal trays in the first floor of the mill. One of these dishes was removed at the beginning of heat treatment and one each at 3, 12, and 24 hr after heaters were turned on. For each species and time period, five

TABLE 4
Temperature Data Observed Within and Among Pilot Feed Mill Floors During August 4–6, 1999, Gas Heat Treatment[a,b]

Floor	Sensor[c]	Temperature (°C) Start	End	Max.	Hours to Reach 50°C	Rate of Increase (degrees C/hr)[d]	Hours above 50°C
1st	1	28.3	63.9	72.2	3.2	6.8	32.8
	2	29.4	61.7	75.0	1.5	13.7	34.5
2nd	1	30.0	63.3	71.7	2.1	9.5	33.9
	2	30.6	63.3	70.6	2.4	8.1	33.6
3rd	1	30.0	61.7	70.0	3.1	6.5	32.9
	2	29.4	62.2	68.9	3.4	6.1	32.6
4th	1	29.4	59.4	64.4	7.2	2.9	28.8
	2	28.9	58.9	58.9	8.0	2.6	28.0

[a] Source: Roesli et al (2003); used with permission.

[b] Heat discharge and outside temperatures ranged from 62.8 to 112.8°C and from 22.2 to 31.2°C, respectively.

[c] At each sensor location, temperature readings were taken hourly for 37 hr ($n = 37$).

[d] The rate of increase from the ambient to the target temperature of 50°C was calculated as (50°C minus starting temperature in °C)/(hours to reach 50°C).

dishes were removed and taken to the laboratory. Mortality assessments were made 48 hr later at room conditions (27°C and 45% RH). The dishes removed just before heat treatment served as controls, and none of the insect species in these dishes died during the heat-treatment period.

Mortality of insects confined in dishes. Adults of all species and the immature stages of *Tribolium* species and *P. interpunctella* larvae confined in plastic dishes died after 3 hr of exposure to heat. All insects exposed for 12 and 24 hr also died.

Experiment II

The pilot feed mill was heated during August 6–8, 2001. The purpose of this experiment was to determine variations in temperature and relative humidity in different locations of the feed mill. Windows and doors of the mill were not sealed to prevent heat loss. In the feed mill, 10 locations among the basement and the four feed mill floors were selected to measure temperature and relative humidity changes. Locations 1 and 2 were in the basement; locations 3–5 were in the first floor; locations 6 and 7 were in the second floor; location 8 was in the third floor; and locations 9 and 10 were in the fourth floor.

Two HOBO data-logging units were placed in each feed mill location to measure temperature and relative humidity during the heat treatment. HOBO units were launched by a computer to record temperature and relative humidity at 15-min intervals. Temperature and relative humidity outdoors were measured by two HOBO units placed at ground level on the south side of the feed mill. Except for location 3, which was at the top of a hopper bin, all locations were at the floor level.

Five natural-gas heaters from Temp-Air (Burnsville, MN) were used to heat the feed mill. Each of the four heaters (THP-550) produced 550,000 BTU/hr (138,050 kcal/hr) and one heater (THP-1400) produced 1,400,000 BTU/hr (352,794 kcal/hr). The airflow rate of a THP-550 heater was 20.3 $m^3 \cdot min^{-1}$ (3,000 $ft^3 \cdot min^{-1}$) and that of a THP-1400 heater was 54.2 $m^3 \cdot min^{-1}$ (8,000 $ft^3 \cdot min^{-1}$). All heaters were placed outside the mill. These heaters bring in air through the burners and heat it to 60–82°C. Heat generated by the units was discharged into the mill floors by 50.8-cm-diameter nylon ductwork with 10-cm diameter openings at regular intervals. Ducts from the THP-550 units (one duct per heater) were placed in the basement and first floor, while ducts from the THP-1400 unit (two ducts per heater) were placed in the third floor. Theoretical engineering calculations, based on the airflow rate of the heaters and the volume of the facility, estimated that the air inside the feed mill was exchanged two to five times per hour, replacing ambient air with hot air during the heat treatment. Heaters were turned on at 8:00 p.m. (local time) on August 6 and turned off at 7:00 a.m. on August 8. Ten fans distributed heat in the first, second, and third floors. Of these, three were Bayley fans with a 50-cm blade diameter, producing an airflow rate of 48.1 $m^3 \cdot min^{-1}$ (7,100 $ft^3 \cdot min^{-1}$), and seven were Schaefer fans with a 90-cm blade diameter and an airflow rate of 311.3 $m^3 \cdot min^{-1}$ (11,000 $ft^3 \cdot min^{-1}$).

Temperature and relative humidity profiles. Starting temperatures at all feed mill locations ranged from 32 to 36°C. Typical temperature and relative humidity profiles observed during heat treatment at the 10 locations are shown in Figure 1. The temperature outdoors during the heat treatment was 23–28°C. The temperature in the southwest corner of the feed mill basement (location 2) never reached 50°C, and the maximum temperature attained there was 46°C (Table 5). Puddles of standing water near the southwest corner could have contributed to the slow heating of this area. In the same basement, temperatures in the northwest corner (location 1) reached 50°C in the shortest time (6 hr). This occurred because location 1 was close to a heating duct. The longest time (19 hr) taken to reach 50°C occurred in the southwest corner of the second floor (location 7). Heating ducts were not placed in the second floor, and heat distribution was primarily due to a chimney effect and air movement facilitated by fans. Temperatures above 50°C among mill locations were maintained for 18–31 hr, and the maximum temperatures attained ranged from 46 to 63°C. Temperatures exceeded 60°C in three of the 10 locations (1, 5, and 8). Heating rates among the feed mill floors ranged from 0.8 to 2.5 degrees C/hr.

Outdoor relative humidity during the heat treatment ranged from 37 to 78%. Relative humidity at the beginning of the heat treatment among the feed mill locations was 34–58% (Table 6). The humidity levels observed during heat treatment were inversely related to temperature (Fig. 1). In the feed mill, the rate of decrease in humidity as the temperature climbed to 50°C was faster (3.9%/hr) in location 1 and slower (0.9%/hr) in locations 4, 7, and 10. Once the temperature reached 50°C, humidity in the feed mill stabi-

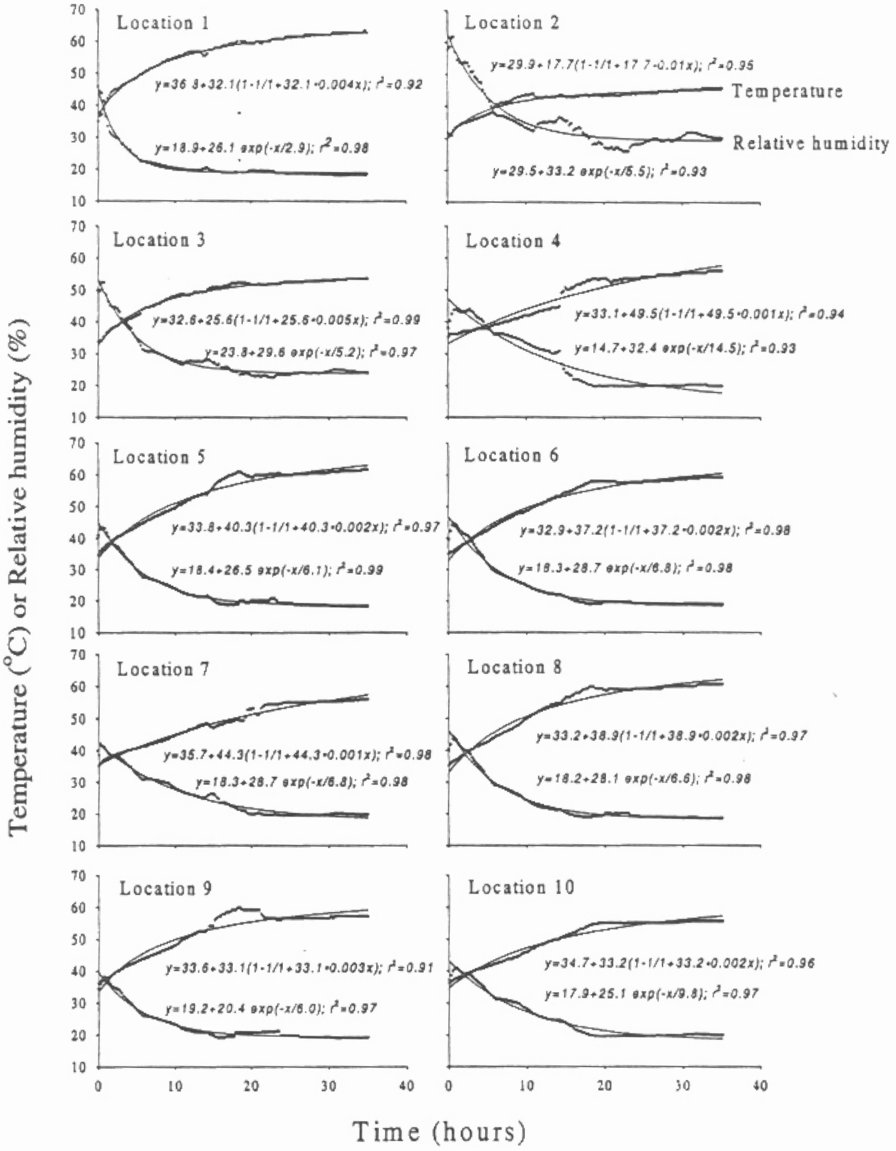

Fig. 1. Observed temperature and relative humidity data at 10 locations during the August 6–8, 2001, gas heat treatment of the Kansas State University pilot feed mill. Two separate nonlinear regression models satisfactorily described these data. Top curves = temperature, bottom curves = relative humidity. (Reprinted, with permission, from Mahroof et al, 2003a)

lized around 19–21%, and the rate of change in humidity above 50°C was generally very small (0.02–0.2%/hr, Table 6).

Norstein (1996) and Dowdy and Fields (2002) reported a similar decrease in relative humidity in flour mills during heat treatment. In the feed mill locations, a slight increase in humidity occurred soon after the heaters were turned on. Dowdy and Fields (2002) also observed a slight increase in humidity at the beginning of heat treatment. Moisture evaporating from flour in the boxes, grain dust, or hygroscopic surfaces in the mill may explain this small rise in humidity during the initial phase of the heat treatment.

Relative humidity may not play a significant role in insect mortality, although Denlinger and Yocum (1999) have suggested that rapid desiccation at high temperatures could contribute to heat-related mortality. High humidity (>60%) helps insect survival only if the temperature where insects are present is below 50°C (122°F). However, if temperatures at or above 50°C are maintained for several hours, insects can be killed even at high humidity levels (B. Subramanyam, *unpublished data*).

Practical conclusions from the experiment. This experiment showed that the stratification of temperatures during heat treatment resulted in different rates of heating among the feed mill floors. Horizontal and vertical stratification of temperatures, poor air movement, less than optimum placement of heaters or ducts carrying hot air, and loss of heat from various surfaces (windows, doors, floor, and roof vents) may have contributed to nonuniform heating observed in sample locations in the feed mill. Therefore, it is important to monitor temperatures regularly at several locations during heat treatment and take corrective action to redistribute heat from hotter to cooler areas of the mill by using additional heaters and/or fans.

Nonuniform distribution of heat within and among floors was also reported during heat treatment of a pet-food- processing facility (Dowdy, 1999), flour mills (Dean,

TABLE 5
Temperature Changes at Pilot Feed Mill Locations During Gas Heat Treatment, August 6–8, 2001[a]

Location	Starting Temperature (°C)	Time to 50°C (hr)	Rate of Increase (degrees C/hr)[b]	Time Above 50°C (hr)	Maximum Temperature (°C)
1	34.9	6.0	2.5	31.3	62.7
2	31.5	...[c]	...[c]	...[c]	45.9
3	33.6	14.3	1.1	22.5	53.5
4	35.3	15.0	1.0	21.8	56.0
5	34.6	10.3	1.5	26.8	61.7
6	35.1	11.3	1.3	26.3	59.2
7	35.3	19.3	0.8	18.3	56.0
8	35.3	10.3	1.4	27.3	60.6
9	36.1	11.0	1.3	24.0	59.2
10	36.1	14.2	1.0	20.8	55.7

[a] Source: Mahroof et al (2003a); used with permission from Elsevier.

[b] (50°C – Starting temperature, °C)/Time to 50°C (hr).

[c] Time to 50°C and time above 50°C could not be computed because temperature did not reach 50°C.

TABLE 6
Relative Humidity Changes at Pilot Feed Mill Locations During Gas Heat Treatment, August 6–8, 2001[a]

Location	Starting Humidity (%)	Rate of Decrease in Humidity Until 50°C (%/hr)[b]	Mean ± SE Humidity (no. observations)[c]	Rate of Decrease in Humidity After 50°C (%/hr)[d]
1	45.7	3.9	19.3 ± 0.1 (116)	0.1
2	57.7	...[e]	34.8 ± 1.4[f] (141)	...[e]
3	49.6	1.5	30.2 ± 0.5 (84)	0.6
4	38.1	0.9	20.2 ± 0.2 (80)	0.2
5	41.0	1.7	19.6 ± 0.2 (99)	0.2
6	39.6	1.4	19.7 ± 0.3 (96)	0.2
7	38.5	0.9	19.2 ± 0.04 (63)	0.1
8	40.3	1.6	19.6 ± 0.2 (99)	0.2
9	34.4	1.1	19.9 ± 0.2 (96)	0.1
10	37.0	0.9	20.1 ± 0.2 (83)	0.2

[a] Source: Mahroof et al (2003a); used with permission from Elsevier.

[b] (Starting humidity – humidity at 50°C)/Time to 50°C.

[c] Mean ± standard error (SE) humidity values were calculated from observations starting at 50°C until the end of heat treatment.

[d] (Humidity at 50°C – humidity at the end of heat treatment)/Time from 50°C until end of heat treatment.

[e] Values could not be calculated because temperature did not reach 50°C.

[f] The mean ± SE humidity value was calculated from observations collected throughout the heat treatment.

1911; Heaps and Black, 1994; Dowdy and Fields, 2002), and a feed mill (Roesli et al, 2003). Dean (1911) observed significant differences in the rate of heating of several flour mill floors and locations within the mill, such as elevator boots and roll stands. The temperature rise was faster at ≥1.5 m above the mill floor when compared with temperatures close to the floor. Dowdy and Fields (2002) reported differences within north and south corners of the second and third floors of the Kansas State University pilot flour mill subjected to a steam heat treatment during March 1998. In their study, the maximum temperatures attained ranged from 48 to 57°C, and the time to reach 47°C took 30–51 hr.

Although temperatures were above 60°C (140°F) in three feed mill locations, no adverse effects on structural integrity of the mill or functioning of mill equipment were observed after the heat treatment.

Sources of Information on Heat Treatments

Kansas State University has been conducting annual heat-treatment workshops since 1999. Presentations and printed material from various experts in this area are posted on a website: http://www.oznet.ksu.edu/grsc_subi. From this main page, go to the link titled, "Conferences/Workshops." A Canadian website (http://res2.agr.ca/winnipeg/storage/pages/heatde.htm) provides information on the use of heat and diatomaceous earth for management of mill insects. A list of companies that conduct heat treatments can be obtained from the World Wide Web.

SUMMARY

Heat treatment of structures is becoming popular as an alternative to structural fumigation, because of the safety to workers and the environment. Food-processing facilities that have been using heat treatments find this to be a viable method for killing stored-product insects. Heat treatments can be conducted with gas, electricity, or steam as energy sources. The effectiveness of a heat treatment depends on proper planning by a "heat-treatment team," conducting a thorough sanitation of equipment and floors, removing heat-sensitive products and materials that could act as heat insulators, determining the heat energy (in BTUs) required for treating a portion or the entire facility, using air movers and fans for uniform distribution of hot air, and monitoring temperatures from as many locations as possible within the facility and then taking corrective action to redistribute heat from hotter to cooler areas.

Heat-treatment effectiveness can be evaluated by monitoring insects several weeks before and after a treatment by using commercial food and pheromone traps and using various life stages of insects in test cages. In addition, the degree and duration of insect suppression obtained by heat treatments can be extended by using other recommended IPM tactics such as exclusion, sanitation, inspection, and pesticide application. The effect of high temperatures on materials used within food-processing facilities is poorly understood and warrants further scientific scrutiny. Heat treatment is both a science and an art, and it is an appealing technology for nonorganic and organic facilities.

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