TABLE OF CONTENTS

Section 1	Safety
Section 2	Heat Treatment/Sterilization
Section 3	Heat Treatment Checklist
Section 4	Facility Preparation
Section 5	Sealing the Facility
Section 6	Types of Heaters
Section 7	Fan and Fan Locations
Section 8	Monitoring Temperatures
Section 9	Estimating Energy Requirements
Section 10	Energy Costs
Section 11	Heat Treatment Research
Section 12	Effects of Heat on Insects
Section 13	Heat and IPM
Section 14	Heat for Control of Insects in Grain
Section 15	Stored-Product Insects
Section 16	Research at K State on Stored-Product Insects IPM
Section 17	Selected References
Section 18	Miscellaneous

Heat Emergencies

Carol Kennedy

Heat Emergencies

Sources:
The Merck Manual, 16th Edition, R. Berkow, M.D., Editor, 1992.
http://www.drkoop.com/adam/std/top/000056.htm

1. Definition
    1. Muscle cramps - caused by loss of salt from heavy sweating.
    2. Heat exhaustion - caused by dehydration.
    3. Heatstroke - causes shock, brain damage and eventually death.
2. General Considerations
    1. Easily preventable.
    2. Take precautions in hot environments.
    3. At risk are children, elderly, and obese people.
    4. Warning signals must not be ignored.
    5. Progresses from muscle cramps to heat exhaustion to heatstroke.
3. Causes
    1. Cardiovascular disease.
    2. Dehydration.
    3. High temperatures or humidity.
    4. Alcohol use.
    5. Excess clothing.
    6. Lack of acclimatization.
    7. Exercise, prolonged or excessive.
    8. Sweat gland dysfunction.
    9. Certain drug usage.
        1. Anticholinergics - used to treat nausea, vomiting, abdominal cramps and stool motility problems.
        2. Phenothiazines - used to correct chemical imbalances in the brain.
        3. Amphetamines -
4. Symptoms.
    1. Early (Muscle Cramps Phase)
        1. Dizziness
        2. Fatigue
        3. Muscle cramps
        4. Nausea
        5. Profuse sweating
        6. Thirst
        7. Weakness
        8. Lightheadedness
    2. Later (Heat Exhaustion)
        1. Cool, moist skin
        2. Dilated pupils
        3. Headache
        4. Pale skin
        5. Irrational behavior
        6. Nausea and vomiting
        7. Unconsciousness

3. Later still. This is a medical emergency!
    1. Dry, hot, and red skin
    2. Fever
    3. Dark urine
    4. Extreme confusion
    5. Rapid, shallow breathing
    6. Rapid, weak pulse
    7. Seizures
    8. Small pupils
    9. Unconsciousness

5. What NOT to do!
    1. DO NOT underestimate the seriousness of heat illness!
    2. DO NOT give the victim medications used to treat fever, such as aspirin!
    3. DO NOT give the victim salt tablets!
    4. DO NOT overlook complications resulting from another medical problem, such as high blood pressure!
    5. DO NOT give the victim liquids that contain alcohol or caffeine!
    6. DO NOT give the victim anything by mouth (not even salted drinks), if heat stroke is suspected.

6. First Aid
    1. Move the victim to a cool location, preferably air conditioned environment.
    2. Have the victim lie down with feet elevated 12 inches.
    3. Apply cool, wet cloths to the skin. Use a fan to help lower the temperature. Place cold compresses on the victim's neck, groin, and armpits.
    4. Give the victim beverages to sip, such as Gatorade. Cool water is OK if salty beverages are not available. Give a half a cup of fluids every 15 minutes.
    5. If muscle cramps, gently massage affected muscles.
    6. Call for emergency medical assistance (911) if there are signs of shock (bluish lips and fingernails, decreased alertness), or seizures.
    7. If the victim loses consciousness, place victim on his side to maintain the airway.
    8. Keep the victim cool until the EMS personnel arrive.

7. Prevention
    1. Wear loose-fitting clothing.
    2. Rest frequently.
    3. Avoid hot places.
    4. Drink enough fluids.
    5. Avoid overheating if you are taking drugs that impair heat regulation, or if you are obese, or elderly.
    6. Exercise gradually and increase salt and water intake.

Call for emergency medical assistance if the victim's condition does not improve with treatment!

Heat Emergencies!

Prevention - drink fluids and increase salt intake!

First Aid: If victim can drink, provide fluids.

Heat Cramps: Muscle cramps (pain). Caused by loss of sodium (salt), sweating due to exertion or high temperatures. Abrupt onset, usually starts in the legs.

Heat Exhaustion: Fatigue, weakness, anxiety, sweating, loss of consciousness, eventually leads to shock (cold, clammy skin, disorientation). Caused by excessive fluid loss.

Prevention - drink fluids!

First Aid: Place victim flat or with head down.

Heatstroke: Headache, dizziness, fatigue, decreased sweating, hot dry skin. Pulse and breathing increased. Disorientation, loss of consciousness.

Prevention - avoid prolonged exposure to heat!

First Aid: Call 911! Immerse in cold water.

Heat Stress Monitoring

Nick Huser, CIH
Kansas State University

Wet Bulb Globe Temperature

- Outdoors with solar load:
  - WBGT = 0.7 NWB + 0.2 GT + 0.1 DB
- Indoors or Outdoors with no solar load:
  - WBGT = 0.7 NWB + 0.3 GT
    - WBGT = Wet Bulb Globe Temperature
    - NWB = Natural Wet Bulb
    - DB = Dry-Bulb Temperature
    - GT = Globe Temperature

Measuring Heat Stress

Heat stress affects millions of people on and off the job. In the summer of 1995 the summer heat was blamed for more than 700 deaths. July 19 through August 1, 1999 at least 191 deaths nation wide have been attributed to the heat.

The Occupational Safety and Health Administration (OSHA) defined heat stress as the aggregate of environmental and physical factors that constitute the total heat load imposed on the body. The environmental factors of heat stress are air temperature and movement, water vapor pressure, and radiant heat. Physical work contributes to total heat stress by producing metabolic heat in the body in proportion to the work intensity. The amount, thermal characteristics, and type of clothing worn also affect the amount of heat stress by altering the rate of heat exchange between the skin and the air.

Assessment of heat stress may be conducted by measuring the climatic and physical factors of the environment and then evaluating their effects on the human body by using an appropriate heat-stress index. There are many different indexes that have been developed since the mid 1950's. The West Bulb Globe Temperature Index (WBGT) is probably the most widely accepted standard.

The WBGT Index was developed originally to provide a convenient method to assess, quickly and with minimum of operator skills, conditions which posed threats of thermal overstrain among military personnel. Because of its simplicity, it has been adopted as the principal index for the Threshold Limit Value (TLV) by the American Conference of Governmental Industrial Hygienist (ACGIH). Also, OSHA printed in their Technical Manual the WBGT-TLV as the recommended procedure for their compliance officers investigating Heat Stress.

WBGT Index requires the computation of temperature readings from three different thermometers, the Black globe thermometer(GT), a natural (static) wet-bulb thermometer(NWB), and a dry-bulb thermometer (DB). The formulas for WBGT:

Outdoors with solar load:

WBGT = 0.7 NWB + 0.2 GT + 0.1 DB

Indoors or Outdoors with no solar load:

WBGT = 0.7 NWB + 0.3 GT

The readings are then plotted on the chart based on the Work Rates/Load. All temperatures in this paper are °C (°F).

Examples of Work Rates/Load

Resting	Sitting quietly
	Sitting with moderate arm movement
Light	Sitting with moderate arm and leg movements
	Standing with light work at machine or bench while using mostly arms
	Using a table saw
	Standing with light or moderate work at machine or bench and some walking about

Moderate	Scrubbing in a standing position Walking about with moderate lifting or pushing Walking on a level a 6 km/hr while carrying a 3 kg weight load
Heavy	Carpenter sawing by hand Shoveling dry sand heavy assembly work on a noncontinuous basis Intermittent heavy lifting with pushing or pulling (e.g., pick-and shovel work)
Very Heavy	Shoveling wet sand

Combine Heavy and Very Heavy for the current TLV. These are separated in the proposed change.

	Work Rate/Load		
Work-Rest Regimen	Light	Moderate	Heavy
Continuous	30 (86)	26.7 (80)	25.0 (77)
75% Work - 25% Rest each hour	30.6 (87)	28.0 (82)	25.9 (78)
50% Work - 50 Rest each hour	31.4 (89)	29.4 (85)	27.9 (82)
25% Work-75% Rest each hour	32.3 (90)	31.1 (88)	30.0 (86)

As workload increases, the heat stress impact on an unacclimatized worker is exacerbated. For unacclimatized workers performing a moderate level of work, the permissible heat exposure TLV should be reduced by approximately 4.5 degrees.

Additionally, a correction factor for the WBGT for clothing:

Summer work uniform	0
Cotton Coveralls	-2 (-3.6)
Winter work uniform	-4 (-7.2)
Water barrier, permeable	-6 (-10.8)

ACGIH has proposed to lower the TLV for Heat Stress to:

Wet Bulb, Globe Temperature Criterion Values for Work Rates that are:

	Light		Moderate		Heavy		Very Heavy	
Hourly Activity	Unacclimatized	Acclimatized	Unacclimatized	Acclimatized	Unacclimatized	Acclimatized	Unacclimatized	Acclimatized
100% Work	27.5 (81.5)	29.5 (85)	25 (77)	27.5 (81.5)	22.5 (72.5)	26.0 (79)	21 (70)	25 (77)
75% Work; 25% Rest	29 (84)	30.5 (87)	26.5 (80)	28.5 (83.5)	24.5 (76)	27.5 (81.5)	22.5 (72.5)	26.5 (80)
50% Work; 50% Rest	30 (86)	31.5 (89)	28.0 (82.5)	29.5 (85)	26.5 (80)	28.5 (83.5)	25 (77)	27.5 (81.5)

25% Work; 75% Rest	31 (88)	32.5 (90.5)	29 (84)	31 (88)	28 (82.5)	30 (86)	26.5 (80)	29.5 (85)

* Work and rest environments are assumed to be the same. When they are different, hourly time-weighted averages (TWA) should be calculated and used. TWAs for work rates should also be used when they vary within the hour.

* Values in the table are applied by reference to the "Work-Rest Regime" section of the Documentation and assume 8-hour days in a 5-day work week with conventional breaks as discussed in the Documentation. When work days are extended, consult the "Application of the TLV" section of the Documentation

The WBGT is not an actual measurement of Heat Stress. It is an environmental measurement from which heat stress is derived. The heat stress TLVs refer to heat stress conditions under which it is believed that nearly all workers my be repeatedly exposed without adverse effects. Heat Stress TLVs are based on the assumption that nearly all acclimatized, fully clothed (e.g., lightweight pants and shirt) workers with adequate water and salt intake should be able to function effectively under the given working conditions without exceeding a deep body temperature of 38 °C (100.4 °F).

Higher heat stress exposures are permissible if the workers have been undergoing medical surveillance and it has been established that they are more tolerant to work in heat than the average worker. Workers should not be permitted to continue their work when their deep body temperature exceeds 38 °C (100.4 °F).

References:

The Daily Oklahoman (July 31, 1999)
The Manhattan Mercury (August 2, 1999)
Occupational Exposure to Hot Environments, 1986, NIOSH
The Industrial Environment - Its Evaluation and Control, 1973, NIOSH
1999 TLVs and BEIs, ACGIH

TABLE 4. Examples of Metabolic Heat Production

Work Rates	Example Activities
Resting	Sitting quietly
	Sitting with moderate arm movements
Light	Sitting with moderate arm and leg movements
	Standing with light work at machine or bench while using mostly arms
	Using a table saw
	Standing with light or moderate work at machine or bench and some walking about
Moderate	Scrubbing in a standing position
	Walking about with moderate lifting or pushing
	Walking on level at 6 km/hr while carrying a 3 kg weight load
Heavy	Carpenter sawing by hand
	Shoveling dry sand
	Heavy assembly work on a noncontinuous basis
	Intermittent heavy lifting with pushing or pulling (e.g., pick-and-shovel work)
Very Heavy	Shoveling wet sand

TABLE 1. Examples of Permissible Heat Exposure Threshold Limit Values [Values are given in °C and (°F) WBGT]*

Work–Rest Regimen	Work Load		
	Light	Moderate	Heavy
Continuous work	30.0 (86)	26.7 (80)	25.0 (77)
75% Work — 25% Rest, each hour	30.6 (87)	28.0 (82)	25.9 (78)
50% Work — 50% Rest, each hour	31.4 (89)	29.4 (85)	27.9 (82)
25% Work — 75% Rest, each hour	32.2 (90)	31.1 (88)	30.0 (86)

*As workload increases, the heat stress impact on an unacclimatized worker is exacerbated (see Figure 1). For unacclimatized workers performing a moderate level of work, the permissible heat exposure TLV should be reduced by approximately 2.5°C.

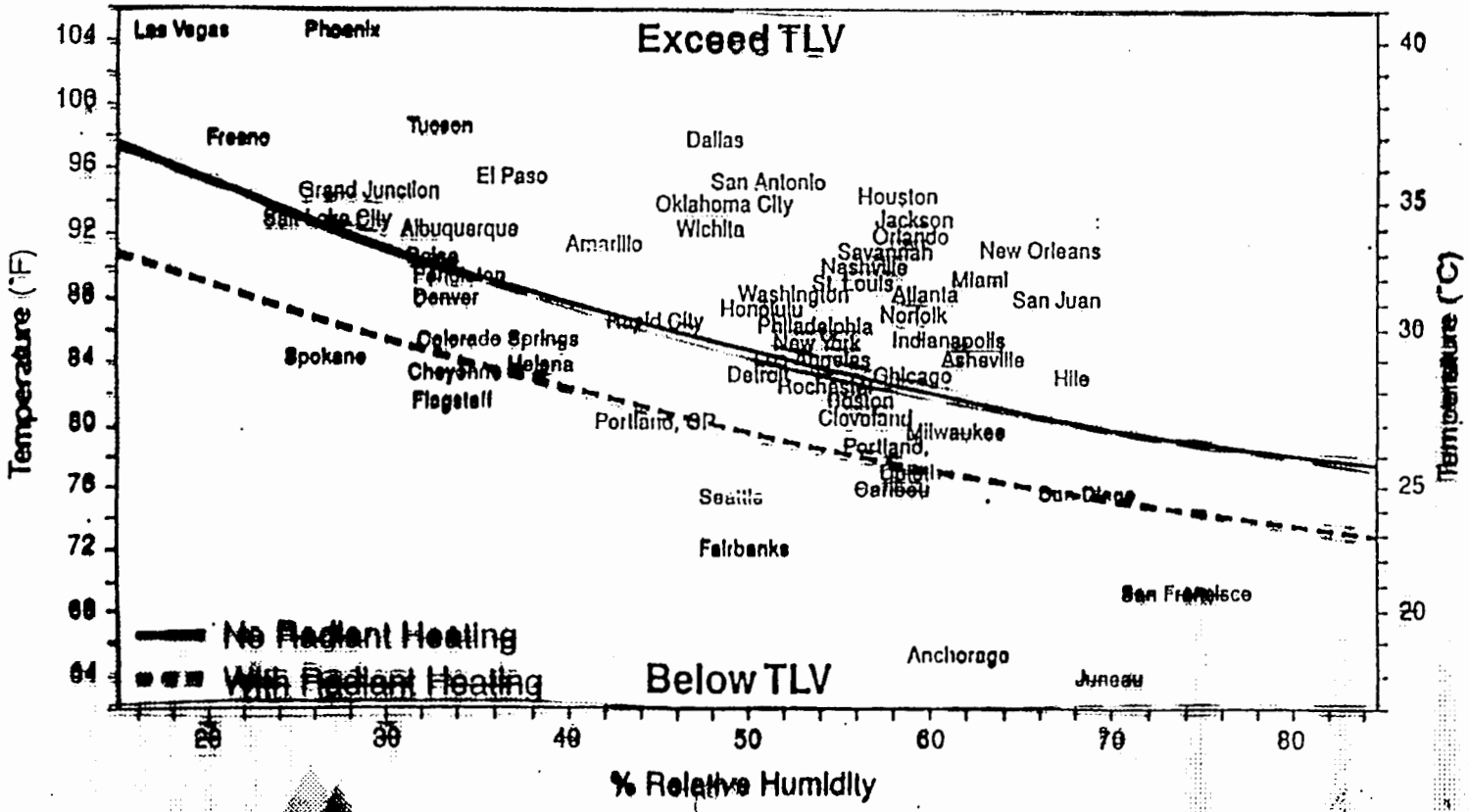
Wet Bulb, Globe Temperature (WBGT) Criterion Values for Work Rates that are:

	Light		Moderate		Heavy		Very Heavy	
Hourly Activity	Unacclimatized	Acclimatized	Unacclimatized	Acclimatized	Unacclimatized	Acclimatized	Unacclimatized	Acclimatized
100% Work	27.5	29.5	25.0	27.5	22.5	26.0	21.0	25.0
75% Work; 25% Rest	29.0	30.5	26.5	28.5	24.5	27.5	22.5	26.5
50% Work; 50% Rest	30.0	31.5	28.0	29.5	26.5	28.5	25.0	27.5
25% Work; 75% Rest	31.0	32.5	29.0	31.0	28.0	30.0	26.5	29.5

Notes:
- See Table 4 and the *Documentation* for Work Rates.
- WBGT values are expressed in °C and are rounded to the nearest half degree.
- Work and rest environments are assumed to be the same. When they are different, hourly time-weighted averages (TWA) should be calculated and used. TWAs for work rates should also be used when they vary within the hour.
- Values in the table are applied by reference to the "Work-Rest Regimen" section of the *Documentation* and assume 8-hour work days in a 5-day work week with conventional breaks as discussed in the *Documentation*. When work days are extended, consult the "Application of the TLV" section of the *Documentation*.

Average Mid-Day, July Temperatures and Humidities vs. Estimated WBGT TLV for Moderate, Continuous Work Wearing Cotton Coveralls

(Do Not Use as a Substitute for Actual WBGT Readings)



OSHA Technical Manual

TABLE OF CONTENTS | NEXT CHAPTER

SECTION III: CHAPTER 4

HEAT STRESS

Contents:

I. Introduction
II. Heat Disorders and Health Effects
III. Investigation Guidelines
IV. Sampling Methods
V. Control
VI. Personal Protective Equipment
VII. Bibliography

Appendix III:4-1. Heat Stress: General Workplace Review
Appendix III:4-2. Heat Stress-Related Illness/Accident Follow-Up
Appendix III:4-3. Measurement of Wet Bulb Globe Temperature

I. INTRODUCTION.

Operations involving high air temperatures, radiant heat sources, high humidity, direct physical contact with hot objects, or strenuous physical activities have a high potential for inducing heat stress in employees engaged in such operations. Such places include: iron and steel foundries, nonferrous foundries, brick-firing and ceramic plants, glass products facilities, rubber products factories, electrical utilities (particularly boiler rooms), bakeries, confectioneries, commercial kitchens, laundries, food canneries, chemical plants, mining sites, smelters, and steam tunnels.

Outdoor operations conducted in hot weather, such as construction, refining, asbestos removal, and hazardous waste site activities, especially those that require workers to wear semipermeable or impermeable protective clothing, are also likely to cause heat stress among exposed workers.

A. CAUSAL FACTORS.

1. Age, weight, degree of physical fitness, degree of acclimatization, metabolism, use of alcohol or drugs, and a variety of medical conditions such as hypertension all affect a person's sensitivity to heat. However, even the type of clothing worn must be considered. Prior heat injury predisposes an individual to additional injury.

2. It is difficult to predict just who will be affected and when, because individual susceptibility varies. In addition, environmental factors

(105.8°F). If body temperature is too high, it causes death. The elevated metabolic temperatures caused by a combination of work load and environmental heat load, both of which contribute to heat stroke, are also highly variable and difficult to predict.

If a worker shows signs of possible heat stroke, professional medical treatment should be obtained immediately. The worker should be placed in a shady area and the outer clothing should be removed. The worker's skin should be wetted and air movement around the worker should be increased to improve evaporative cooling until professional methods of cooling are initiated and the seriousness of the condition can be assessed. Fluids should be replaced as soon as possible. The medical outcome of an episode of heat stroke depends on the victim's physical fitness and the timing and effectiveness of first aid treatment.

Regardless of the worker's protests, no employee suspected of being ill from heat stroke should be sent home or left unattended unless a physician has specifically approved such an order.

B. HEAT EXHAUSTION. The signs and symptoms of heat exhaustion are headache, nausea, vertigo, weakness, thirst, and giddiness. Fortunately, this condition responds readily to prompt treatment. Heat exhaustion should not be dismissed lightly, however, for several reasons. One is that the fainting associated with heat exhaustion can be dangerous because the victim may be operating machinery or controlling an operation that should not be left unattended; moreover, the victim may be injured when he or she faints. Also, the signs and symptoms seen in heat exhaustion are similar to those of heat stroke, a medical emergency.

   Workers suffering from heat exhaustion should be removed from the hot environment and given fluid replacement. They should also be encouraged to get adequate rest.

C. HEAT CRAMPS are usually caused by performing hard physical labor in a hot environment. These cramps have been attributed to an electrolyte imbalance caused by sweating. It is important to understand that cramps can be caused by both too much and too little salt. Cramps appear to be caused by the lack of water replenishment. Because sweat is a hypotonic solution (±0.3% NaCl), excess salt can build up in the body if the water lost through sweating is not replaced. Thirst cannot be relied on as a guide to the need for water; instead, water must be taken every 15 to 20 minutes in hot environments.

   Under extreme conditions, such as working for 6 to 8 hours in heavy protective gear, a loss of sodium may occur. Recent studies have shown that drinking commercially available carbohydrate-electrolyte replacement liquids is effective in minimizing physiological disturbances during recovery.

D. HEAT COLLAPSE ("Fainting"). In heat collapse, the brain does not receive enough oxygen because blood pools in the extremities. As a result, the exposed individual may lose consciousness. This reaction is similar to that of heat exhaustion and does not affect the body's heat balance. However, the onset of heat collapse is rapid and unpredictable. To prevent heat collapse, the worker should gradually become acclimatized to the hot environment.

E. HEAT RASHES are the most common problem in hot work environments. Prickly heat is manifested as red papules and usually appears in areas where the clothing is restrictive. As sweating increases, these papules give rise to a

2. *Cool Rest Area:* Where heat conditions in the rest area are different from those in the work area, the metabolic rate (M) should be calculated using a time-weighted average, as follows:

Equation III:4-1. Average Metabolic Rate

$$Average\,M = \frac{(M_1)(t_1)+(M_2)(t_2)+\ldots+(M_n)(t_n)}{t_1+t_2+\ldots+t_n}$$

where: M = metabolic rate
t = time in minutes

In some cases, a videotape is helpful in evaluating work practices and metabolic load.

FIGURE III:4-1. ACTIVITY EXAMPLES

- Light hand work: writing, hand knitting
- Heavy hand work: typewriting
- Heavy work with one arm: hammering in nails (shoemaker, upholsterer)
- Light work with two arms: filing metal, planing wood, raking the garden
- Moderate work with the body: cleaning a floor, beating a carpet
- Heavy work with the body: railroad track laying, digging, barking trees

Sample Calculation: Assembly line work using a heavy hand tool

Walking along		2.0 kcal/min
Intermediate value between heavy work with two arms and light work with the body		3.0 kcal/min
Add for basal metabolism		1.0 kcal/min
	Total:	6.0 kcal/min

Source: ACGIH 1992.

TABLE III:4-1. ASSESSMENT OF WORK

C. WET BULB GLOBE TEMPERATURE INDEX.

1. Wet Bulb Globe Temperature (WBGT) should be calculated using the appropriate formula in Appendix III:4-2. The WBGT for continuous all-day or several hour exposures should be averaged over a 60-minute period. Intermittent exposures should be averaged over a 120-minute period. These averages should be calculated using the following formula:

Equation III:4-2. Average Web Bulb Globe Temperature (WBGT)

$$Average\ WBGT = \frac{(WBGT_1)(t_1)+(WBGT_2)(t_2)+\ldots+(WBGT_n)(t_n)}{t_1+t_2+\ldots+t_n}$$

For indoor and outdoor conditions with no solar load, WBGT is calculated as:

$$WBGT = 0.7NWB + 0.3GT$$

For outdoors with a solar load, WBGT is calculated as

$$WBGT = 0.7NWB + 0.2GT + 0.1DB$$

where:

WBGT	=	Wet Bulb Globe Temperature Index
NWB	=	Nature Wet-Bulb Temperature
DB	=	Dry-Bulb Temperature
GT	=	Globe Temperature

2. The exposure limits in Table III:4-2 are valid for employees wearing light clothing. They must be adjusted for the insulation from clothing that impedes sweat evaporation and other body cooling mechanisms. Use Table III:4-3 to correct Table III:4-2 for various kinds of clothing.

3. Use of Table III:4-2 requires knowledge of the WBGT and approximate workload. Workload can be estimated using the data in Table III:4-1, and sample calculations are presented in Figure III:4-1.

D. MEASUREMENT. Portable heat stress meters or monitors are used to measure heat conditions. These instruments can calculate both the indoor and outdoor WBGT index according to established ACGIH Threshold Limit Value equations. With this information and information on the type of work being performed, heat stress meters can determine how long a person can safely work or remain in a particular hot environment. See Appendix III:4-2 for an alternate method of calculation.

TABLE III:4-2. PERMISSIBLE HEAT EXPOSURE THRESHOLD LIMIT VALUES

Clothing type	Clo* value	WBGT correction
Summer lightweight working clothing	0.6	0
Cotton coveralls	1.0	-2
Winter work clothing	1.4	-4
Water barrier, permeable	1.2	-6

*Clo: Insulation value of clothing. One clo = 5.55 kcal/m^2/hr of heat exchange by radiation and convection for each degree °C difference in temperature between the skin and the adjusted dry bulb temperature.

Note: Deleted from the previous version are trade names and "fully encapsulating suit, gloves, boots and hood" including its clo value of 1.2 and WBGT correction of -10.

Source: ACGIH 1992.

V. CONTROL.

Ventilation, air cooling, fans, shielding, and insulation are the five major types of engineering controls used to reduce heat stress in hot work environments. Heat reduction can also be achieved by using power assists and tools that reduce the physical demands placed on a worker.

However, for this approach to be successful, the metabolic effort required for the worker to use or operate these devices must be less than the effort required without them. Another method is to reduce the effort necessary to operate power assists. The worker should be allowed to take frequent rest breaks in a cooler environment.

A. ACCLIMATIZATION.

1. The human body can adapt to heat exposure to some extent. This physiological adaptation is called acclimatization. After a period of acclimatization, the same activity will produce fewer cardiovascular demands. The worker will sweat more efficiently (causing better evaporative cooling), and thus will more easily be able to maintain normal body temperatures.

2. A properly designed and applied acclimatization program decreases the risk of heat-related illnesses. Such a program basically involves exposing employees to work in a hot environment for progressively longer periods. NIOSH (1986) says that, for workers who have had previous experience in jobs where heat levels are high enough to produce heat stress, the regimen should be 50% exposure on day one, 60% on day two, 80% on day three, and 100% on day four. For new workers who will be similarly exposed, the regimen should be 20% on day one, with a 20% increase in exposure each additional day.

B. FLUID REPLACEMENT. Cool (50°-60°F) water or any cool liquid (except alcoholic beverages) should be made available to workers to encourage them to drink small amounts frequently, e.g., one cup every 20 minutes. Ample

surrounding the worker assists in cooling because the worker's body radiates heat toward them.

With some sources of radiation, such as heating pipes, it is possible to use both insulation and surface modifications to achieve a substantial reduction in radiant heat. Instead of reducing radiation from the source, shielding can be used to interrupt the path between the source and the worker. Polished surfaces make the best barriers, although special glass or metal mesh surfaces can be used if visibility is a problem.

Shields should be located so that they do not interfere with air flow, unless they are also being used to reduce convective heating. The reflective surface of the shield should be kept clean to maintain its effectiveness.

D. ADMINISTRATIVE CONTROLS AND WORK PRACTICES.

1. Training is the key to good work practices. Unless all employees understand the reasons for using new, or changing old, work practices, the chances of such a program succeeding are greatly reduced.

2. NIOSH (1986) states that a good heat stress training program should include at least the following components:

   - Knowledge of the hazards of heat stress;
   - Recognition of predisposing factors, danger signs, and symptoms;
   - Awareness of first-aid procedures for, and the potential health effects of, heat stroke;
   - Employee responsibilities in avoiding heat stress;
   - Dangers of using drugs, including therapeutic ones, and alcohol in hot work environments;
   - Use of protective clothing and equipment; and
   - Purpose and coverage of environmental and medical surveillance programs and the advantages of worker participation in such programs.

3. Hot jobs should be scheduled for the cooler part of the day, and routine maintenance and repair work in hot areas should be scheduled for the cooler seasons of the year.

E. WORKER MONITORING PROGRAMS.

1. Every worker who works in extraordinary conditions that increase the risk of heat stress should be personally monitored. These conditions include wearing semipermeable or impermeable clothing when the temperature exceeds 21°C (69.8°F), working at extreme metabolic loads (greater than 500 kcal/hour), etc.

2. Personal monitoring can be done by checking the heart rate, recovery heart rate, oral temperature, or extent of body water loss.

3. To check the heart rate, count the radial pulse for 30 seconds at the beginning of the rest period. If the heart rate exceeds 110 beats per minute, shorten the next work period by one third and maintain the same rest period.

encumber the worker and thus permit maximum mobility. Cooling with ice is also relatively inexpensive.

2. **Wetted clothing** is another simple and inexpensive personal cooling technique. It is effective when reflective or other impermeable protective clothing is worn. The clothing may be wetted terry cloth coveralls or wetted two-piece, whole-body cotton suits. This approach to auxiliary cooling can be quite effective under conditions of high temperature and low humidity, where evaporation from the wetted garment is not restricted.

3. **Water-cooled garments** range from a hood, which cools only the head, to vests and "long johns," which offer partial or complete body cooling. Use of this equipment requires a battery-driven circulating pump, liquid-ice coolant, and a container.

   Although this system has the advantage of allowing wearer mobility, the weight of the components limits the amount of ice that can be carried and thus reduces the effective use time. The heat transfer rate in liquid cooling systems may limit their use to low-activity jobs; even in such jobs, their service time is only about 20 minutes per pound of cooling ice. To keep outside heat from melting the ice, an outer insulating jacket should be an integral part of these systems.

4. **Circulating air** is the most highly effective, as well as the most complicated, personal cooling system. By directing compressed air around the body from a supplied air system, both evaporative and convective cooling are improved. The greatest advantage occurs when circulating air is used with impermeable garments or double cotton overalls.

   One type, used when respiratory protection is also necessary, forces exhaust air from a supplied-air hood ("bubble hood") around the neck and down inside an impermeable suit. The air then escapes through openings in the suit. Air can also be supplied directly to the suit without using a hood in three ways:

   - by a single inlet;
   - by a distribution tree; or
   - by a perforated vest.

   In addition, a vortex tube can be used to reduce the temperature of circulating air. The cooled air from this tube can be introduced either under the clothing or into a bubble hood. The use of a vortex tube separates the air stream into a hot and cold stream; these tubes also can be used to supply heat in cold climates. Circulating air, however, is noisy and requires a constant source of compressed air supplied through an attached air hose.

   One problem with this system is the limited mobility of workers whose suits are attached to an air hose. Another is that of getting air to the work area itself. These systems should therefore be used in work areas where workers are not required to move around much or to climb. Another concern with these systems is that they can lead to dehydration. The cool, dry air feels comfortable and the worker may not realize that it is important to drink liquids frequently.

C. RESPIRATOR USAGE. The weight of a self-contained breathing apparatus

A. Type of business
B. Heat-producing equipment or processes used
C. Previous history (if any) of heat-related problems
D. At "hot" spots:

- Is the heat steady or intermittent?
- Number of employees exposed?
- For how many hours per day?
- Is potable water available?
- Are supervisors trained to detect/evaluate heat stress symptoms?

ARE EXPOSURES TYPICAL FOR A WORKPLACE IN THIS INDUSTRY?

A. Weather at Time of Review

- Temperature
- Humidity
- Air velocity

B. Is Day Typical of Recent Weather Conditions?
(Get information from the Weather Bureau)

C. Heat-Reducing Engineering Controls

- Ventilation in place?
- Ventilation operating?
- Air conditioning in place?
- Air conditioning operating?
- Fans in place?
- Fans operating?
- Shields or insulation between sources and employees?
- Are reflective faces of shields clean?

WORK PRACTICES TO DETECT, EVALUATE, AND PREVENT OR REDUCE HEAT STRESS.

A. Training program?

- Content?
- Where given?
- For whom?

B. Liquid replacement program?

C. Acclimatization program?

D. Work/rest schedule?

E. Scheduling of work (during cooler parts of shift, cleaning and maintenance during shut-downs, etc.)

F. Cool rest areas (including shelter at outdoor work sites)?

G. Heat monitoring program?

H. Personal Protective Equipment

- Reflective clothing in use?

Equation III:4-4. Indoor or Outdoor Wet Bulb Gobe Temperature Indexes (WBGI)

Indoor or outdoors with no solar load

$$WBGT = 0.7NWB + 0.3GT$$

Outdoors with solar load

$$WBGT = 0.7NWB + 0.2GT + 0.1DB$$

where:

WBGT	=	Wet Bulb Globe Temperature Index
NWB	=	Natural Wet-Bulb Temperature
DB	=	Dry-Bulb (air) Temperature
GT	=	Globe Thermometer Temperature

The determination of WBGT requires the use of a black globe thermometer, a natural (static) wet-bulb thermometer, and a dry-bulb thermometer. The measurement of environmental factors shall be performed as follows:

1. The range of the dry and the natural wet-bulb thermometers should be -5°C to +50°C, with an accuracy of ±0.5°C. The dry bulb thermometer must be shielded from the sun and the other radiant surfaces of the environment without restricting the airflow around the bulb. The wick of the natural wet bulb thermometer should be kept wet with distilled water for at least one-half hour before the temperature reading is made. It is not enough to immerse the other end of the wick into a reservoir of distilled water and wait until the whole wick becomes wet by capillarity. The wick must be wetted by direct application of water from a syringe one-half hour before each reading. The wick must cover the bulb of the thermometer and an equal length of additional wick must cover the stem above the bulb. The wick should always be clean, and new wicks should be washed before using.

2. A globe thermometer, consisting of a 15 cm (6-inch) in diameter hollow copper sphere painted on the outside with a matte black finish, or equivalent, must be used. The bulb or sensor of a thermometer (range -5°C to +100°C with an accuracy of ±0.5°C) must be fixed in the center of the sphere. The globe thermometer should be exposed at least 25 minutes before it is read.

3. A stand should be used to suspend the three thermometers so that they do not restrict free air flow around the bulbs and the wet-bulb and globe thermometer are not shaded.

4. It is permissible to use any other type of temperature sensor that gives a reading similar to that of a mercury thermometer under the same conditions.

5. The thermometers must be placed so that the readings are representative of the employee's work or rest areas, as appropriate.

Once the WBGT has been estimated, employers can estimate workers' metabolic heat load (see Tables III:4-1 and III:4-2) and use the ACGIH method to determine the appropriate work/rest regimen, clothing, and equipment to use to control the heat exposures of workers in their facilities.

NOTICE OF INTENDED CHANGE— †HEAT STRESS AND HEAT STRAIN

Both heat stress and heat strain must be assessed in evaluating worker safety and health. A decision-making process such as that shown in Figure 1 is required.

HEAT STRESS is the net heat load on the body from the combined contributions of metabolic heat production and external environmental factors, which include air temperature and water-vapor content, radiant heat exchange, and air movement, as these are affected by clothing.

HEAT STRAIN is the net physiological load resulting from heat stress.

The TLVs specified in Table 1 refer to heat stress conditions under which it is believed that nearly all adequately hydrated, unmedicated, healthy workers, wearing light-weight summer clothing may be repeatedly exposed without adverse health effects. To ensure that the values are appropriate to each situation, they must be used in conjunction with the flow chart of Figure 1.

Section I: Physical Barriers to Heat Loss. Evaporation of sweat from the skin may be a person's most important heat removal mechanism. Free movement of cool, dry air over the skin's surface enhances heat removal by both evaporation and convection. Water vapor impermeable, air impermeable, or thermally insulating clothing, encapsulating suits, and similar convective and evaporative barriers can severely

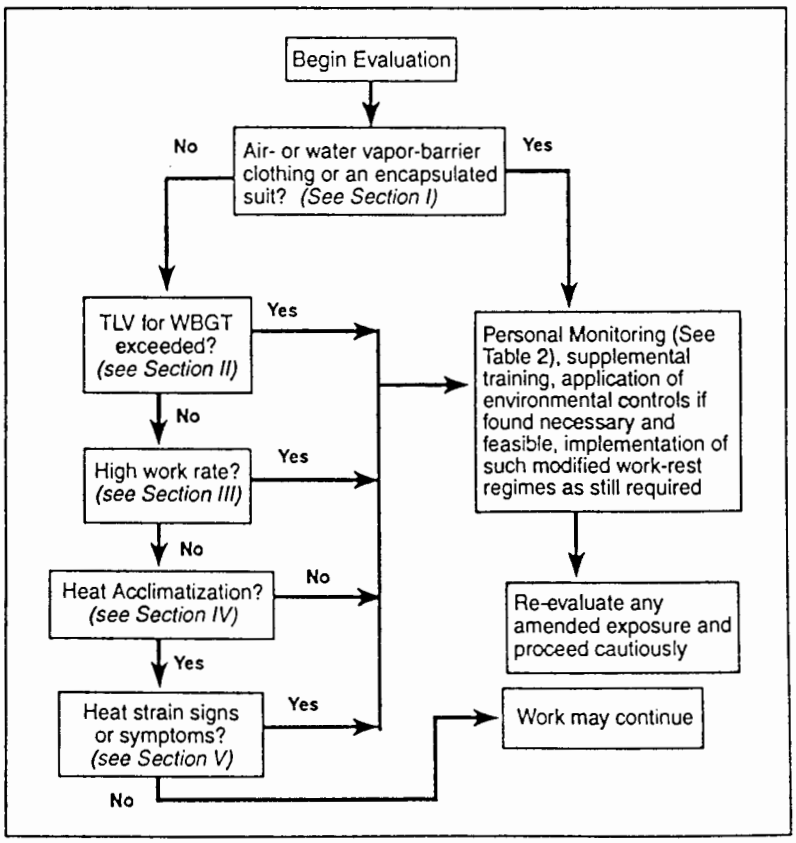


Figure 1—Evaluating Heat Stress and Strain.

TABLE 1. TLVs for Heat Exposure

Wet Bulb, Globe Temperature (WBGT) Criterion Values for Work Rates that are:

	Light		Moderate		Heavy		Very Heavy	
Hourly Activity	Unacclimatized	Acclimatized	Unacclimatized	Acclimatized	Unacclimatized	Acclimatized	Unacclimatized	Acclimatized
100% Work	27.5	29.5	25.0	27.5	22.5	26.0	21.0	25.0
75% Work; 25% Rest	29.0	30.5	26.5	28.5	24.5	27.5	22.5	26.5
50% Work; 50% Rest	30.0	31.5	28.0	29.5	26.5	28.5	25.0	27.5
25% Work; 75% Rest	31.0	32.5	29.0	31.0	28.0	30.0	26.5	29.5

Notes:
- See Table 4 and the *Documentation* for Work Rates.
- WBGT values are expressed in °C and are rounded to the nearest half degree.
- Work and rest environments are assumed to be the same. When they are different, hourly time-weighted averages (TWA) should be calculated and used. TWAs for work rates should also be used when they vary within the hour.
- Values in the table are applied by reference to the "Work-Rest Regimen" section of the *Documentation* and assume 8-hour work days in a 5-day work week with conventional breaks as discussed in the *Documentation*. When work days are extended, consult the "Application of the TLV" section of the *Documentation*.

restrict such heat removal so that metabolic heat may produce life-threatening heat strain even when ambient air temperature, radiant heat gain, and relative humidity are low. The guidelines in Table 2 should be followed when water vapor impermeable or air impermeable clothing components are worn. For other clothing, the factors in Table 3 should be added to the environmental WBGT measurement for comparison with the TLV.

Section II: Wet Bulb, Globe Temperature. The WBGT offers a useful, first-order index of the portion of heat stress due to the net effects of dry air temperature, radiant heat transfer, and humidity. It may not, however, sufficiently reflect the effects of air movement on convective heat transfer or evaporative heat loss, typically major avenues of heat loss, and it does not account for heat produced by physical work, often a major source of heat strain.

TABLE 2. Guidelines to Heat Exposure Limiting Conditions

Always monitor signs and symptoms of heat-stressed workers. When WBGT-TLV criteria (Table 1) are exceeded, when impermeable clothing (such as an encapsulated suit) is worn, or when work rates are heavier than those addressed in Table 4, exposure to environmentally or activity induced heat stress should be discontinued at any time:

For individuals:

- ✓ A worker's sustained heart rate is in excess of 180 minus age beats per minute, in individuals with normal cardiac performance; or
- ✓ In unselected, unacclimatized workers, deep body temperature is greater than 38°C (100°F); or
- ✓ In selected and acclimatized personnel, deep body temperature is greater than 38.5°C (101.3°F); or
- ✓ A worker experiences profuse and prolonged sweating; or
- ✓ In conditions of regular daily exposure to the stress, 24-hour urinary sodium excretion is less than 50 mmoles; or

For the group:

- ✓ There are complaints of sudden and severe fatigue, nausea, dizziness, or lightheadedness.

If a worker appears to be disoriented or confused, or suffers inexplicable irritability, malaise, or flu-like symptoms, the worker should be removed for rest in a cool location with rapidly circulating air and kept under skilled observation. Immediate emergency care may be necessary. If sweating stops and the skin becomes hot and dry, immediate emergency care followed by hospitalization is essential.

TABLE 4. Examples of Metabolic Heat Production

Work Rates	Example Activities
Resting	Sitting quietly
	Sitting with moderate arm movements
Light	Sitting with moderate arm and leg movements
	Standing with light work at machine or bench while using mostly arms
	Using a table saw
	Standing with light or moderate work at machine or bench and some walking about
Moderate	Scrubbing in a standing position
	Walking about with moderate lifting or pushing
	Walking on level at 6 km/hr while carrying a 3 kg weight load
Heavy	Carpenter sawing by hand
	Shoveling dry sand
	Heavy assembly work on a noncontinuous basis
	Intermittent heavy lifting with pushing or pulling (e.g., pick-and-shovel work)
Very Heavy	Shoveling wet sand

Section V: Heat Strain: Signs, Symptoms, and Adverse Health Effects. The incidence and severity of heat strain will vary widely among people, even under identical heat stress conditions. However, the overall pattern of effects is generally similar.

Profuse and prolonged sweating should be eliminated for long-term routine tasks. It can produce dehydration and loss of body electrolytes, and may lead to heat exhaustion or muscle cramps. It can also disturb normal cardiovascular functions. This effect, in situations where sweat evaporation is sufficiently restricted (e.g., by encapsulating suits), may rapidly cause a decrease in blood flow to the central nervous system, leading to diminished motor control and fainting before the increases in core temperature or heart rate reach the limits recommended in Table 2. Although prompt reduction of heat stress generally results in full recovery, the possibility of associated accidents and injury must be recognized.

A prime objective of heat stress management must always be the prevention of heat stroke, which is life-threatening and the most serious of the heat-induced disabilities. The heat stroke victim is often manic, disoriented, confused, delirious, or unconscious. The victim's skin is hot and dry, sweating has ceased, and the body temperature may be 40°C (104°F) or higher. Immediate, appropriate emergency care and hospitalization are essential if signs of heat stroke develop.

TABLE 3. Additions to Measured WBGT Values For Insulating Effects of Clothing Which is Permeable to Water Vapor and Air

Clothing Type	Clo Value☆	WBGT Addition
Summer work uniform	0.6	0.00
Cotton coveralls	1.0	+2
Winter work uniform	1.4	+4

☆ Clo: Insulation value of clothing. Refer to *Documentation* for sources of values. These values must not be used for encapsulating suits or other garments which are impermeable to water vapor or air.

WBGT values are calculated using one of the following equations:

1. When solar radiant heat is present:

$$WBGT = 0.7\ (NWB) + 0.2\ (GT) + 0.1\ (DB)$$

2. When solar radiant heat is absent:

$$WBGT = 0.7\ (NWB) + 0.3\ (GT)$$

where: NWB = natural wet bulb temperature
GT = globe temperature
DB = dry bulb temperature

As Table 1 indicates, acceptable WBGT levels depend on the rate of metabolic heat production, the degree of heat acclimatization, and the balance of work and rest periods.

Section III: Work Rate. Correct assessment of work rates is of overriding importance in evaluating the acceptability of a work situation. The metabolic heat resulting from activity can be an especially serious threat for someone wearing water-vapor-barrier, heat insulating, or air-impermeable clothing, or an encapsulating suit. Even in cool and dry ambient conditions, high work rates or wearing such clothing requires that the guidelines in Table 2 be followed. Table 4 provides broad guidance for applying the work rate criteria in Table 1. If it becomes necessary to quantify actual levels of metabolic heat production, for example when their time-weighted averaging is called for, apply the guidance in the *TLV Documentation.*

Section IV: Heat Acclimatization is critical to the acceptability of an activity continuing if the upper limits of stress suggested by the TLV criteria are approached or exceeded. Acclimatization is a set of physiological responses, development and loss of which is described in the *Documentation.* Heat acclimatization is acquired only gradually, being fully achieved over up to three weeks of continued physical activity under heat stress conditions similar to those anticipated for future work. Its loss begins when the activity under those heat stress conditions is discontinued and may occur even over three or four days.

Prolonged increases in deep body temperatures may also be associated with temporary infertility for people of both genders and, during the first trimester of pregnancy, may endanger the fetus.

Section VI: Optimizing Safety and Health. When assessing the acceptability of apparent heat stress conditions by the criteria of Table 1 and applying the guidelines of Table 5, it should be confirmed that if heat stress conditions exist, those exposed are appropriately clothed, in good general health and physical condition, not obese, and adequately hydrated with electrolyte concentrations in normal ranges.

TABLE 5. Guidelines for Optimizing Safety and Health

For people working in hot conditions or in vapor impermeable suits

- ✓ Provide accurate verbal and written instructions, frequent training programs, and other information about heat stress and strain so that it is possible to be assured of co-worker observation to detect signs and symptoms of heat strain in others exposed;
- ✓ Provide work settings with good ventilation both for general air movement and for removal of process heat and water-vapor, with shielding from radiant heat sources;
- ✓ Encourage drinking small volumes (approximately 1 cup) of cool, palatable water about every 20 minutes (refer to *Documentation* for choice of the contents provided in drinks for fluid replacement);
- ✓ Monitor WBGT-TLVs (Table 1) and guidelines (Table 2) for heat exposure limiting conditions;
- ✓ Pay extra attention to those who take medications that may compromise normal cardiovascular, blood pressure, body temperature regulation, renal, or sweat gland functions;
- ✓ Implement an ongoing cardiovascular conditioning program in conjunction with a heat acclimatization program and consider the use of preplacement medical screening to identify those susceptible to systemic heat injury; and
- ✓ Pay extra attention to those returning to work after absence from hot exposure situations, or who abuse or are recovering from the abuse of alcohol or other intoxicants.

— NEVER ignore anyone's signs or symptoms of heat strain —

Regulatory and Safety Issues to Consider During Heat Treatments

Gary Thompson

Issues

- Heat exposure
- Chemical exposure

Typical Scenario

- 120-130+ F
- 24-30 hours
- Periodic visual observations

Heat Exposure

- Heat rash
- Heat syncope
- Heat cramps
- Heat exhaustion
- Heat stroke

Know Signs and Symptoms

- Heat rash - prickly heat - hot humid environments
- Heat syncope - fainting
- Heat cramps - tired muscles

Serious

- Heat exhaustion - fluid loss
  - –Sweaty, fatigued, weak, experience vertigo, nausea, or headache. Skin clammy and body temperature normal or slightly elevated.

Life Threatening

- Heat Stroke - heat regulation system shuts down.
  - –Hot dry skin, rapid pulse, no sweat, low blood pressure.

Safety Issues

- Heat Induced Accidents
  - –Impaired grip strength due to sweat.
  - –Dizziness
  - –Safety glasses fogging
  - –Burns from hot surfaces

Worker Protection

- Safety Hierarchy of Control
  - –Eliminate the hazard
  - –Implement administrative controls
  - –Personal Protective Equipment

Hazard Elimination

- Infrequently observed and expensive to implement
  - –Thermocouple remote temperature reading devices.
  - –Accurate, dependable temp. thermostats and regulating devices.
  - –Preventive maintenance

Administrative Controls

- Limited exposure to the hot environment
  - –Rotation of workers
  - –Cool areas
  - –Buddy system
  - –Water and electrolyte availability

Personal Protective Equipment

- Insulated gloves
- Thermal protective vests

Medical

- Worker observation
- Worker training and awareness
- Employer awareness

Chemical Exposure

- Volatiles
  - –Solvents
  - –Pesticides

Regulatory and Safety Issues to Consider During Heat Treatments

Association of Operative Millers

Fort Worth, TX
May 16-18, 1999

Why Use Heat for Pest Control

- →Heat can control the entire life cycle of insects (eggs, larvae, pupae, adult)
- →Heating may diminish the frequency of plant shutdowns or remediation when compared with other methods
- →Heating does not require the same level of sealing/containment of the treated area as may be necessary with other methods

Why Use Heat for Pest Control

- →Heating is cost competitive and perhaps considerably less expensive than other methods
- →Heating is universally available and acceptable. Heat probably will not be legislated out of existence
- →Heating is well suited for most sizes of treatment areas including very large and huge

ENERGY OPTIONS

Electricity

Advantages

→ Versatile

→ Portable

→ Readily available either on-site or from rental generators

Electricity

Disadvantages

→ Cost of energy
- at $.06/kwh (house power) 1M BTU's cost $17.60
- at $.16/kwh (generator power) 1M BTU's cost $46.80

→ Size & cost of electrical distribution & service
1M BTU's = 460 volt/400 amp

→ Need for many pieces of equipment. Largest readily available unit is 150KW (500,000 BTU's)

→ Temperature rise generally very low which can equate to longer shutdowns of facility

Steam/Hot Water

Advantages

→May be available on-site

→Distribution/equipment may be in place

→Practical in hard to reach areas

Steam/Hot Water

Disadvantages

→High cost if generating capacity is not available on site

→High cost if installing distribution system (supply & return lines, insulation)

→Minimal equipment options in marketplace except very small or custom

→Physical size of equipment can limit portability & versatility

Gas (Propane / Natural)

Advantages

→ Least expensive energy cost
- Propane at $.80/gallon = $8.64/1M BTU's
- Natural gas at $.50/therm = $5/1M BTU's

→ Largest range of equipment available

→ Versatile & portable

→ Low electrical requirement
- 1M BTU unit = 460 volt/10 amp

→ Low installation cost

→ High temperature rise

Gas (Propane / Natural)

Disadvantages

→ Some codes may not allow gas fired equipment or propane

→ May not be safe to use in certain areas or buildings

EQUIPMENT OPTIONS

Permanent Equipment in Place

Advantages

→No new installation costs

→No new capitalization costs

Permanent Equipment in Place

Disadvantages

→Probably not enough total capacity unless specifically designed for high temperature applications

→Plant & plant employees bear operation, repair, maintenance costs

Permanent Equipment Added

Advantages

→One-time installation cost (may be considerable)

→System designed specifically for each building or site

Permanent Equipment Added

Disadvantages

- → Cost (internal/external) for system design
- → Capital requirements
- → Repair/maintenance costs added to plant operation costs

Rent/Lease Equipment Only

Advantages

- → Specific to each site
- → Costs are annual operating expense, not single large capital outlays
- → No direct dedicated repair/maintenance costs

Rent/Lease Equipment Only

Disadvantages

→Operating expense rather than amortization/depreciation

→Costs and performance of design, implementation and operation functions are borne by the site

→Equipment goes in and out

Contract Service

Advantages

→Specific to each site

→Costs are annual operating expense, not single large capital outlays

→Assistance in design, implementation and operation of system from supplier

→Repair/maintenance costs borne by supplier

Contract Service

Disadvantages

- → Operating expense rather than amortization/depreciation
- → Equipment goes in and out

Combination of any or all of the above

Association of Operative Millers BULLETIN

Forum: Insects' Control Alternatives to Methyl Bromide

These presentations were presented at this forum during the 1994 Annual Technical Conference in Calgary, Alberta, Canada.

Introduction

Dr. John R. Pedersen, Department of Grain Science & Industry, Kansas State University, Manhattan, Kansas, USA; was the moderator.

Grain processors have been concerned about control of insects in grain processing facilities for over 100 years and even though many tools have been available for insect control, the problem still hasn't been licked. Now processors are faced with losing one of the most valuable and efficient tools that has been available for facility disinfestation, methyl bromide.

Some of the first recorded efforts at facility disinfestation occurred near the turn of the century. Ironically, those efforts involved temperature alternation, one of the alternatives being considered today. Heat treatment of facilities appeared reasonably effective and was safe but gave way to fumigation, first with cyanide and later with methyl bromide and still later with phosphine.

Methyl bromide has been a valuable tool in plant disinfestation for over 50 years and its apparent impending demise has caused the grain processing industry to seek alternatives to offset this apparent loss. Because of its classification as an ozone depletor, methyl bromide is scheduled to be phased out for most uses by January 1, 2001.

This Forum was organized and presented to explore alternatives and innovations to cope with the changes that are foreseen with the loss of methyl bromide as a pest control tool. The keynote speaker at the 1994 Annual Technical Conference and Trade Show emphasized that we must prepare for change in the way marketing occurs under NAFTA. This concept of preparation for change is appropriate to our situation also. We must prepare for possible change in the way insect control is accomplished in grain processing facilities.

With this concept in mind, our Forum speakers will address five topics: Temperature Control, Alternative Chemicals, Structural and Equipment Design, Effective Cleaning, and Integrated Pest Management.

Temperature Control for Insect Elimination

By Jerry Heaps, B.C.E.

Why worry? Why can't it be business as usual? Just read the newspapers, listen to the evening news or one of several "news" shows on TV during prime time. The future for pesticides as we know them does not look rosy.

In the face of ever-increasing vocal pressure from consumers and environmentalists, the Clinton Administration has proposed to reform longstanding regulatory policies governing the use of synthetic chemical pesticides in agriculture and the food industry. The Delaney clause is one of the problems. It came about in the 60's after Rachel Carson's infamous book, ***Silent Spring***, was published. The clause forbids the use of any known carcinogenic material, pesticide or otherwise, that leaves a detectable residue in the processed food. Zero tolerance, Nothing. It makes no difference that technology has vastly improved since the origin of the law where now we can detect residues of parts per trillion versus originally, parts per million.

The only thing constant is change and that's why we, in our industry, need to look for non-conventional insecticide control methods for pest control. Environmental temperature control is one such option.

Background

Using temperature control, either heating or cooling of an environment, is not a new technology to eliminate insects. Within our food industry, heat was used at the turn of the century to kill stored product insects (SPI). The procedure was abandoned because of the damage it caused wooden floors and equipment. Belts could melt and grease liquefy, running out of unsealed bearings. Presently, with technology advances in building equipment design, we've come full circle and utilizing such methods as an integral piece of an overall, plant-wide integrated pest elimination program is viable. This approach is currently being used by several national food companies. (Imholte, 1984. Cooney, 1985. Heaps, 1988).

Whether we agree or disagree with it, federal, state and local regulatory agencies are, with quickness and regularity, eliminating most of the conventional insecticides the food industry has relied on for years to control SPI. For example, ethylene dibromide (EDB), carbon tetrachloride (CC14), and, more recently DDVP (Vapona) have been eliminated. True fumigants such as methyl bromide has been classified under the Clean Air Act as an ozone depletor and is subject to cancellation. Phosphine gas is under serious investigation as a chromosome-damaging material. If concluded as such, its cancellation is most likely forthcoming. Our hands will really be tied with the loss of these two materials.

SPI, as with all insects, are excellent at genetically building resistance to conventional insecticides in the organophosphate, carbamate, or even the "newer" synthetic pyrethroid groups.

For all the above reasons, we must find safe, effective, economical and prac-

Stored Product Insects Temperature Effects — Table 1

Zone	Temp (°C)	(°F)	Effect
Lethal	50 - 60	120 - 140	Death in minutes
	45	113	Death in hours
Suboptimum	35	95	Stops development
Optimum	25 - 33	77 - 91	Maximum development rate
Suboptimum	13 - 25	55 - 77	Slows development
	13 - 20	55 - 68	Stops development
Lethal	+5	41	Death in days, no movement (non-acclimated)
	-10 - +5	14 - 41	Death in weeks to months (acclimated)
	-18	0	Most die
	-25 to -15	-13 - 0	Insects freeze - death in minutes

Insect species, stage of development and food moisture content will influence temperature response. Source: Fields, Paul G. The Control of Stored Product Insects and Mites with Extreme Temperatures. J. Stored Product Res., 1992.

tical alternatives to eliminate SPI versus using conventional insecticides.

Worden (1987) has documented the use of freeze-outs in Canadian flour mills for insect control. Although effective, it's practicality is somewhat limited as is the time of year (i.e. winter) it can be done.

We do know that SPI will show a significant decrease in activity at temperatures below 60°F (15°C) or above 95°F (35°C). See Table 1. The key is not to allow the SPI to acclimate to the temperatures until the critical point is reached where death occurs. Insects' body fluids act like an antifreeze and it is only below a critical temperature that they will freeze and die. At the opposite end of temperatures, extreme heat kills insects by either dehydration, coagulating body protein - destroying key enzymes or combination thereof.

Since the author has been personally involved in facility heat sterilizations (HS) to eliminate SPI, this will be discussed in detail. By simple definition, a HS is a process by which an area/material is heated to target temperatures of between 130°F to 140°F (54° - 60°C) and maintained for an adequate time period to ensure penetration of the heat has occurred into the desired location. This may be a few hours for a simple piece of machinery or 24 hours for a facility.

Getting Started

Because of its scope, a HS project requires the cooperation of many departments within a facility. Production, engineering, sanitation, maintenance, shipping/warehousing and personnel representatives need to interact/plan every step of the process. From the top down, everyone should be committed to successfully complete such a task.

It should be emphasized that any form of temperature control to kill insects is not an end in itself or panacea for the facility. It's part of a total, plant-wide integrated pest elimination program that also includes: raw material inspections, using master sanitation schedules to document other than daily cleaning of equipment/areas, using written cleaning procedures, doing at least monthly documented facility self-inspections with a multi-disciplinary membership team, as determined by a pest monitoring program using such tools as glue boards, insect pheromone traps or insect blacklight traps, the timely use of insecticides per label directions plus finished product - warehouse - food storage or distribution center GMP/pest control inspections by qualified personnel.

How Often Do You Use Heat

This is really determined by your specific facility pest elimination needs and geographical location. In temperate climates with true cold winters, four to six HS could be done. Since under ideal conditions, the minimum time frame used for SPI life cycles (egg, larva, pupa, adult) is 30 days, more frequent (i.e. every two months) HS can be done during the warmer months when SPI activity and reproductive rates are high. From late fall through winter, timing between HS can be lengthened to, for example, every three months. Ideally, after initial HS are done and the SPI populations are under manageable control or virtually eliminated, a HS could be done in late winter/early spring to set yourself up for warmer weather, do another HS around Memorial Day to carry you into the heat of summer, do one HS mid-summer and one late summer/early fall so you're set up for winter. This spacing should provide disruption of the SPI's life cycle. If your plant is located in an area with no true winter and it's predominantly warm/hot year round with SPI activity high, more frequent HS may be necessary.

Scheduling

When scheduling a HS, be sure it's planned to fit anticipated facility production schedules to allow adequate downtime/personnel to do the job without compromising the re-starting of the facility for production after HS. The first few HS, remembering you learn ways each time to do it better/more efficiently, allow yourself extra time.

To Heat/Don't Heat Areas

Normally, the entire facility is not HS simultaneously. The following criteria can be used to help determine where to or where not to HS. First, where are your SPI problems now or where is there a high probability for problems? Secondly, the area(s) under consideration for HS need to be able to attain/maintain HS temperatures. You also need to have designated areas to place items that could be damaged by HS temperatures. Because of the temperatures in coolers/freezers and their low risk of SPI infestations, such areas are not HS.

Consideration also needs to be given to the number of cubic feet you must HS effectively/economically and logistically be able to fit enough heaters into the area.

Type of Heaters

Heaters can be electric, high- or low-pressure steam, or natural gas powered. Air is normally heated and discharged. They can be portable or permanently built into the area to be HS (either inside or even roof mounted). The benefit of using portable heaters is their flexibility to move them during an actual HS if more/less heat is needed somewhere else.

Efficiency and economics do not want to be compromised. Heater BTU range (i.e. energy) varies with size. Experience has shown that it's better to have too much BTU capacity versus not enough.

The number of heaters and their location in areas to be HS is dependent upon the number of BTUs needed to attain target HS temperature, their logistics of fitting within current building/equipment design patterns, energy source used and volume of area to be heated. Before any HS is done, engineers need to do BTU calculations, figure heat loss and other pertinent information such as HS temperatures effect of facility structure/equipment.

One of the most important factors to keep in mind is to keep the hot air moving; for example, blow it down from the ceiling to the floor to the outside walls to every part of the HS area is adequately heated. Additional fans can be used/positioned to help air movement too.

Heaters should have thermostats/temperature setting capabilities to allow the regulation of heat output during a HS. More heat initially, less after target temperatures are attained is the general rule. All heating equipment should be designed to work properly in an HS environment (i.e. special high temp motors/electrical components needed?) Put HS temp specifications into the purchase order so suppliers realize up-front what's going on.

Temperature Monitoring

Obviously, this is a critical part of a HS. Air, equipment and structural (floors, ceiling, side walls) temperatures need to be continuously monitored. Initially, this is done more frequently until your HS experiences/knowledge of such parameters increases to the point where you know a decrease in frequency is allowable.

Examples of temperature monitoring devices used are: thermocouples, automatic recording charts (do not use normal ink as HS temps tend to damage pens), hand held LCD temperature display units or a temperature sensitive tape (available with many different target temperatures) designed to turn black when target reached.

Getting Ready

Before any heat is turned on, a good suggestion would be to take a complete inventory of raw materials or equipment in the HS area(s). Manufacturers should then be checked with to determine if HS temperatures - duration will adversely affect their material. Let it be known, though, that many will give your generic/vague answers as they may not have good data to tell you "yes" or "no". Since each HS is unique, some item may not be bothered during one HS but damaged in another one, especially if hot air from a heater is directed directly onto it or it's in a "hot spot" where temperatures may exceed 140°F. With each HS, you'll be doing your own unique experimentation/learning process. One consolation is that normal HS temperatures are, many times, not outside the safe zone for most commonly used raw materials or processing equipment that we find in use in our facilities.

An excellent machine cleaning and general sanitation cycle is very important before a HS. Your goal is to eliminate accumulations that may harbor SPI and/or also allow them to insulate themselves against the heat. Waste containers need to be emptied cleaned, cabinets, dust collectors, piping, equipment, etc. where practical, need to be cleaned. To

allow for more effective heat penetration, it is helpful to leave equipment open after cleaning if possible safe.

Suspect materials that may be heat damaged could be heated in an oven at HS temperatures - time duration then examined for damage. Also, test samples of such items can be left out in a HS area during one and again, checked afterwards for damage. Experience has shown that the following items should be looked at protected from HS heat: remove fire extinguishers (place in nearby cool, accessible area), fork trucks, aerosol cans, paper packaging materials as they may warp, welding construction materials that may be flammable (check contractor's gang boxes), tanks of oxygen or other flammables, vitamins, alcohol-based flavorings, unplug drinking fountains, drain Vortex filters of oil/condensation, steam/ammonia system checked for concerns because of possible expansion, watch for Tygon tubing damage, schedule 40 PVC not as heat-tolerant as schedule 80, use high temperature (above 200°F) sprinkler heads in HS area, power down PLC units, can use Vortex units to cool electrical panels, glued belting could melt versus vulcanized belts, check hoses - air fittings for damage as heat may cause expansion and "popping" off, do not direct heater hot air flow on plastic light/electrical equipment. This listing is by no means inclusive.

The bottom line is, each facility should make its own, specific HS preparatory checklist and document its successful completion. Remember, anything that is removed from a HS area should be SPI free upon return as heat offers no residual toxic protection like some conventional insecticides.

Mechanics should inspect equipment in the HS area after it's done to see if obvious damage is detected. This could also be a good opportunity to do normal preventative maintenance work, too.

Test Insects

Test vials/cages of SPI should be placed within HS areas to help determine its effectiveness. Any or all life stages of SPI may be used, as well as different species. Control samples can also be kept in non-HS areas to use as a comparison. Use a check list to document placement - retrieval of such samples so none are lost/forgotten and end up causing you a major food safety problem. Try to place test insects in areas were you may think it will be difficult for heat to penetrate as well as obvious open sites. You want to generate data on heat penetration and effectiveness. Exposed stages of SPI are easily killed during a normal HS.

Walk through HS areas during and after the process to observe SPI activity/locate harborages. Document such sites for subsequent treatment. The initial HS or two usually has a "cleaning out" effect of SPI from harborages (i.e. floor cracks, wall holes, equipment leg base-floor junctions, equipment voids). Such sites can be sealed to prevent re-infestation. If you consistently find many dead insects in the same vicinity after a HS, a harborage(s) is being missed.

Personnel Concerns

Personnel being exposed to HS temperatures should be cleared by a physician, BEFOREHAND, that they are physically able to do such. Training should also cover common signs of heat exhaustion - heat stroke with pertinent people so they are aware of this and avoid symptoms. Cooling-type vests are available but not practical as one does not intend to spend but a few minutes at a time, at intervals, in the actual HS area. The buddy system should be used, though, whereby at least two people always go out into the HS area. Make sure emergency personnel (i.e. local fire and police) have been notified of your intentions and emergency phone lines and numbers are available if needed.

Final Preparation

Areas being HS need to be sealed from adjacent non-HS areas. Elevator shafts, stairwells, roof/wall vents-exhausts are examples of areas that may need to be sealed to prevent heat loss. Nothing fancy/expensive need be used for sealing, and if some heat escapes, it may be trivial to the whole process. Plastic film, tarps or styrofoam insulation could be used.

To protect against SPI escaping from the HS area into a nearby non-HS one, residual insecticides can be applied per label directions around the perimeters. Treatment could be done both inside/outside of the HS area. Manufacturers and/or technical representatives should be checked with first to help determine if HS will break down/make ineffective the material being used. Insect pheromone traps and double-sided sticky tape (around door/ledges, windows) can also be used to monitor SPI activity.

Don't get caught short of time manpower. Since all facility areas are not HS, work can still be done in the non-HS sites.

It's critical that the heat be turned on as soon as possible as each hour delay means fewer hours to HS, cool down and prepare for restart-up. an eight- to twelve-hour shift may be needed to prepare the HS area. To prevent thermal shock to equipment or the structure, a good rule of thumb to follow is do not raise the HS temperature more than 10°F/hour. The warmer the outside and ambient air temperatures are in the HS area, the quicker target temperatures are attained. Ground floor temperatures may require longer to heat because of low soil temperatures under the slab.

Cool Down

Buildings normally cool down quicker during cooler weather. Ventilation and types of building materials also affect cool down. Be sure you allow yourself ample time for the HS area to cool down to temperatures that allow employees to work there comfortably.

The first finished product off the line should be scrapped, as it may contain SPI that entered the system during the HS.

Cost

Many variables are figured into the cost of a HS. For example, do you want to own the heaters or rent them? Do you want to use portable heaters, build them into the facility, or use a combination of the two options? Also of significance would be the scope of your HS and the amount of energy or BTUs you'll need. The energy source, either natural gas, electricity, steam generated from in-plant boilers or diesel fuel used to power electric generators also varies in cost from region to region and season of the year. State/local/federal taxes may also be added to fuel costs. Rental equipment may also have a freight/set-up charge in addition to the rental fee.

By far though, the most expensive piece of a HS is the plant downtime and labor. Labor from outside sources (i.e. pest control operator, rental equipment personnel) and, more importantly, in-house labor costs add up quickly. Depending on when the HS is done, over a week-end and/or holiday period, wages paid can be time-and-a-half to double-time normal, straight pay. Facility production, sanitation, quality assurance and maintenance personnel will be involved in preparing for a HS, plus some will be working during the HS providing coverage on all shifts.

Finally, temperature monitoring devices will also need to be purchased for their important role during a HS.

Future

Temperature control for SPI elimination works. It is also safer, more practical/economical when compared with conventional fumigations using currently available fumigants.

Research is currently underway (Mueller, 1994) using heat (32-37°C) in combination with CO_2 (5%) and phosphine (65-100 ppm). Initial flour mill work with this combination appears successful. Both heat and/or CO_2 causes insects to increase respiration rates, simultaneously opening up their spiracle-tracheal systems more. This makes them more susceptible to water loss, toxic gas uptake and quicker death.

Work has also been done using heat (104°F) in combination with CO_2 (75-85%) and time (15 hours). Such a combination proved to be effective in field tests. (Vail, et al., 1990).

References Cited

Imholte, T.J., Engineering for Food Safety and Sanitation. 219-226 (1984)

Cooney, K.M., 1985. "If You Can't Stand the Heat." *Food Sanitation 1:24, 37-39.*

Heaps, J.W., "Turn on the Heat to Control Insects." *Dairy* and *Food Sanitation* vol 8, no. 8, 416-418. (August, 1988).

Worden, G.C., "Freeze-Outs for Insect Control." AOM Bulletin, January, 1987. 4903-4904.

Vail, R., Buckley, M. and Paolocci, L., "Modified Atmospheres Combined with Elevated Temperatures." AOM Bulletin, April, 1990. 5671-5675.

Mueller, D.K., "New Method of Using Low Levels of Phosphine in Combination with Heat and Carbon Dioxide". *Pest Control*, vol. 62, number 3, 42-48 (March, 1994).

About the Author . . .

Jerry Heaps is Manager - Sanitation & Pest Control for The Pillsbury Company, Minneapolis, Minnesota, USA. From 1988 through 1992 he was a Regional Field Sanitarian for the American Institute of Baking, Manhattan, Kansas, USA, covering Minnesota, North Dakota and parts of Wisconsin. From 1984 through 1988 he was a plant sanitarian at the Nabisco Brands Cream of Wheat plant in Minneapolis, then a Corporate Environmental Health Auditor for them. While at the Cream of Wheat plant, Jerry was directly involved in the design/implementation of the heat sterilization program for this plant which the plant continues to use today. At Pillsbury, he is working on the design/implementation of heat sterilization systems in several of their facilities. Other responsibilities include coordination of sanitation, pest control, GMP's and chemical control programs.

At the time of going to press, we had not received the presentation from Bob Richardson on "Alternative Chemicals".

Sanitation Considerations in Facility Design and Construction

By William L. Bradbury, P.E.

I am pleased to talk to you about sanitation considerations in facility design and construction. The focus will be on two major topics. The first is a discussion of building and equipment materials and details as related to facility sanitation. The second area of discussion is on heat sterilization.

Building and Equipment Materials

There are three important sanitation principles which should be followed in designing new buildings, renovating existing buildings, and selecting and installing of process equipment. These three principles are as follows:

1. Minimize ledges where dust could collect and require cleaning.

2. Eliminate unsealed void areas where dust may collect and be very difficult or next to impossible to clean.

3. Eliminate cracks and crevices, which are usually very difficult to clean.

We will cover two types of buildings and the sanitation aspects as related to each. The first is constructed of slipform concrete, and the other type constructed of precast concrete.

Many grain based food processing facilities, are constructed of both slipform concrete and precast concrete. Warehouse finished product loadout structures are often constructed of precast double-T concrete. Processing and finished product storage towers are usually constructed of slipform concrete. Slipform concrete towers are a continuous pour from the mat slab to the underside of the roof. It is an integral mass of structural concrete, including walls, pilasters, interior columns, and most floor beams. It is a very desirable structure in satisfying all three sanitation principles. Once the building is slipped, the structure is completed by the installation of the remaining floor beams and overhead floor slabs. Interior pilasters are integral with walls. Overhead floor slabs are placed over slipformed floor beams. With the floor cast over the beams, there are virtually no ledges resulting from the floor support system. From a sanitation viewpoint, it is very desirable - no ledges, no unsealed void areas, and no cracks or crevices for dust to accumulate in.

The other type of building construction frequently used for manufacturing facilities is precast concrete. Precast concrete members are trucked to the site and erected on concrete foundations. Twenty-four inch deep double-T's are frequently used to construct the floors. Once in place, a concrete topping is placed over the top of the double-T's. This topping is usually 2" to 2 1/2" in thickness. All joints between precast concrete members are caulked. All vertically formed surfaces are rubbed and sacked to close all surface voids or "bug-holes" which form when the members are cast.

This shows the ends of the double-T's being supported by a structural steel tube, which is welded to weld plates embedded in a cast-in-place concrete shear wall (see Figure 1). There are many horizontal bearing ledges in a precast facility which collect dust unless eliminated. The ledge on top of the support tube between the T stems has been eliminated by the installation of a filler panel. The panels measure approximately 44" in length and 22" in height and have radiused corners to conform to the shape of the double-T sections. They are constructed of 2" expanded polystyrene and are furnished with a cement board protective covering. They are installed by trimming as necessary and gluing and caulking into place to seal the void which is created behind the panel. The cement board finish may be painted as shown here; but, if it is unpainted, it is of a concrete color and blends well with other surrounding concrete. The ledge on top of the tube is completely eliminated by the installation of this closure panel.

This is another example of a closure panel installation. This is taken from the underside of a floor looking up at the closure panel. Please note the caulk joints which occur at 8' centers with precast concrete panels. This picture was

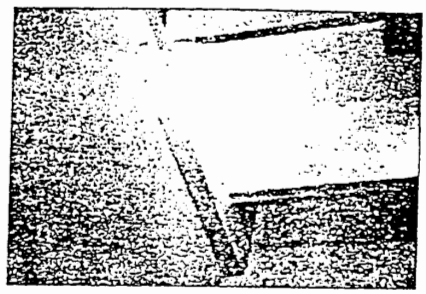


Figure 1
Use of a filler panel to eliminate a ledge.

taken in a production room and shows the roof double-T's bearing on an inverted precast concrete T beam with closure panels installed to eliminate ledges on the inverted T beam. Here is a close-up of a closure panel installed at the intersection of a roof T with an inverted T beam. Potential dust ledges are totally eliminated by the installation of these closure panels.

This view shows a precast concrete flour mill. This entire structure is insulated by the use of insulation which is sandwiched into the precast concrete between structural and nonstructural panels. The tan panels installed in the face of this mill are explosion release panels, which are insulated sandwich panels with steel facings. These panels are installed with horizontal spans. They are installed with horizontal spans so vertical support members may be utilized for any intermediate panel supports to be installed on the inside of the facility. In this case, a vertical support is installed at the mid-span of one of the panel assemblies (see Figure 2). The vertical support results in no dust ledges. If the panels spanned vertically, horizontal intermediate supports would create dust ledges.

This is an example of a header beam installed above a section of panels which are removable for equipment access. The

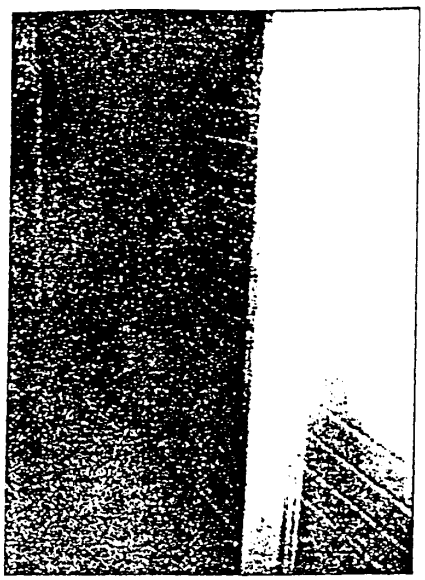


Figure 2
Vertical mid-span support for an explosion release panel.

horizontal header beam has a steel dust shed installed on top of it, which provides a sloped surface and eliminates the collection of dust on top of the header (see Figure 3).

There are various items to keep in mind when utilizing structural steel as building components or for equipment supports. For sanitation reasons, there is always a preference for closed end tube steel or round pipe. Solid rods are often used for bracing as dust does not collect on these rods. Solid deck plate is preferred over expanded walkway grating or open grating as sanitation problems develop when dust pockets are created where open grating is supported by structural steel beneath. Tube steel is often rotated to eliminate flat ledges. When possible, it is preferred to hand equipment rather than support it from the floor to make floor cleaning easier. This shows a support structure for cyclones located above sifters. The support structure is hung from the overhead roof double-T's, and the sifters are hung from this structure. This shows tube steel installed for the support of roller mill motor bases (see Figure 4). The tube steel has been rotated to eliminate dust ledges and to provide for easier belt tensioning. These bucket elevators are not supported from the floor at the boot sections but are supported by the overhead floors above. Therefore, the floor may be easily cleaned beneath the boot sections. This equipment support structure shows a diagonal tube brace rotated so that dust does not collect where the diagonal brace intersects the vertical members. This steel sloped pedestal at the base of a column provides for ease in sanitation and cleaning of the floor around the base of the column.

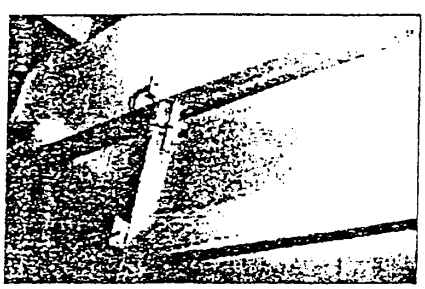


Figure 3
Dust shed above a header beam.

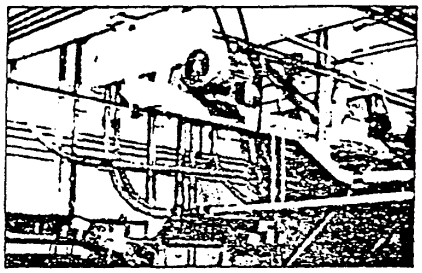


Figure 4
Rotated tube steel support.

This shows one of two exit stairways for a milling facility. The stair is constructed with plate steel stringers, solid checked deck plate, and closed end handrail tubing. The stringers are held 1 1/2" to 2" from the face of the stairway wall to allow for ease in cleaning of the wall.

Here is a support for a stairway which accesses a piece of equipment. This type of pedestal support provides for ease in cleaning at the base of the stairs.

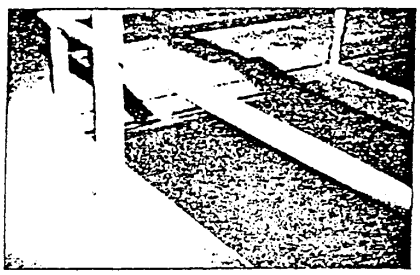


Figure 5
Integral solid deck and toe plate.

This shows the proper use of deck plate for a walkway platform with integral toe plate (see Figure 5). The toe plate is formed by shop bending up the last 4" of the deck plate. This is a very sanitary installation as compared to installations where bar grating or walkway grating is used. In those cases, material may drop through the grating and collect in pockets formed on top of intermediate supports.

This shows how structural tube steel may be utilized to support equipment by handing from an overhead double-T roof. The horizontal struts and bracing between the tube steel vertical members are solid steel rods and do not allow for the accumulation of dust (see Figure 6).

Where subject to impact damage from forklift traffic, precast concrete columns are often wrapped with a steel protective covering, which is continuously welded at a vertical seam and caulked continuously

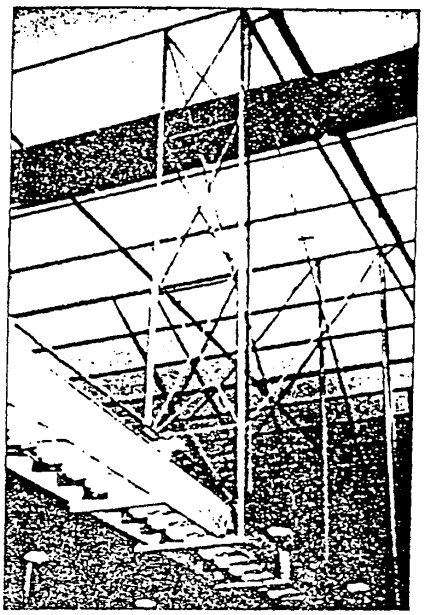


Figure 6
Tube steel and solid rod support system.

at the top and bottom of the steel.

What should be done regarding caulking and painting? These two go together as there is a considerable amount of coordination required between the caulking and painting trades people. For cost, sanitation, and heat sterilization reasons, we like to see epoxy floor caulking utilized only for high forklift traffic areas, which are normally in the warehouse. Urethane caulking should be utilized for all other areas. Epoxy painting is usually utilized for walls and ceilings only in wet wash down areas and for floors in process areas. Because it will stretch and not crack and not yellow like epoxies do, we prefer to see acrylic latex paint utilized for walls and ceilings in all other areas. You should consider using penetrating hardeners and sealers for floors in packaging and warehouse areas.

Saw-cut floor joints are later caulked prior to floor painting. Where the floor is not subject to heavy forklift traffic joints are caulked with a urethane caulking. The saw-cut shrinkage control joints are spaced at approximately 16' centers each way and result in a slab-on-grade with virtually no cracks other than those which occur at the saw cuts. The saw-cut joints are often made utilizing a soft cut saw, which allows the saw cuts to be placed sooner in the slab than that allowed by conventional sawing. Soft-cut saw cutting starts immediately after troweling.

If equipment is placed low to its support surface, adequate space should still be provided to allow for a broom to be pushed underneath the equipment for cleaning. A minimum of 8" is preferred.

After caulking is completed, the ceilings and walls were painted with vapor barrier primer and an acrylic latex finish. Floors in process areas are painted with epoxies.

In the installation of equipment, the

planning should allow for proper clearance around all equipment as necessary for cleaning of the facility. Two feet to three feet around all pieces of equipment is ideal. You should also make sure that all support bases are caulked where they are in contact with walls, floors, or ceilings.

Spouting methods frequently used are either butt junction, which is frequently done utilizing aluminum spouting, butted end to end and connected with band clamps or utilizing a second method which requires flaring of the ends of steel spouts and connecting with flared end connectors. I feel there is a greater chance of flared spouting leaking or, on angled spouts, for accumulation of material in the base of the spout at the point of flaring. Butt-end type spouting, which is commonly referred to as "speed spouting", results in a more sanitary installation. Speed spouting is also much faster to install as compared to the time required to install flared spouting.

Miscellaneous finishes include the use of masonry block, floor vinyl, and ceilings. Sheet vinyl flooring with 6" high integral base cove and heat welded seams are often used for employee welfare areas. This type of flooring system eliminates cracks and crevices which are present when either 1' square floor tiles are installed or where sheet vinyl with glued seams is installed. Masonry block walls are terminated 4" to 6" above the underside of the ceiling. Block wall terminations are always made in food plant with solid cap blocks to seal off the masonry block cells below. This view also shows a door and a window. Once a frame is installed, the void areas of the frame are foam-filled to eliminate voids; and the frame perimeter is caulked. This shows an exit corridor with precast concrete on the left and masonry blocks construction on the right, with the heat-welded sheet vinyl flooring.

This is a control room for a flour mill and pasta plant. The drop-in ceiling is a vinyl-coated gypsum board, which may be easily wiped clean. This type was selected for sanitation reasons due to the closeness of this area to potentially dusty areas. The electrical panels on the left have an aluminum-faced sandwich panel installed along the edge of the panels, from the top of the panel through the ceiling, to eliminate any ledges on top of the panel and to hide the electrical conduit runs above the panels (see Figure 7).

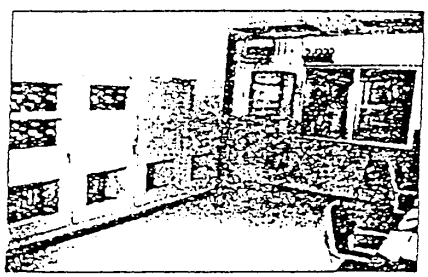


Figure 7
Ledges eliminated on the top of electrical panels.

Regarding mechanical and electrical, it is important that Unistrut and all-thread rods not be utilized in the process areas to eliminate dust ledges.

By panning precast concrete T stems, it is possible to create a "topless" duct which does not need to be cleaned. This slide shows how a "topless" HVAC air duct may be constructed by panning beneath two adjacent precast concrete T stems (see Figure 8). The duct is formed by the bottom metal pan, the sides of the two precast concrete T stems, and the underside of the roof panel of the precast double-T. The T stems are panned by holding the steel pan a couple of inches above the bottom of the T stems to allow for steel flanges to be attached to the side of the stems. Aesthetically, this is very pleasing as you view these ducts through the length of the plant and can still see all T stems. This is another view of duct panning of a double-T. If the plant is wider than one roof span of double-T's and you wish to extend to duct panning to the next span of double-T's, the duct must be constructed around the bottom side of the intermediate inverted T beams. This is a view of such an installation.

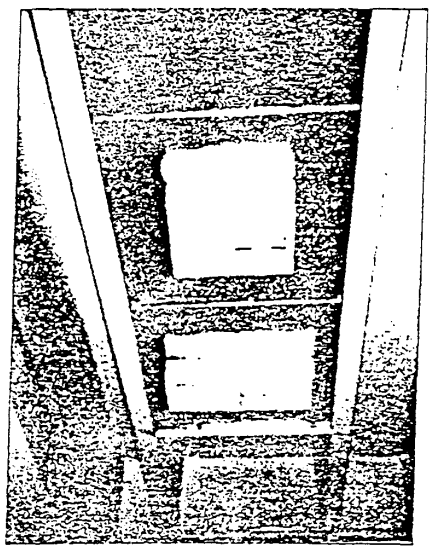


Figure 8
"Topless" HVAC air duct.

In the upper left-hand corner of this view, a round air duct is utilized to extend an HVAC system to receiving and loadout control rooms. The round duct is preferred over a rectangular duct as a rectangular duct would collect more dust and require more frequent cleaning.

This view shows a conduit support system which does not utilize Unistrut. Unistrut collects dust and is very difficult to clean. Any fixtures mounted to ceilings or walls should be caulked so that dust may not accumulate behind the fixtures. Pipe supports should be installed using rods threaded at the ends only as necessary rather than using all-thread rods.

We have primarily used two types of single ply rubber membrane roofing systems, either rock ballasted or mechanically fastened/fully adhered.

Two types of insulated roofing systems with single-ply rubber membranes are frequently used. For the roofs of flour mills, a fully adhered system should be used. Rock ballasted systems are often used for production, packaging, and warehousing facilities. Even though the fully adhered system is approximately double the cost of a rock ballasted system, it is utilized on the top of flour mills as the exhaust from various filters could, potentially, emit dust. Cleaning of any emitted dust from a rock ballasted roof would be extremely difficult and could result in unsanitary conditions. A rock ballasted roof is utilized in those areas where the risk of dust emission and entrainment in the rock is very low.

Heat Sterilization

There are certain items to consider if you are contemplating using heat sterilization as a means to control insect infestation. You must first consider the effects on buildings, primarily due to the increase in temperature and the resulting thermal expansion. You should also consider the effects on building components from the increase in temperature, including effects on sprinkler heads, paint, and so forth.

Like most materials, concrete expands with increases in temperature. The coefficient of thermal expansion for plain, normal-weight concrete and for reinforcing steel are very similar. The coefficient of expansion for reinforced concrete is six-millionths on an inch of expansion per inch of length per degree Fahrenheit of temperature rise. This converts to an expansion of 0.72" for an initial length of 100' and for a temperature rise of 100°F.

For cast-in-place or slipform concrete mill towers, normally no expansion joints are installed except where these structures may abut an adjacent structure. We believe that heat sterilization may be successfully performed in cast-in-place or slipform concrete structures provided the outside temperature is 40°F or warmer, resulting in a temperature differential from the inside to the outside of 100°F. This assumes that the target temperature for heat sterilization is 140°F.

Often, precast concrete buildings are constructed adjacent to mill towers to provide for processing, packaging, and warehousing as was done in the design and construction of a facility in North Dakota. The precast structure adjacent to the mill tower is 716' long and 160' wide. The owner requested that the structure be designed to allow for heat sterilization. Throughout the 716' length, 1/2" expansion joints were placed at the column lines, which were either at 28' or 32' centers. Due to the very cold ambient temperature at the time of erection and for added safety, four additional expansion joints were utilized. A 1" expansion

joint was utilized where the manufacturing facility abutted the flour milling tower. A 2" expansion joint was installed 216' to the east of the mill face to allow for expansion of the production and packaging areas. Another 180' to the east at a shear wall, a 1" expansion joint was placed for the opposite end of the packaging area and a 1 1/2" expansion joint for one end of the warehouse. To date, they have not utilized heat sterilization at this facility. However, in the next month, they plan to heat sterilize the facility one area at a time, starting with the production room.

For new facilities, heat sterilization should be planned into the design of your facility from day one. If you are contemplating utilizing heat sterilization from an existing facility, you should review such use very closely with the structural engineer who designed your building. As is being done in North Dakota, you should also consider heating up your building one area at a time, which could also be a more manageable process. You should also empty bins to allow for heat-up of the bin interiors and to avoid any thermal packing and subsequent bridging of stored materials.

There are other items which you should consider prior to heat sterilization. Some of these have been previously discussed. For any areas which are to be heat sterilized, make sure that any caulking of saw-cut floor joints and precast wall/ceiling joints is done using a compressible caulking material. A urethane caulking with backer rod is very suitable. For high forklift traffic areas, you may wish to utilize an epoxy caulking for the saw-cut joints. However, please realize that the epoxy is a very hard filler and essentially glues the concrete together at the joint. Therefore, any thermal expansion stress relief which could occur at the joint would not be able to occur with the hardened epoxy in place. We recommend that epoxies be utilized only in high forklift areas, such as warehouses where you may not be utilizing heat sterilization.

Because epoxy paints dry extremely hard and will not stretch, we recommend that acrylic latex coating systems be utilized when painting over caulk joints or in any areas which may be heat sterilized. This type of paint will stretch and is more economical than epoxy paints. Epoxy paints will crack at caulk joints or wherever they may be any movement. If you wish to paint your floors, there may be no other choice other than using urethanes or epoxies. You may wish to consider applying a penetrating floor hardener and sealer, many of which are available in the marketplace. One that we have used successfully in packaging and warehouse areas is Lapidolith an manufactured by Sonneborn.

Certain materials, such as polystyrenes, which may be a component of interior partition walls or of closure panels for eliminating ledges on precast concrete T beams, are rated for a service temperature of 165°F and an intermittent temperature of 180°F. Because of these types of materials, which are fairly close to the target temperatures of 140°F, you should be very careful to avoid hot spots throughout the facility which could cause localized damage.

Fire protection sprinkler heads are normally designed to activate at 212°F. Again, due to the possibility of hot spots during heat sterilization, we recommend that the sprinkler heads be installed for activation at 286°F. This should be reviewed with your insurance specialists and local building officials.

Any electronic components for control systems, etc., could be damaged due to the sterilization heat-up. You should check with your suppliers to see which components should be removed from the plant prior to heat-ups.

In closing, I would like to recommend to you a very useful resource book, which is *Engineering for Food Safety and Sanitation*. It was written by Thomas J. Imholte for the Technical Institute for Food Safety in Crystal, Minnesota. It is a very useful book, which provides detailed, practical knowledge on food plant safety and sanitation. If you don't already have a copy, I would highly recommend that you contact the current publisher, Thompson & Company, to buy a copy. Their address is: Thompson & Company, 4600 Longfellow Avenue So., Minneapolis, MN 55407, Phone: 612 722-4235.

Bibliography

Handbook of Concrete Engineering, Second Edition, Van Nostrand Reinhold, New York, 1985.

Imholte, Thomas J. *Engineering for Feed Safety and Sanitation*, Technical Institute for Food Safety, Crystal, Minnesota, 1984. Current publisher is Thompson & Company, Minneapolis, Minnesota.

PCI Design Handbook Precast and Prestressed Concrete, Fourth Edition, Precast/Prestressed Concrete Institute, Chicago, Illinois, 1992.

About the Author . . .

William Bradbury is a Vice President for Younglove Construction Company of Sioux City, Iowa. He has worked for Younglove as a Project Manager for the past 17 years on design and construction of grain storage, grain milling and processing, and pasta manufacturing facilities. Bill obtained his Bachelor of Science and Master of Science in Civil Engineering from Iowa State University and his MBA degree from the University of South Dakota. He is a registered professional engineer. Bill is also an adjunct for the Business Department of Morningside College in Sioux City, Iowa where he teaches a course in Production and Operations Management.

Insect Control Alternatives to Methyl Bromide/Indepth Scheduled Cleaning

By William Pursley

With greater restrictions on chemical controls, alternative controls for food plant insect control are continually being investigated. We could hope that another fumigant or a single step control such as heat will be found and utilized. However, it's more likely we will be looking at all of our IPM (Integrated Pest Management) tools, and while most will not work as a direct replacement for Methyl Bromide, in combination and through effective scheduled cleaning, design, etc., they are effective.

Other topics today address IPM concepts such as temperature control, chemicals, design, etc., but the most important, is likely schedule indepth cleaning.

Even if Methyl Bromide were to remain a tool for insect control in our industry, restrictions that are inevitable would likely make its use impractical (i.e., time requirements, employee safety concerns, liability, residue concerns, etc.). While economically Methyl Bromide may seem more attractive, if truly costed out, it's likely more expensive than first thought and costs will continue to increase, making alternatives such as scheduled indepth cleaning more attractive.

If we assumed you had the perfect facility in structural design and without voids, cracks or false areas and all of your equipment was accessible for cleaning and properly designed, and your schedules were so that you could have adequate time for proper cleaning frequencies which interrupted the life cycle of the pest, then schedule cleaning alone would control insects.

Understanding the basic biology of the insect and assuming that the life cycle is approximately four to six weeks for stored product insects at optimum temperatures (85°F+ or -), then thorough scheduled cleaning of the structure and equipment to interrupt the life cycle, cleaning alone will provide control. Unfortunately this food processing facility doesn't yet exist. It should be understood though that the application of indepth scheduled cleaning as your primary pest control tool (particularly for stored product insects) is the most effective option we have and will have in the future.

In developing an effective cleaning program, we need to schedule cleaning just as effectively as you would your processing schedules. Develop a Master Cleaning Schedule of structures, facility areas, equipment, etc., incorporating frequencies to interrupt life cycles (i.e. four hours to clean a drop bottom screw conveyor system, eight hours for cleaning a warehouse overhead), equipment require-

ments (vacuums, brooms, dust pans, high lifts and scaffolding) and engineering support into equipment, electrical panels, silos, etc., are required to effectively complete the task to assist in planning and labor projections. Cleaning requires down time for processing equipment, and for man power requirements it requires planning, supervision and management. It also requires commitment. Without schedules, equipment, planning and support, it won't work. In the past it was considered a costly overhead and often times lost out to production when scheduling man power and support. The loss of cheaper alternatives (i.e. chemicals) requires us to reevaluate our alternatives.

Accepting that scheduled and well-designed cleaning programs are our most affective tool in controlling insect pests and microbial concerns, we need to review dry cleaning technologies and frequencies in the milling industry.

With regard to cleaning frequencies, the basic biology of the life cycle of the insect pest is required. Some very generic guides for various insect pests at optimum conditions are:

PEST	CLEANING FREQUENCY
Stored Product Insects - Beetles & Moths	3-4 Weeks
House Flies	Twice per Week
Molds	Every Few Hours

The major restriction on cleaning is generally accessibility into equipment and structures to facilitate thorough cleaning. The first rule of cleaning is, the easier it is to clean, the more likely it will be cleaned.

An example where simple design makes the cleaning task easier might be a simple file cabinet. If mounted or left directly on the floor, it's unlikely that the cabinet will be moved regularly and swept under. It would require assistance to move or lift and unless specifically requested, would likely be missed. However, if mounted off the floor where a vacuum or broom can easily reach, it will be cleaned every time, without supervision. The same is true out in the mill. If equipment is accessible and off the floor, dirt can be dislodged, fall to the floor and easily swept up. In addition, special brooms such as spout drags, etc., can be designed and used to make cleaning easier and more effective. The more accessible or easier it is to clean, the more likely scheduled cleaning will be accomplished. For this reason using engineering to improve accountability is extremely important.

When selecting the most effective cleaning procedure, ideally we would use vacuum systems where we capture and contain the filth and dispose properly. Numerous systems are available from central systems with pick-up outlets located throughout the operation at strategic points, to portable systems for carrying into isolated areas (some with battery packs).

The obvious advantage of vacuum systems is that they capture the filth and contain it for easy disposal. A disadvantage is that it's often cumbersome in overhead or restricted areas. For these reasons providing support equipment from working platforms to accessories are important. Again, the simpler and easier it is, the better.

Our second choice would be a broom and pan, moving and collecting the filth load and disposing of it properly. While the broom and dust pan are very effective, it's very labor intensive, yet it remains the most commonly selected cleaning method.

Often times because of limitation and accessibility, we use compressed air. While it's difficult to say anything good about compressed air cleaning, it's often times a reality. For this reason our employees must understand that the best methods for using air, restricting air pressure, moving the filth load to a spot where it can be properly collected and properly disposed of, and not projecting it throughout the facility creating a dust storm and creating an even greater opportunity for insect pest development.

The other keys to scheduled cleaning are follow-up and inspection. Food processing facilities, mills included, are not static facilities. The process is constantly being modified slightly because of equipment upgrades, process changes, personnel changes and equipment and facility fatigue. To keep up with these changes requires a constant inspection and follow-up of the cleaning program. Just as the cleaning program requires disciplined schedules to insure that we don't overlook a known task, inspection requires the same discipline.

While we all have self inspection programs, if not disciplined, we tend to inspect past or known deficiencies where failures have occurred before. While that's important, it's equally important that we systematically inspect the process, including the entire facility periodically. Setting the facility up on a grid or other system and scheduling each section on a cycle will insure that the entire facility, the equipment and practices (either employee or operational) can be studied. As defects are noted, corrective procedures can be scheduled, which may include scheduled cleaning, maintenance, engineering or simply a procedural change.

We also need to continue to investigate new cleaning technologies, their potential uses and cost savings. A few recent technologies or old tools which have been improved on to assist in cleaning include:

1. A new dry bulk car cleaning system by a company in North Dakota, M-BAR-D. Using low pressure abrasive (silca) wands with vacuums, they have replaced wet washing (difficult during winter months) and disposal problems.

2. Several improvements to high volume central vacuum systems along with improved design and support making vacuum systems very competitive and easier to use.

3. CO_2 Blast Cleaning, a few companies have targeted the food industries as a potential market using this technology. Using dry ice pellets with a high pressure wand, similar to wet washing, the technology is very effective but cumbersome and very expensive. The manufacturers are continuing to work on more compact systems and reducing the cost of supplying the dry ice pellets.

4. Another blast system, Armex (a division of Church and Dwight) has developed a system using baking soda (Sodium Bicarbonate). Again a pressure wand using in this case an abrasive (baking soda) is used to clean difficult buildups, avoiding water systems.

In addition to equipment and procedures, properly scheduled indepth cleaning, inspections, and training of our employees are equally important. Video training from the AOM and reference books such as *A Flour Mill Sanitation Manual* by Robert Mills and John Pedersen note suggested cleaning frequencies and procedures and discusses inspection tips for finding hidden areas and common points of infestation. Tom Imholte's book *Engineering for Food Safety* is another valuable resource for your engineering department.

In addition, we need to work with our engineers and equipment suppliers in designing and installing equipment and building features to facilitate scheduled cleaning. Encourage equipment suppliers to provide cleaning and P.M. procedures with their equipment. Review design features and encourage modifications before the purchase and when revisions are possible.

Review the AOM *Sanifacs Booklet* available during this conference with your engineers and mill employees to remind them of the benefits of good design and hopefully encourage them to think of improved design and new procedures at your facility.

Cleaning and inspections are probably the oldest and most important IPM tools available in our industry. If each employee understands the reasons behind scheduled indepth cleaning and the pest and the thoroughness of the cleaning requirements to control pest, the better chance our other IPM tools will work. None of our tools will work alone, they need to be used together. Remember, cleaning doesn't work by accident, it only works if properly planned, supported, supervised and understood.

About the Author . . .

William Pursley is Vice President - Sanitation Education, American Institute of Baking, Manhattan, Kansas. He has a Bachelor of Science in Biology and a Master of Science in Grain Science from Kansas State University. Bill works in developing product safety and quality assurance programs within numerous food plants throughout the United States, Canada, Europe and the Middle East. In addition, he has been responsible for developing numerous seminars, courses and workshops along with two major publications on food product safety and sanitation. Bill is a registered sanitarian and certified pest control operator. Bill is currently serving on the AOM's Food Protection Committee.

Appendix D

Heat Sterilization Checklist

Prepared by the AOM Food Protection Committee

The following is a checklist of items that should be completed before, during, and after a plant super-heat. This checklist is by no means complete, since requirements will vary with plant/equipment design, climate, and heat sources.

I. Prior to Super-heat

1. Check all unit heaters.
   a. Inspect coils and steam lines for leaks.
   b. Check steam traps.
   c. Lubricate bearings.
   d. Check motor starters and heaters.
   e. Direct heater vents away from heat-sensitive items.
2. Use up feed-in product or setback.
3. Communicate with contractors working in areas to be heated so that any heat-sensitive equipment and supplies can be removed.
4. Empty as many product bins as possible. Leave hatches and clean-up doors open so heat can circulate internally.
5. Remove any pressurized containers and cylinders such as aerosol cans and CO_2 fire extinguishers.
6. Repair damaged doors, windows, or other openings that would allow heat to escape to a cool area.
   a. Eliminate all drafts.
7. Apply approved crack-and-crevice insecticide at perimeters and window ledges, paying particular attention to elevator shafts and personnel doors to cool areas. Spray stairwells.

8. Remove the tension from drive belts to avoid stretching. Glued belting may separate from the heat.

9. Thoroughly clean all glue applicator equipment at package lines.

10. Use polyethelene sheets or bags to seal off air handlers, make-up air systems, and dust collector exhausts to outside.

11. Remove heat-sensitive product or ingredients from heated areas. Examples would be sugar, powdered shortening, soda, phosphate, vitamins, flavorings, etc. If in doubt, check with the manufacturer.

12. Empty all in-house byproduct bins.

13. Any electronic equipment that cannot be removed should be de-energized.

14. Remove electronic scales from heated areas.

15. Re-position wall or pillar-mounted fans to aid in air circulation to known cool spots.

16. Open and empty as much equipment as possible.
    a. Drop the bottoms from the Carter discs, Duo aspirators; open separators, uniflows, roll stands, purifiers, gravity tables, etc.

17. Dump all product carts and trash containers. Store trash containers and tubs upside down once they are emptied and leave them in the heated areas.

18. Close all doors and windows to outside.

19. Sprinkler heads should be replaced with 260°F heads.

20. Communicate with internal security or guards.

21. Use check off lists to assure completeness of preparations.

I. During Super-heat

1. Set out insects in test cages at the beginning of the heat-up. These should be located in areas where effective temperature has historically been difficult to achieve. Areas could include heated areas with poor air circulation, ground levels, or basements. Both adult and larval stages of insects can be used.

2. Supple[illegible] insect test cage placement with chart temperature recorde[illegible] monitor heat characteristics over the entire heat period.

3. Thermometers should be placed throughout the heated areas at pre-determined positions. A crew responsible for monitoring and regulating the heat should read the thermometers every two hours.

4. Locations have reported varied time/temperature successes ranging from 20-30 hours maintaining temperatures of 120 to 150°F.

5. Turn off high-pressure sodium vapor lights. The combination of super-heat plus the light transformer heat may damage the lights.

III. After Super-heat

1. Remove chart recorders and thermometers.

2. Open only doors and windows with screens in place.

3. Remove covers from air handlers, make-up air systems, dust collector exhausts, and air conditioners and turn them on.

4. Remove test cages and record mortality and survival. Where survival occurs, check for insect activity. Treat with pesticide any areas where survival occurs.

5. Re-lubricate all equipment and tighten all belts.

6. Replace CO_2 fire extinguishers.

7. Check equipment that was open during super-heat (before closing) for any internal infestation.

8. Re-install electronic scales (reprogram if necessary).

9. Check for any equipment or areas that maintenance is needed due to heat failure or damage.

10. First product off lines should be discarded since it might contain dead insects.

Association of Operative Millers - Bulletin, October, 1987. (Contributed by Gary Thompso Sanitation Superviser, Quaker Oats Co., St. Joseph, Missouri).

Heat Treatment Workshop
Pilot Feed Mill
Kansas State University
August 4-6, 1999

Pre-Treatment Preparation of the Feed Mill

by
Keith Behnke and Fred Fairchild
Department of Grain Science and Industry
Kansas State University
Manhattan, Kansas

Prior to the heat treatment of the Kansas State University pilot feed mill many things had to be considered, addressed and accomplished. The following is a listing of the major items:

- ❑ Review Layout and Physical Characteristics of the Building.
- ❑ Determine Type of Building Materials Used in Building Including Walls, Floors, Roof, Windows and Doors for Heat Loss Calculations.
- ❑ Locate and Identify Means of Egress and Building Access both Internally and Externally.
- ❑ Calculate Volume of the Building.
- ❑ Determine Air Passage Ways Between Rooms And Floors.
- ❑ Calculate Amount of Air and Heat Required.
- ❑ Calculate the Number of Heaters Required for Heat-up.
- ❑ Determine Locations of Heaters, Pre-heated Air Source and Access to Blow Heated Air Into Mill.
- ❑ Determine Locations of Circulating Fans in the Mill.
- ❑ Determine Utility Needs (Electrical and Gas), Access and Connection to Heaters and Fans.
- ❑ Install Necessary Temporary Electrical Circuits.
- ❑ Gather Materials and Seal Exterior Building Openings and Cracks .

- ❑ Seal Around Heat Ducts from Exterior Fans.
- ❑ Do a General Cleaning of the Building.
- ❑ Lock-out/Tag-out Machinery Electrical Circuits and Open and Clean Out Machinery. Leave Machinery Open During Heat Treatment.
- ❑ Reduce Bulk Inventory in Bins to Minimum or None.
- ❑ Open Bins by Removing Covers and Opening Gates on Empty Bins.
- ❑ Remove Bagged Goods, Barrels, Drums and Sealed Containers and Fumigate or Treat Separately.
- ❑ Disconnect and Remove all Computer and Heat sensitive Equipment from the Areas to Be Heat Treated.
- ❑ Leave Air Conditioner on in the Control Room to Protect Non-Portable Control Equipment.
- ❑ Isolate Electrical Motor Control and Transformer Rooms
- ❑ Seal All Ductwork and Cyclone Discharges That Discharge to Exterior of Building
- ❑ Provide Opening In Upper Part of Mill to Allow Heated Air To Escape if Needed. This Can Be Equipped with A Removable Cover.
- ❑ Provide Proper Personal Protective Equipment for Personnel as Required.
- ❑ Determine Appropriate Locations and Place Temperature Sensors in the Mill to Monitor and Control Area Temperatures and Monitor Heat Distribution.
- ❑ Provide Oxygen Monitoring Equipment to Test Heated Areas Prior to Entering the Mill During and Immediately Following the Heat Treatment.

DALE EUSTACE

1. Empty trash containers.

2. Remove sacked product or samples left from previous milling.

3. The mill and cleaning house should be fairly clean with no piles of stock on floor.

4. Check bag filters for stock.

5. Close and cover air inlets and exhausts on roof.

6. Close all windows and exterior doors.

7. Cover freight elevator doors with paneling.

8. Turn on cooling tower fan and Day Filter to circulate air in cleaning house. Position portable fans where necessary for even heat distribution.

9. Open doors between mill and cleaning house.

10. Open covers and slide gates on empty storage bins.

11. Turn off electrical scales.

12. Spray Tempo 20WP on floor by exterior doors and in corners of each floor.

13. Turn on heat and take temperature reading in the mill at the center of each wall at floor level. Also take the temperature of heat vent on each floor as well as the temperature of the Smico filter, sifter stub, purifier 1, and the Bemis packer. When the equipment temperature reaches 120°F hold for 12-15 hours and then turn off the heat. Heat vent temperatures need to be over 140°F.

    In the cleaning house measure the temperature at the center of each wall at floor level if possible. The equipment temperature needs to be 120°F for 12-15 hours.

General Comments

Incoming steam temperature from the university power plant needs to be at least 230°F or it will take more than 2 days to get the temperature desired. There is no need to open sifters or any other equipment besides empty storage bins. Fire extinguishers need not be removed as long as the temperature does not exceed 150°F.

Outside weather can affect our heating process. A cold, 40°F, windy day is not good. March, July, August, or November are better. Two heat treatments a year can provide good insect control. After the facilities have cooled a thorough cleaning with the vacuum system is necessary.

HEAT TREATMENT FOR CEREAL INSECT CONTROL CHECK LIST
GENERAL GUIDELINES - By: Ole Dosland 12/99

PRIOR TO HEAT-UP

1. Appoint site heat-up planning team (include engineering) with Plant Manager as chairman.
2. Identify specific areas to be heated and make plot plan. Determine local heat source(s).
3. Identify heat sensitive structures and supports including roofs. If protection or engineering assurances cannot be developed, then abort heat concept.
4. Identify heat sensitive equipment. Develop protection measures or protect with cool zone.
5. Identify sealing materials needed inside heat zone and outside.
6. Identify air movement plan, circulation equipment, fan placement, type and number.
7. Establish fire protection plan. Check with insurance carrier.
8. Repair damaged doors, windows or other openings that would allow heat to escape. Eliminate major drafts from non heated 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 4 to 6 mil polyethylene sheets to seal off exhaust fans, dust collectors or air make-up systems that exhaust to the outside. Clearly note the ones to be used for de-heating.
13. Remove heat sensitive products or raw materials from heated area. Examples are vitamins, shortenings and some packing materials. Most products are not conducive to heat-treating.
14. Remove pressurized containers and cylinders from heated area. Label the fire extinguishers with proper location for emergency "near by use" during heat treatment.
15. Where possible, remove electronic equipment; any that cannot be removed must be de-energized. Where computer programs are involved, backup copies should be made.
16. Empty all trash, waste and product containers. Set containers upside down in the heated area.
17. Check sprinkler system and head sensitivity for > 200 degrees F. If not, replace each. An option is to drain the sprinkler system and post fireguards during inactivation period. Check system for tripped heads and refill slowly prior to activation.
18. Older sodium or mercury vapor lights should be turned off during heat. Check with engineering or supplier. Identify alternative lighting plan to minimize plant power use.

PRIOR TO HEAT-UP (Cont...)

19. Check bearing and belt types. Loosen where necessary.

20. Check lubricant type and reservoirs. Provide for expansion.

21. Identify plastic related materials including PVC piping and tygon tubes. Check for heat strength, remove where possible or monitor. Check for pneumatic line plastic connectors. Change over to soft metal i.e. aluminum where feasible.

22. Double check temperature limitations on all solid state equipment such as any electronic controllers, small computers, photo eyes. Remove or protect with cool zone.

23. Double check magnets since some magnets such as rare earth type, are sensitive to high temperature and can be demagnetized if exposed to temperature beyond their designed limits.

24. Remove loose rubber gaskets and sensitive caulking. Replace with heat resistant materials.

25. Establish employee safety plan; warning signs, buddy system, clothing, drinking/eating, heat stress first aid (ambient room - not air conditioned), first aid kit - burns or rashes, emergency phone numbers, employee heat tolerance (need for physicals), cool vests, etc.
    - Identify and provide appropriate personal protective equipment (PPE) such as bump hats with cloth lining, cloth gloves and light loose clothing.
    - Note any metal should not contact the skin directly such as glasses or bras.

26. Establish temperature monitoring plan; key locations, sensors, frequency, thermometers, personnel resources, problem response. Calibrate all monitoring tools.

27. Identify areas adjacent to the heated areas. Spray with residual insecticide to preclude insect migration to non-heated areas. A Tempo 20 WP or Demand CS products are options to consider for excellent overall residual insecticides for heat-ups.

28. Determine numerous locations for insect test cages with temperature indication charting. Make notes on plot plan. Use flour beetle or target insect stages for mortality evaluation. Order/make sufficient number of cages and temperature indication charts.

29. Identify "predicted" ambient temperature and weather conditions for the treatment period. Determine heat up and cool down plan. It is suggested not to exceed 10 degrees F. per hour.

30. Develop floor by floor and area by area specific checklist for planned preparation of various sensitive equipment within the heat treatment zones.

31. Identify the level of cleanliness needed for the treatment area, product inventory levels, material removal, which equipment to open & close, etc. Verify one week before treatment.

32. Identify the time and person responsible to turn off plant power, if necessary. This same person should also turn on the plant power during cool down.

DURING HEAT-UP

1. Target temperature is 120 - 140 degrees F. with humidity between 20 - 30% for 24 hours (structural) or 12 hours (equipment). Areas with temperature exceeding 140 degrees F. should be lowered to target zone immediately.

2. Aggreko, Inc. or Temp-Heat will be responsible for the operation of the rental power and/or heating equipment and assisting with temperature & humidity monitoring.

3. Heaters will be positioned in various areas to be treated. Many 24" to 36" air circulators will be used to provide general uniform heat distribution. Box fans can be used for small areas.

4. Plant and/or pest control service personnel with assistance of Aggreko or Temp-Heat personnel will monitor overall temperatures and humidity. Plant maintenance personnel will monitor specific structure areas and heat sensitive equipment in addition to providing "fire watch".

5. Monitor and record temperatures and humidity at predetermined locations, initially every hour, then bi-hourly after temperatures are stabilized. Check areas near insect cages hourly.

6. Establish the central heat treatment command center office with phone, first aid, communication boards i.e. flip chart paper, in a convenient ambient environment.

AFTER HEAT-UP

1. Discontinue heat operation (Aggreko, Inc. or Temp-Heat) after the desired exposure time and temperature is achieved. Keep fans running.

2. Uncover roof/wall vents, air intakes, etc. Open screened windows.

3. Turn on plant power when temperature cool down reaches 110 F.

4. Recover insect test cages and temperature indication charts. Record initial mortality %.

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

6. Start exhaust fans in heated areas. Monitor cooling temperatures.

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

8. Start removing portable power or heater equipment and begin re-assembly of plant equipment preparing for normal operation.

9. Remove all sealing equipment and complete post treatment cleanup. "Flush" the initial material out of the process and dispose to trash.

10. Heat-up planning team reviews treatment activity, effectiveness, etc. making suggestions while memory is fresh to improve future application.

FACILITY PREPARATION
HEAT TREATMENT

BRIEF HISTORY

- *MOBILE PROGRAM - Allowed us mobility to develop history - which led to stationary development.*
- *Allowed increased flexibility to production vs. traditional fumigations.*

Develop A Multi-Functional Heat Team

- *ELECTRICIANS*
- *PIPE FITTERS*
- *MILLWRIGHTS*

- OWNERSHIP FROM ALL DISCIPLINES

FACILITY PREPARATION - CONSIDERATIONS

HEAT EFFECTS ON DRY SPRINKLER SYSTEM

- *High temperature sprinkler heads should be specified for areas which will be heated. High temperature heads*

  (286 degrees f) should be used because hot spots do develop. This will prevent the accidental water release by one of the sprinkler heads.

HEAT EFFECTS ON CONTROL AND ELECTRICAL EQUIPMENT

- *Identify Control and Equipment Concerns*
- *Contact Manufacturer - Describe Scenario*

  140 Degrees - 18-24 Hours

HEAT EFFECTS ON EQUIPMENT LUBRICATION

- *Oil - Grease*

  Most probably will withstand 140 degrees.

  If there are some special lubricants that have lower operating temperatures, check with the manufacturer for the effect of 140 degrees F. The device may have to be relubricated following heat sterilization.

- *Gear Boxes -*

  The air (and the oil) in the gear box will expand when heated. If expanded, warm air can escape through the breather, there will be no problem. If there is no breather, pressure inside the gear box may force the lubricant out of the seals. Or, if the gear box is full of oil, it will also expand and spill or be forced through the seals.

BUILDING AND EQUIPMENT HEAT LOSSES

- *Close and/or seal all fire doors, man doors, roof vents, wall vents, and windows.*
- *Areas which are not to be included must be partitioned off if the area cannot be isolated - tarps and plastic can be used as makeshift walls.*
- *Exhaust and intake vents should be closed and/or sealed.*

REVIEW OF COMBUSTIBLE AND HEAT SENSITIVE MATERIALS IN TARGET AREAS

- *Aerosol Cans*
- *Adhesives*
- *Sugar*
- *Packaging Supplies*
- *Fire Extinguishers*
- *Contractor Materials*

- *A pre-heat walk through should identify any concerns not listed above.*

PRE-HEAT PREPARATION

- *Run equipment empty*
- *Elevator Boots opened and cleaned*
- *All sweepings and trash receptacles cleaned*
- *Sacks of product removed and portable buggies emptied*
- *Open as much processing equipment as possible - Dust Collectors, Bins, Hammer Mills, Feeders, Screw Conveyors, etc.*
- *An approved residual spray should be applied at floor-wall junctures and across doorway thresholds to unheated bldgs.*

THERMAL SHOCK

- *90 Degree differential rule*

HEAT TREATMENTS: NON-FOG & FUME PLACARDED BLDGS. QUALIFICATION CHECKLIST

- If one-person teams are deployed, they must be in radio/walkie-talkie contact with someone outside the heated area
- Must inform your outside contact of approximate length of time you will be in heated area and the route you will be taking.
- Team members must provide a copy of the heat injury chart and plant emergency phone numbers to the outside contact person and at the heat treatment location.
- Doors and entrances to heated areas must be placarded.
- Know symptoms and First Aid procedures for heat stress, heat exhaustion, and heat stroke.

MYTHS

- *Heat not successful because temperatures at floor level were not reached.*
- *Cannot heat entire facility at once, so partial treatments are not successful.*
- *Fumigants work better.*

Armstrong-Hunt, Inc.

EQUIPMENT CONSIDERATIONS
HEAT STERILIZATION FOR INSECT CONTROL

Jim Wonderly / Jim Powell

By Thomas J. Clark
Sales Manager Armstrong-Hunt, Inc.

Plant Locations:
1 Armstrong Road, Milton, Florida 32583 - USA Phone: (904) 626-0051
648 Moeller Street, P. O. Box 355, Granby, Quebec J2G 8E5 - Canada Phone: (514) 378-2655

PREFACE

The Food Industry has successfully utilized heat sterilization for insect control for some time at several plants. However, the use of chemicals to accomplish this task has been much more predominant. Recent pronouncements concerning the use of chemicals around food and the release of these chemicals to the atmosphere have focused increased attention on the use of heat.

This paper addresses steam heating equipment and the design and application considerations that a successful heat sterilization installation require.

THE OBJECTIVES AND CONSTRAINTS OF HEAT STERILIZATION

Of course, the main objective of any insect control program is to eliminate the living and eggform population. With heat sterilization, however, there are several other considerations that must be taken into account. They are:

1. Although the entire floor area must be brought up to terminal temperature (about 140 degrees F), heat must first be concentrated on the places that insects are most likely to be found.
2. The temperature needs to be brought up to terminal temperature as quickly as possible.
3. The maximum space temperature must be controlled to avoid damage to buildings and equipment.
4. Delicate equipment such as electronics need protection from high output temperatures.
5. Humidity levels must be controlled if equipment is present that may be damaged by dry heat.
6. The heating equipment must be installed and operated properly to ensure adequate heatup and long reliable life.

The following items address these objectives in detail.

TYPES OF STEAM EQUIPMENT USED

The most prevalent type of heat sterilization equipment in use is the permanently installed unit heater. Where it can be mounted reasonably low and be out of the way during normal operations of plant and equipment it provides the best option for correct placement. More precise direction of air flow can be achieved with unit heaters than with other means.

Permanently installed fan/coil units are also an option. These units actually combine several permanently mounted unit heaters into one unit. They fit best where there are large open areas to be heated and they are usually the most economical choice.

Portable unit heaters are best suited for solving cold spot problems and for directing heat to locations where a permanently mounted unit would get in the way of normal plant operations. As selection of unit locations before installation is still an artform, cold spots may show up and require portable units as an afterthought.

When ceilings are high, circulating fans can be installed to drive the hot air at the ceiling back to the floor level. Air is hottest there, sometimes reaching 170 degrees or higher. This hot air has been paid for so take advantage of it.

PLACEMENT RECOMMENDATIONS

Heating equipment should be placed as low to the floor as possible. Since heat rises when introduced to a colder area, the lower the equipment the more heat will find its way to the floor.

The units should be placed so that air is directed toward the locations most likely to harbor the insects. Some of these are:

1. Under equipment
2. Behind storage bins & tanks
3. Near Material hoppers

Attention should be paid to the location of the heaters regarding obstructions to air flow from conveyers, cookers and other such equipment.

If possible, when accomplishing the above, make sure that the air is directed toward an outside wall. Since heat loss is greater there, we want to keep outside walls as warm as possible. Often there is an option to either direct the air away from or toward these walls. Always take the latter option.

CONTROL OF TEMPERATURE

As stated earlier, consideration must be given not only to raising space temperatures but to controlling the heat to prevent temperatures from becoming too high. There are three common methods of temperature control:

1. On-off operation of the fan
2. On-off operation of the steam supply
3. Steam pressure modulation

The first method is commonly used with unit heaters for comfort heating applications. In the case of heat sterilization, this will not work too well once terminal temperature is reached. Cutting off the air flow stops mixing action. When this happens areas of the room that lose heat more quickly to the outside may get cold even while the room thermostat senses a proper temperature.

The second method is to turn the steam on and off. This will accomplish the desired temperature control (with wider swings) but it is not the best operating environment for the heating equipment itself. This method can result in water hammer with potential damage to the heating equipment.

The third and preferred method is through modulated steam pressure control. With this method, the steam temperature is regulated by reducing the steam pressure. The reduced steam temperature results in a lower air temperature rise.

HUMIDITY CONTROL

Sifters and other such equipment made of wood are subject to damage from low humidity. There are two methods that can prevent this. The first is to discharge the condensate generated by the heating equipment to a floor drain. Whenever condensate is discharged from a high to a lower pressure some of the condensate flashes back to steam. This steam can act to humidify the air being heated. This humidity is mixed with the air as a result of the turbulence generated by the heating equipment fans. This method cannot be controlled.

A second method is to install steam humidifiers to direct live steam into the room air. The amount of humidity or humidity level is easily controlled with a properly installed humidistat. Depending upon the natural humidity level of the environment, one or both of these methods may be used.

CORRECT EQUIPMENT AND OPERATING CHOICES

This subject is probably the least understood aspect of heat sterilization. The discussion to follow will present specific arguments for the proper selection of equipment and operating conditions.

USE HIGHER PRESSURE STEAM IF POSSIBLE

Higher pressure (higher saturation temperature) steam allows the use of less expensive equipment. The equipment's heating element can be smaller due to the greater rate of heat transfer attainable from higher temperature steam.

BTU output decreases with increased room temperature. A basic fundamental in heat transfer dictates that as the difference in temperature between the steam and the air decreases, so too does the amount of heat transferable.

Figure 1 is a graph depicting the percent of base BTU output vs rising ambient entering air temperatures for identical units using 2 psig and 50 psig steam. Base output is the output at a 60 degree air temperature entering the unit's coil.

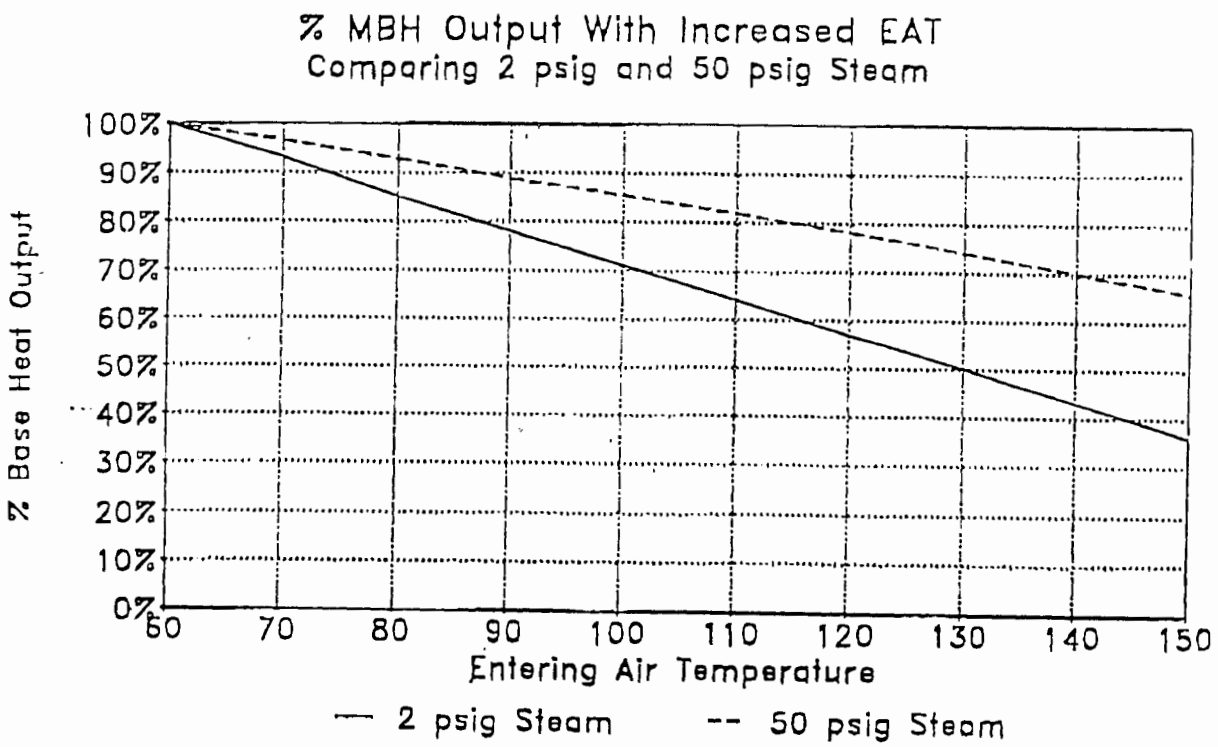


Figure 1

The greatest heat loss to the outside takes place at the terminal room temperature. When the entering air temperature reaches the terminal room temperature of 140 degrees F, Figure 1 shows that the heat output of the unit utilizing 2 psig steam drops to 43% of the rated base output. At that same temperature, the 50 psig unit maintains 70% of its rated base output. This data indicates that we would need approximately twice the equipment using 2 psig steam to accomplish the same heating as that using 50 psig steam.

The normal argument for using lower pressure steam in heating equipment is based on long term usage. The lower the steam pressure the greater the latent heat available for heating. In this case, however, usage is short term and the same economics do not exist.

USE HIGHER AIR FLOW, LOWER AIR TEMPERATURE RISE EQUIPMENT

There are Three arguments that lead to this conclusion. First, a lower air temperature rise means that the air from the heater is cooler and less buoyant in the surrounding air. As such, it will stay at floor level much longer. The term used to describe this is *throw*. It defines the effective reach of the air discharged from the unit. Throws can be increased by utilizing high velocity discharge devices. However, this gain decreases air stream width.

The second argument deals with maximum leaving air temperatures. As stated earlier, the terminal room temperature must be attained but we must also limit the maximum temperatures of the room and equipment. To do this, we must limit the leaving air temperatures of the heaters. A common limit is 160 degrees F. This is high enough to maintain temperature but low enough to protect most equipment from damage.

The problem is, the two row unit must discharge air at a high temperature to maintain its rated heat output. But, if we limit the leaving air temperature it cannot do this as the entering air temperature rises. Figure 2 illustrates the effect of temperature limitation on heat output.

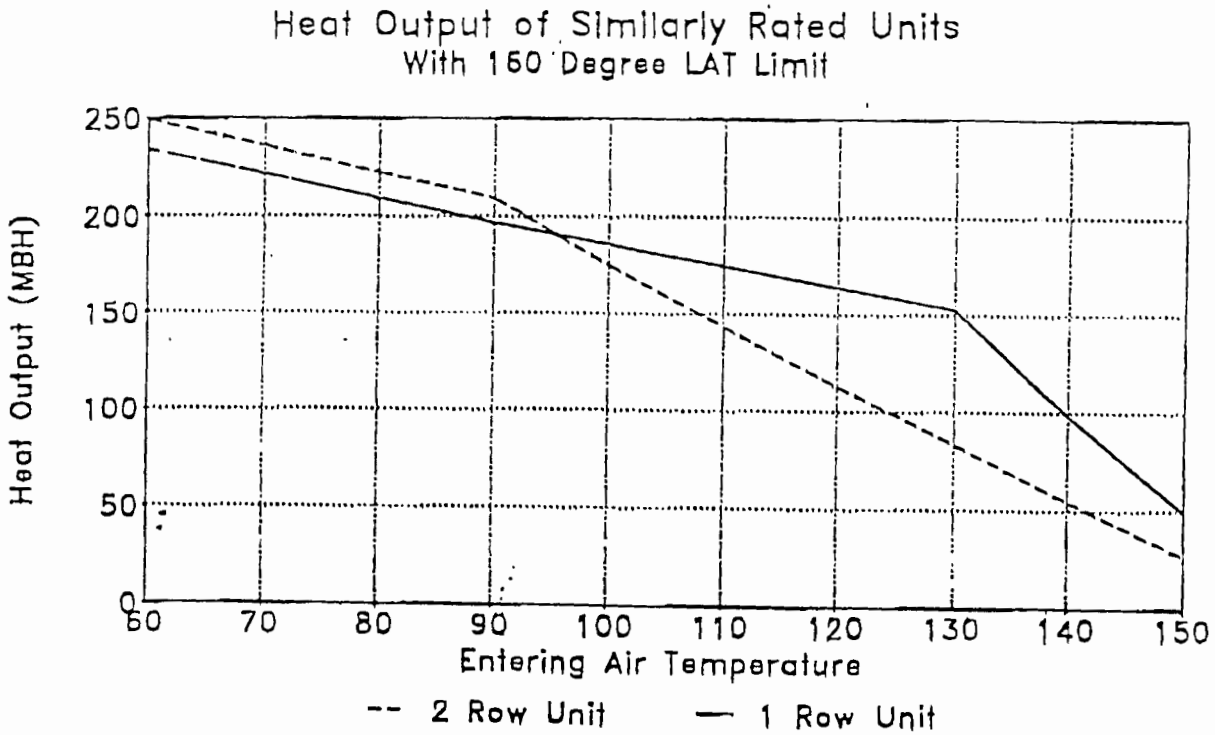


Figure 2

Without the temperature limitation the two lines would remain parallel at all ranges of entering air temperatures. With the limitation, however, we see that the two row unit must be modulated at any entering air temperature above 90 degrees. The one row unit can maintain output up to 130 degrees entering air temperature without modulation. Further, at 140 degree entering air (assumed at terminal room temperature), the one row unit's output is double that of the two row

unit. This is so even though the two row unit started out with about the same output at 60 degrees. Subsequent discussions in this paper will assume a temperature limitation of 160 degrees F.

Thirdly, the combination of lower leaving air temperatures and higher air output provide the same BTU output while covering a wider floor area. Heat soaking of the floor area and its equipment is what heat sterilization is all about. An argument can be put forth that higher temperature air hitting the floor and equipment makes the temperature rise faster. The fact is, less equipment will be reached by this air, resulting in cold spots.

To illustrate this difference, we present a term called coverage. The formula for coverage (C) is shown below:

$$C = \frac{CFM \times Throw \times Temperature\ Rise}{1{,}000{,}000}$$

Simply stated, coverage is a measure of how much air is spread over what distance and at what temperature. The graph of figure 3 compares the coverage of 1 row and 2 row units of the same BTU output rating.

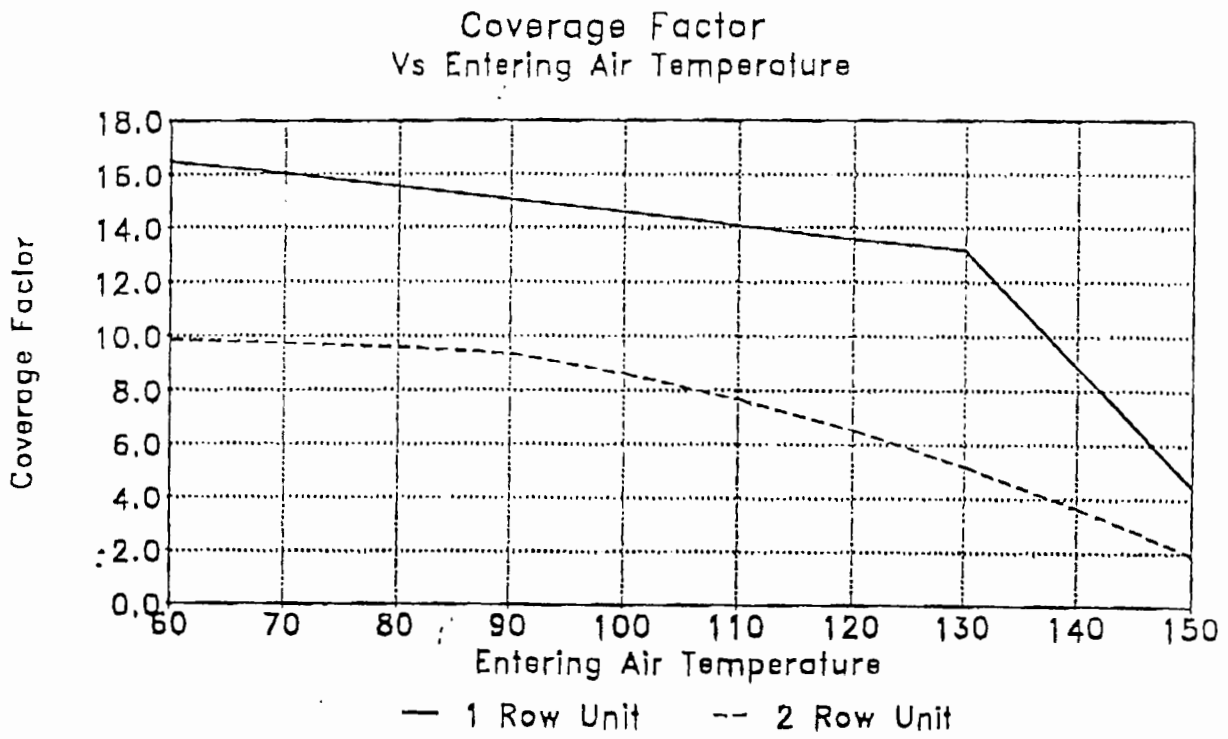


Figure 3

The 1 row unit puts out higher CFM with a greater throw but at a lower temperature than the 2 row unit. It is obvious that the effect of the higher CFM and throw outweigh any advantage of higher air temperature. Even at terminal temperature the 1 row unit has double the coverage.

TAKE GOOD CARE OF THE HEATING UNITS

All too often the best quality heating units are installed and maintained improperly resulting in less than satisfactory performance and life. The following are general guidelines for installation and maintenance of heating units. Reference to the manufacturer's I O & M manuals is recommended for more detailed information.

1. Use only F & T or Inverted Bucket type traps. All others operate by backing up condensate between discharge cycles. Backup of condensate into heat exchangers is not recommended. If a bucket trap is used it should have a large bucket vent or be supplemented by a separate air vent.
2. Always install a vacuum breaker downstream of the unit but before the steam trap to ensure adequate drainage during shutdown or under modulating conditions.
3. Provide a means to completely drain the unit during shutdown. The best way is to install an automatic temperature sensing valve that opens at around 100 degrees. This valve will stay open at all times during shutdown. Remember, these units will be shut down most of the time and steam valves are notorious for leaking.
4. If condensate must be lifted or if the condensate system is pressurized, install a check valve downstream of the steam trap.
5. Make sure motors are rated for operation at maximum ambient air temperatures.

COST

The cost of a heat sterilization installation can vary greatly from plant to plant. Some of the variables affecting cost are:

1. The amount of outside wall space.
2. The climate of the plant location.
3. The height of the ceiling.
4. The amount of insulation in the walls and ceilings.
5. The amount and type of glass area.
6. The amount and type of equipment located in the space to be heated.
7. The availability of wall and floor space to mount the units.

Items 1 through 6 pertain to the heat loss through the walls and ceiling of the space to be heated. Before the equipment can be sized a thorough study of heat loss should be conducted with strong consideration for these items.

A recent installation for a room 90 x 65 ft x 18 ft ceilings with one outside wall and a fair amount of open space cost $25,500. This cost included the heating units along with traps, control valves and all other hardware exclusive of installation and condensate piping.

The equipment list included eight one row unit heaters nominally rated at 156 MBH using 2 psig steam. The actual steam pressure was 50 psig. One of the eight units was portable.

Heat Treatment Sealing Needs

Ole Dosland

Technical Training Director

Copesan®

SPECIALISTS IN PEST SOLUTIONS

Heat Treatment Sealing Needs

- Why Seal a Structure or Space?
  - Be Effective and Efficient
  - Lower Costs
    - Use Less Heat and Energy
  - Assure Insect Mortality
    - Drafts Not Planned Can Create Cool Zones

Heat Treatment Sealing Needs

- Some Common Questions
  - What Strategy Is Needed For Sealing?
    - Basic Common Sense
  - How Thorough Do You Have To Seal?
    - Stop The Major Heat Loss
  - Does Sealing For Heat Need To Be As Tight As For Fumigation?
    - No

Heat Treatment Sealing Needs

- "De-Draft"
  - Close The Windows
  - Close The Doors, Note Underside Openings
  - Close All Air Louvers
  - Close The Exhausts
  - Close The Intakes
- Protect Sensitive Areas e.g. computer rooms
- "Close", "Close", "Close"

Heat Treatment Sealing Needs

Heat Treatment Sealing Needs

- Allow For Some Air Movement
  - Equipment
  - Bins
  - Silos
  - Small Rooms
  - Chimney Effect
    - Heat Rises
    - Plan For It

Heat Treatment Sealing Needs

- Some Unusual Needs
  - Large Openings and "False Walls"
    - 2" Styrofoam in 2 x 4's wrapped in plastic
    - Save for next time
    - Use for temporary doors
    - Heat blankets an open
    - Compare cost to do
  - Q & A Discussion

Heat Treatment Sealing Needs

- Not Complicated
- Basic Common Sense
- Prevent Major Heat Losses
- KISS Approach

Heat Treatment Sealing Needs

- Thank You

Copesan®
SPECIALISTS IN PEST SOLUTIONS

Types of heater: Gas

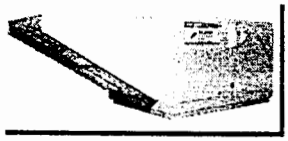
Why Use Gas-fired Heating Equipment

- Most economical heating source
- Wide variety of equipment available
- Most common source of heating in all applications
- Available far into the future

Types of Gas Heating Equipment

Permanent, Direct-fired

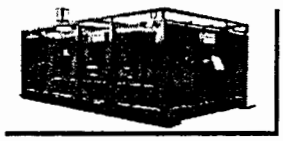
- Roof top "Make-up air" style
  - No loss of energy out the flue vent
  - Low temperature discharge
  - Contained flame
  - Equipment out of the way



Types of Gas Heating Equipment

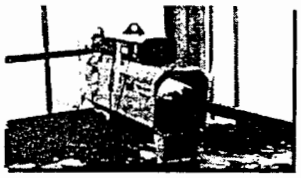
Temporary, Indirect-fired

- Large physical size for amount of heat output
- Contained flame
- Requires venting - loss of energy
- Limited uses
- Lower discharge temperatures
- Minimal clearance from combustibles



Types of Gas Heating Equipment

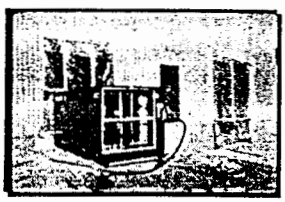
Temporary, Direct-fired



- "Tube-type" style
  - Higher discharge temperatures, relative to CFM, with hot spots as high as 700°F
  - Open flame
  - Greater clearance from combustibles
  - Low CFM of air

Types of Heating Equipment

Temporary, Direct-fired



- "Make-up air" style
  - Lower temperature raise, from 90°F low fire to 220°F high fire
  - Contained flame
  - Minimal clearance from combustibles
  - Expansive range of styles and sizes
  - Highest fuel efficiency

Gas (Propane / Natural)

Advantages

- Least expensive energy cost
  - **Propane at $.80/gallon = $8.64/1M BTU's**
  - **Natural gas at $.50/therm = $5/1M BTU's**
- Largest range of equipment available
- Versatile & portable

Gas (Propane / Natural)

Advantages Con't.

- Low electrical requirement
  - **1M BTU unit = 460 volt/10 amp**
- Low installation cost
- High temperature rise

Gas (Propane / Natural)

Disadvantages

- Some codes may not allow gas fired equipment or propane
- May not be safe to use in certain areas or buildings

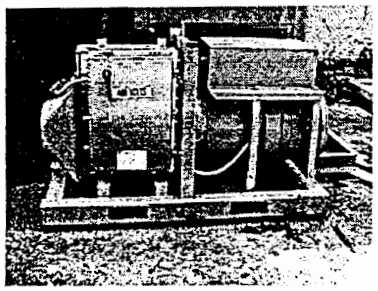
Types of heaters: Electric

Electric Heaters

What is available on the Market today

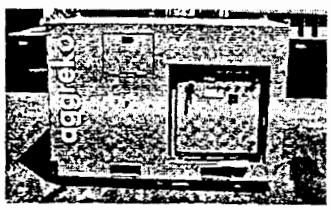
50kW Hi-Temp Heater

- 175,650 btu's
- 570 - 4000 cfm
- 56 amps @ 480VAC
- 12" Discharge
- Internal Breaker
- 300 degree F Maximum output



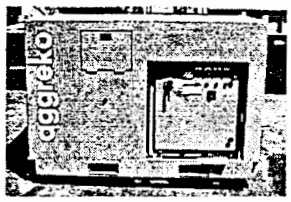
100kW Hi Temp Heater

- 341,300 btu's
- 1200-6500 cfm
- 115 amps @ 480VAC
- 20" Discharge
- Internal Breaker
- 300 degree F Maximum output



150 kW Hi-Temp Heater

- 511,950 btu's
- 1800 - 9000 cfm
- 179 amps @ 480VAC
- 20" discharge
- Internal Breaker
- 300 degree F Maximum output

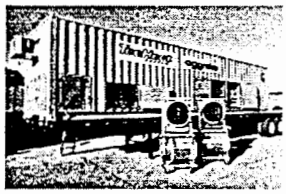


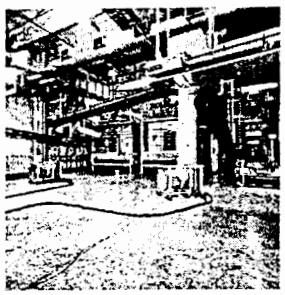
560kW TecHeat System

- 7 x 80kW Heaters
- 7 x 6000 cfm fans
- 1.9MM btu's
- 722 amps @ 480 VAC
- 1750' cable
- Onboard Control Room
- External Breakers

1120kW TecHeat System

- 14 x 80kW Heaters
- 14 x 6000 cfm fans
- 3.8MM btu's
- 1430 amps @ 480VAC
- 3500' cable
- Onboard Control Room
- External Breakers





Types of Heaters
Steam

Quaker Oats
St. Joseph, MO

Steam Heaters

- Why use steam heaters
- How they work
- Types of steam unit heaters
- Advantages/disadvantages
- Start-up process for steam heating
- Process during heat treatment
- Post heat treatment follow-up procedures

Steam Heaters

- Why use steam heaters
- How they work
- Types of steam unit heaters
- Advantages/disadvantages
- Start-up process for steam heating
- Process during heat treatment
- Post heat treatment follow-up procedures

Why Heat Treat with Steam????

- *Boiler in place*
- *Boiler capacity*
- *Heaters already in place*

How Steam Heaters Work...

- *Coils, fans, housing, dampers, traps, strainer, check valve, thermostats, etc.*
- *Coils are heated by steam passing through them*
- *Air is heated as fan pulls air up through heated coils*
- *Fans aid in dispersion of heated air throughout area*
  - *To decrease heat: open damper*
  - *To increase heat: close damper*

Types of Steam Heaters

- *Portable units*
- *Fixed units*
  - *Ceiling mounted*
  - *Floor mounted*

Portable Steam Heaters

- Advantages
  - Can be used in areas where heat is slow to rise
  - Can be moved around where needed
  - Easy to clean and maintain
- Disadvantages
  - Additional storage area
  - May get lost

Fixed Steam Heaters

- Ceiling mounted heaters
  - Maintain floor space
  - Smaller, considered space savers
  - Do not get damaged as easy
  - Harder to access for cleaning and maintenance
  - Ability to direct heat in all directions

Fixed Steam Heaters

- Floor mounted heaters
  - More heat at floor level initially
  - Easier to clean and maintain
  - Get damaged more easily
  - Generally larger than ceiling mounted units
  - Ability to shoot heated air in all directions

Advantages of Steam Heaters

- *Hotter heat*
- *Better control of steam heat if heaters are working properly*
  - *Open dampers if area gets overheated*
  - *Close dampers if area needs more heat*
- *Cheaper than gas/electric*
- *Steam provides much of the humidity (30-50%) necessary for wooden equipment (sifter boxes)*
- *Safer than gas fired/electric heaters*

Disadvantages of Steam Heaters...

- *Boiler capacity-necessary steam pressure*
- *Coils must be clean so they will heat efficiently*
- *Maintenance of traps, steam pipes, valves, couplers, fans, motors, etc.*
- *Employee safety concerns: burns*
- *System may become water logged resulting in slow or ineffective heat-up*

Quaker Oats - St. Joseph, MO

- *Goal: Core temperature 130°F / 30 hrs*
- *6 heat-ups/year*
  - *Mar, May, July, Aug, Oct, Nov*
- *Heat 3.5 million cubic feet*
- *145-150 steam heaters*
  - *various sizes*
  - *ceiling/floor mounted units*
- *3 gas fired heaters*
- *Departmental prep checklists*
- *Post heat follow-up procedures*

Pre-Heat Treatment Checklist For Steam Heating...

- *2 week inspection prior to heat*
  - *inspect fan motors on heaters*
  - *check couplers*
  - *inspect coils*
  - *check traps*
  - *repair steam leaks*
  - *inspect unit heater coils*
  - *inspect condensate return lines*
  - *ensure system is ready for heat treatment*

Pre-Heat Treatment Checklist For Steam Heating...

- *Day of heat treatment*
  - *Increase boiler pressure to maximum capacity (25,000-30,000 pounds)*
  - *Set all heaters to manual mode*
  - *Set thermostats on unit heaters at 140°F*
  - *Ensure steam valves and return lines are open at heaters*

Pre-Heat Treatment Checklist For Steam Heating cont...

- *Turn on main header valves to get steam to unit heaters*
- *Heat unit heater coils*
- *Turn fans on to unit heaters*
- *Set out thermometers*

Steam Heaters During Heat-Up...

- *Auto vs. manual mode*
  - *Heaters started in manual mode*
  - *Once temperatures heat up, positioned in auto mode if thermostats are working*
- *3 pipefitters per shift to monitor heat progress*
  - *Temperature readings every two hours*
  - *Maintain 130°F for 30 hours*
  - *Making repairs as necessary*

Steam Heaters During Heat-Up...

- *Slow Heat-Up*
  - *system may be waterlogged*
    - *check condensate return line*
    - *ensure steam valves are open*
    - *waterlogging will cause slow heat in all areas*
  - *ensure fan on heater is running if area(s) are cool*
  - *check unit heater coils for buildup if area(s) are cool*
  - *ensure openings to outside are closed*

Steam Heaters During Heat-Up...

- *Fast Heat-Up*
  - *use auto mode to shut heat off at desired temperatures*
  - *open up dampers with fan running*
  - *throttle steam back at heaters*
  - *shut heater fan off*
  - *reduce steam pressure if fast heat-up is noted in all areas*

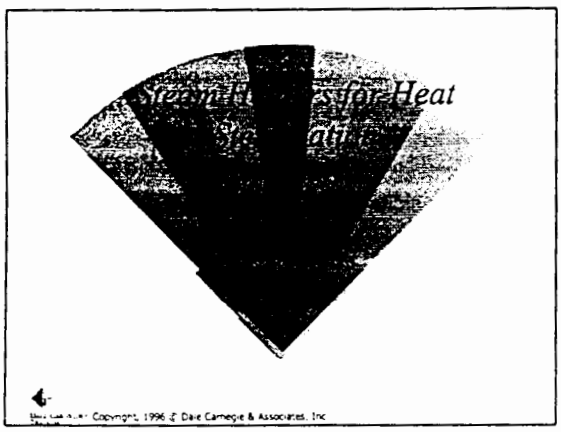
Other Factors Affecting Heat Treatment Success...

- *Wind*
- *Outside temperature*
- *Rain*
- *Openings to outside not properly sealed*
- *Knowledge and/or preferences of pipefitters/maintenance personnel running the heat treatment*

Post Heat Follow-Up Includes...

- *Determine shutdown time*
- *Shut boiler down two hours prior*
- *Coast 2 hours*
  - *pickup thermometers*
  - *shut off header valves / unit heater valves*
  - *leave fans running for circulation*
- *Departments open up for cool down*

****



Quaker Oats, St. Joseph, Mo.

- Area to be sterilized: Approx. 3.5 million cu.ft.
- Initial steam load: 50,000 lbs. Per hr.

Production Area

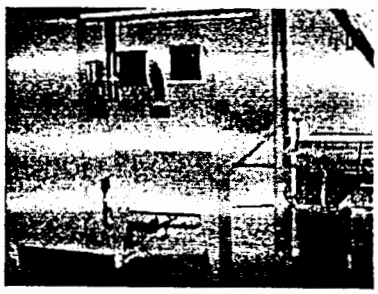
- Central production in 10 story tower
- Construction: Brick and concrete
- Single pane windows removed, replace with glass block to conserve energy.

Upgrade existing steam heaters

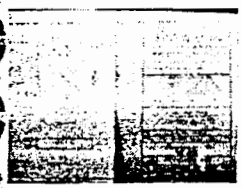
- Existing free standing air movers were upgraded using new high capacity steam coils
- Location of existing air movers we.e evaluated for overall performance

Advantage/Disadvantage of floor mounted equipment

- ADVANTAGES
- High air volume
- High heat output
- Low cost to upgrade
- DISADVANTAGES
- Takes up floor space
- Easily block by material

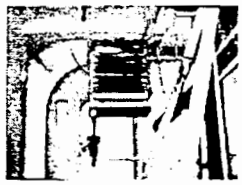


Heater manufacturer support

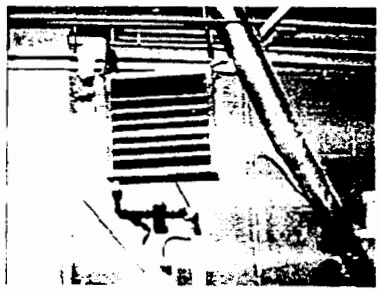


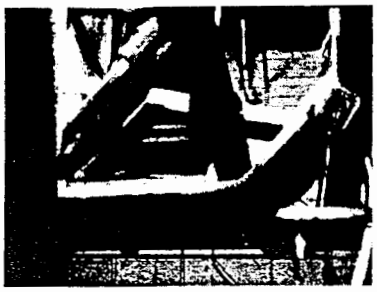
- Steam coil manufacture provide detail drawings for future reference
- Performance data included in drawing file

Unit heaters compliment floor heaters



- Ceiling hung unit heaters require no floor space
- Location critical to performance



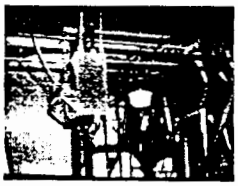


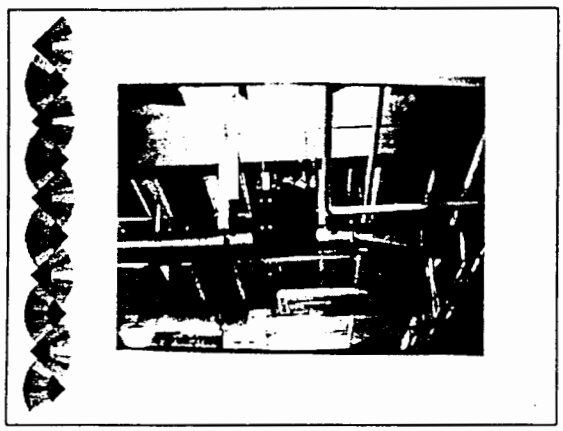
Installation considerations:

- General Rule: Heat the exterior walls
- Provide a heater with enough "throw" to cover the required area

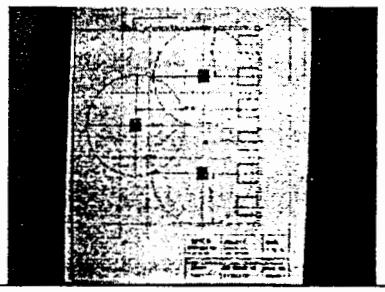
Installation considerations cont.

- Install the heaters with minimal obstruction.
- Free access to heater required for later service for the trap and cleaning of the coils



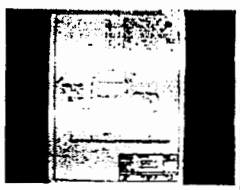


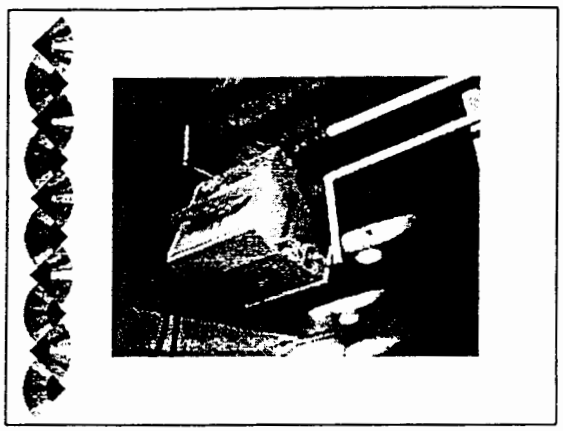
Good design includes overall floor plan

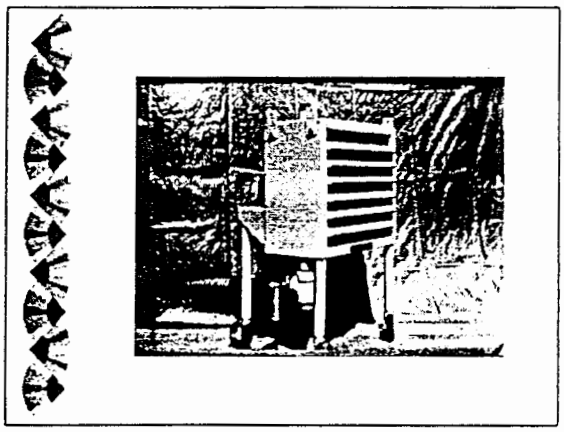


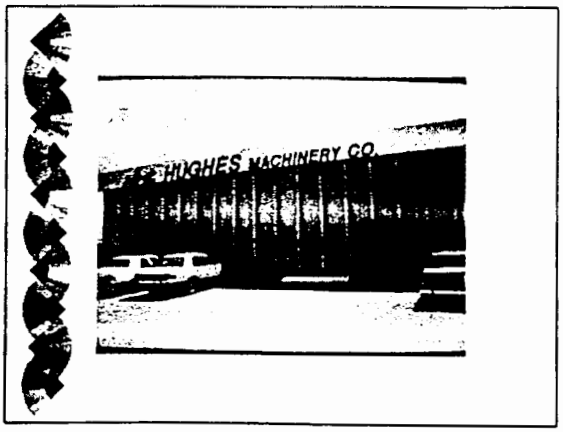
Installation consideration cont.

- Mounting height important to vertical air flow unit heaters
- Consideration must be given to control function








HUGHES MACHINERY CO.

SPECIAL REPORT

Using Portable Rented Electric Heaters to Generate Heat and Control Stored Product Insects

By Jerry W. Heaps, B.C.E. and Tom Black

This report was presented to Flour City District at their April Meeting on Heat Treatment.

Abstract

Portable rented electric heaters, totaling 500 KW, powered by a 750 KW diesel-fueled electric generator, were used for a heat sterilization (HS) in a food plant dry mix area. Approximately 350,000 cubic feet were gradually heated to temperatures approaching 130°F and held for a period of 24 plus hours. Confused flour beetle (**Tribolium confusum**) bioassays (eggs, larvae and adults) were used to evaluate insect mortality efficacy. Leavening ingredients were also exposed to the heat and evaluated for damage. Simultaneously, equipment in the HS was also observed for damage both during and after the heat treatment. The rental equipment provides a feasible alternative to conventional methyl bromide general facility fumigations. Less preparation work/sealing is required and since the HS temperatures do not pose an immediate toxic effect toward humans, work can be continued in other non-HS plant areas. Insect mortality was found to be 95% for adults/larvae combined (some test cages placed in obvious areas where heat was not going to penetrate). The heat also pointed out previously unknown insect harborages. Only two computer input cards were suspected of being heat damaged. No issues were found with the leavening ingredients based on testing start-up production samples. These results indicate that heat can be a safe, economical, and practical alternative to conventional insecticides used to control stored product insects.

Key Words:

Portable rental heaters, heat sterilization, **Tribolium confusum** control.

Purpose

To assess the process of heat sterilization for insect control by using portable rented heaters to heat a food plant dry mix area to 130°F, holding it and evaluating confused flour beetle bioassays for mortality. Simultaneously, leavening ingredients and equipment within the heated area were evaluated for heat damage.

Background

Heat sterilization is not a new technology for stored product insect (SPI) control. At the turn of the century, it was used but later avoided due to equipment/structural damage. Equipment technology improvement and removing wood as a main component of structures has allowed this pest control option to be used more frequently now.

Food processors are also being forced to look for more non-conventional insecticide approached to controlling SPI as such materials commonly used and relied upon for years, have been eliminated or severely use-restricted. HS is extremely effective in killing exposed life stages of SPI. Insect mortality is seen at 120°F and virtually all SPI killed at prolonged exposure to 130°F (Imholte, 1984. Cooney, 1985; Heaps, 1988).

The issue of a heat generation source continues to be questioned. Many companies that have conducted HS have had excess boiler capacity to generate the needed BTU's using high- or low-pressure steam.

Aggreko, Inc. is an equipment rental company (North American Headquarters at New Iberia, Louisiana) specializing in temperature control. Their involvement in "heat treatment" has been in the chemical industry, construction sites, shipping warehouses and at athletic/entertainment events. As a by-product to this, they were called upon last fall to literally dry out several flour mills located along the flooding Mississippi River lowlands. It was theorized at that time that this process could be done for pest control purposes, too.

In January, 1994, Aggreko conducted a trial HS of the Kansas State University flour mill in Manhattan, Kansas. The treatment was very effective with >95% test insect mortality and NO major equipment malfunction issues. (Dr. Jack Pedersen, personal communication.)

Materials and Methods

The area to be HS was approximately 350,000 cubic feet, has an upper and lower level, in on-concrete slab construction with pre-fab concrete wall sections. The last eight feet of wall height consists of one-inch fiberglass block insulation around the room perimeter. Ceilings are concrete topped with a flat, membrane-type roof. A series of metal grate catwalks was in place to gain access to upper floor levels. For heat, Aggreko, Inc. supplied a 760 KW diesel powered electric generator with trailer, eight 50 KW plus one 100 KW portable heaters. To assist in air movement, several large fans were positioned on the ceiling catwalk to blow down/circulate hot air rising toward the ceiling. This assists the heating-up process and helps prevent hot air spots/stratification from occurring.

The trailer with its electric generator was parked outside the building. Cables, necessary to distribute electricity to the heaters inside, were placed through a partially opened exterior door near the trailer. This was sealed with a plastic film overhand during the HS. Accessibility to the outside trailer area was needed during the HS so Aggreko personnel could monitor the generator.

The parameters for heating were to start at ambient room temperature (75°F), heat at a rate not to exceed 10°F/hour to a target temperature of 130°F. Maintain this temperature for 20 hours and cool down the HS area at a rate no greater than 10°F/hour. These 10°F/hour restrictions were taken under advisement from engineers to help prevent thermal shock to the concrete structure. Maximum temperature allowed will be 145°F. Copper/constantan thermocouples, at 30 different sites, monitored every hour were used to track temperatures. (Table 3)

Confused flour beetles (CFB) adults and larvae (10/card - individual cards) fog checks (purchased from LSB Products, Manhattan, Kansas) were used as HS mortality test insect cards. Additionally, to be used as bio-assays, CFB eggs, larvae and adults were grouped and each placed in enough flour to fill

Heat Treatment of Dry Mix Feb 19–21, 1994 — table 3
Thermocouple locations

Upper Dry Mix	
	1 04 TANK CEILING
	2 05 TANK CEILING
	3 COOKIE BLENDER
	4 04 SALP TANK
	5 05 SAPP TANK
	6 MIDDLE OF ROOM GRATE
	7 ABOVE RJ's
	8 ELEVATOR
2nd level dry mix	
	9 04 FLOUR SCREWS
	10 05 FLOUR SCREWS
	11 COOKIE BLENDER
	12 COOKIE FLOUR TANK BOTTOM
	14 RJ TOP
	15 RJ BOTTOM
	16 ELECTRICAL BOX ON WEST WALL
	17 ELECTRICAL BOX ON EAST SIDE
	18 FLOUR RETURN FROM PRODUCTION
	19 FLOOR MIDDLE OF 2ND LEVEL
	20 EAST SIDE 4 FT HIGH
	21 CENTER 4FT HIGH
	22 WESTSIDE 4 FT HIGH
	23 GLUTEN AUGER
	24 BUTTERMILK AUGER
Lower dry mix	
	26 DUST FLOUR SIFTER FRAMEWORK
	27 SUGAR SIFTER FRAMEWORK
	28 ENRICHMENT AUGER
	29 CAVE AREA
	30 MCC ROOM
	31 TOP OF DUST FLOUR TANK
	32 INSIDE DUST FLOUR HOLDING TANK

These locations were monitored during the heat treatment. #4 SALP tank, #5 SAPP tank #16 electrical box west, #17 electrical box east, #18 flour return from production and #30 MCC room were not included in any of the averages.
This is due to the fact that these were to monitor specific issues and not determine the heat up rate

BIO ASSAY LOCATIONS — table 2

	SURVIVORS ADULT	LARVAE
UPPER DRY MIX		
1 TOP OF ELEVATOR COMPRESSORS	0	0
2 CATWALK BY 04 TANK	0	0
3 SUGAR TANK	0	0
4 05 FLOUR TANK	0	0
5 ABOVE COOKIE TANK	0	0
6 TOP OF 04 FLOUR TANK	0	0
7 BEAM ABOVE 04 FLOUR TANK	0	0
8 CORNER NW OF CATWALK	0	0
9 UNDER STEPS ON FLOOR, ABOVE ELEVATOR	10	4
2ND LEVEL DRY MIX		
10 ELECTRICAL PANEL BY 04 LINE ICE MACHINE	10	5
11 COOKIE FLOUR TANK	0	0
12 04 SCREW AUGER	0	0
14 COOKIE BLENDER	0	0
15 05 SCREW AUGER	0	0
16 TOP OF RJ	0	0
17 BOTTOM OF RJ	0	0
18 ELECTRICAL PANEL BY ELEVATOR	10	5
19 05 FLOUR CONTROL PANEL	0	0
1ST LEVEL		
20 DUST FLOUR SIFTER	0	0
21 INSIDE BLOWER FOR EAST SIFTER	0	0
22 GRANULATED SUGAR AUGER	0	0
23 INSIDE SUGAR CONTROL PANEL	0	0
24 CAVE AREA	0	0
25 CORN SUGAR PLATFORM	0	0
26 DUST FLOUR ELEC. CONTROL PANEL	10	5
27 SIMCO UNIT ABOVE WEST SIFTER	0	0

Bioassays were placed with 10 adults, 5 larvae and egg material in each location. The egg material will be incubated to determine if the eggs survived.

Results: Overall for these bio–assays, using petri dish, with flour glued on cardboard base, the mortality was 85% of the adults and and 88 % of the larvae. If the electrical panel locations; #10, #18, #26, are not included the results are 97% for the adults and the larvae. These electrical boxes were not opened to evaluate if these panels need to be opened.

small plastic petri dishes. Dishes were covered/sealed with their lids. A dish containing eggs, larvae or adults was adhered with tape to a piece of cardboard. Similar control samples were kept in an ambient temperature area. The fog check and bioassay petri dishes were then randomly placed within the HS area to be evaluated for mortality.
(Tables 1 and 2)

FOG CHECK BIO ASSAY LOCATIONS — table 1

	SURVIVORS ADULT	LARVAE
UPPER DRY MIX		
1 S E corner of top of insul. pipes	5	7
2. South wall inside eletrical box–SM 800	0	0
3. Top of sugar tank–01/05 lines between pipes	0	0
4 Center of catwalk grid middle of room.	0	0
5 On top of heat in plastic bag not sealed	0	0
6 Taped to west exhaust fan	0	0
2ND LEVEL DRY MIX		
7 Dureflow blower– Cookie sugar tank	0	0
8 Cookie sugar tank inside air filter for blower	0	0
9 Pre–mix cut in ben seller, behind electrical box	0	0
10 Flour tank auger 05 inside blower filter container	0	0
11 Electrical box under RJ – 14M36–05 vac. motor	0	0
12 South wall across from sugar tanks on electrical conduit	0	0
1ST LEVEL		
13 Side of main enterance to dry mix, by plywood wall.	0	0
14 On underside of metal detector, conveyor belt	0	0
15 West side of cave area	0	0
16 Under platform of portable scales (short wts)	0	0
17 Inside sock of the chute from ribbon blender	0	0
18 Behind clock above main enterance to dry mix	3	4
19 Inside Elec. box to east flour system.	0	0
20 Vacant room east of MCC room	8	8
21 East side of cave area on concrete	0	0

Fog checks were purchased from LSB, Inc.
Results The mortality of adults was 92% and larvae was 91%.

Additionally, cigarette beetle pheremone traps were placed at exit areas and we captured 5 beetles 5 adult male cockroaches were placed in closed petri dishes and place by exit locations. Rapid movement of roaches was noted, but mortality was 100%.

Five adult male German cockroaches (**Blatella germanica**) were placed in several closed plastic petri dishes. Each dish was placed on the concrete floor near exit locations and evaluated for mortality after the HS.

Cigarette beetle specific pheromone traps (Serrico brand, purchased from Insects Limited, Indianapolis, Indiana) were also placed at several wall perimeter areas/exit locations and monitored for catches during/after the HS. There were used to test the hypothesis that an SPI capable of flying would try and escape the HS as it warmed up.

Samples of salt, soda, SAAP, SALP, KCL, sweetmilk, buttermilk, GDL, vital wheat gluten, xanthan gum, sucrose and dextrose were each placed in a standard size paint can so as to fill it. These were placed on a portable cart, left uncovered in the HS area to be later evaluated for HS temperature damage. Similar control samples were kept in an ambient temperature area. Ingredient suppliers contacted indicated that only vital wheat gluten and SALP could be damaged by HS temperature.

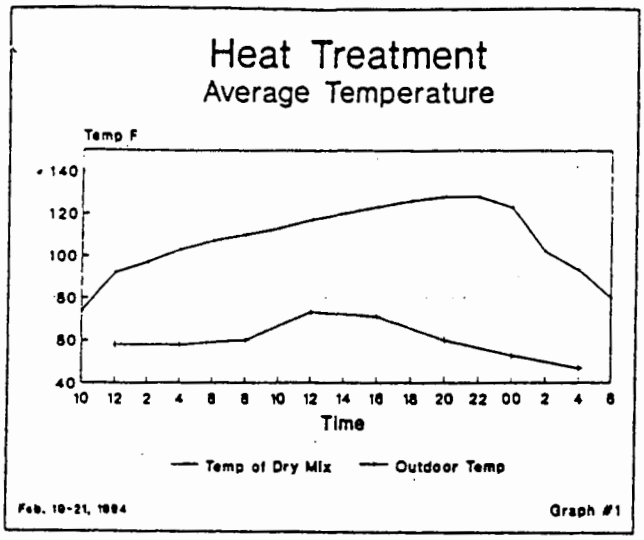
Terminix Pest Control Company, along with pest control personnel from Pillsbury, worked together to monitor insect activity during the HS. No residual insecticide sprays were applied in the HS area prior to the treatment.

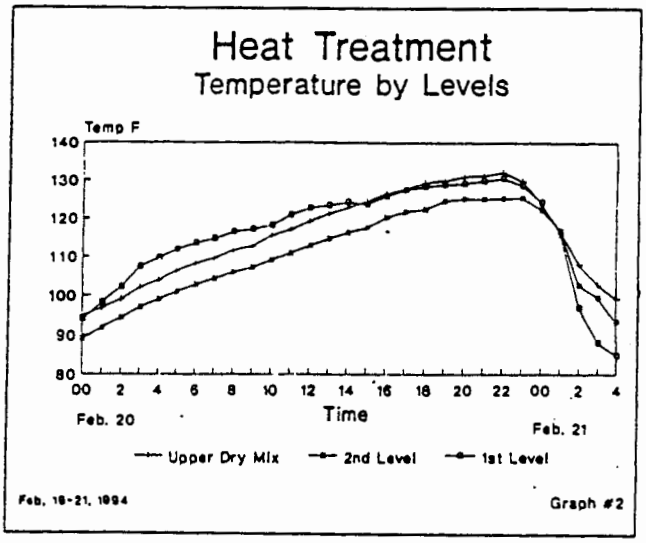
Aggreko, Inc. personnel arrived on-site on Saturday afternoon (2/19/94). A final planning meeting was held with all HS-affected workers from both companies. Safety issues and plant policies were reviewed. Aggreko's team worked to locate equipment in proper places, while Pillsbury/Terminix worked to place thermocouples and test insect cards/bioassays. The HS area/equipment underwent a complete sanitation cycle prior to treatment. Equipment was left open there practical.

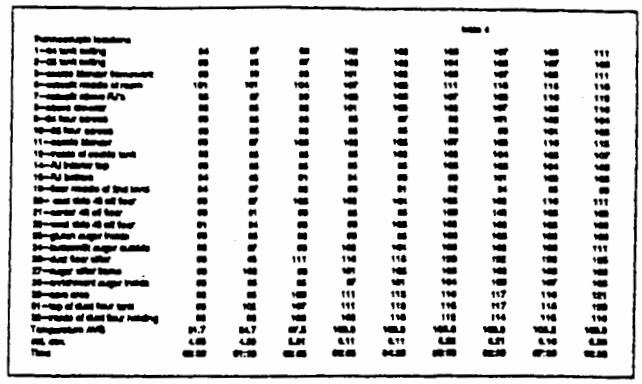
Results and Discussion

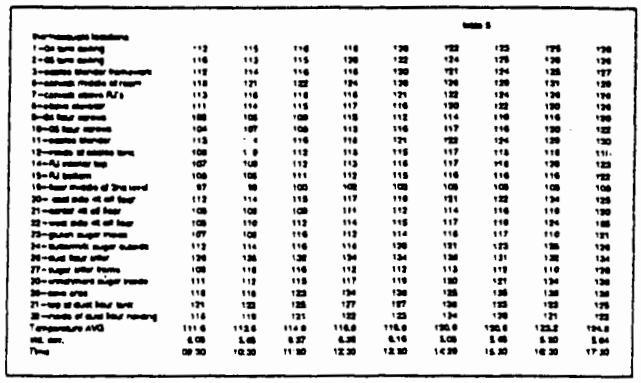
The set-up required 5.5 hours. At 2130 hours, a final walk through inspection of the HS area was done. At 2200 hours, the heaters were turned on. The ambient room temperatures in the HS areas were 75°F. Temperature monitoring began at 0030 hours on 2/20/94 and continued hourly for the remainder of the HS. (Graph 1) Temperatures were also broken down by separate upstairs/downstairs level. (Graph 2)

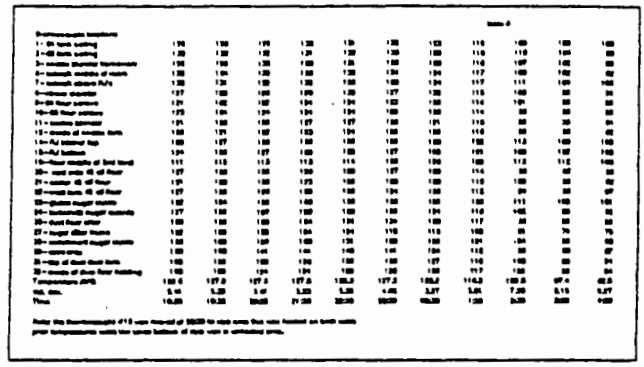
Data indicated the time to reach the target temperature of 130°F was greater than initially calculated. (Tables 4, 5 and 6) The initial objective was to reach 130°F and maintain for 20 hours. This trial resulted in 120°F achieved at 1300 hours on 2/20. This temperature was consistently maintained for another 12 hours. Cool down began at 0100 hours on 2/21. Within three hours, 90°F temperatures were reached in the treated area. Outside temperatures, throughout the HS, were also noted as this does play a major role in how quickly the heat is











brought up, maintained and cooled down.

The highest temperature recorded was 143°F in the open mezzanine area above an electrical room in the lower level between floors. Evaluation of insect bioassays at 8,12, and 16 hour intervals was not completed as it took too long to reach/maintain the 120°F target for this test.

SPI beetle activity was observed in several known and previously unknown areas as it is possible, and a good idea, for personnel to spend 10 minute intervals per hour in the HS area during treatment to inspect/observe what's going on.

Cost for the treatment was $12,000 for equipment rental/set up. Cumulative, indirect labor hours spent were: 40 hours for sanitation, 50 hours for quality assurance and 120 hours for maintenance. Additionally, Terminix provided 38 hours for the placement of thermocouples and insect bioassays.

Aggreko, Inc. personnel felt the reason for the extended time to achieve target temperatures was due to heat loss through the fiberglass insulation blow-out panels in the upper level of the dry mix room. Cool air infiltration from the unheated mixer rooms, underneath this dry mix level also caused some cooling. Ingredients in bulk tanks in the HS area also served as a heat sink to draw heat from the rooms. Future HS here will account for these losses.

The mortality of T. confusum adults and larvae in the LSB, Inc. fog check cards was 92% and 91% respectively. Cigarette beetle pheromone traps only caught a total of five adults, in all the traps. With the German roach males, mortality was 100%. Rapid movement of them was observed as temperatures rose. Due the their excellent ability to run, if you can prevent their escape from the heated area, roaches will be killed by HS.

Overall, for the petri dish bioassays, adult mortality was 85% and larval mortality was 85%. If the electrical panels #10, #18 and #25 are not included in this data, adult/larvae mortality is 97%. These electrical panels were purposely left closed to see if the bioassay samples would be HS treated.

The rental heater equipment provides a feasible alternative to methyl bromide fumigation. Less preparation is required (i.e. sealing) and personnel can work in unheated plant areas and/or safely enter the HS area without preparing oneself with the needed safety equipment required with methyl bromide. Heat leaks are acceptable whereas methyl bromide leaks are unacceptable/dangerous.

From a user-friendly standpoint, personnel are much more comfortable knowing only hot air is present versus a toxic gas (i.e. menthyl bromide or phosphine).

The only equipment problems that could have been heat caused were two computer input cards damaged/needed replacement. These cards were inside a panel and damage could have been caused by the combination of heat - "old" age as the temperatures recorded in area were not above the acceptable zone received from the card manufacturer.

No damage issues were noted with the leavening ingredients based on testing of dough retention times at start up production. Further samples exposed to HS, and controls, have been

submitted to suppliers for more detailed analysis. No negative effects on these samples have been reported.

Future

Additional bioassays will be used to more closely evaluate time/temperature/mortality rates (i.e. less time/lower temperatures feasibility). This HS data showed insect mortality was achieved in less than 20 hours and less than 130°F.

The cost of electricity will be broken down to allow the feasibility of capitalization of electrical distribution by using the plant's power source versus needing an outside generator.

Data also indicated the need to open large electrical boxes to allow heat penetration and/or pressurize them with vortex cooling units so they can be kept clean/closed/pest free. Analysis of heats' effect on computer cards will also be conducted.

Acknowledgement

We thank Mark Mire, Aggreko Corporation; Bill Engebretson, P.E., The Pillsbury Company; and Ray Thompson, Ph.D., The Terminix Pest Control Company for their technical assistance in this project.

References Cited

Imholte, T.J. Engineering for Food Safety and Sanitation. 219-226 (1984).

Cooney, K.M. 1985. "If You Can't Stand The Heat". *Food Sanitation* 1:24, 37-39.

Heaps, J.W. "Turn on The Heat to Control Insects". *Dairy and Food Sanitation* vol. 8, no. 8, 416-418 (August 1988).

About the Author . . .

Jerry Heaps is Manager - Sanitation & Pest Control for the Pillsbury Co., Minneapolis, Minnesota. From 1988 through 1992 Jerry was a Regional Field Sanitarian for the American Institute of Baking, Manhattan, Kansas, USA, covering Minnesota, North Dakota and parts of Wisconsin. From 1984 through 1988 he was a plant sanitarian at the Nabisco Brands Cream of Wheat plant in Minneapolis, then a Corporate Environmental Health Auditor for them. While at the Cream of Wheat plant, Jerry was directly involved in the design/implementation of the heat sterilization program for this plant continues to use today. At Pillsbury, he is working on the design/implementation of heat sterilization systems in several of their facilities. Other responsibilities include coordination of sanitation, pest control, GMP's and chemical control programs.

Association of Operative Millers

Technical Bulletins Volume IV – 1944-1975

NOTE: Volume IV contains 550 pages of selected Bulletins, completely different from those in Volume III.

SUMMARY OF CONTENTS BY SECTIONS

MANAGEMENT	AIR EXHAUST & PNEUMATICS	MILL CONSTRUCTION
FOOD MILLING	CORN MILLING	SPECIALTY MILLING
EXPERIMENTAL MILLING	PACKING & LOADING	RESEARCH
SANITATION-FOOD PROTECTION	ENVIRONMENTAL CONTROL	SAFETY
COSTS	PERSONNEL	BULK FLOUR & FEED

CONTACT THE AOM OFFICE FOR ORDER INFORMATION.

FAN PLACEMENT FOR HEAT TREATMENTS

BY JERRY W. HEAPS, THE PILLSBURY COMPANY

FAN PLACEMENT FOR HEAT TREATMENTS

- NEED TO MOVE AIR
- USE DUCTWORK OR FANS
- CRITICAL TO DISTRIBUTE AIR
- PULL WARM AIR DOWN TO FLOOR
- HIGH LEVEL CATWALKS

07-14-99 03:47pm From-TPC GPS QUALITY 6123502544 T-270 P 03/04 F-263

FAN PLACEMENT FOR HEAT TREATMENTS

- SET AROUND PERIMETER
- CLOCKWISE CIRCULATION
- DO NOT DIRECT DIRECTLY ON EQUIPMENT
- MOVE AROUND AS TEMPERATURE DATA INDICATES

Air Circulation Considerations for Heat Treatments

Ole Dosland
Technical Training Director

Copesan
SPECIALISTS IN PEST SOLUTIONS

Determining Heater and Fan Requirements

- Electric Heaters
- Gas Heaters
- Steam Heaters
- Fan Placement
  - Air Circulators

- Energy Availability
- Internal Capabilities
- Outside Services
- Combination

Determining Heater and Fan Requirements

- Efficient Economical Distribution Of Heat
- Uniform Distribution Of Heat
- Minimize Structure And Equipment Damage
- Heat Treat Time Line Impact Requirements
  - Set up, start heaters and fans
  - Heat retention
  - Cool down
  - Remove heaters and fans

Determining Heater and Fan Requirements

- Ease Of Monitoring
  - Temperature and Humidity
  - Insects
  - Humans
- Achieve Insect Mortality
  - Lethal Hot Air Must Reach The Insect
    - In equipment
    - In structures
    - Both

Air Circulation Considerations

- Identity Air Movement Within Heat Zone (s)
  - One way positive pressure slow exhaust approach
  - Horizontal or vertical "swirl" return air approach
  - Combination
    - side rooms and equipment blockage
    - leakage factor
      - window and door frame work
      - air exhausts and intakes
- 3 "B's"

Air Circulation Considerations

- Be Flexible
  - Air circulators that swivel are better than fixed
  - Large units (i.e. 36"air circulators)
    - larger spaces
  - Small units (i.e. 20" box fans)
    - smaller spaces
      - side rooms and equipment blockage
  - Identify a quick exhaust plan, if needed

Air Circulation Considerations

- Be Windy
  - Too many air movers are better than too few
  - Use built in existing fixed air movers
    - don't restrict from the air movement plan
    - supplement with portable units
  - Create a noticeable breeze to the skin
  - Too much air movement is better than not enough
  - Protect sensitive equipment with dedicated units

Air Circulation Considerations

- Be Cautious
  - The first few hours will be a busy activity of monitoring and adjusting air movement
  - Learn from the initial heat treatment
    - keep an accurate map of heaters and air movers
    - develop a thorough report for future reference
  - Each facility's heat treatment will be different
    - no two heat treat zones are alike
    - no two days are alike
  - Have a back up energy plan in place

Today's Situation

- The Food Industry
  - Learning curve
  - Food experts
- The Pest Control Industry
  - Learning curve
  - Pest experts
- Working Together To Meet A Need
  - "Lead, follow or get out of the way"

Today's Situation

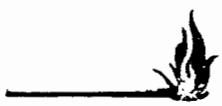
- "Back To The Future" Heat Technology
- Looking Forward To Futuristic Technology
  - Specialized equipment
  - Remote monitoring
  - Instantaneous data tracking
- Field Application Research and Education
  - Prevent horror stories from neophyte attempts
  - Protect viability of using heat for insect control

A Final Thought

- Planning, Preparation and Practice Prevents Pitiful Performance
- Rule of "3"
  - Experiment and Learn
  - Scale Up and Write SOP's
  - Repeat with Comfort

Air Circulation Considerations for Heat Treatments

- Thank You



Determining Heater & Fan Requirements
Gas Heaters

Fuel Source

Propane

- Tank Placement
- Vaporizer Requirement

Determining Heater & Fan Requirements / Gas Heaters

Fuel Source

Natural Gas

- Location of Service
- Pressure and Size of Service
- Permanent Piping Available

Determining Heater & Fan Requirements / Gas Heaters

Building Layout

- Number of Ground Level Openings
- Interior Plenums

Electrical Requirements

- House Power (minimum requirement)
- Temporary Power

Heater and Fan Requirements

Electric Heat

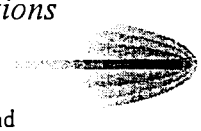
What needs to be taken into consideration?

- Size of building - Length, Width, Height
- Building Make Up - Brick, Cinder Block, Insulated Metal
- Roof Material
- Number of Floors
- Building Integrity
- Equipment in Room

Considerations continued

- Ambient Conditions
- Time allowed for Heat Treatment
- Available Power
- Temperature target

Temperature Monitoring Considerations

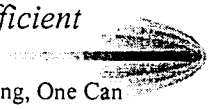


Ole Dosland
Copesan Services, Inc

Know Your Temperature

- Instantly & Timely
- Move & React & Adjust
- Data Analysis
- Results Posting
- What About Humidity?

Be Effective And Efficient

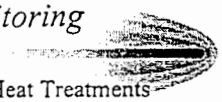


- With Thorough Monitoring, One Can Achieve Effectiveness and Efficiency
- A Goal Within A Goal
  - First Reach 120 to 140 Degrees F.
  - Second 130 Degrees F. $\pm$ 5 Degrees F.
- Maximize The Mortality
- Minimize The Damage

Temperature Monitoring

- Various Approaches Through The Years
- New Tools, Technology Arriving Every Day
- Measure The Surfaces Where The Insect Is At
  - Frequently
  - Planned
- Monitor The Air Temperature & Humidity
  - Less Frequent

Temperature Monitoring



- Tips From Successful Heat Treatments
  - Most Of The "Work" Is Done Early
  - Emphasis On Measuring Surfaces
  - Seek Out Cool Areas
  - Look For Problematic Areas - Equipment
  - Strive For Temperature Consistency
- Infrequent Monitoring = Inconsistent Results

Temperature Monitoring

- Do Not Turn On The Heat And Leave
  - Done In The Past; Lead To "Stories"
- Historical Heat Treatments
  - Inconsistent Results
    - Lack of temperature
    - Lack of time
    - Not knowing humidity
  - Affects current reputation of using heat

Temperature Monitoring Options

- Thermometers- Non-Contact e.g. Laser, Infrared
  - Advantages
    - Instant Surface Measurements
    - With Laser Option, You See What You Are Measuring
    - Computerized Data Analysis
  - Disadvantages
    - Difficult To Do Internal Measurements
    - Different Surfaces Vary In Temperature Measurement
  - Cost
    - Expensive = $300 to $3000

Temperature Monitoring Options

- Thermometers - Contact e.g. Traditional
  - Advantages
    - Many Options Available
    - Effective For Air Measurements
    - Thermolabels Good For Verification Activity
  - Disadvantages
    - Glass, Mercury, Metal
    - Have To Wait Or Leave In The Area
  - Cost
    - Economical = $5 to $100

Temperature Monitoring Options

- Thermometers - Penetrating e.g. Probes
  - Advantages
    - Internal Measurements
    - Many Options Available
    - Computerized Data Analysis
  - Disadvantages
    - Difficult To Use
  - Cost
    - Reasonable = $50 to $500

Temperature Monitoring Options

- Thermohygrometers - Ambient Humidity
  - Advantages
    - Many Options Available
    - Instant
  - Disadvantages
    - Can Be Complicated
  - Cost
    - Reasonable = $5 to $500

Recommendation

- Utilize A Combination Of Options
  - Availability
  - Based Upon The Overall Measurement Plan
- Calibration
  - Designate A Thermometer "Champion"
    - Eliminates Multi-Measurement Inconsistency
    - Who Do You Believe?
  - Boiling Water = 212 Degrees F.

Recommendation

- Intensify Frequency Early
  - Minimum Of Hourly
  - Every Other Hour Later
- Post Results In An Ongoing Manner
  - Make Notes In Time Log Of Adjustments
- Be Effective & Efficient
  - Know How You Are Doing In An Ongoing Manner

Estimating Heat Requirements for Insect Control in Food Plants

by:

James G. Linak
Senior Engineer
Quality & Regulatory Operations
General Mills, Inc.

Presented to the Association of Operative Millers
1998 Summer Meeting
and
Technical Conference

14 August 1998

Heat Basics

Estimating the energy requirements to heat a food plant for insect control is more easily accomplished if there is a basic understanding of how heat flows. Some heat basics:

1. Heat transfer is the transfer of energy occurring as a result of a driving force called temperature difference. Heat flows from areas of high relative temperature to areas of low relative temperature.
2. Heat transfer rate (i.e., how fast heat travels) is proportional to this temperature difference.
3. Heat transfer occurs via three mechanisms:
    a) Conduction – heat can be conducted through solids, liquids and gasses. Heat is conducted by the transfer of energy of motion between adjacent molecules.
    b) Convection – convection heat implies the transfer of heat due to bulk transport and mixing of macroscopic elements of liquid or gas. Convective heat involves the motion of fluids. If convection is induced by the density differences within the fluid, it is said to be natural convection. If the motion of the fluid is the result of an outside force (as might be exerted by a pump impeller or fan blade), then it is called forced convection.
    c) Radiation – the transfer of heat by radiation is energy transfer by electromagnetic radiation, or photons, having a certain range of wavelengths. The same laws that govern the special range of radiation called visible light also govern the radiation of the energy that is called heat. Although radiant energy can travel through solids, liquids and gasses, these media absorb some or all of the energy. Energy is radiated most efficiently through empty space (e.g., heat from sun).

Pertinent Heat Transfer Equations

1. Each substance/medium has an associated thermal conductivity (k), a proportionality constant that can be used to calculate the amount of thermal energy the substance will pass per unit of time, per unit of material thickness, per degree temperature difference. Common units for thermal conductivity are:

$$k, \text{BTU}/(\text{hr} \cdot \text{ft} \cdot {}^\circ\text{F})$$

2. For a flat, solid surface (such as a wall), the thermal energy flowing from the high temperature side to the low temperature side [q] is conductive, and can be expressed in the application of the simplified Fourier conduction equation[1]:

$$q, (\text{BTU/hr}) = \frac{-k \cdot A \cdot [T_{inside} - T_{outside}]}{\Delta X}$$

A = area of barrier, ft^2

[1] Assumes thermal conductivity is constant with temperature, cross sectional area is constant and q is identical at all cross sections. These are reasonable assumptions for building materials and flat walls.

T_{inside} = inside surface temperature of barrier, °F
$T_{outside}$ = outside surface temperature of barrier, °F
ΔX = thickness of barrier, ft

3. The conductive heat flow for multiple layered barriers can be calculated by writing the Fourier equation for each layer and by understanding that for steady state heat flow, q is the same through all layers. Rearranging the multiple equations gives, for a three layer system in this example, the heat flow through a multiple layered flat surface:

$$q_{conductive} = [T_{inside} - T_{outside}] / [\Delta X_a/(k_a \cdot A) + \Delta X_b/(k_b \cdot A) + \Delta X_b/(k_b \cdot A)]$$

A = area of barrier
T_{inside} = inside surface temperature of barrier layers
$T_{outside}$ = outside surface temperature of barrier layers
k_x = thermal conductivity of layer x
ΔX_x = thickness of layer x

4. In most transport processes, heat transfer is accompanied by some sort of fluid motion so that the heat transfer does not occur by conduction alone. As fluids of a high [relative] temperature move by a surface of a lower [relative] temperature, the fluid adjacent to the plate (wall) cools. The zone of fluid in which the temperature lies between the fluid bulk temperature and the plate/wall temperature is known as the thermal boundary layer. The thermal boundary layer can profoundly affect the heat transfer through the plate/wall. Although the exact analysis is complicated, it is common practice in engineering to write the rate of convective heat transfer in terms of a heat transfer coefficient h as:

$$q_{convective} = h \cdot A \cdot [T_{surface} - T_{medium}]$$

A = surface area of barrier, ft^2
$T_{surface}$ = surface temperature of barrier, °F
T_{medium} = bulk temperature of the fluid medium, °F
h = heat transfer coefficient of fluid, $BTU/(hr \cdot ft^2 \cdot °F)$

5. In systems where the heat is transferred by a series of conduction and convection, it is possible to derive an overall equation that describes the rate of heat transfer based on knowledge of the [conductive] barrier thermal conductivities and the [convective] fluid heat transfer coefficients. The overall heat transfer coefficient, U, is derived through mathematical manipulation of a series of equations for both the convective and conductive heat transfer. For a flat plate (i.e. wall), U is defined as:

$$U = 1/[(1/h_{inside}) + (\Delta x_a/k_a) + (\Delta x_b/k_b) + (1/h_{outside})]$$

h_{inside} = inside fluid heat transfer coefficient
$h_{outside}$ = outside fluid heat transfer coefficient
Δx_a = thickness of barrier layer "a"
Δx_b = thickness of barrier layer "b"
k_a = thermal conductivity of barrier layer "a"
k_b = thermal conductivity of barrier layer "b"

6. For a thermal barrier composed of both inside and outside convective heat transfer and a two layer wall, the overall heat transfer can be described as:

$$q = U \cdot A \cdot [T_{inside} - T_{outside}]$$

A = surface area of barrier, ft^2
T_{inside} = inside fluid bulk temperature, °F
$T_{outside}$ = outside fluid bulk temperature, °F
U = overall heat transfer coefficient of system, $(BTU/(hr \cdot ft^2 \cdot °F)$

Heat Loss through a Barrier

By combining equation 8 and 9, one can arrive at a new equation that can be used to estimate heat loss through a barrier such as a wall, ceiling or window. For clarity, the equation below is for a two-layered barrier ("a" and "b"). However, by adding additional terms in the denominator ($\Delta x_c/k_c$, $\Delta x_d/k_d$, $\Delta x_e/k_e$, etc.) it can be used for barriers having any number of layers.

$$Q = [A \cdot (T_{inside} - T_{outside})] / [(1/h_{inside}) + (\Delta x_a/k_a) + (\Delta x_b/k_b) + (1/h_{outside})]$$

Q heat loss through barrier in units of BTU/hr
A = surface area of barrier, ft^2
T_{inside} = inside fluid bulk temperature, °F
$T_{outside}$ = outside fluid bulk temperature, °F
h_{inside} = inside fluid heat transfer coefficient, $BTU/(hr \cdot ft^2 \cdot °F)$
$h_{outside}$ = outside fluid heat transfer coefficient, $BTU/(hr \cdot ft^2 \cdot °F)$
Δx_a = thickness of barrier layer "a", ft
Δx_b = thickness of barrier layer "b", ft
k_a = thermal conductivity of barrier layer "a", $BTU/(hr \cdot ft \cdot °F)$
k_b = thermal conductivity of barrier layer "b", $BTU/(hr \cdot ft \cdot °F)$

It is this equation that we will use to estimate heat loss through the walls and ceiling of the structure being heated.

In heat up situations, air is normally the fluid both inside and outside the barrier. Still air has a convective heat transfer coefficient value, h, between 0.5 and 4 $BTU/(hr \cdot ft^2 \cdot °F)$. Moving air has a convective heat transfer coefficient value, h, between 2 and 10 $BTU/(hr \cdot ft^2 \cdot °F)$. The faster the air is moving, the higher the coefficient will be.

TYPICAL THERMAL CONDUCTIVITIES FOR CONSTRUCTION MATERIALS

Thermal conductivities, k, vary widely depending on the material under consideration. It should be apparent that insulating materials (such as fiberglass, Styrofoam and cork) will have lower thermal conductivities than thermally conductive materials (such as iron). Some of the more common construction materials are listed below:

Thermal Conductivities Table

N°	Material	Thermal conductivities, k, BTU/hr ft F
1	Acoustic tile	0.034
2	Bakelite	0.134
3	Blocks, boards & pipe insulation, calcium silicate	0.036
4	Blocks, boards & pipe insulation, polystyrene, rigid, extruded (R-12)	0.016
5	Blocks, boards & pipe insulation, polystyrene, rigid, molded beads	0.023
6	Blocks, boards & pipe insulation, rubber, rigid foamed	0.018
7	Brick, ordinary construction	0.416
8	Brick, refractory, carborundum	10.689
9	Brick, refractory, chrome-brick	1.340
10	Brick, refractory, fire clay brick	0.578
11	Celluloid	0.120
12	Cement mortar	0.416
13	Cement plaster, sand aggregate	0.416
14	Charcoal, powder	0.029
15	Clay	0.751
16	Coal, anthracite	0.150
17	Concrete, (stone mix)	0.809
18	Concrete, cinder	0.410
19	Concrete, sand & gravel	1.050
20	Cork, granulated	0.028
21	Corregated cardboard	0.037
22	Cotton	0.034
23	Cotton wool	0.035
24	Earth, 42% water	0.620
25	Foam, polystyrene	0.015
26	Foam, polyurethane	0.019
27	Glass window	0.451
28	Glass, pyrex	0.590
29	Graphite, solid	87.000
30	Gravel	0.220
31	Gypsum board	0.062
32	Gypsum plaster, sand aggregate	0.127
33	Hardboard, siding	0.054
34	Ice	1.260
35	Insulation, asbestos paper, laminated	0.038
36	Insulation, balsam wool blanket	0.021
37	Insulation, boards, Celotex, Insulite	0.029
38	Insulation, cabot's quilt	0.027
39	Insulation, cellular glass blocks	0.033
40	Insulation, cork board	0.023
41	Insulation, corrugated	0.031
42	Insulation, diatomaceous earth, asbestos and bonding material	0.045
43	Insulation, diatomaceous earth, silica, powder	0.037
44	Insulation, fiberglass block, PF612	0.023
45	Insulation, fiberglass block, PF614	0.021
46	Insulation, fiberglass block, PF617	0.020

Thermal Conductivities Table, continued

N°	Material	Thermal conductivities, k, BTU/hr ft F
47	Insulation, fiberglass, metal mesh blanket, #900	0.020
48	Insulation, glass fiber, coated; duct liner	0.022
49	Insulation, glass fiber, paper faced	0.027
50	Insulation, glass wool blanket	0.022
51	Insulation, hairfelt blanket	0.022
52	Insulation, Kaylo	0.032
53	Insulation, loose fill glass fiber, poured or blown	0.025
54	Insulation, micro quartz blanket	0.021
55	Insulation, vermiculite flakes	0.039
56	Insulation, wood, shredded & cemented	0.050
57	Insulaton, cellular glass	0.034
58	Kaolin wool	0.059
59	Leather, sole	0.092
60	Loose fill cellulose, wood or paper pulp	0.023
61	Loose fill perlite, expanded	0.031
62	Loose fill vermiculite, expanded	0.039
63	Plywood	0.069
64	Polystyrene (styrofoam)	0.021
65	Pumice, powdered	0.110
66	Rock, limestone	1.242
67	Rubber, hard	0.092
68	Rubber, hard	0.092
69	Rubber, soft, vulcanized	0.080
70	Sand, dry	0.188
71	Sawdust, dry	0.042
72	Silica gel, powder	0.049
73	Silica, fused	0.830
74	Soil, dry	0.075
75	Soil, dry, including stones	0.300
76	Teflon	0.231
77	Titanium dioxide	0.041
78	Wood, aspen	0.069
79	Wood, balsa	0.034
80	Wood, basswood	0.058
81	Wood, douglas fir	0.063
82	Wood, elm	0.097
83	Wood, fir, white	0.069
84	Wood, hemlock	0.066
85	Wood, larch	0.078
86	Wood, maple	0.094
87	Wood, oak	0.099
88	Wood, pine, southern yellow	0.078
89	Wood, pine, white	0.060
90	Wood, red cedar	0.053
91	Wood, redwood	0.062
92	Wood, spruce	0.052
93	Wool, pure	0.021

Energy to Heat Air

Whatever heat source is used (electric, gas fired, steam, etc.), air is the medium through which heat is transferred to the building and equipment. Before the building and equipment are heated, the air must be heated. We will work through how a heating value is derived for raising the temperature of the air.

During a heat up, every effort should be made to seal openings through which the hot air can escape. Generally, heat sterilization is accomplished by recirculating air with no air being exhausted. Despite best efforts, however, no building can be made perfectly hermetic; there will be infiltration of air. This infiltration is normally estimated to be one or two complete air exchanges per hour.

To determine the BTU/hr required to raise the air temperature from outside to the heat-up temperature, use the following formula:

$$q = n \cdot V \cdot [T_{\text{sterilization}} - T_{\text{outside}}] \cdot 0.018$$

n = number of air exchanges per hour, $(hr)^{-1}$
V = volume of building/room, ft^3
$T_{\text{sterilization}}$ = sterilization temperature, (°F)
T_{outside} = outside air temperature, (°F)
0.018 = specific heat of air, BTU/ $[ft^3 \cdot (°F)]$

For a fairly new, "air tight" building, use n = 1. For an older, draftier building, use n = 2.

Energy to Heat Building and Equipment Steel

Substantial heat is absorbed by the steel in the building structure and equipment and must be taken into account when determining overall heat up requirements.

To determine the BTU/hr required to raise the building and equipment steel from ambient room temperature to the heat-up temperature, use the following formula:

$$q = [W \cdot [T_{\text{sterilization}} - T_{\text{ambient room}}] \cdot 0.12] / t$$

W = weight of building and equipment steel, lbs
$T_{\text{sterilization}}$ = sterilization temperature, (°F)
$T_{\text{ambient room}}$ = starting temperature of steel, (°F)
0.12 = specific heat of steel, BTU/ $[lb \cdot (°F)]$
t = desired time to reach sterilization temperature, hr

Estimating the total weight of all the building steel and equipment can be an involved process. For steel framed buildings, a simple way to arrive at this total weight is to assume that the steel weighs 10 pounds per square foot of the building space. A simple way to arrive at an estimated weight of the equipment is to multiply the square footage of the building by 100 pounds. Food manufacturing plants are considered to be light industry, and for light industry, floors are normally designed for a 250-pound loading.

For purposes of estimating equipment weight for heat up calculations, one can use 50 pounds/ft^2 for low asset density spaces, 100 pounds/ft^2 for average asset density spaces and 150 pounds/ft^2 for high asset density spaces.

To avoid thermal shock to the building, it is desired to bring up the temperature slowly. This is accomplished by raising the air temperature to 140°F and holding it for 24 hours. Most building materials are not good conductors of heat, and it takes a long time to raise the hollow cores of walls to the 120°F to 140°F level. To accommodate this slow rise, 23 hours is chosen as "t" in the heat requirement formula above.

Heat Loss through Grade Level Floor

Reasonable estimates of the heat lost through grade level floors can be obtained by assuming 2 BTU/hr per ft^2 of floor space.

Total Heat Estimate

The total heat to be supplied in order to achieve and maintain the desired heat up temperature is the sum of:

- Heat loss through all barriers (walls, windows, ceilings, etc.)
- Heat loss through grade level floor
- Energy to heat the air
- Energy to heat building steel
- Energy to heat equipment

Each distinct room and/or floor must be evaluated individually since the internal walls and floors will generally localize heat (i.e., internal walls and floors prevent heat migration.)

Heating Sources and Methods

Once the total heat in BTU/hr for each floor/room has been calculated, it is necessary to determine how the heat will be delivered. Many food-processing plants utilize unit operations that employ heat, e.g., dryers, toasters, etc. This readily available heat can and should be used when possible during heat-ups. Dryer doors, for example, can be fully opened while the dryer heat is turned on. In addition, existing heating systems should be fully on as well.

Normally, however, there is not enough heat generating capacity in unit operations and heating systems to raise the air temperature to and maintain it at 140 °F. In these cases, it is necessary to add supplemental heating. The amount of supplemental heating is determined by subtracting the heat that can be obtained from existing processing equipment and from existing heating systems portion from the total heat required. Supplemental heating is used for any remainder, see below.

Total Heat Required For Room/Floor, BTU/Hr
- (Heat Available from Existing Processing Equipment + Heating Systems), BTU/Hr
= Amount of Supplemental Heat Required, BTU/Hr

A typical single heater unit mounted on a cart complete with a pressure regulator, steam traps and valves with a nominal output of 300,000 - 350,000 BTU/hr costs approximately $2000. To determine the number of supplemental heaters required, divide the total heat that must be supplied by supplemental heating (in BTU/hr) by 350,000 BTU/hr. Round up the result to the nearest integer.

For steam heating systems, both portable and permanently mounted supplemental units are common. Portable units have the advantage of mobility; thus they can be located where the heat is needed. Moreover, portable units can be used to heat several locations, (albeit not simultaneously!) Both single units and double units are generally used and can be easily fabricated.

Since they are typically hard-piped, permanently mounted units allow for shorter set-up times and, therefore, faster heat-ups.

REFERENCES

Bennett, C.O., & Meyers, J.E. (1982). Momentum, Heat and Mass Transfer (3rd ed.). New York: McGraw-Hill.

Imholte, T.J. (1984). Engineering for Food Safety and Sanitation. Crystal, MN: Technical Institute of Food Safety.

Electrical Costs

Quantity	Model Number	Daily Electricity Consumption (Kw/day)	Cost Per Kw	Cost Per Day
1	THP-1400	88.3 Kw / day	0.06 $ / Kw	$5.30
1	THP-550	43 Kw / Day	0.06 $ / Kw	$2.58

Natural Gas Costs

Quantity	Model Number	Daily Gas Consumption (dkt/day)	Cost Per dkt	Cost Per Day
1	THP-1400	33.6 dkt / Day	5.00 $ / dkt	$168.00
1	THP-550	13.2 dkt / Day	5.00 $ / dkt	$66.00

Natural Gas Costs at Partial Load (50%)

Quantity	Model Number	Daily Gas Consumption (dkt/day)	Cost Per dkt	Cost Per Day
1	THP-1400	16.8 dkt / Day	5.00 $ / dkt	$84.00
1	THP-550	6.6 dkt / Day	5.00 $ / dkt	$33.00

REPORT

1994 HEAT TREATMENT OF KSU FLOUR MILL/CLEANING HOUSE

Prepared by John R. Pedersen
Department of Grain Science and Industry
Kansas State University
Manhattan, Kansas 66506

INTRODUCTION

The concept of heating flour mills for insect control is not new. Early attempts were conducted by USDA and Kansas State University researchers as early as 1911. Some commercial cereal processing companies, such as Quaker Oats, have used the technique routinely for several years. The current emphasis on Integrated Pest Management and recently enacted or envisioned restrictions on the use of pesticides, i.e. methyl bromide and dichlorvos, have prompted several cereal processing companies to undertake plant "heat-ups" as an alternative to fumigation and/or space treatments. Flooding in the central United States this past year (1993) led to the identification of a heat supply resource for plant heat-up without capital investment in plant heating capacity. Ole Dosland, Sanitarian for ConAgra, had the responsibility of getting two flooded flour mills back in production with minimum lost time and in a sanitary condition. Contact was made with Aggreko, Inc. in conjunction with flood recovery efforts in Des Moine, IA that Ole visited. The power, heat and dehumidification capabilities of Aggreko were demonstrated in the recovery of the two mills. Ole recognized the heat-up potential to the industry and shared his experiences with the Association of Operative Millers', Food Protection Committee.

The decision to heat-treat the Kansas State University flour mill and cleaning house for insect control began with discussions between Mark Mire (Aggreko), Brad Peck (Aggreko), Bill Pursley (AIB) and Jack Pedersen (Grain Science-KSU) in November 1993. It appeared that a demonstration heat-up in the KSU facilities would benefit all concerned. The KSU flour milling facilities were badly in need of an alternative to fumigation because of the insect situation in the mill and cleaning house. The mill and cleaning house as well as offices, laboratories and other pilot

plant facilities are housed within Shellenberger Hall which in turn is connected to other campus buildings by means of heat tunnels making fumigation an undesirable alternative. Aggreko was interested in a trial heat-up of a food processing plant in anticipation of a tentatively planned heat treatment at a ConAgra mill. These factors led to the joint effort conducted by Aggreko, Inc., the Department of Grain Science and Industry at Kansas State University, and many industry individuals who volunteered to monitor the heat-up trial.

PREPARATION FOR THE HEAT-UP.

Planning. Initial planning for the heat treatment began in early December 1993 and originally included the KSU feed mill, warehouse and the Extrusion Laboratory. Because of scheduling conflicts and other factors the feed mill, warehouse and extrusion laboratory were dropped from the plans about a week prior to the scheduled heat treatment.

A "Super Heat Treatment Check List" was prepared for the KSU flour mill, cleaning house, feed mill, extrusion laboratory and warehouse. General guidelines were based on a "Heat Sterilization Check-list" prepared by Gary Thompson, Quaker Oats, Co. and published by the Food Protection Committee in the AOM Bulletin, October 1987. Individual specific guidelines for the flour mill/cleaning house, feed mill, extrusion laboratory and warehouse were prepared to supplement the general guidelines. This check list was used as a final check prior to starting the heat-up.

Sprinkler System. A major concern was the fire sprinkler system in the mill and cleaning house. Sprinkler heads were designated to trip at 160°F. After meeting with Department of Public Safety and other officials on campus, it was decided that the sprinkler system could be shut down and drained prior to the heat-up. This required provision of a "fire watch" during the time the system was shut down. Replacement sprinkler heads were obtained for heads that might trip during the heat-up. If heat-up becomes a regular part of the insect control program, current sprinkler heads should be replace with 200°F. heads.

Building Sealing. Sealing of roof vents was accomplished as indicated in the guidelines, however, during the heat-up the sealing was found inadequate to prevent significant heat loss. It

was obvious that roof vents need to be completely and securely sealed, as for a fumigation, to prevent heat loss. This is in contrast to personnel and freight elevator doors where no sealing was accomplished.

Power and Heating Equipment. The power and heating equipment supplied by Aggreko arrive at approximately 8 a.m. on Sunday morning, January 9, 1994. The generator power unit, mounted on a semi-trailer chassis, was parked adjacent to the feed mill warehouse and flour mill loading dock. Eleven portable heater units (50KW size) were delivered on a 48 ft. flatbed trailer along with two circuit breaker panels, power cables and heat ducting. Tony Little, Aggreko Service Manager, supervised the unloading of equipment and laid the the power cabling assisted by three students (Steve Traylor, Wes Twombley and Dale Fredrickson). Mark Mire, Aggreko, positioned the heater units in the various mill and cleaning house areas.

Heater units were transported to the various floor levels of the mill by freight elevator and placed as follows:

Cleaning House	Flour Mill
4th Floor - 1 unit	5th Floor - ducted from 4th
3rd Floor - 1 unit	4th Floor - 2 units; 1 ducted to 5th
2nd Floor - 1 unit	3rd Floor - 1 unit
1st Floor - 1 unit	2nd Floor - 2 units; 1 ducted to sub
	2nd Sub-floor - ducted from 2nd Floor.
	Power/manlift/locker area - 1 unit

In most instances, heaters were directed toward the center of the area being heated. Heat was ducted from the 4th to the 5th floor because there was no provision to get a heater to the 5th floor (no freight elevator; heaters weigh about 1000 lbs.). A second heater was positioned on the 2nd floor in the flour mill and ducted to a sub-floor area beneath the roll stands. A heater was positioned in a manlift area with passage to a power room and locker room. Splitter ducts were not available to allow good distribution of heat to these three area. This, and the lack of fans, proved

to be a problem in getting good distribution of heated air to the floor region of these areas. Heaters were installed and checked out by about 5 p.m. on January 9, 1993.

Temperature monitoring thermocouples. Prior to the arrival of the heating equipment, thermocouples had been positioned at 40 various locations throughout the mill and cleaning house. A special effort was made to position thermocouples at locations where electronic control devices were present. A few thermocouples were place within pieces of equipment to determine heat penetration into the equipment. The temporary thermocouple wires were directed to hallway locations inside Shellenberger Hall for ease of taking readings at regular intervals during the heat-up and cool down periods. Temperatures were also taken at two locations outside of Shellenberger Hall and on each of three floor levels in hallways adjacent to the flour mill/cleaning house interior walls.

Thermocouple wire used was 20 gauge copper/constantan (Type "T") thermocouple extension wire with a stated accuracy of +/-2°F. Each wire had an individual coating of PVC and these were in turn within a PVC jacket. This makes the wire more durable for repeated use. Single insulated wire of lighter gauge could have been used and is less expensive. The extension wire happened to be available for immediate use.

Plugs used on the thermocouple wires are called Mini-Plugs. Type"T" plugs are required for copper/constantan wire. Both the wire and plugs were obtained from Marlin Manufacturing Corporation, Cleveland, OH. Marlin has a reader, however, the one used was from Adkins in Gainsville, FL. (Model #39658) and costs about $200 less than Marlin's.

Test Insects. Confused flour beetle adults and larvae were used to monitor the effectiveness of the heat treatment. Test insects placed in the flour mill and cleaning house for the duration of the treatment were placed in two 6 oz. plastic cups which were glued to a piece of corrugated cardboard with hot-melt glue. One cup on each board contained 25 adult insects in approximately 5 grams of whole wheat flour; the other cup contained 10 larvae in an equal amount of flour. Forty-eight (48) test units were placed at various locations ranging from near the floor to near the ceiling. In most instances, 5 test units were placed on each floor of the flour mill and of the cleaning house.

Special test units were set up at each of two (2) locations on the second floor; one in the

flour mill and one in the cleaning house. Each test unit consisted of a metal can 6 inches in diameter and approximately 6.5 inches tall. Two metal wire test cages, one containing 25 adult confused flour beetle adults and the other, 10 confused flour beetle larvae (each containing about 5 grams of whole wheat flour), were placed in the center of the cans surrounded by either whole wheat or a flour/bran/shorts mixture.

Two replicate units were placed at each of three (3) levels (sprinkler, table top and floor levels) in the flour mill and in the cleaning house. Units in the cleaning house contained wheat; those in the flour mill contained flour mix. Thermocouples were positioned adjacent to the insect test cages within each container and another thermocouple positioned outside the units at each of the three levels.

Control insects were maintained in a constant condition room at 77°F and 65% relative humidity.

During the heat-up, a few short term insect tests were conducted to determine time to kill insects at various temperatures, the effect of small amounts of food on mortality and the positioning of insects within a closed sifter.

RESULTS AND CONCLUSIONS

Sprinkler System. The sprinkler system was shut off at approximately 8 a.m. on Monday, January 10, 1993. The water was drained from the system without incident. The heaters were activated at about 9 a.m.

Following the heat treatment (heaters were shut down at 12 p.m. (noon) on January 11, 1993), a thorough inspection was made to determine whether any of the sprinkler heads had discharged. No discharged heads were found. Individuals were positioned on each of the cleaning house and flour mill floors as spotters as the sprinkler system was reactivated. The system was reactivated without incident between 4 and 5 p.m.

Temperatures. A complete record of thermocouple temperatures is included as Exhibit F. Temperatures were recorded at approximately 30 minute intervals during the primary heat-increasing period (9 a.m. until 6 p.m.) and again during the cool down period (noon until 4 p.m.). During the "level" heat period, temperatures were monitored hourly.

Average temperatures for each of the floors in the cleaning house and flour mill are shown in Figures 1 (Cleaning House) and 2 (Flour Mill). The average temperature on the 4th floor of the cleaning house remained low in comparison to other floors. This resulted from one of the thermocouples being place next to an east window where readings remained near 100°F for nearly the entire duration of the treatment. This suggests that where windows exist efforts should be made to direct or circulate air across these cool surfaces. Average outside air temperatures ranged between 23 and 57°F during the heat treatment period. In warmer months this may not be a serious problem. In general, average temperatures in the cleaning house were between 130 and 140 °F. from 6 p.m. on Monday until noon on Tuesday. Even though average temperatures on the 1st floor of the cleaning house were between 130 and 140°F. from about 8 p.m. on Monday until heaters were shut down on Tuesday, insect mortality counts showed survivors at the floor level.

Average flour mill temperatures for the 5th floor indicate the sealing problem that was encountered at about noon on Monday. Even though the vents on the roof were resealed, it appeared difficult to raise the temperature to the desired 130°F level. The heater ducted into the sub-floor fed a relatively small confined space and showed tendencies of overheating the area. Frequent temperature readings provided the opportunity to regulate the heating units and maintain a fairly uniform heat once the desired level was reached. Figures 3 and 4 illustrate temperatures attained within product where the penetration of heat into wheat and a flour mix was about 3 inches. Temperatures lagged the average room temperature by as much as 6 hours, however, sufficient time at the elevated temperatures allowed for 100% mortality of test insects. Temperatures at all three levels (sprinkler, about 18 inches from the ceiling; scale, about 4 feet above floor level; and floor level) were nearly identical. The heater was aimed almost directly at the area where samples were placed. In Figure 4, floor level samples had an average temperature considerably lower than those about 4 feet above floor level or 18 inches below the ceiling. Even though temperatures in the floor level samples did not reach 120°F. until after midnight on Monday, there evidently was sufficient time at these elevated temperatures to kill the insects.

When the heaters were shut down at noon on Tuesday, fans on the units were allowed to run until the heaters cooled down. Roof vents were opened shortly after fan shut-down and plywood panels used to partially cover stair wells in the cleaning house and manlift holes on the 2nd and 3rd

floors of the flour mill were removed. At about 1 p.m. interior doors to the 1st, 2nd and 3rd floors of the mill and cleaning house were opened. Outside doors to the 4th floor cleaning house and 5th floor flour mill were opened about 1:30 p.m. Windows that were opened on the 3rd floor of the flour mill were reclosed because cooling was too rapid.

Insect Control. When compared with the insect mortality data, the temperatures attained appear to have given very good results.

Table 1 summarizes the mortality data. All adults and larvae were killed except where the test insects were placed adjacent to windows on the east wall. Four larvae survived at this location. No survivors were found on the 2nd or 3rd floors. On the 1st floor of the cleaning house, seven larvae survived at floor level in the SE corner and 18 adults and 12 (all) larvae survived in the NW corner at floor level. Whether this is a result of poor air circulation or whether insufficient heating of the floor at ground level (unexcavated below) is uncertain.

Similar problems were encountered in the manlift/power/locker area, also at ground level (unexcavated below). All but one adult and all larvae survived in the power room and half the larvae survived in the NE corner of the manlift area adjacent to a door to the hallway. Temperature in the power room reached and maintained 130°F for 7 hours before the heater shut down but this was measured at about 7 feet above floor level. Drafts noted inside the door NE corner suggest inward drafting of air should be eliminating or reduced by sealing of the doors to hallways. It was obvious that there was little if any heat escape into hallways (See Figures 1 and 2). No surviving insects, adults or larvae, were found on the 2nd, 3rd, 4th or 5th floors of the flour mill. Over all, there was a 96.7 percent mortality of adults and 92.6 percent mortality of larvae.

A few mortality tests were conducted during the heat-up period to look at possible short term effects of the heat on test insects. Test A (1-10-94) was conducted over a 5 hour period of time to determine the effect of tempertures of about 135°F on adult confused flour beetle adults in 5 grams of food material. Duplicate samples were used. The test could have bee terminated after the 1st hour where 100% mortality was obtained. Counts after 48 hours indicated no recovery insects.

Test B (1-11-94) was conducted over a shorter time span and compared insects in test cups with food with insects in empty cups (Table 2). After 10 minutes at 141°F there were no survivors in the non-food cup and 3 survivors in the cup containing food. After 20 minutes, all insects were

dead under both conditions.

Test C (1-11-94) elaborated on Test B to a certain extent (Table 3). Insects were exposed for shorter periods of time and at a temperature that ranged between 125 and 130°F. All insects in both empty and food-containing cups were alive after 5 minutes exposure. All adults were dead at 15 minutes exposure. In the containers without food, 96% mortality was attained at 30 minutes exposure. Counts made 24 hours later indicated some delayed mortality under both food conditions, however, all insects from the 5 minute exposure survived at the 24 hour count.

Insects placed in a closed sifter box where temperatures reached 140°F were all dead following the heat treatment.

SUMMARY OF PROBLEMS ENCOUNTERED DURING HEAT-UP

1. Roof vents not sufficiently sealed to prevent loss of heat. This involved the exhaust vent from the freight elevator space, the exhaust vent from the air conditioning system, one exhaust fan vent from the flour mill, two exhaust fan vents from the cleaning house and the fresh air intake for the cleaning house. These vents were resealed more securely during the heat-up when it was noted that temperatures on the top floors were not increasing commensurate with the other floors.
2. The Great Western agitator was disassembled for the heat-up with top removed and the bottom left in the support frame. After the heat-up the bottom section was noticed to have warped or spread between points of attachment to the frame. The agitator was fabricated from PVC which apparently softened during exposure to the heat. The heater in the area was not directed at the agitator but was located near the agitator.
3. A 3/4 inch PVC deionized water line passed through the second floor of the mill and cleaning house at about sprinkler system height. After the heat-up it was noted that the PVC pipe had sagged between hangers. The presence of the PVC pipe was not recognized before the heat-up. It delivers deionized water from a tank (approximately 1000 gallon capacity) located in SH 319 (a laboratory) located on the third floor to laboratories located on the second and first floors at the south end of Shellenberger Hall. Luckily the PVC pipe only sagged and didn't break.

4. A Tygon air line which supplied air to the Kice fan motor frame on the 5th floor of the flour mill softened and broke at some time during the heat-up process. It was discovered during the cool down period.

5. There were three locations in the cleaning house where 100% mortality of insects was not obtained: 1) On a window ledge next to an outside window on the fourth floor - adults 100%, larvae 55%; 2) On the floor in the S. E. corner of the first floor - adults 100%, larvae 42%; and 3) On the floor in the N. W. corner of the first floor - adults 28%, larvae 0%.

There were two locations on the first floor level of the flour mill (power room and manlift area) where 100% mortality was not obtained: 1) On the floor in the center of the power room - adults 4%, larvae 0%; and 2) on the floor at the N. E. corner of the manlift area - adults 100%, larvae 50%.

All survivors (except on the 4th floor of the cleaning house) were in test containers placed on the floor of the ground level floor.

6. Aggreko heaters of old design tripped their breakers because of the high temperatures. This was remedied by opening the control panels and circulating air through the control panel by means of 20 inch box fans (household models). They ran fine at 140°F. Newer heater units used by Aggreko had fans installed in the control panels and were no problem.

HEAT-UP TEMPERATURES
CLEANING HOUSE

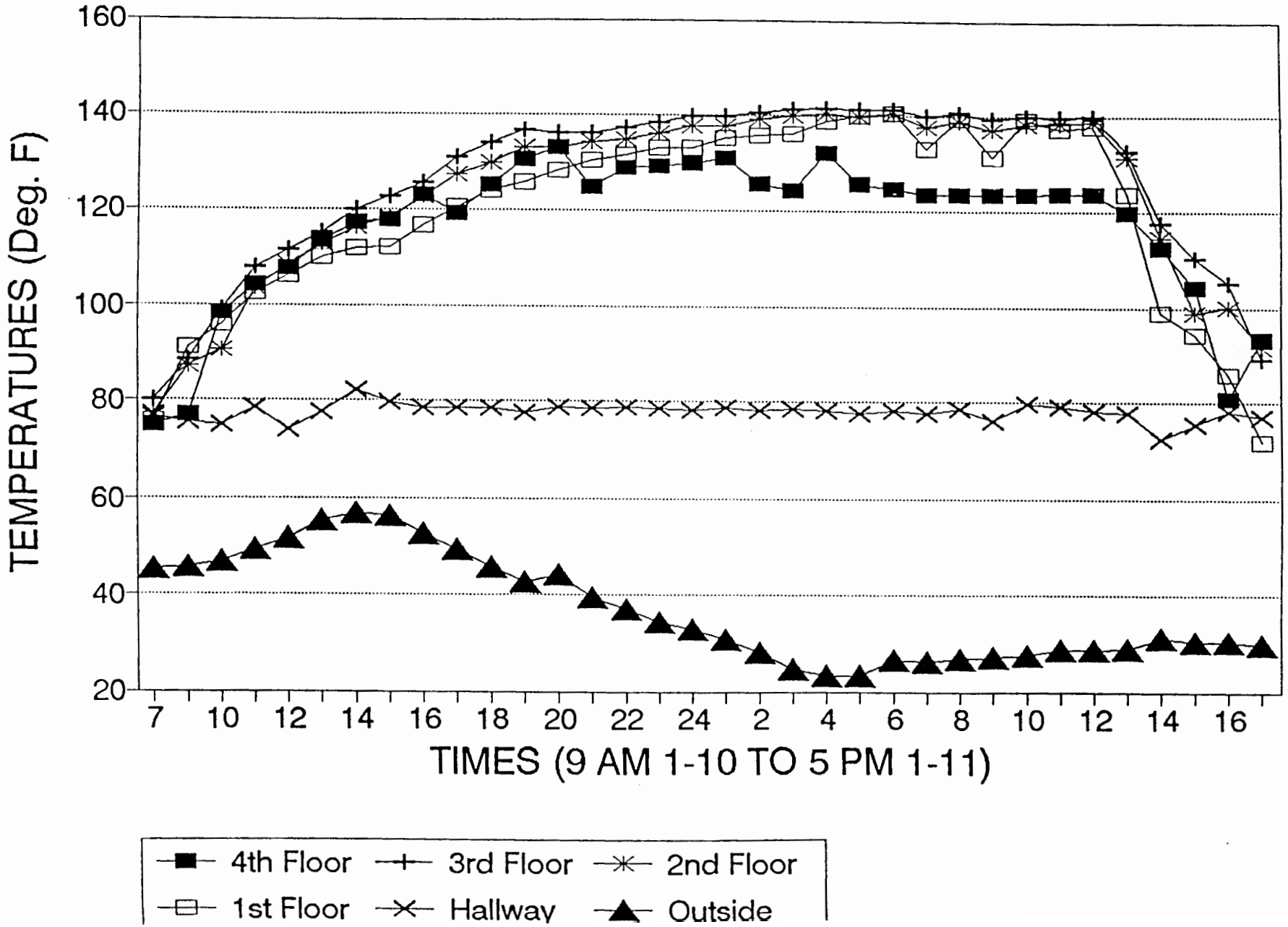


FIGURE 1

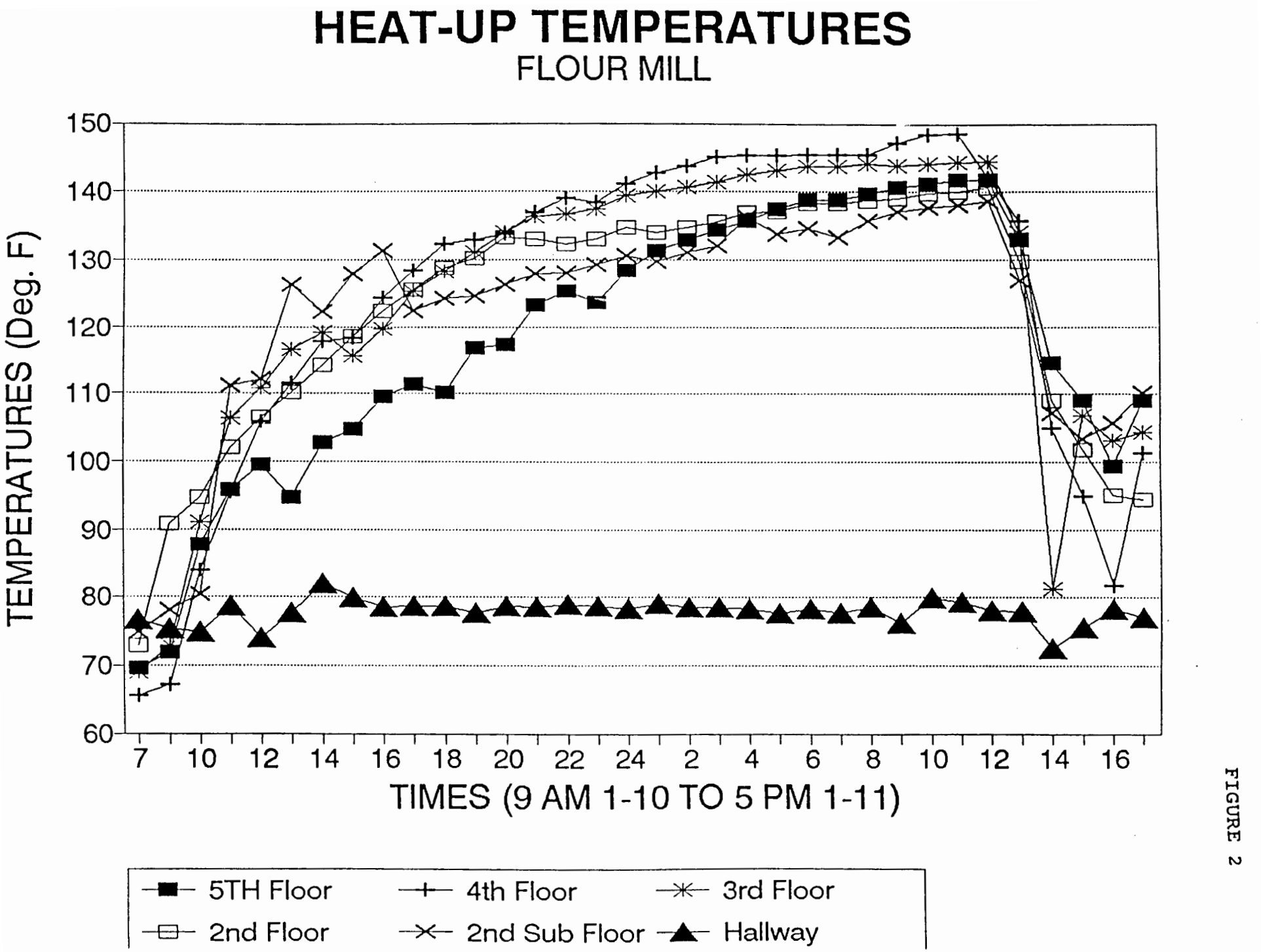

HEAT-UP TEMPERATURES
FLOUR MILL
TEMPERATURES (Deg. F)
150
140
130
120
110
100
90
80
70
60
7
10
12
14
16
18
20
22
24
2
4
6
8
10
12
14
16
TIMES (9 AM 1-10 TO 5 PM 1-11)
5TH Floor
4th Floor
3rd Floor
2nd Floor
2nd Sub Floor
Hallway

FIGURE 2

HEAT-UP TEMPERATURES

WHEAT IN CONTAINER

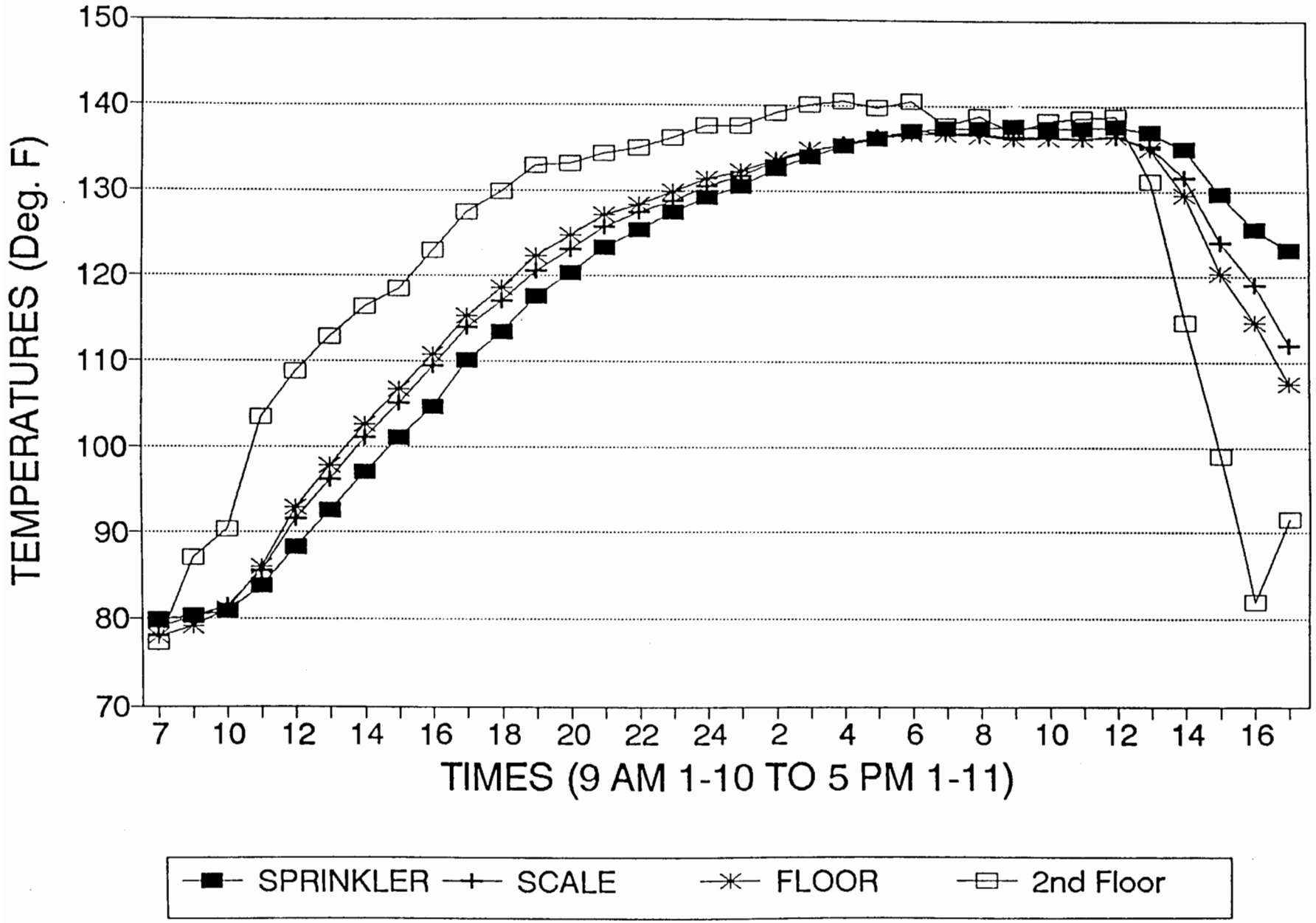


FIGURE 3

HEAT-UP TEMPERATURES

FLOUR IN CONTAINER

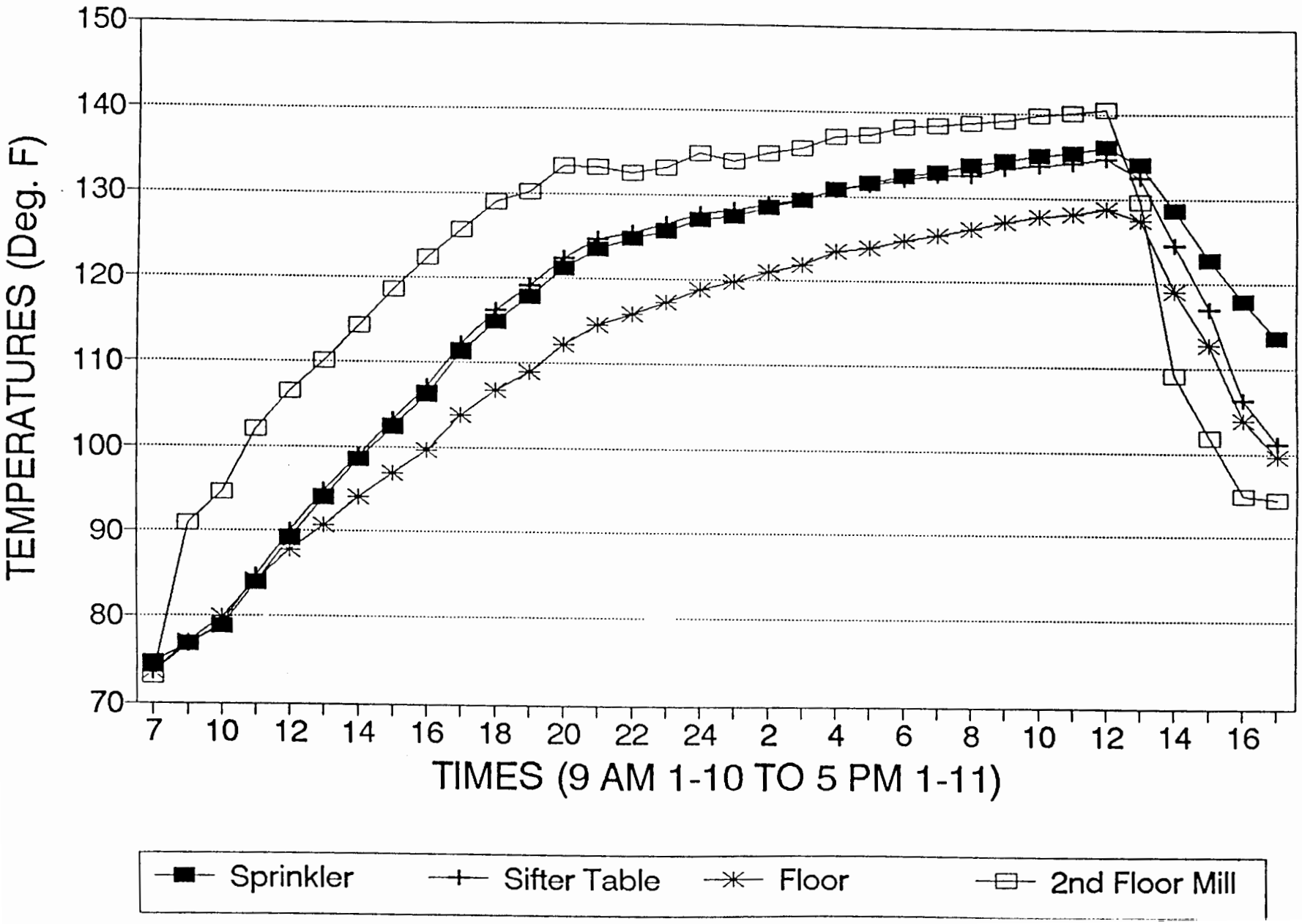


FIGURE4

FLOUR BEETLE MORTALITY

FLOUR MILL/CLEANING HOUSE

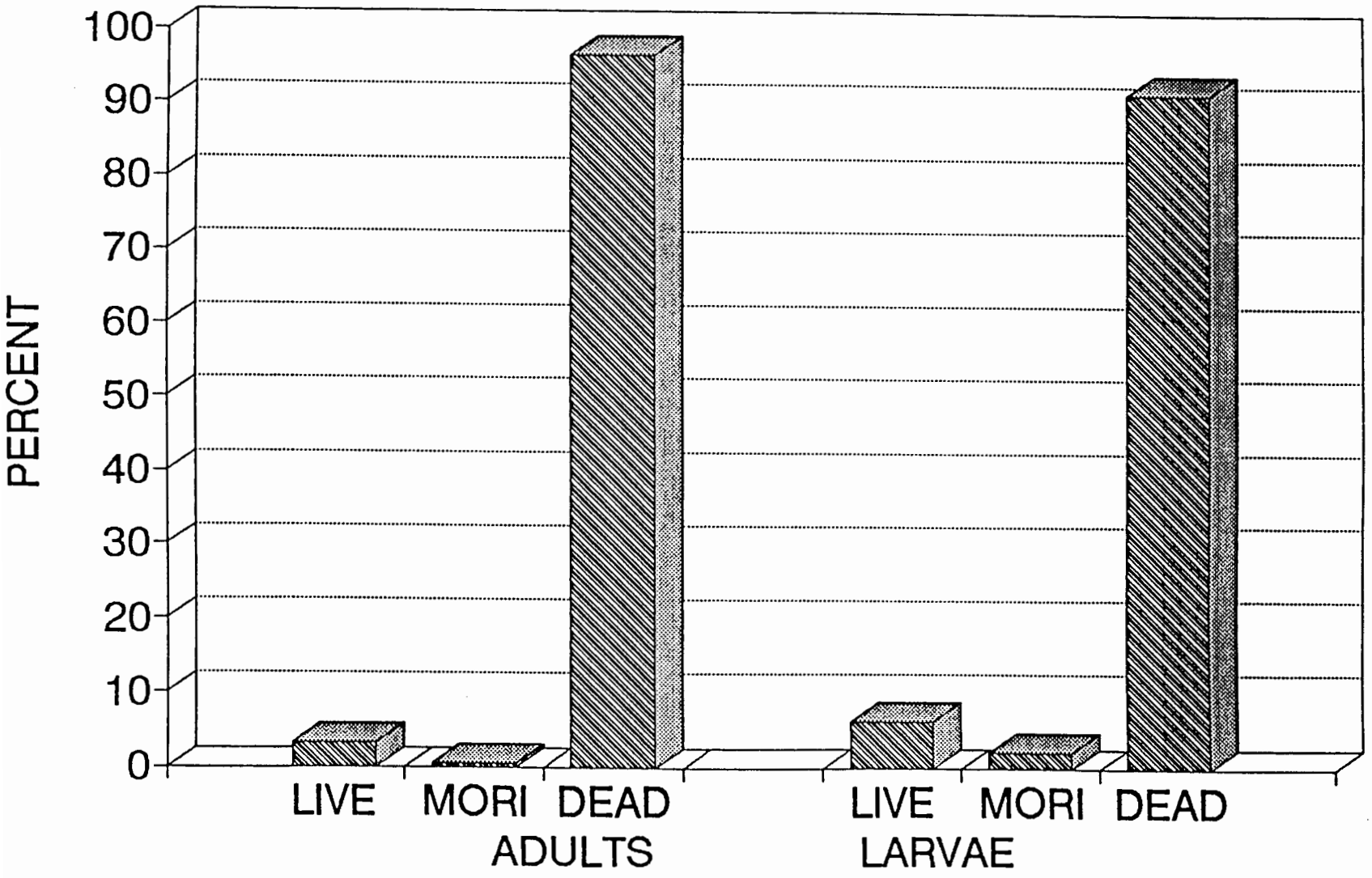


TABLE 1 KSU FLOUR MILL/CLEANING HOUSE HEAT TREATMENT

SUMMARY OF INSECT MORTALITY

CLEANING HOUSE	ADULTS LIVE	ADULTS MORI	ADULTS DEAD	LARVAE LIVE	LARVAE MORI	LARVAE DEAD
4TH FLOOR	0.0	0.0	126.0	1.0	3.0	44.0
3RD FLOOR	0.0	0.0	120.0	0.0	0.0	43.0
2ND FLOOR	0.0	0.0	125.0	0.0	0.0	46.0
1ST FLOOR	15.0	3.0	107.0	15.0	4.0	35.0
FLOUR MILL						
5TH FLOOR	0.0	0.0	149.0	0.0	0.0	60.0
4TH FLOOR	0.0	0.0	126.0	0.0	0.0	51.0
3RD FLOOR	0.0	0.0	128.0	0.0	0.0	50.0
2ND FLOOR	0.0	0.0	124.0	0.0	0.0	48.0
2ND SUB FLOOR	0.0	0.0	49.0	0.0	0.0	20.0
1ST FLOOR	23.0	0.0	102.0	14.0	3.0	39.0
TOTAL	38.0	3.0	1156.0	30.0	10.0	436.0
PERCENT	3.2	0.3	96.6	6.3	2.1	91.6

INSECT MORTALITY DURING SELECTED PERIODS OF HEAT TREATMENT

TEST A (1-10-94)

		FOOD (A)			FOOD (B)			
TIME	DURATION	LIVE	DEAD	% MORT.	LIVE	DEAD	% MORT.	TEMP. (F.)
5:00 PM	START	24.0	0.0	0.0	25.0	0.0	0.0	129.9
6:00 PM	1 HOUR	0.0	24.0	100.0	0.0	25.0	100.0	133.0
7:00 PM	2 HOURS	0.0	25.0	100.0	0.0	25.0	100.0	135.2
8:00 PM	3 HOURS	0.0	25.0	100.0	0.0	25.0	100.0	135.5
9:00 PM	4 HOURS	0.0	25.0	100.0	0.0	25.0	100.0	136.4
10:00 PM	5 HOURS	0.0	25.0	100.0	0.0	25.0	100.0	137.4
	CONTROLS	26.0	0.0	0.0	26.0	0.0	0.0	ROOM
				RECOUNT (48 HOURS)				
	1 HOUR	0.0	24.0	100.0	0.0	25.0	100.0	
	2 HOURS	0.0	25.0	100.0	0.0	25.0	100.0	
	3 HOURS	0.0	25.0	100.0	0.0	25.0	100.0	
	4 HOURS	0.0	25.0	100.0	0.0	25.0	100.0	
	5 HOURS	0.0	25.0	100.0	0.0	25.0	100.0	
	CONTROLS	26.0	0.0	0.0	25.0	1.0	4.0	

INSECT MORTALITY DURING SELECTED PERIODS OF HEAT TREATMENT

TEST B (1-11-94)

		NO FOOD			FOOD			
TIME	DURATION	LIVE	DEAD	% MORT.	LIVE	DEAD	% MORT.	TEMP. (F.)
1:27 AM	START	25.0	0.0	0.0	25.0	0.0	0.0	141.0
1:37 AM	10 MIN	0.0	25.0	100.0	3.0	22.0	88.0	141.0
1:47 AM	20 MIN	0.0	25.0	100.0	0.0	25.0	100.0	141.0
	TERMINATED							
	CONTROLS	25.0	0.0	0.0	25.0	0.0	0.0	ROOM
				RECOUNT (48 HOURS)				
	10 MIN	0.0	25.0	100.0	5.0	20.0	80.0	
	20 MIN	0.0	25.0	100.0	0.0	25.0	100.0	
	CONTROLS	25.0	0.0	0.0	25.0	0.0	0.0	

INSECT MORTALITY DURING SELECTED PERIODS OF HEAT TREATMENT

TEST C (1-11-94)

		NO FOOD				FOOD				
TIME	DURATION	LIVE	MORIBUND	DEAD	% MORT.	LIVE	MORIBUND	DEAD	% MORT.	TEMP. (F.)
2:18 AM	START	25.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	125.4
2:23 AM	5 MIN	25.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	125.4
2:28 AM	10 MIN	0.0	10.0	15.0	60.0	24.0	0.0	1.0	4.0	125.4
2:33 AM	15 MIN	0.0	0.0	25.0	100.0	25.0	0.0	0.0	0.0	125.4
2:38 AM	20 MIN	0.0	0.0	24.0	100.0	16.0	4.0	5.0	20.0	125.4
2:43 AM	25 MIN	0.0	0.0	25.0	100.0	16.0	5.0	4.0	16.0	125.4
2:48 AM	30 MIN	0.0	0.0	25.0	100.0	0.0	1.0	24.0	96.0	125.4
	CONTROLS	26.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	ROOM
					RECOUNT (24 HOURS)					
	5 MIN	25.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	
	10 MIN	1.0	11.0	13.0	52.0	24.0	1.0	0.0	0.0	
	15 MIN	0.0	0.0	25.0	100.0	24.0	1.0	0.0	0.0	
	20 MIN	0.0	0.0	25.0	100.0	19.0	1.0	5.0	20.0	
	25 MIN	0.0	0.0	25.0	100.0	11.0	2.0	12.0	48.0	
	30 MIN	0.0	0.0	25.0	100.0	1.0	0.0	24.0	96.0	
	CONTROLS	26.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	

INSECT MORTALITY DURING SELECTED PERIODS OF HEAT TREATMENT

SIFTER TEST (1-11-94)

		FOOD (1)			FOOD (2)			
TIME	DURATION	LIVE	DEAD	% MORT.	LIVE	DEAD	% MORT.	TEMP. (F.)
9:00 AM	START	25.0	0.0	0.0	25.0	0.0	0.0	135.4
9:20 AM	20 MIN	0.0	25.0	100.0	0.0	23.0	100.0	
9:40 AM	40 MIN	0.0	24.0	100.0	0.0	26.0	100.0	
10:00 AM	60 MIN	0.0	25.0	100.0	0.0	25.0	100.0	139.9

NO CONTROLS WERE MAINTAINED ON THIS TEST AND NO RECOUNTS MADE.

Temperature Distribution During a Heat Treatment of the Cleaning House and Flour Mill at Kansas State University, June 25-27, 1999

Alan K. Dowdy,[1] Bh. Subramanyam[2] & Tom Danley[3]

Because of the increasing interest in using high temperatures to manage insects in food processing facilities, a demonstration project was conducted in the pilot cleaning house and flour mill and Kansas State University. The flour mill has been heated three to four times per year since 1995 whereas the cleaning house has previously been heated only in 1995 by Dr. Pedersen.

A new heating system was used during this heat treatment that heat air from outside the building and delivered it inside using cloth ducting. This created a positive pressure within the building that resulted in heated air being forced out of cracks and other openings in the building. The objective of this method is to facilitate the movement of heat into areas where stored-product insects may be hiding to escape the heat.

HOBO® (Onset Computer Corp., Pocasset, MA) temperature loggers were evenly distributed at floor level in the cleaning house and flour mill in a loose grid fashion using 16 to 22 per floor in each room. Additional sensors were placed outside the building to monitor outside temperatures during the heat treatment. The loggers were set to record at 10-minute intervals during the heat treatment.

The results of this heat treatment are presented in the following table and Figures 1 through 3.

Table 1. The length of time and the time to reach target temperature of 50°C (122°F) (± SEM) and the maximum temperature attained during the heat treatment of the cleaning house and flour mill at Kansas State University, June, 1999.

Room	floor	time above 50°C (hr)	time to reach 50°C (hr)	maximum temperature (°C)
cleaning house	1	27.5 ± 2.6	11.7 ± 4.2	57.9 ± 1.2
	2	23.0 ± 2.4	14.9 ± 2.1	56.6 ± 1.3
	3	21.4 ± 2.4	19.7 ± 2.3	55.4 ± 0.8
	4	17.8 ± 2.0	23.2 ± 2.5	53.8 ± 0.5
flour mill	sub floor	13.2 ± 3.4	23.7 ± 4.4	53.3 ± 1.2
	2	22.6 ± 2.9	16.3 ± 3.3	59.1 ± 2.1
	3	28.2 ± 1.2	14.0 ± 1.0	57.7 ± 0.5
	4	22.9 ± 2.0	19.3 ± 2.0	55.3 ± 0.6
	5	22.4 ± 2.3	20.0 ± 2.0	55.1 ± 0.6

This is a report of research results only. Mention of a proprietary product does not constitute an endorsement by USDA or Kansas State University at the exclusion of other products.

[1] USDA, ARS, Grain Marketing & Production Research Center, Manhattan, KS
[2] Department of Grain Science &Industry, Kansas State University, Manhattan, KS
[3] TempAir, Inc., Burnsville, MN

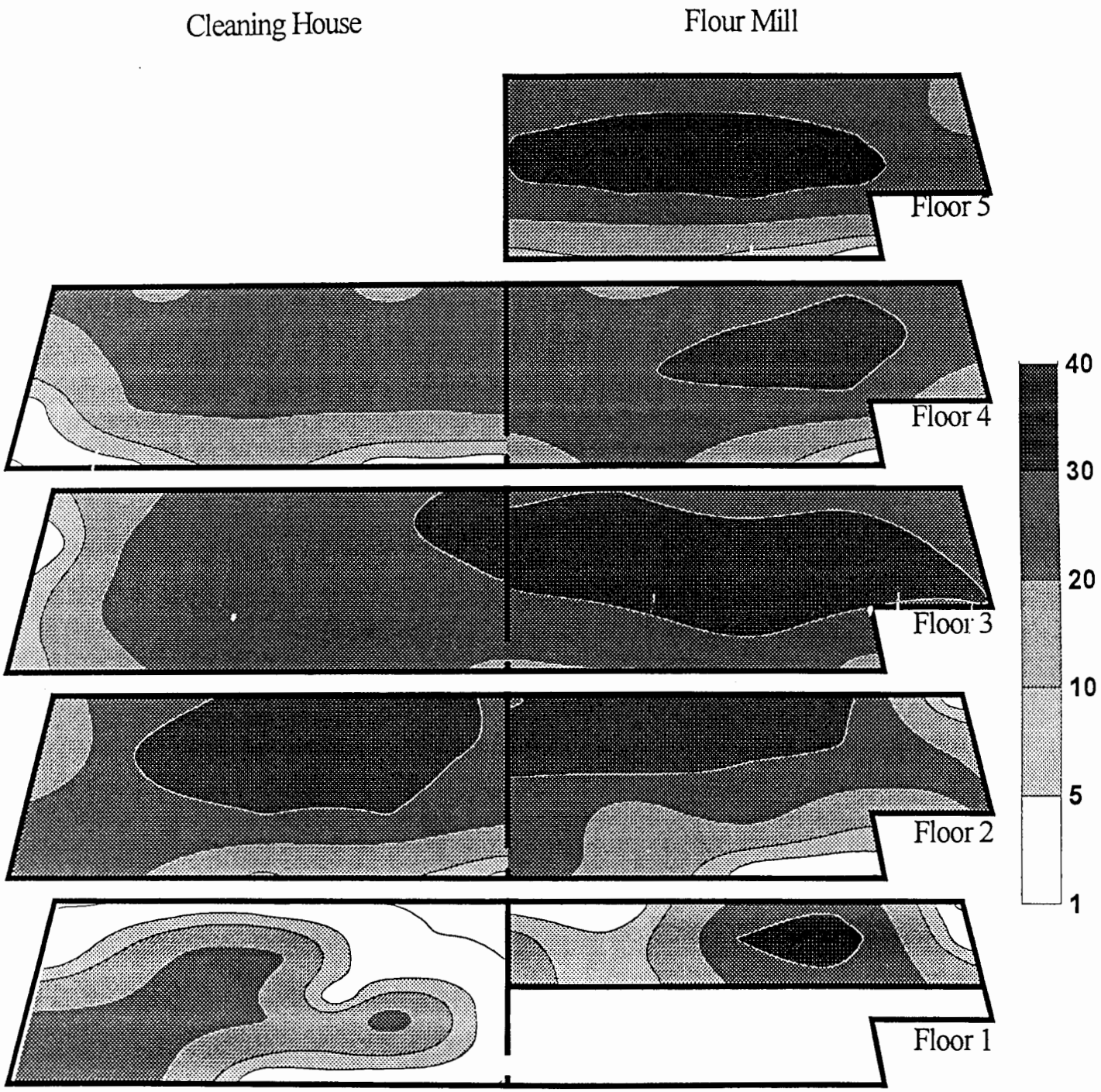


Figure 1. The length of time the temperature was above 50°C during the June, 1999 heat treatment in the cleaning house and flour milll and Kansas State University.

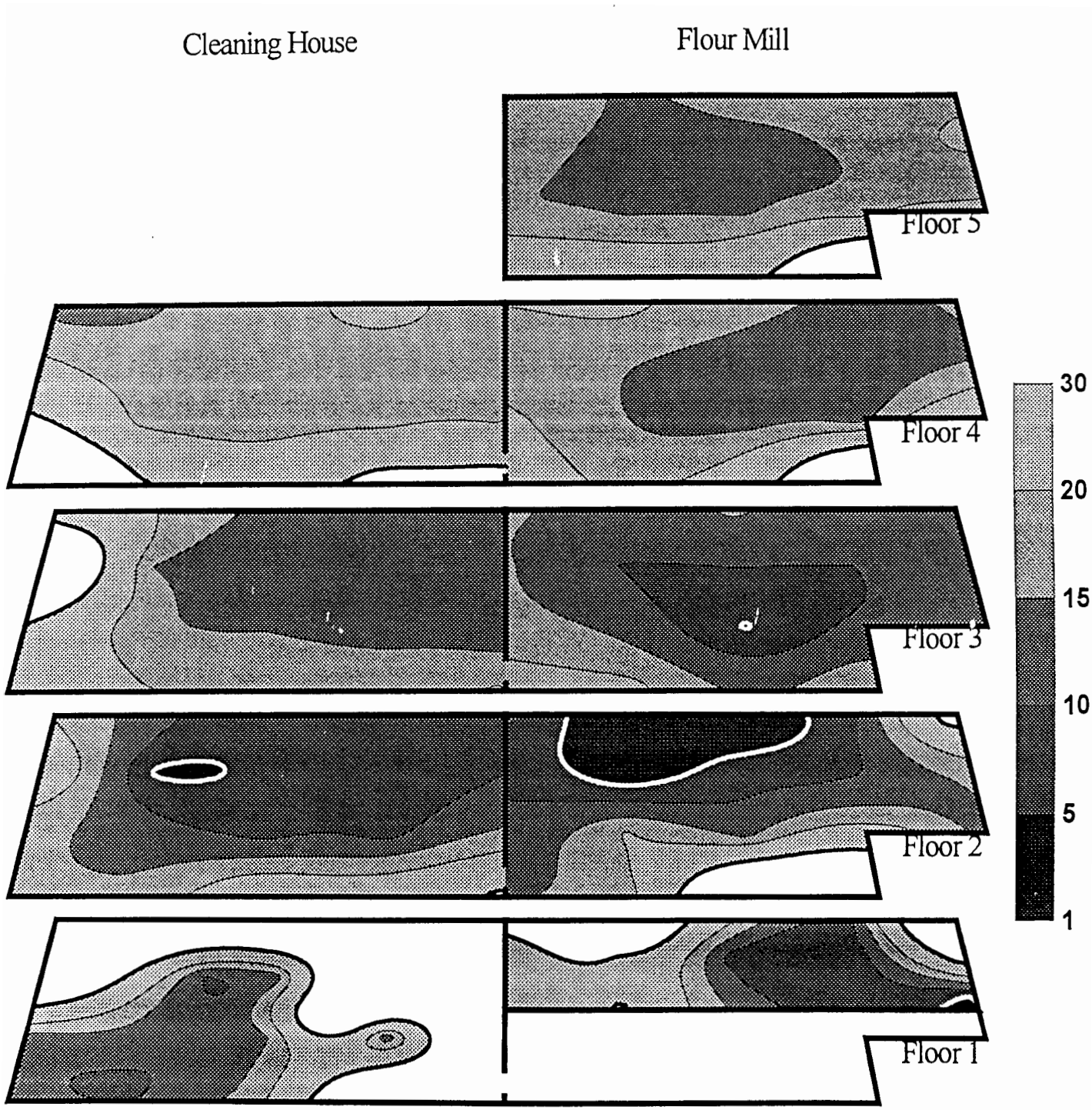


Figure 2. The length of time to reach the target temperature of 50°C during the June, 1999 heat treatment in the cleaning house and flour mill and Kansas State University.

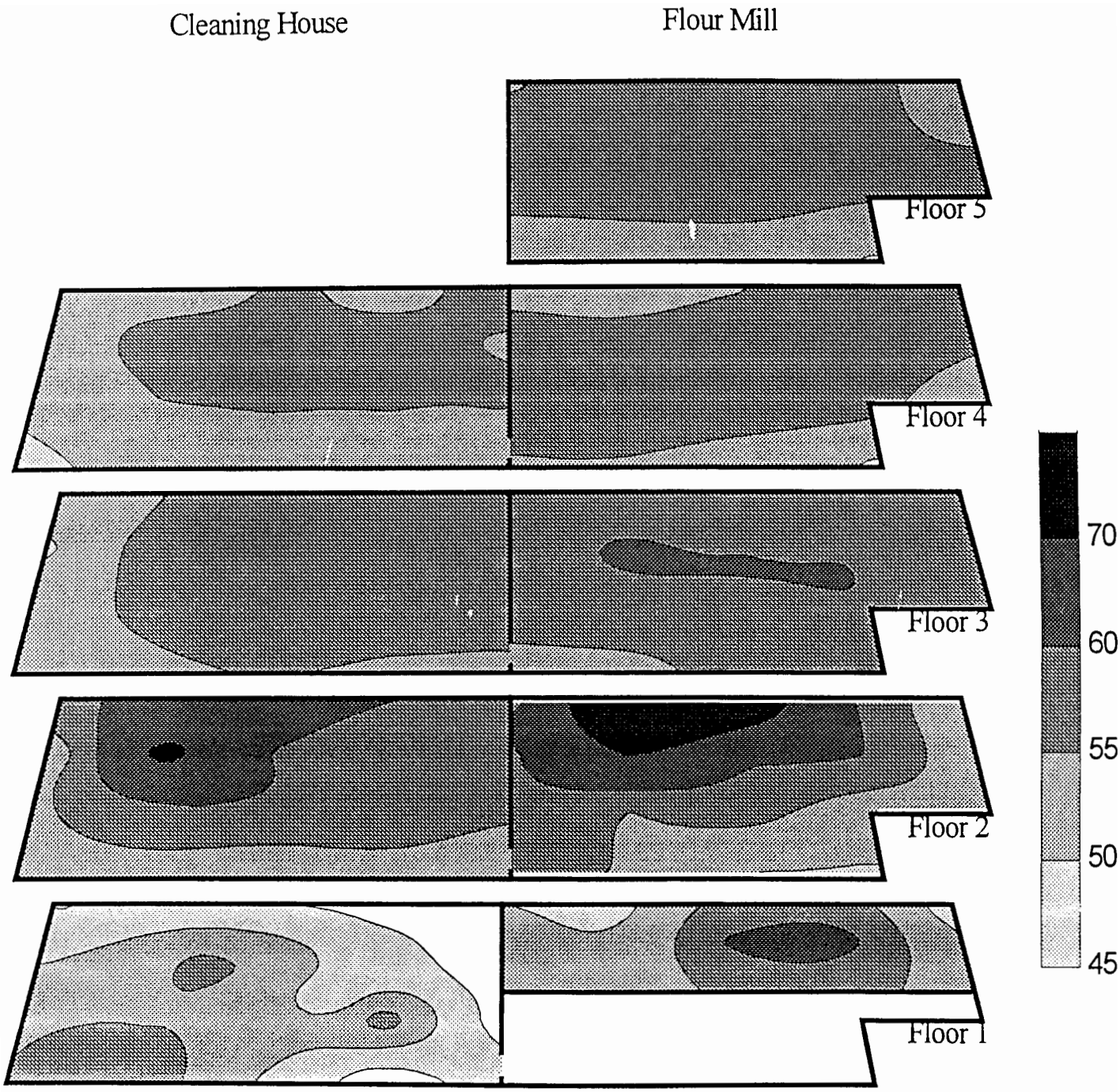


Figure 3. The maximum temperature attained during the June, 1999 heat treatment in the cleaning house and flour milll and Kansas State University.

Penetration of Heat into Cereal-Grain Processing Equipment during a Facility Heat Treatment

Alan K. Dowdy, Ph.D.
United States Department of Agriculture, Agricultural Research Service
Grain Marketing & Production Research Center
Manhattan, Kansas, USA

Introduction. During a heat treatment to control insects in food processing facilities, one of the limiting factors is the amount of time necessary for the heat to penetrate into closed spaces such as processing equipment and wall voids. Insects must be directly exposed to lethal temperatures for enough time in order for mortality to occur otherwise a control failure may result.

The objectives of this project were to study heat penetration into selected pieces of equipment commonly found in cereal-grain processing facilities.

Methods. Heat penetration into five kinds of cereal-grain processing equipment was examined during a full plant heat treatment. Access panels and covers were opened on half of each type of equipment during the heat treatment while the remaining equipment remained closed. Temperatures were monitored at 10-minute intervals. The temperature sensors were placed inside the opened and closed equipment as well as outside and adjacent to the equipment to compare heat penetration. The maximum temperature attained and the length of time that the temperature was above 50°C are reported here.

The target temperature and time combination for this particular facility was 50°C for 20 hours.

Results. The maximum temperatures recorded outside the equipment ranged from 58.9°C to 64.3°C that indicates that the target temperature was attained in all areas monitored.

The length of time that the temperature was above 50°C outside the equipment ranged from 30.6 hours to 66.2 hours indicating greater variability than observed with the maximum temperatures.

The maximum temperatures attained and the length of the time that the temperature was above 50°C (± SEM) during the heat treatment conducted July 2-5, 1998.

	outside of equipment	inside opened equipment	inside closed equipment
	maximum temperature attained (°C)		
large aspirator	58.9 ± 0.3	58.2 ± 0.2	59.2 ± 0.0
small aspirator	59.7 ± 0.4	58.5 ± 0.5	60.2 ± 0.7
gravity table	63.2 ± 0.2	62.7 ± 0.2	62.5 ± 0.1
huller	64.3 ± 0.1	63.2 ± 0.3	62.7 ± 0.3
seperator	63.0 ± 0.2	62.7 ± 0.7	64.0 ± 0.4
	hours the temperature was above 50°C		
large aspirator	30.6 ± 0.7	27.5 ± 0.5	32.3 ± 0.1
small aspirator	44.7 ± 2.3	38.2 ± 6.7	47.9 ± 5.0
gravity table	62.4 ± 0.4	60.7 ± 0.5	62.1 ± 0.9
huller	59.2 ± 0.8	61.0 ± 0.5	61.4 ± 0.3
seperator	66.2 ± 0.6	66.0 ± 1.3	66.8 ± 0.8

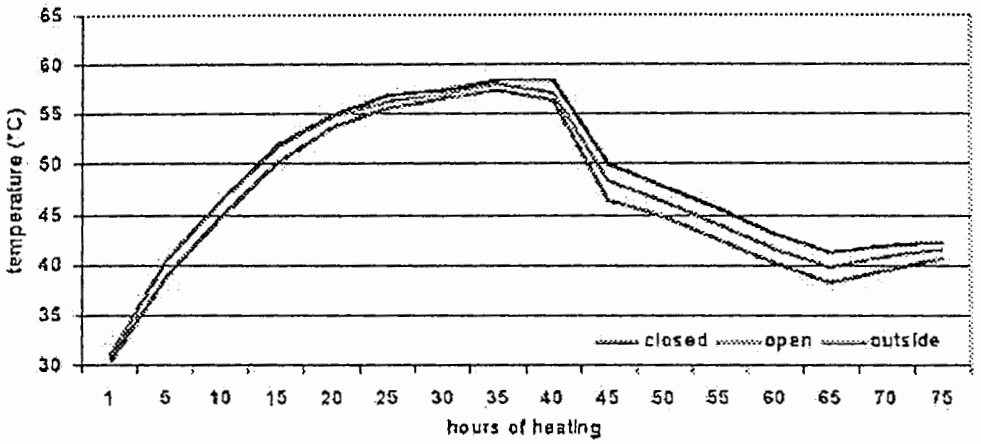
The maximum temperatures recorded inside the processing equipment were similar to those recorded outside regardless of whether the equipment was opened or closed during the heat treatment. Additionally, the amount of time that the temperature in excess of 50°C inside the equipment was similar to that outside and was not dependant upon whether the equipment was opened or closed.

The maximum temperature attained and the length of time that the temperature was above 50°C tended to be slightly greater inside the closed equipment than inside the open equipment or outside. This appeared to be due to a lag in cooling after the treatment; heat was retained inside the closed equipment

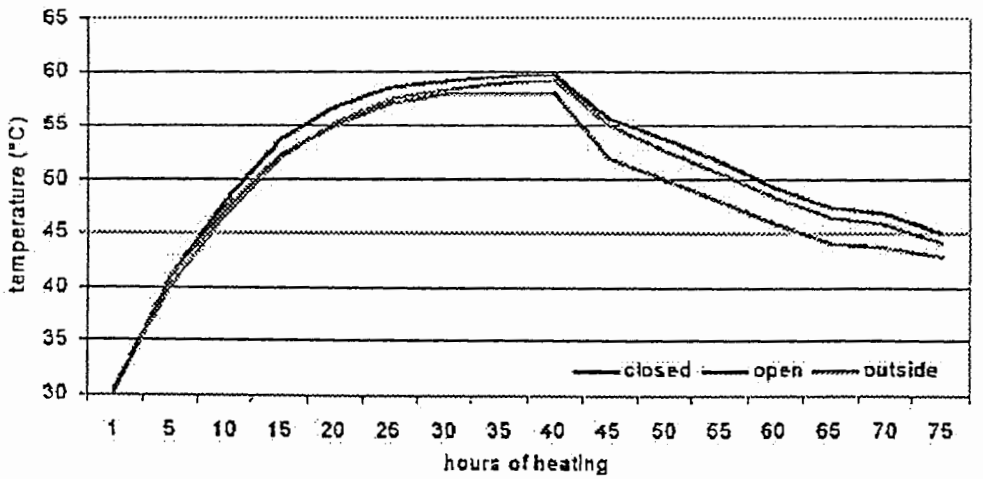
while the open equipment cooled at a rate similar to the temperatures outside of the equipment.

Summary. While adequate heat was applied inside the closed equipment during this heat treatment, the results may not have been so clear-cut if less heating had occurred outside the equipment. Typically, processing equipment is opened and cleaned prior to a heat treatment. To best facilitate the heating processes and minimize the potential of insects escaping lethal temperatures, it would be prudent to leave equipment open during the heat treatment. If processing equipment is not left open during the heat treatment, these data indicate that adequate heat will still probably penetrate into the equipment.

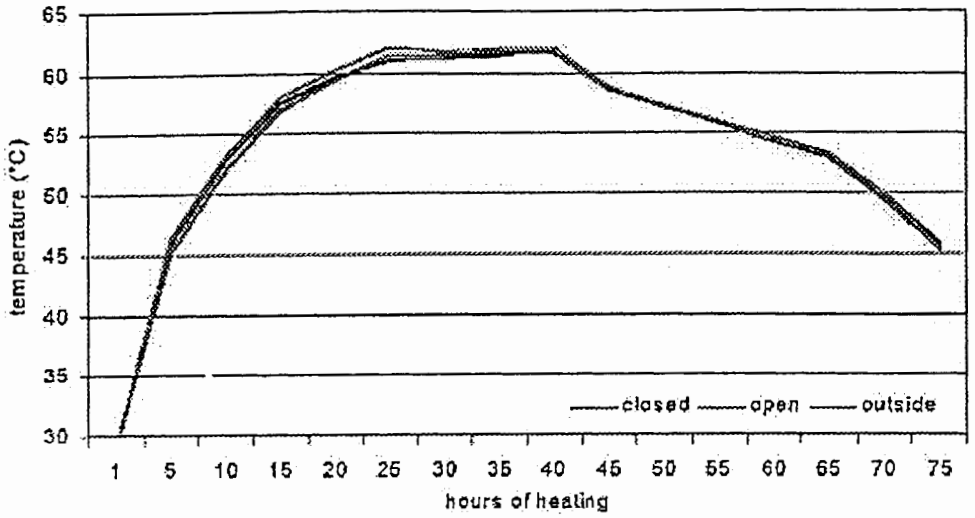
Penetration of heat into large Carter Day aspirators (Model CXY1-X) during a heat treatment in a cereal-grain processing facility.



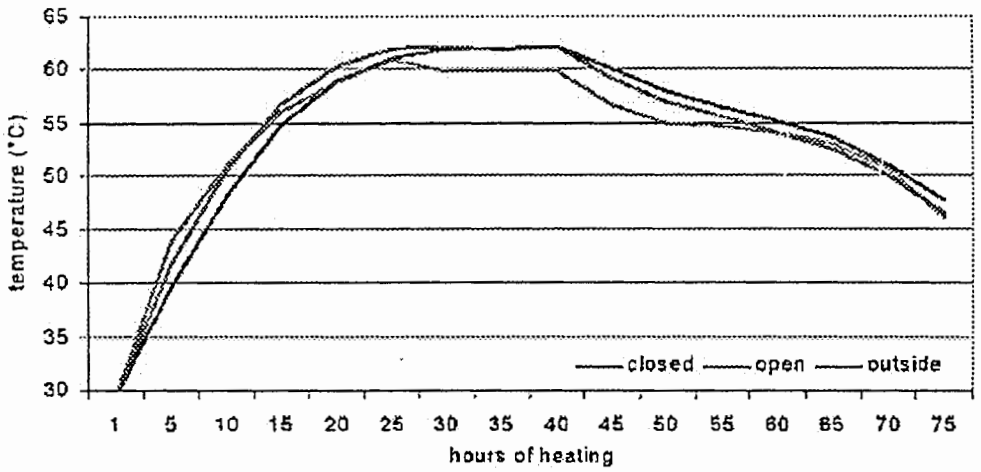
Penetration of heat into small Carter Day aspirators (Models CRK1-X, CRL1-X) during a heat treatment in a cereal-grain processing facility.



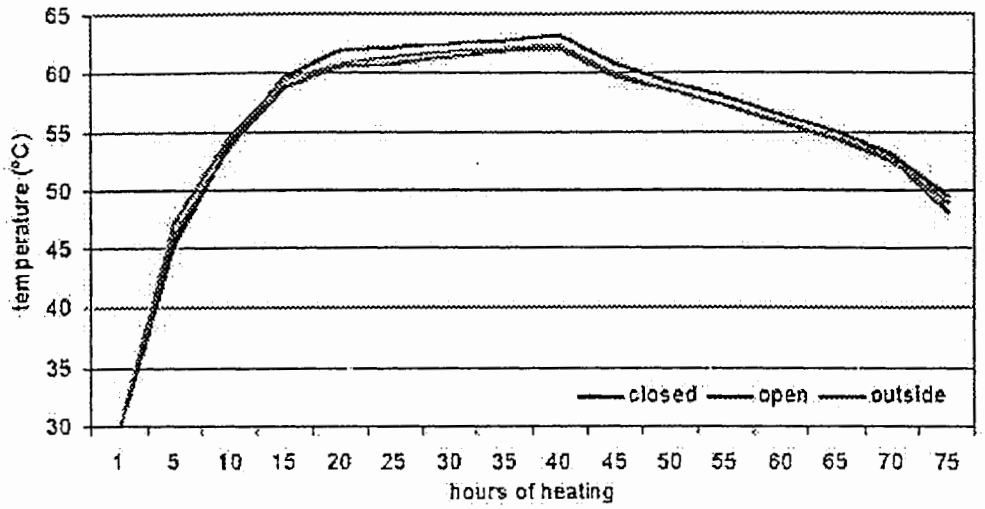
Penetration of heat into Forsberg gravity tables (Models 50-V-SAN, 60-V-SAN, 90-V-SAN) during a heat treatment in a cereal-grain processing facility.



Penetration of heat into FM Smith custom style hullers during a heat treatment in a cereal-grain processing facility.



Penetration of heat into Carter Disc seperators (Model ZT4) during a heat treatment in a cereal-grain processing facility.



Dr. Alan Dowdy
GMPRC
1515 College Ave.
Manhattan, KS 66502
dowdy@usgmrl.ksu.edu

Last Edited: 02/05/99

Biological Research Unit

Heat Treatment as an Alternative to Methyl Bromide Fumigation in Cereal Processing Plants

Alan K. Dowdy, Ph.D.
United States Department of Agriculture, Agricultural Research Service
Grain Marketing & Production Research Center
Manhattan, Kansas, USA

With the impending loss of methyl bromide for controlling stored-product insects in food processing facilities, many companies are revisiting the use of heat treatments for insect management. The use of heat treatments is often being considered when new facilities are being designed. This study was conducted to evaluate the application of three heat treatments to one room of a cereal grain processing facility.

Temperatures in one room on the top floor of a cereal grain processing facility located in the Midwestern United States were monitored during heat treatments during May, August and November 1997. The room measured 12 m by 30 m with a 6 m ceiling. The floor and ceiling were made of steel reinforced poured concrete supported by pillars of the same construction set on 4 m centers. Walls were constructed of painted brick rising 2 m from the floor, sliding windows (about 1 m) and about 3 m of glass blocks to reach the ceiling. An expanded metal mezzanine was situated about 2 m from the ceiling to support equipment and to allow access to various segments of the processing system.

Many pieces of processing equipment, product storage tanks and associated ducting were located on the floor and mezzanine of this room. Figure 1 indicates the general layout of the room. Specific information about the types and location of equipment in this room are not indicated in the figure due to a confidentiality agreement with the company.

This facility uses steam in processing their products. For heat treatments in this room, the steam was diverted to two heater units and one fan (Fig. 1) to enhance air circulation.

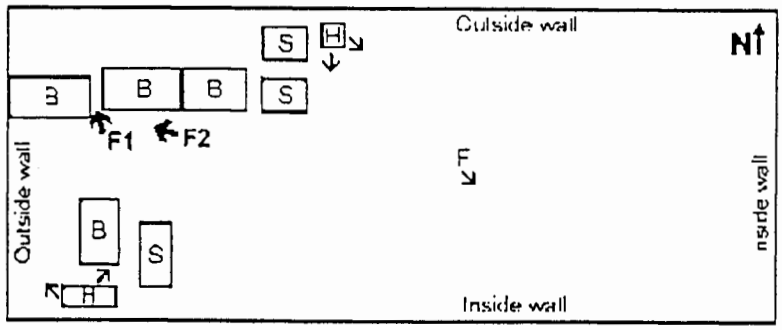


Figure 1. Location of heaters, fans and largest objects in room to be heated; B = bulk storage bin, S = seperator/filter, H = heater, F = fan; F1 = location of additional fan during August treatment, F2 = location of additional fan during November treatment, arrows indicated direction of air flow from heaters and fans.

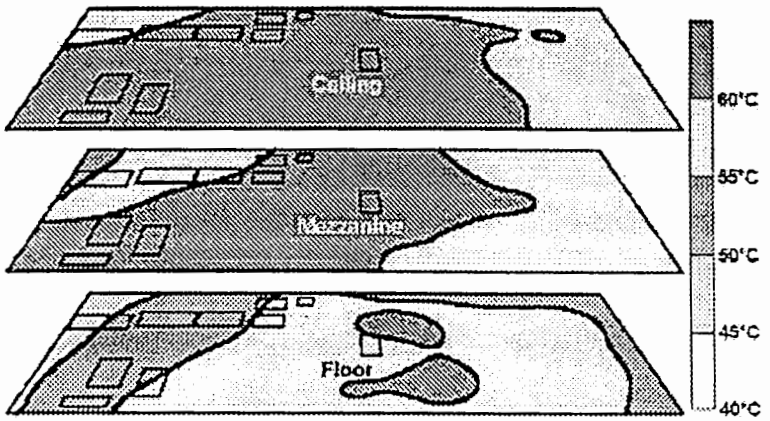
An additional fan was used during the August and November heat treatments in an attempt to increase the temperature of the northwest corner of the room. An open doorway was installed in the middle of the south wall prior to the November heat treatment but no other structural changes were made to the room

during the year.

Temperatures were recorded using HOBO Temp temperature loggers (Onset Computer Corp., Pocasset, Massachusetts). The temperature loggers were placed in a loose grid fashion about 5 to 6 m apart. A total of 120 points were monitored and were evenly divided among the floor, mezzanine and ceiling levels. Additional temperature loggers were situated between pieces of equipment where airflow may be restricted. The location of each temperature logger was identified using X, Y, Z coordinates. The heat treatment target was to maintain 50°C for 20 hr.

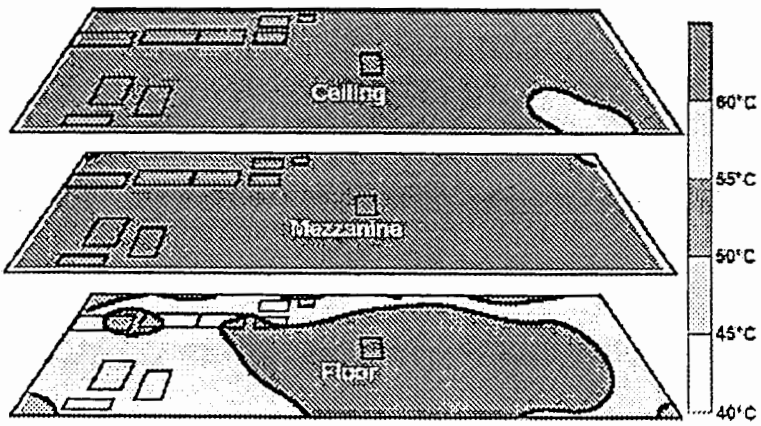
Maximum temperatures attained during three heat treatments.

May



Maximum temperature attained during heat treatment in May 1997. All areas of the ceiling and mezzanine levels were heated to or above 50°C. The west end at the floor level reached maximum temperatures of 45-50°C. The northwest corner of the room is generally cooler than the rest of the room, especially at floor and mezzanine levels and to a lesser degree at the ceiling.

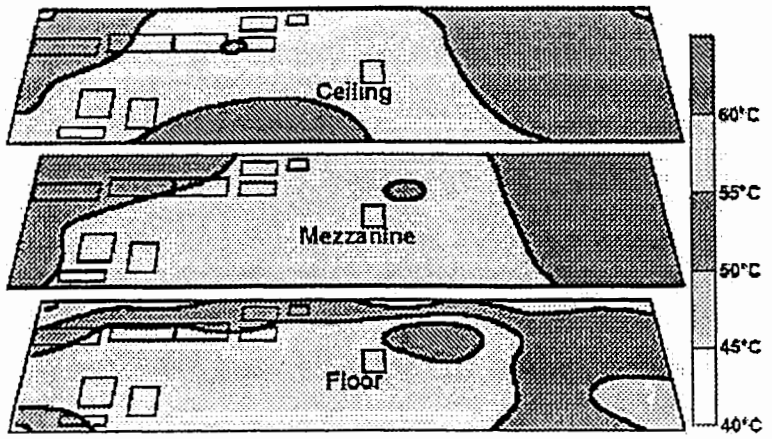
August



Maximum temperature attained during heat treatment in August 1997. All areas of the ceiling and mezzanine were heated above 55°C. At the floor level, there were a few isolated spots where the temperature was 50-55°C. A fan located at F1 assisted the movement of hot air into the northwest corner. This facilitated a more even heat treatment than what had occurred in May.

November

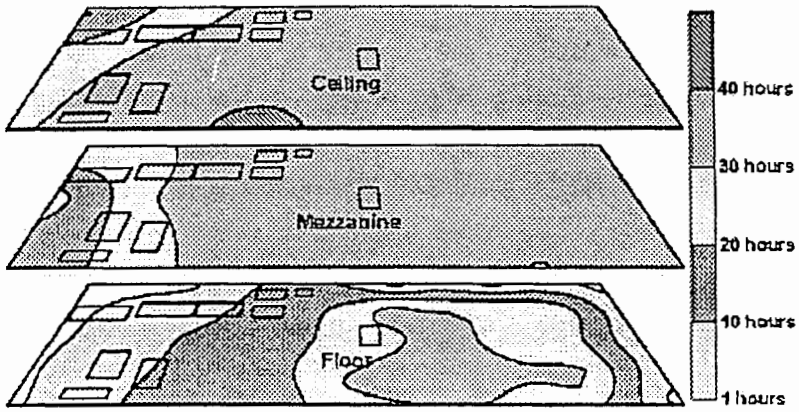
Maximum temperature attained during heat treatment in November 1997. Temperatures were typically lower at all levels than what was recorded during the previous treatments due to lower outside temperatures. All areas of the ceiling and mezzanine had maximum temperatures above 50°C. Along the walls at floor level reached maximum temperatures of 45-50°C. The fan placed at F2 again assisted in moving hot air behind the storage bins in the northwest corner of the room.



Number of hours the temperature was above 50°C during three heat treatments.

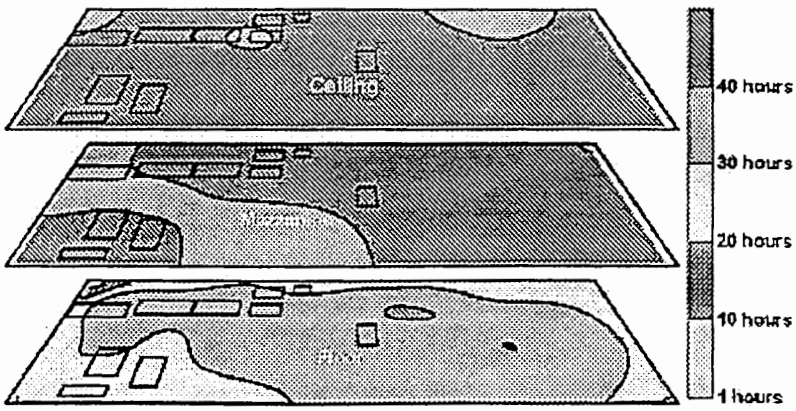
May

The length of time that the temperature was above 50°C during heat treatment in May 1997. The north end of the ceiling, mezzanine and most of the floor did not attain the target of 20 hours. There were areas at floor and mezzanine levels where either the temperature never reached 50°C or the temperature was attained for less than 1 hour.



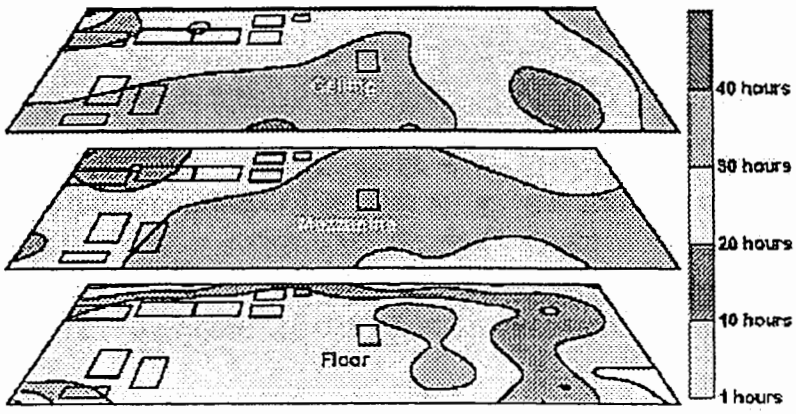
August

The length of time that the temperature was above 50°C during heat treatment in August 1997. All of the ceiling and mezzanine levels were heated for more than 30 hours to temperatures above 50°C and most of these levels for more than 40 hours. All but a small area in the northeast corner of the floor level was exposed to 50°C for at least 20 hours. The addition of the fan (F1) appears to have improved the length of time that the temperature was above 50°C.



November

The length of time that the temperature was above 50°C during heat treatment in November 1997 was similar to the distribution of heat in May at the ceiling and mezzanine levels. At floor level, several areas were exposed to 50°C for less than 20 hours but not in the same areas that were identified during the May treatment. Compared to the May treatment, the additional fan (F2) appeared to improve hot air circulation in the north end of the room. The poorer heating on the south end may be due to a new doorway in the south wall or inadequate heating in the adjoining room.



Conclusions

- The time and temperature factors associated with the heat treatment of a room in a processing plant are influenced by the placement of heaters and fans in relation to the processing equipment as well as outside weather conditions.
- When determining how to heat a room, it is important that heater units be properly sized to the space and to allow good airflow away from the heater units and around the processing equipment. Either permanently installed or portable fans improve air circulation and can improve heating efficiency by minimizing cool spots and dispersing hot air from near the ceiling to mix with cooler air near the floor.
- The heat treatment program should be redressed when new equipment is added to the production system or when structural changes are made to the room that may influence air flow.
- The efficiency of heat treatments can be improved by examining temperature distribution and stratification within a room and adjusting heat and airflow parameters accordingly.
- By efficiently using the heat that is generated through good air circulation, insect management can be improved and energy costs for heat treating may be reduced.
- In facilities with equipment that can withstand temperatures up to 55°C, heat treatment for stored-product insect management may be a viable alternative to fumigating with methyl bromide.

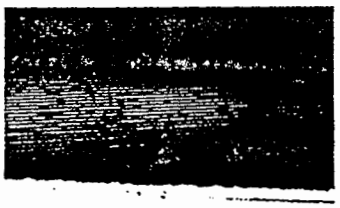
The information in this report is published in the Proceedings of the 7th International Working Conference on Stored Porduct Protection; Beijing, China; 1998.

Heat treatment: A viable alternative to methyl bromide for managing insects

by Anil Menon, Bhadriraju Subramanyam, Alan K. Dowdy and Rennie Roesli

Methyl bromide has been used for decades as a space fumigant to disinfest flour mills, feed mills and other food-processing plants. With the impending phase-out of methyl bromide by both the developed and developing nations, effective alternatives are being sought as a replacement.

The use of high temperatures (at or above 122°F or 50°C) has been an effective, safe and viable alternative to methyl bromide fumigation for insect management in food-handling establishments. The use of this technology, however, is not new.



Red flour beetles killed in flour mill roll stands after a heat treatment.

Heat from the sun (sun drying) has been used since ancient times for killing stored-grain insects. The first report of the use of heat in a U.S. flour mill dates back to 1901. A miller used heat to control flour-infesting insects after he observed insects dying in the vicinity of steam pipes leading to a corn dryer.

In 1911, G.A. Dean investigated the practical application of heat and its effectiveness on insects. He proposed a method that was successfully adopted by some mills across the country. However, this technology never gained widespread acceptance because of warping and cracking of wooden structural components and equipment.

EFFECT OF HEAT ON INSECTS. Insects are susceptible to extremely low or high temperatures. Generally, across all stored-product insects, development stops at or below 61°F (16°C) and at or above 100°F (38°C). The optimum temperatures for maximum survival, faster development and maximum reproduction range from 82° to 93°F (28° to 34°C).

High temperatures kill or adversely affect the development of eggs, larvae, pupae and adults of stored-product insects (see table below). However, the magnitude of adverse effects vary with the insect species and the developmental stage exposed.

How does heat kill insects? Death may be due to desiccation/dehydration, or adverse changes in the structure of proteins and lipids. Although exposures to temperatures at or above 122°F (50°C) are required to cause rapid death, insects may experience problems in development, survival, and reproduction between 104° and 122°F (40° and 50°C).

To effectively suppress insect populations in food-handling establishments, it is essential to raise the temperatures to about 122°F and hold it at this level for about 24 hours. Depending on the insect species and the life stage exposed, death can occur within minutes or a few hours at these high temperatures.

It is important to provide enough time for the heat to penetrate all parts of the facility, especially within equipment and hidden spaces. Insects seeking refuge within bulk grain or flour may escape the heat treatment because of poor heat transfer. Therefore, proper sanitation of the plant, including the equipment, is essential for enhancing the efficacy of a heat treatment.

A heat treatment, from set-up to cool down, typically lasts from 30 to 48 hours. Heat treatments are frequently scheduled during a weekend or over holidays so that it does not disrupt regular plant production activities.

ART OR SCIENCE? Heat treatment becomes an art when coupled with past experience, especially for determining the amount of heat required and how best to use fans to distribute heat within a food-handling establishment.

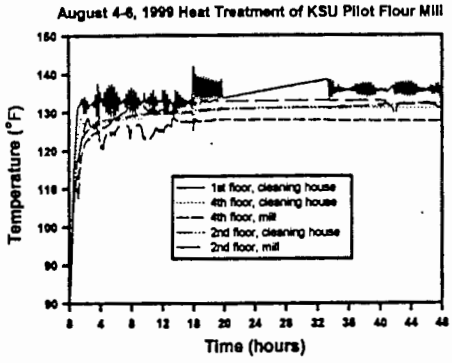
There have been limited scientific studies that deal with the optimum use of heat within a facility, the minimum amount of heat required to kill insects, the role of humidity on insect survival, adverse effects on insects surviving a heat treatment, determining heater requirements and economics of heat treatments. Kansas State University, Manhattan, Kansas, U.S., and the U.S. Department of Agriculture have been conducting experiments to answer a few of these questions.

One experiment simulated heat treatment in programmable ovens to determine the effects of increasing temperatures on developmental time, survival and reproduction of several stored-product insects. The populations of stored-product insects in K-State's pilot flour and feed mills were monitored before and after a heat treatment to provide a quantitative basis for determining effectiveness of heat treatments. If insect populations increased in certain areas of the food-handling establishment, control efforts could be focused in these problematic areas.

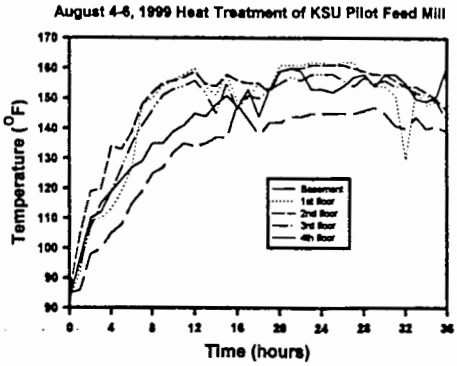
Response of stored-product insects to lethal temperatures

Temperature range (°C)	Effects
122°-140°F (50°C)	Death in minutes
113°F (45°C)	Death in hours
95°F (35°C)	Development stops
91° - 95°F (33°-35°C)	Development time is prolonged; reduced oviposition and survival

Source: Modified from Paul Fields (1992, Journal of Stored Products Research, Vol. 28, pp. 89-118)



Temperature rise in selected floors of the KSU flour mill. (Data courtesy of Aggreko)



Temperature rise in five floors of the KSU feed mill. (Data courtesy of Rupp Industries)

Current experiments deal with calculating costs associated with heat treatments. Coupled with the information on the degree and duration of insect suppression, this information may lead to a more cost-effective means of managing insect populations in food-handling establishments.

A heat treatment workshop held at K-State last August included a heat treatment of the Department of Grain Science and Industry's pilot flour and feed mills.

The flour mill was heated with electric heaters, and the feed mill with gas heaters. The starting temperature was about 85°F (29°C) and the target temperature of 122°F was reached within three hours.

Eggs, larvae, and adults of the red and confused flour beetle were placed in cages, with and without flour, in the flour mill during the treatment. All stages were killed within the first three hours. Dead insects also were observed in roll stands and beneath several pieces of equipment.

OTHER RESEARCH RESULTS. A few months before the workshop, in June 1999, the pilot flour mill was heated with gas heaters. Temperatures in each of the four floors of the cleaning house and flour mill were monitored with 10 temperature measuring devices scattered throughout the floor. Temperatures also were measured during the August heat treatment with electric heaters.

A comparison of contour maps of temperatures obtained across each floor with gas and electric heaters showed the temperature distributions to be essentially similar. Also similar was the time it took to reach 122°F (11 to 24 hours) and the number of hours that temperatures above 122°F — the level at which all exposed life stages of stored product insects are killed — were maintained (13 to 28 hours).

Information about the 1999 K-State heat treatment workshop is available on CD-ROM. For a copy, log on to http://www.oznet.ksu.edu/dp_grsi and choose the "Heat Treatment Workshop" link. Current research results on heat treatment also are posted at this site.

The comparison presented is qualitative, and should not be construed as an endorsement of gas heaters over electric and vice versa. Grain or flour is a poor conductor of heat, and during a heat treatment the high temperatures required to kill insects may not be attained in grain and flour residues. Therefore, sanitation of equipment pieces, spouts and storage bins is important to increase the effectiveness of a heat treatment. Opening up the various pieces of equipment does not significantly improve heat penetration.

Another experiment sought to determine whether humidity affects insect survival during a heat treatment. The mortality of adult red flour beetles at varying humidities (24% to 78%) was studied during a November 1999 steam heat treatment in the pilot flour mill. At temperatures above 110°F (43°C) and exposures greater than 21 hours, there was 100% mortality of the adult beetles, irrespective of the level of humidity.

Pheromone traps also are important pest monitoring tools in food-handling establishments. These traps, baited with specific insect pheromones or lures, are placed within the facility for early detection of insects and also to judge the degree and duration of insect suppression. Depending on the number of traps used, it may be cumbersome to remove traps before and replace them after a heat treatment.

Tests were carried out to determine if heat had any deleterious effect on the condition and efficacy of the pheromone traps. The sticky material in traps was unaffected by exposure to high temperatures. Also, the pheromone concentrations of the Indianmeal moth and the almond moth lures showed very little degradation. However, the concentration of the red/confused flour beetle lures dropped nearly 40% during the heat treatment. Therefore, during a heat treatment, it is not necessary to remove Indianmeal moth and almond moth traps and lures, but it is important to remove and replace the red or confused flour beetle lures.

How quickly do insects return following a heat treatment? Insect populations were reduced after a heat treatment, and hundreds of insects inside the equipment also died, as seen from floor counts of dead insects. However, small numbers of insects of various species were captured in traps within two to four weeks after a heat treatment. The insects may have entered the facility in raw ingredients or may have re-infested from sources within the facility that were not eliminated by heat. A similar rebound in populations also can be observed following a fumigation of the facility. ■

About the authors: Anil Menon and Rennie Roesli are post-doctoral research associates and Bhadriraju Subramanyam is an associate professor in the Department of Grain Science and Industry, Kansas State University, Manhattan, Kansas. Alan K. Dowdy is a research entomologist at the U.S. Department of Agriculture's Grain Marketing and Production Research Center in Manhattan. *The authors thank Jerry Heaps, The Pillsbury Company, Inc., and Tom Danley, Rupp Industries, for reviewing an earlier draft of this article.*

Questions or comments about this article may be sent to worldgrain@sosland.com.

Heat Sterilization

AN OLD, BUT NEW METHOD FOR ELIMINATING INSECTS IN FEED MILLS

Portable heaters have the advantage of flexibility in moving to wherever they are needed during a heat sterilization. Photo courtesy of Aggreko Inc., New Iberia, LA.

FEED INDUSTRY TRENDS

Brian Bursiek

Using temperature control, either heating or cooling, is not a new technology to eliminate insects in agricultural facilities. Within the feed and food industries, heat sterilization of production facilities to kill stored product insects dates back to the turn of the century.

The procedure was abandoned because of the damage caused to wood floors, melting of belts, and grease becoming liquified and running out of unsealed bearings. Today, with advances in building and equipment technologies and increased regulation over conventional insecticides, heat sterilization can be an effective means of eliminating insects.

By simple definition, heat sterilization is a process by which an area or material is heated to a target temperature, generally between 130 and 140 degrees, and maintained for an adequate time period to ensure penetration of the heat to desired locations throughout the building. This may be a few minutes for a single piece of equipment or up to 24 hours for an entire facility.

Getting Started

Because of its scope, a heat sterilization project requires the cooperation of many departments. Production, engineering, sanitation, maintenance, shipping, warehousing, and personnel need to interact to plan every step. Much preparation and coordination is needed to ensure success.

It should be emphasized that any form of temperature control to kill insects is not, by itself, a cure-all for every type of facility. It should be part of a total, plantwide integrated pest elimination program that also includes:

- Raw material inspections.
- Daily housekeeping.
- Equipment cleaning.
- Routine self-inspections.
- Pest control programs.
- Finished product rotation.

Areas to Heat Treat

It may not be necessary to perform heat sterilization of an entire facility. The following criteria should be considered:

- Where are your stored product insect problems now, or where is there a high probability for problems?
- Areas targeted for heat sterilization need to be able to attain and maintain heat sterilization temperatures.
- Items that could be damaged by heat sterilization must be moved to temporary storage.
- Low stored product infestation areas such as coolers and freezers need not be heat-treated.

Consideration also needs to be given to the cubic-foot area to be heat treated to fit enough heaters into that area to do the job effectively and economically.

Types of Heaters

Heaters can be electric, high- or low-pressure steam, or natural gas-powered. Air normally is heated and discharged. Heaters can be portable or built permanently into the area to be treated. The benefit of using portable heaters is their flexibility for moving them during an actual heat sterilization if more or less heat is needed elsewhere.

Effieiency and economics should not be compromised. Heater BTU range varies with size. Experience has shown that it's better to have too much BTU capacity than not enough.

The number of heaters and their location in areas to be sterilized depends on the number of BTUs needed to attain the target temperature, the logistics of fitting them within current building and equipment design patterns, the energy source used, and the volume of area to be heated. A building engineer should do a BTU calculation first, figuring building heat loss and the effect heat sterilization temperatures will have on the facility structure and equipment.

One of the most important factors to keep in mind is to keep the hot air moving. For example, blow it down from the ceiling to the floor, to the outside walls, and to every part of the heat sterilization area. Additional fans may be needed.

Heaters should have thermostat capabilities to allow the regulation of heat output during a heat sterilization. More heat will be required initially, with less after target tempera-

tures are attained.

Getting Ready

A thorough machine cleaning is very important before a heat sterilization. Your goal should be to remove accumulations that may harbor stored product insects and/or allow them to be insulated against the heat.

Waste containers need to be emptied, and cabinets, dust collectors, and other equipment, where practical, should be cleaned and sealed against heat loss. To allow more effective heat penetration, doors on all equipment should be left open.

Personnel Concerns

Personal exposure to heat sterilization temperatures is an important consideration. Employee training should cover common signs of heat exhaustion and heat stroke. The buddy system should be used, even when

---

...Any form of temperature control to kill insects is not, by itself, a cure-all for every type of facility. It should be part of a total, plantwide integrated pest elimination program...

---

time spent in the heat sterilization area is only a few minutes.

Make sure emergency personnel have been notified about your operation and that emergency phone numbers are available, if needed.

Cost

Many variables must be figured into the cost of a heat sterilization, including the equipment, fuel, and many of the items already mentioned. In addition, facility downtime and labor should be considered. Labor from outside sources such as pest control, rental equipment and personnel, and in-house labor costs add up quickly. Depending on when a heat sterilization is done, weekend or holiday pay could be more. Facility production, sanitation, quality assurance, and maintenance personnel will be involved.

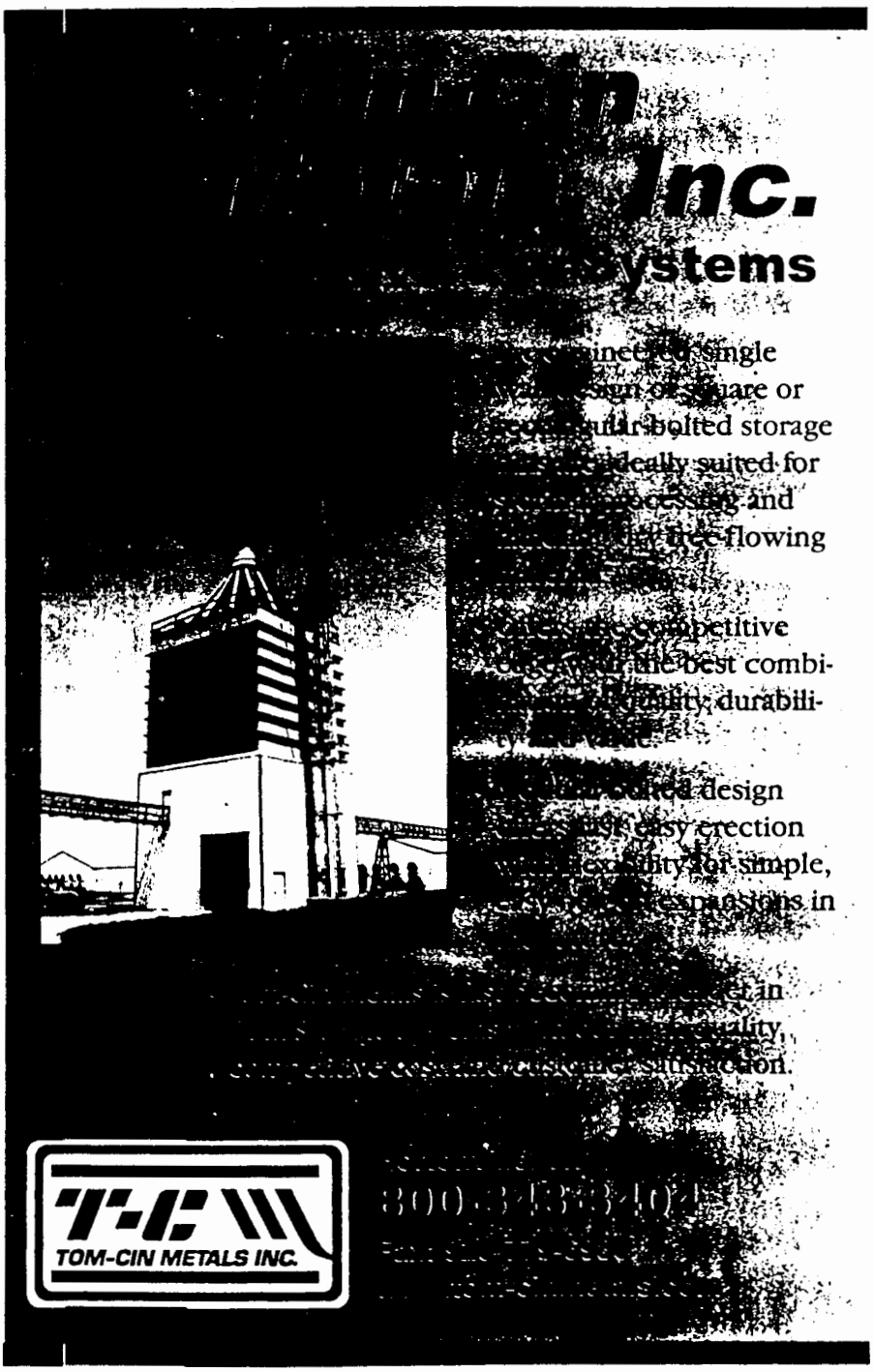
Finally, monitoring devices must be purchased to ensure that proper heat sterilization temperatures have been reached.

For More Information

Dr. Bhadriraju Subramanyam at the Department of Grain Science and Industry at Kansas State University (KSU) recently conducted a heat treatment workshop at the KSU feed mill.

He is available at 785-532-4092 or by e-mail at bhs@wheat.ksu.edu to answer questions regarding heat sterilization, facility preparation, and the results that can be expected.

Brian Bursiek is director of feed production for the American Feed Industry Association (AFIA), Arlington, VA; 803-524-0810; e-mail: bbursiek@afia.org.



Response No. 1951

Technical Quarterly

Volume [illegible]

MASTER BREWERS ASSOCIATION
OF THE AMERICAS

Volume 36, Number 2 • 1999 • Pages 223-226

Technical Quarterly

Practical Research to Determine Effective Heat Parameters for the Control of Stored Product Insects

By Ole Dosland

Poster presented at the MBAA 111th Anniversary Convention, Minneapolis, Minnesota, September, 1998.

ABSTRACT

The use of heat as a non-chemical alternative to fumigation is a feasible treatment for stored-product insect control. The concept for heating a structure for insect control is not new. Attempts were made in the early 1900s and encouraged some food processing companies to use the technique for several years. However, the use of heat disappeared. This was due to concerns of equipment and structural damage, especially with the amount of wood in the structures at the time. Since fumigants were available, the use of heat was put on the back burner. The current consumer attitude toward chemicals, along with subsequent restrictions, have provided a challenge to control stored-product insects without fumigants (i.e. methyl bromide).

Several heat treatment experiments in structures and laboratory experiments were conducted to determine the minimum effective heat parameters that will minimize equipment degradation while improving treatment efficiency. Many factors are involved in heat treatments: temperature and humidity levels, length of time, structural considerations, and equipment necessary to produce the desired results.

The studies and experiments that were conducted, are summarized and the temperature, time and humidity parameters needed for effective control of stored-product insects suggested.

Keywords: fumigation, heat, humidity, insect mortality

SINTÉSIS

El uso de calor como una alternativa no quimica a la fumigacion es un tratamiento factible para el control de insectos para producto almacenado. El concepto de calentar una estructura para el control de insectos no es nuevo. Se hicieron pruebas a principios de 1900 y promulgaron a algunas compañias procesadoras de alimentos a usar esta tecnica por varios años. Sinembargo, el uso de calor desaparecio. Esto fue debido a preocupacion de causar daños estructurales o a equipos, especialmente con la cantidad de madera utilizada en las estructuras en ese tiempo. Desde que existen fungicidas, el uso de calor ha sido descartado. La actual actitud del consumidor hacia quimicos, conjuntamente a subsecuentes restricciones, han dado un reto al control de insectos de productos almacenados sin fungicidas (eje. bromo metilico).

Dosland ha participado en varios experimentos de tratamiento por calor en estructuras y ha conducido varios experimento de laboratorio para determinar los parametros efectivos de calor minimos que minimicen degradacion de equipos mientras mejoran la efectividad de tratamiento. Muchos factores estan envueltos en el tratamiento por calor: temperatura y niveles de humedad, duracion, consideraciones estructurales, y equipos necesarios para producir los resultados deseados.

El proposito de este poster es el de resumir los estudios y experimentos que fueron efectuados, y sugerir la temperatura, y parametros de tiempo y humedad necesarios para el control de insectos en productos almacenados.

INTRODUCTION

The use of heat as a non-chemical alternative to fumigation is a feasible treatment for stored product insect control in food processing facilities. The current consumer attitude toward chemicals along with subsequent restrictions have provided a challenge to control stored product insects in flour mills and food processing facilities without these fumigants i. e. methyl bromide. Some practical research was needed to determine minimum effective heat parameters that would minimize equipment degradation while improving treatment efficiency. Depending on who you talked with or what you read, you may discover various parameters of temperature, time and humidity. Temperature varies from 110° F to 160° F., time varies from 12 hours to 36 hours and not much is known about humidity. Structural, mechanical and electrical (computerized automation) concerns make it important to clarify parameters that are effective for insect control yet not damage these materials, especially with repeated treatments.

BACKGROUND

The wide range of temperature may be attributed to variables such as insect type, stage or acclimation along with time and humidity. The wide range of time may be attributed to variables such as type of heat source, amount of air movement, amount of heat loss and equipment or structural material (heat penetration). The level of humidity will influence any minimum temperature and time parameters.

Ole Dosland has over 25 years of experience in the quality assurance and food protection aspects of the food industry.

The specific temperature for effective insect mortality will depend upon the type of insect and "genetic" heat tolerance. Common stored product insects such as flour beetle may require different parameters than other beetles such as cigarette beetle (generally known to be more heat tolerant). Other common insects such as weevils, cockroaches, moths and flies may require higher or lower temperatures. It is generally accepted that specific temperature for mortality will vary depending upon the stage of the insect life cycle. It is assumed insects acclimated to higher temperature will become more tolerant to heat than those not acclimated. It is important to identify the insect type and know their characteristics before establishing any heat parameters.

The specific time will depend upon ambient conditions, application technique, and building/equipment design. Specific time requirements and application technique for a structural heat treatment should be developed with help from engineering or experienced heat treatment experts.

The specific humidity will depend upon ambient conditions, design of building and equipment, application technique (humidification) and type of heat i. e. electric. In order to determine effective temperature and time, humidity must be maintained at a known level.

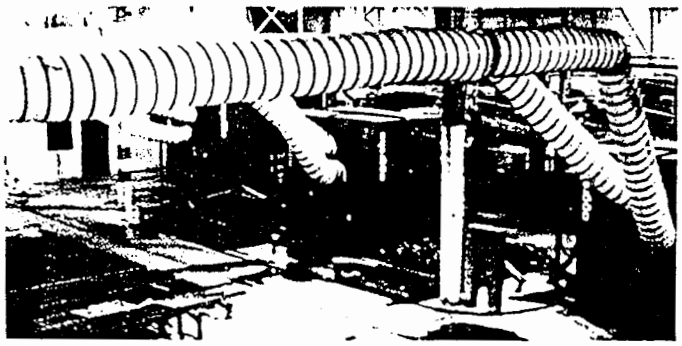


FIGURE 1
View of Internal Heaters and Ducting

TEST INSECTS

The University of Nebraska-Lincoln, Department of Entomology provided *Tribolium castaneum* (red flour beetle), *Trogoderma variable* (warehouse beetle) and *Blattella germanica* (German cockroach) raised in their laboratory environment. They were acclimated to and kept in a 70 - 75° F. and 50 - 55% relative humidity environment.

INCUBATOR

A microbiological incubator with temperature range of 85°F to 160°F accurate to 2°F with ventilation rate of twelve exchanges per hour from heat source provided by 115v electric coils was used for all studies.

STUDY # 1 – Increasing Temperature

Ten various instar nymphal German cockroaches, ten adult German cockroaches, ten various instar larvae with four adult warehouse beetles and twenty adult red flour beetles were exposed to slowly increasing temperature starting at 85°F and stopping at 125°F for a two hour period at 26 - 28% humidity.

FIGURE 2
Air Ducting to Outside Structure

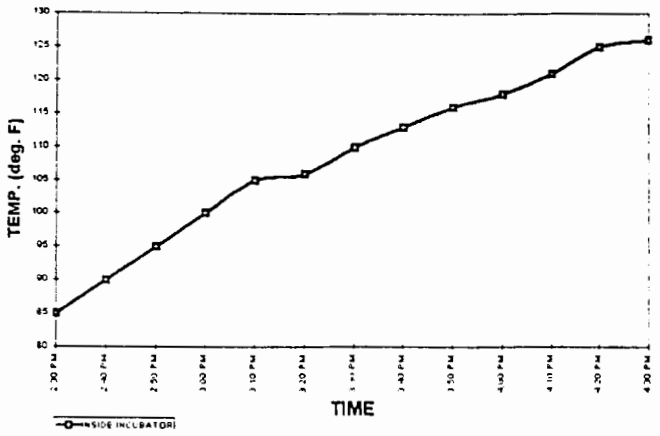


FIGURE 3
Heat Treatment Insect Study #1
Temperature Throughout the Study

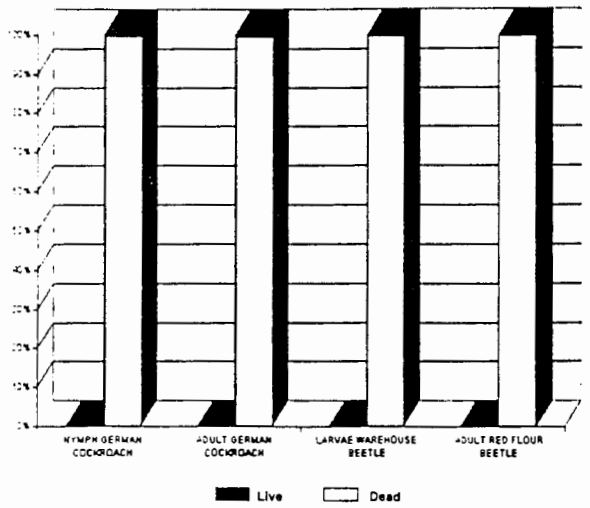


FIGURE 4
Heat Treatment Insect Study #1
Cockroach and Beetle Mortality

CONCLUSION

Insect mortality was 100%, but temperatures varied with insect. The minimum lethal temperature for German cockroaches is 110 - 115°F. The minimum lethal temperature for adult warehouse beetles is slightly less than the larvae lethal temperature of 118 - 120°F. The minimum lethal temperature for adult red flour beetles is 116 - 120°F. Mortality started at 105°F and ended at 120°F at 26 - 28% humidity.

STUDY # 2 – Length of Exposure

Four groups of ten adult red flour beetles were exposed to a temperature stabilized at 118° F. with 26 - 28% humidity. The insects were held until inactive & removed at 5 minute intervals.

CONCLUSION

The minimum lethal heat parameters for adult red flour beetle is 116 - 120° F for 15 to 20 minutes at 26 - 28% humidity.

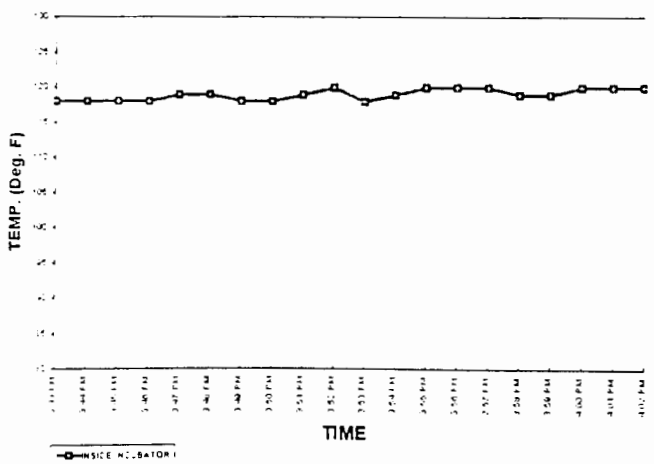


FIGURE 5
Heat Treatment Insect Study #2
Time at 118º F to 120º F Temperature at 26%-27%RH

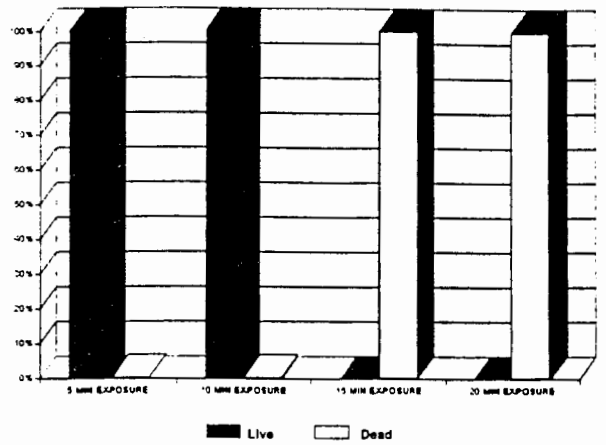


FIGURE 6
Heat Treatment Insect Study #2
Red Flour Beetle Mortality

STUDY # 3 – Humid Environment

Four groups of ten adult red flour beetles were exposed to a temperature stabilized at 118° F with 74 - 76% humidity. The insects were held until inactive & removed at 5 minute intervals.

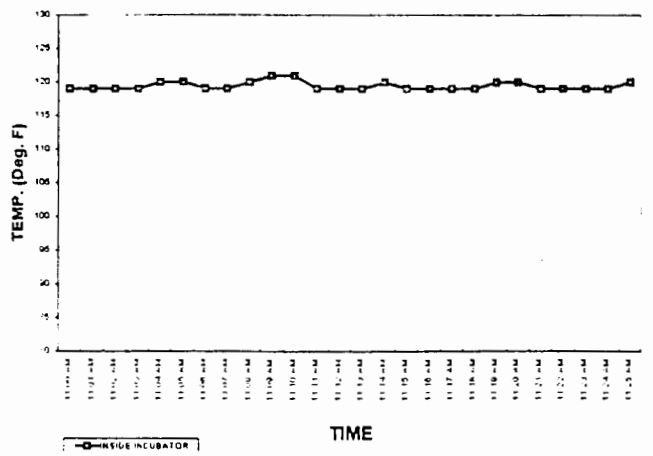


FIGURE 7
Heat Treatment Insect Study #3

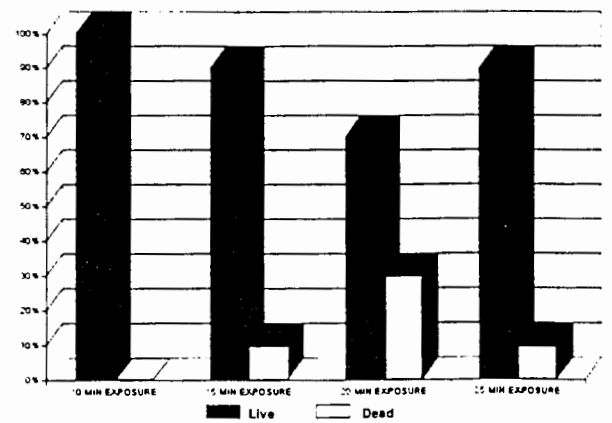


FIGURE 8
Heat Treatment Insect Study #3
Red Flour Beetle Mortality

CONCLUSION

The minimum lethal heat parameters for adult red flour beetle is not 116 - 120°F for 15 to 20 minutes at 74 - 76% humidity.

Higher humidity significantly reduces red flour beetle mortality at 116 - 120° F for 15 to 20 minutes.

Dehydration is probable means of death at 116 - 120° F for 15 to 20 minutes at 26 - 28% humidity.

STUDY # 4 – Temperature Survival

Two groups of 20 adult red flour beetles were exposed to increasing temperature starting at 85° F and 36% humidity and stopping at 114° F and 27% humidity for a four hour period.

CONCLUSION

Most adult red flour beetle can survive heat of 110 - 114° F at 27 to 36% humidity for 3 hours.

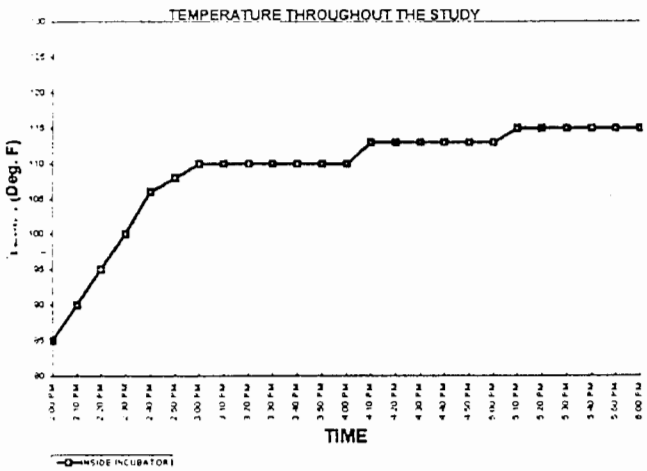


FIGURE 9
Heat Treatment Insect Study #4
Temperature Throughout the Study

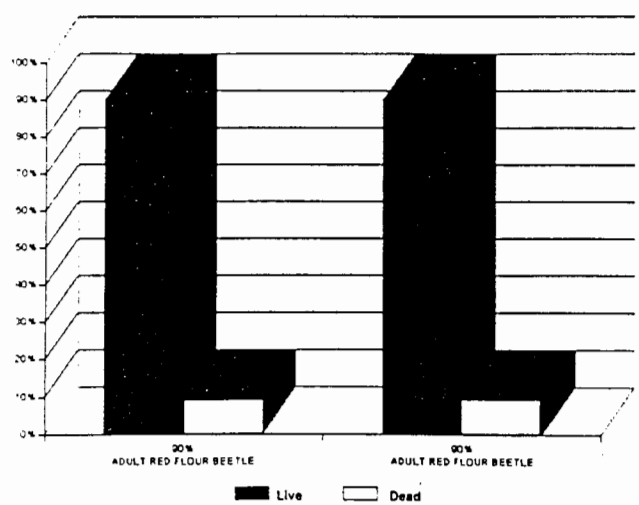


FIGURE 10
Heat Treatment Insect Study #4
Temperature Throughout the Study

RECOMMENDATION

Before suggesting heat parameters for the control of stored-product insects in food processing facilities, it is important to know your P's and Q's. Know your pest, know your plant, know your process, know your product, know your problem and know your parameter. The big Q is the question of how to get this lethal parameter to the insect. Based upon the variability of insect types, stages, acclimation, etc. a minimum heat parameter could be a moving target! More research is needed especially in the application of plant wide "space" and/or specific equipment wide "local" heat treatments. Death will result when stored product insects (the insects themselves, not the environment the insects are within) are exposed to the suggested heat parameters. This is a low heat parameter that is effective and will minimize structural and/or equipment degradation.

SUGGESTION

The results of this research indicate the following heat parameter is suggested as the lowest guideline for the control of most stored-product insects: a temperature of 120-125°F at 25-30% humidity for 20 to 30 minutes.

FIGURE 11
Outdoor Application of Temperature and
Humidity Treatment

DRAFT ONLY

Tactical Heat Treatment for Pest Control in a Flour Mill

Alan Carpenter — Food Pest Management Programme, Crop & Food Research, Private Bag 11 600, Palmerston North, New Zealand, carpentera@crop.cri.nz

David Hammond
Mark Greenwood — Genera Ltd, Pestfree Division, P.O. Box 4106, Mount Maunganui South, New Zealand

Aim: To test the use of heat tactically in a flour mill for pest control in specific areas- roll stands and plansifter.

The Mill: Champion Flour Mill, Mt Maunganui, is a small roller mill with 4 breaks, a X break, and A-H reduction rolls. It works about 5 days per week milling largely Canadian grain for use in plant bakeries and for New Zealand's largest producer of frozen dough and related products. It is on the Mt Maunganui wharf in a mild sub-tropical climate.

Heater: we used a small Kroll heater, diesel powered, imported from Germany. It has two air ducts out and warm air can be recycled to give a warmer output temperature. Delta H is 50 degrees Celsius, thus if warm air is reheated, the output temperature can be raised.

Test systems:
Bioassays were included in each test. Seven temperature probes recorded temperature changes and humidity was tracked with one recorder.
There were several types of bioassay:

- 2 ml microcentrifuge tubes with a trace of flour and either *Tribolium confusum* or *Cryptolestes spp. (turcicus?)* adults. A small hole in top to allow air exchange and for some *Cryptolestes* to fly out.
- 2 ml microcentrifuge tubes with 1 g flour and *T confusum* adults, small hole as above.
- 20 ml plastic pottles with a 2 mm hole in lid covered with mesh with 4 g flour and *T. confusum* adults.
- 20 ml plastic pottles half full of flour with populations of either *T. confusum* or *Cryptolestes*.
- 10 ml tubes with top of lid and bottom both replaced with mesh containing 1 g flour and *T. confusum* adults.

Mortality was assessed 4 (sifter trial) or 5 days (roll stand) after treatment.

04/08 '99 WED 14:10 FAX 64 6 351 7050 CROP & FOOD 002

Roll stands- a bank of five roll stands were sealed in plastic sheeting. A small basement under the stands was also heated.

Plansifter- a 2x3 configuration Simon plansifter with a metal box was covered in plastic sheeting. The three banks of sifter trays were removed form one side of the box. The other three banks on the other side of the sifter were left in place.

Results & Discussion:
The temperature curves and humidity curves are shown in the attached figures. The target temperature was 47 degrees Celsius for 1 hour.

Observations:
We only attained the target temperature in parts of the roll stand set up, and then not for very long. A large number of confused flour beetle left via the hopper spout to the basement floor below where it was much cooler- maybe 30-34 degrees Celsius. A group of beetles (15+) vacated the hopper door catch on one roll stand, which was not an area where I had found them living before. In G roll there was a fold in the metal of the hopper door where there were a great many beetles, and also from behind the feed gate. In this mill G roll is a low throughput roll and the beetles clearly find the conditions in such a system to their liking.

In the sifter the smaller volume made it much easier to heat and the process was much faster. Three events were of interest:

- the sifter banks where the trays were left in did not heat up significantly, but where the metal could conduct the heat to there was very significant expulsion and subsequent death of confused flour beetle.
- there were confused flour beetle falling dead out of the roof of the empty sifter box from places that didn't appear to offer living space.
- heat caused the veneer on the sifter trays to peel back where the glue had started to fail. This was the only sign of temperature effects on the equipment.

Heat went up the spouts but not down, and may have contributed to heat loss from the area being treated.

Bioassay results
These are shown in Table 1
As was expected the amount of flour present affected the results. In part taking a mean of the mortality data gives a misleading picture as most bioassays had either 100% mortality or almost none. Therefore the mortality contours as a function of temperature hold the key. Unfortunately the bioassays were not placed with the probes. The method used does not give data on the effects of heat on the larval stages.

Table 1: Mortality of insects in bioassays in mill treatment (mean)

			Mortality			
			Roll stands		Sifter	Control
			Cryptolestes sp.	*T. confusum*	*T. confusum*	
Bioassay type						
Container	Number	Flour				
2ml	5	trace	50%	65%	17%	4%
2ml	5	1 g	-	60%	85%	0%
10 ml	14	trace	-	83%	87%	2%
20 ml	5	4 g	-	71%	88%	0%
20 ml	2	10 ml	0	0	0%	0%

Conclusions:
In many ways this experiment worked very well. Areas of beetle infestation that had not been previously recognised were identified, and despite temperatures being on the low side, insect mortality was high. The bioassay with two open ends appears to give goo indication of real mortality effects, and should probably be repeated with different levels of flour and with larvae present.

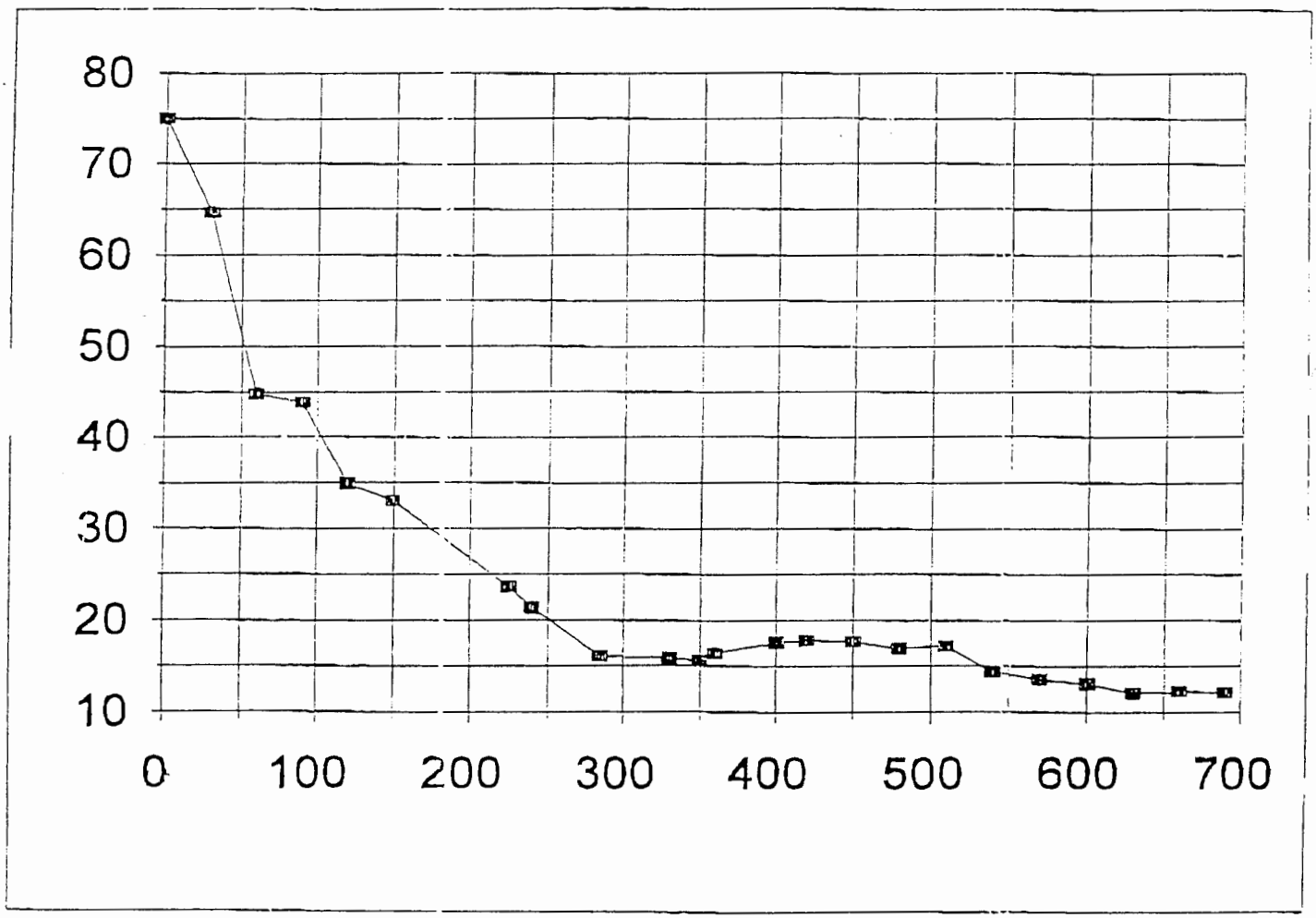
The way ahead:
For the roll stands we have to get more heat into the system more quickly. This might be achieved with something more substantial than plastic sheeting to enclose the area for treatment, and would certainly benefit with a better heat distribution manifold, similar perhaps to that used by the Norwegians in their similar trials. Mortality data has to be worked so that it can be related to spot temperatures.

There can be no doubt that insects in these tests were affected that would not have ben accessed by the fogging that is currently used for pest control in New Zealand flour mills.

Acknowledgements
Without the support of: Gary Urwin, Mill Manager; Gary Gray, Mill Engineer; and Tony Mason, Head Miller, at Champion Four Mills, Mt Maunganui, this work would not have been possible.

04/08 '99 WED 14:11 FAX 64 6 351 7050 CROP & FOOD 004

Figure 1. Relative humidity in the roll stands during treatment. Time in minutes=X axis, temperature in degrees Celsius = Y axis.



04/08 '99 WED 14:11 FAX 64 6 351 7050 CROP & FOOD 005

Figure 2. Relative humidity in the sifter during treatment. Time in minutes=X axis, temperature in degrees Celsius = Y axis.

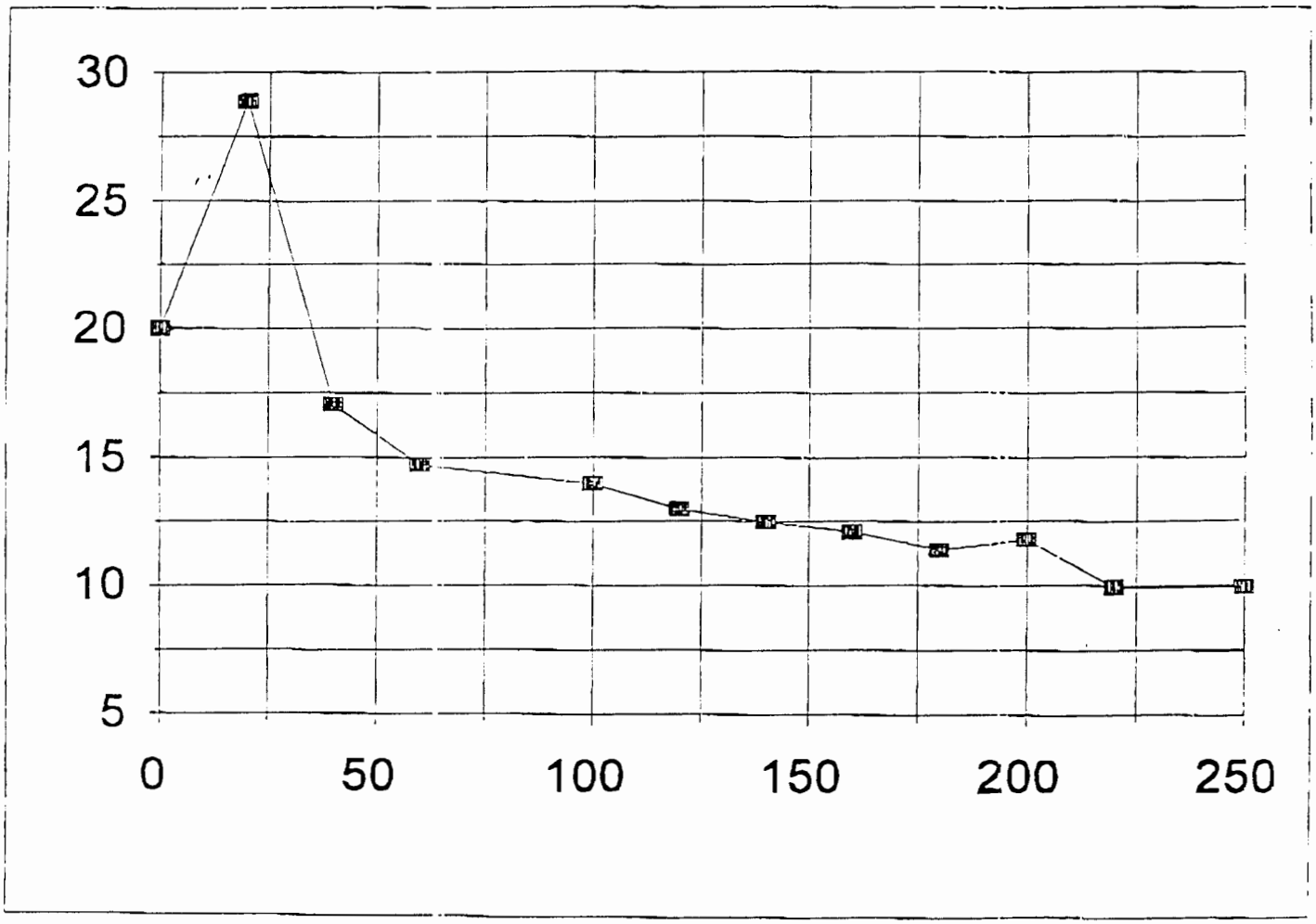
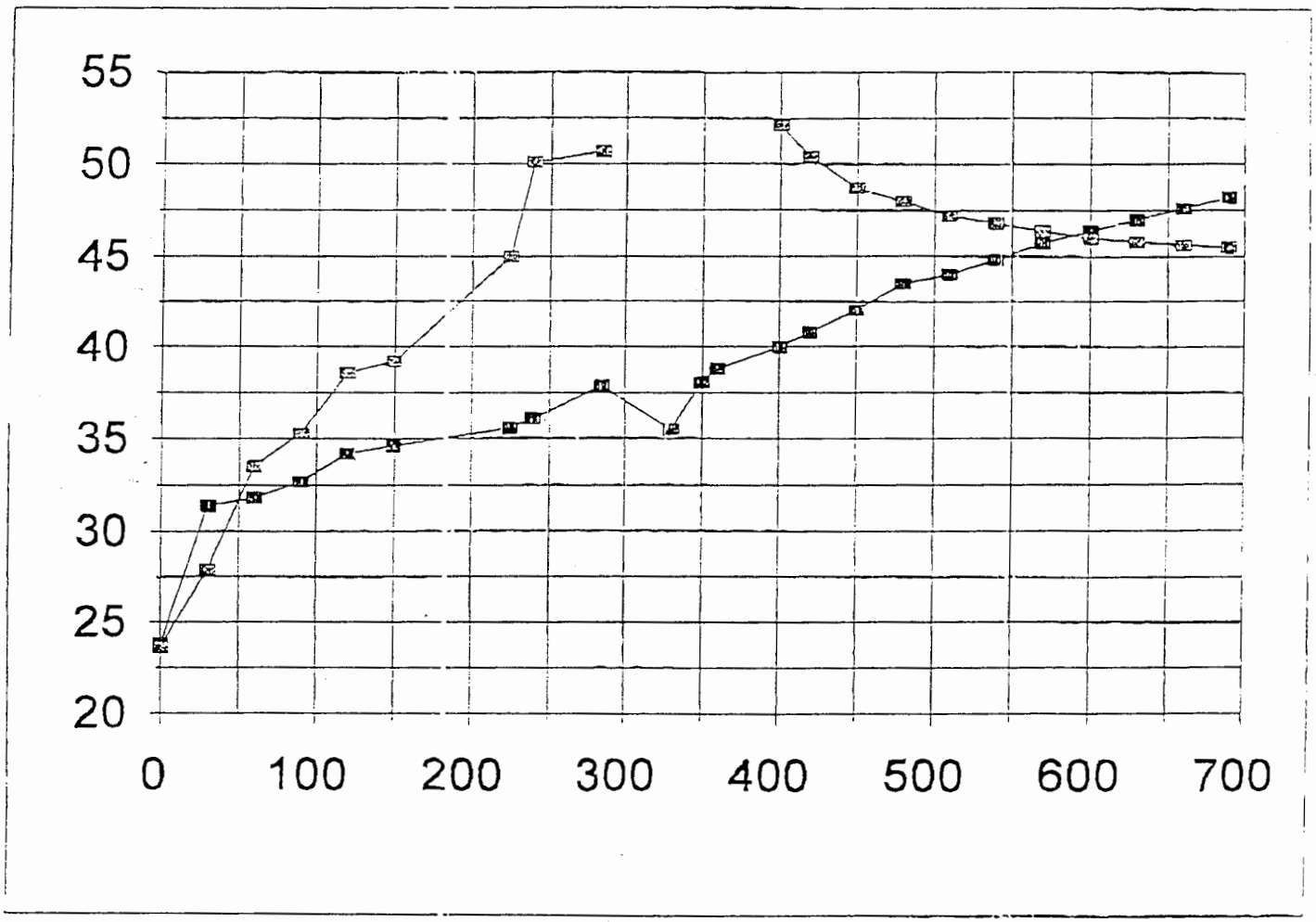


Figure 3 Temperature of the rolls during treatment. Time in minutes=X axis, temperature in degrees Celsius = Y axis



04/08 '99 WED 14:12 FAX 64 6 351 7050 CROP & FOOD 007

Figure 4 Temperature in the roll stand hoppers during treatment. Time in minutes=X axis, temperature in degrees Celsius = Y axis

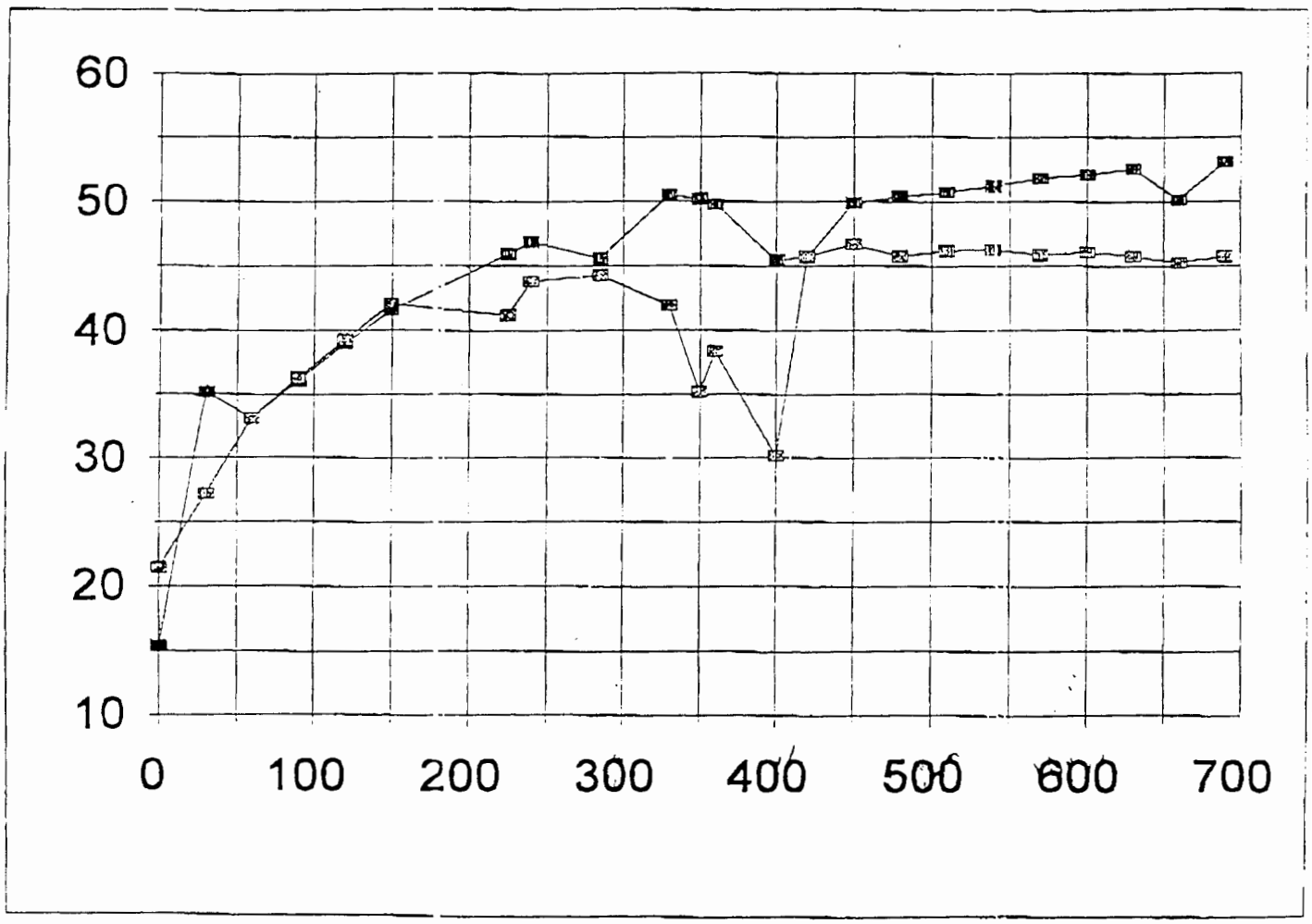


Figure 5 Temperature behind a feed gate and in a roll stand sight glass during treatment. Time in minutes=X axis, temperature in degrees Celsius = Y axis

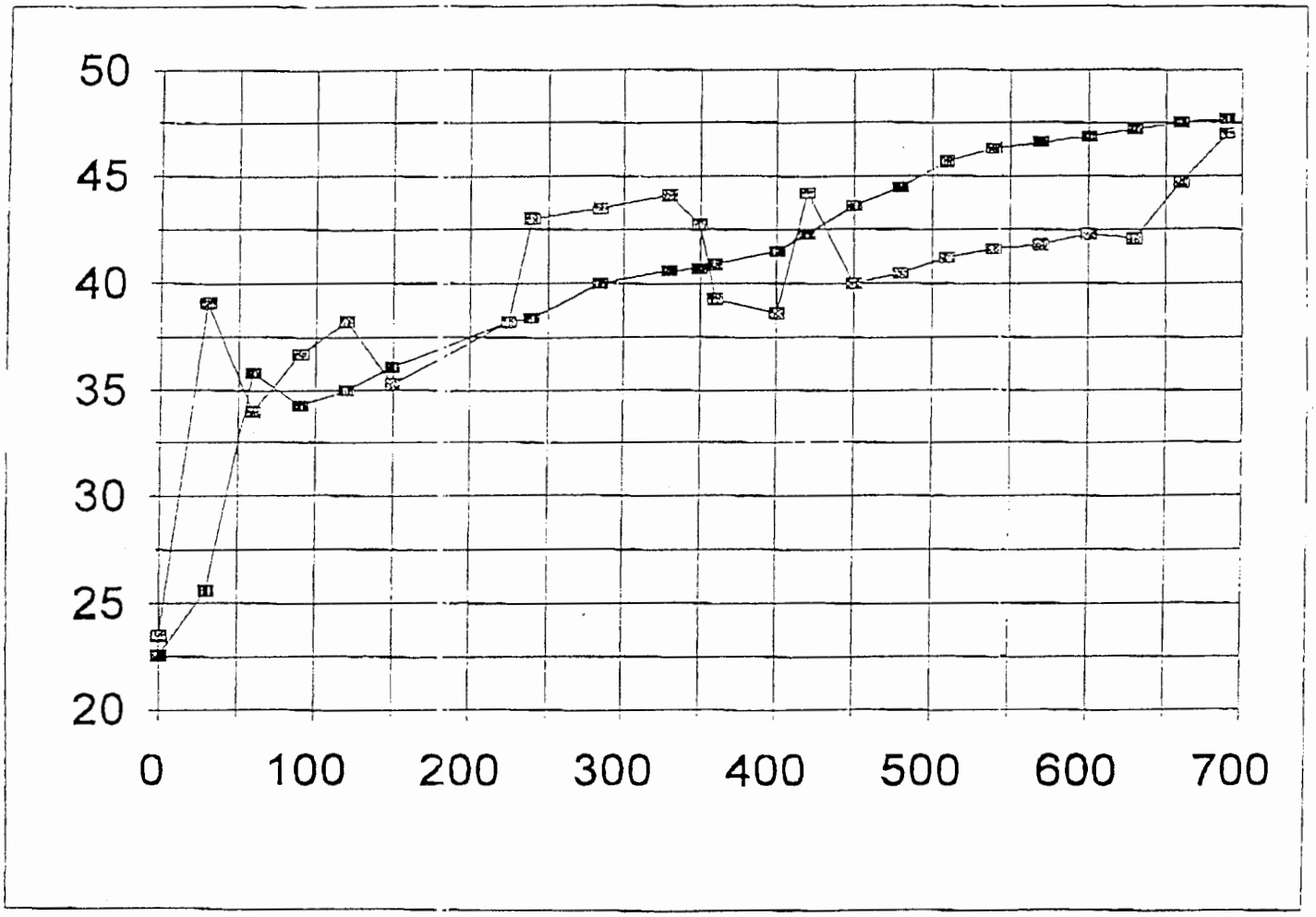


Figure 6 Temperature of inlet air during roll stand treatment. Time in minutes=X axis, temperature in degrees Celsius = Y axis

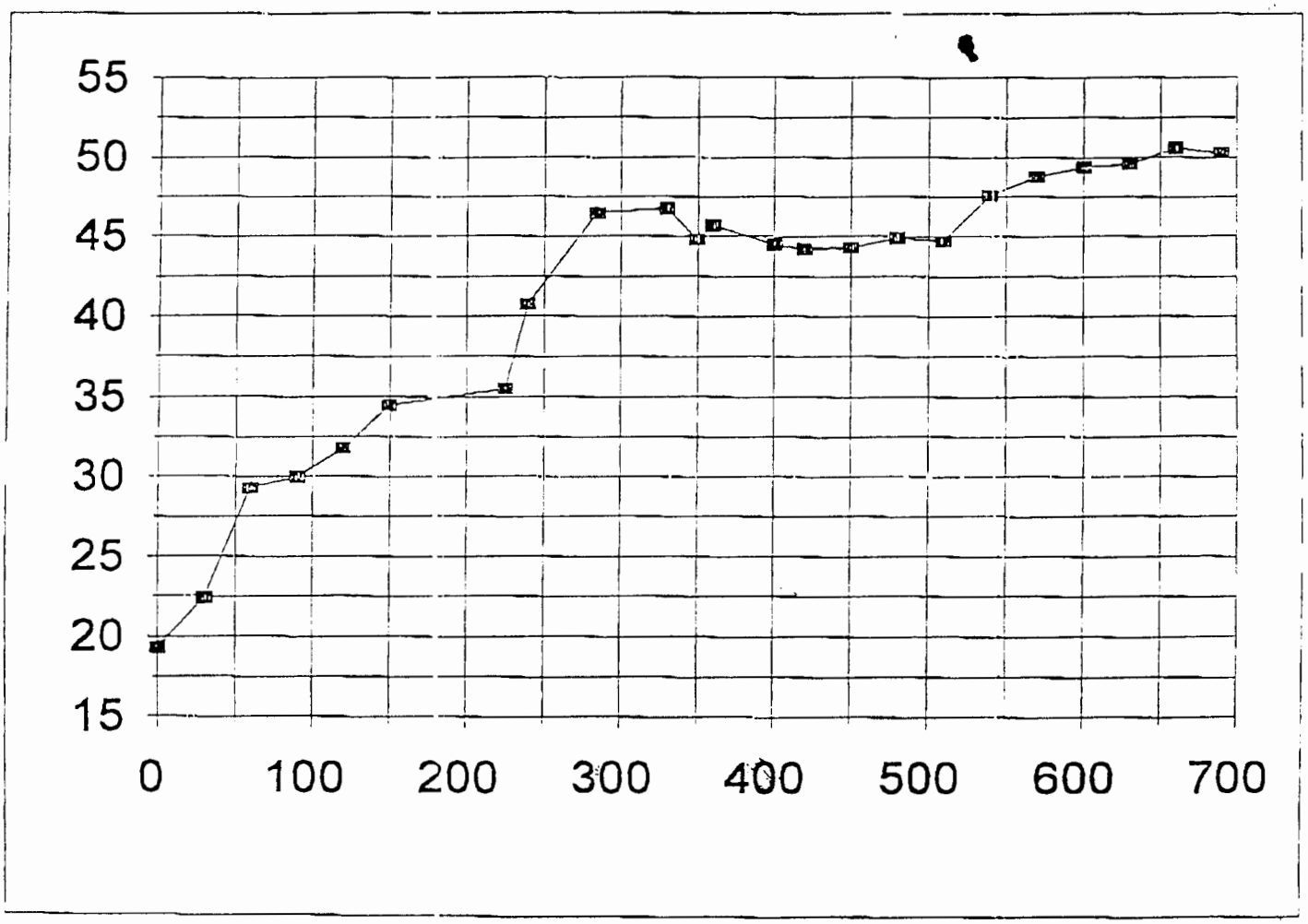


Figure 7 Temperature in a stack of sifter trays during treatment. Time in minutes=X axis, temperature in degrees Celsius = Y axis

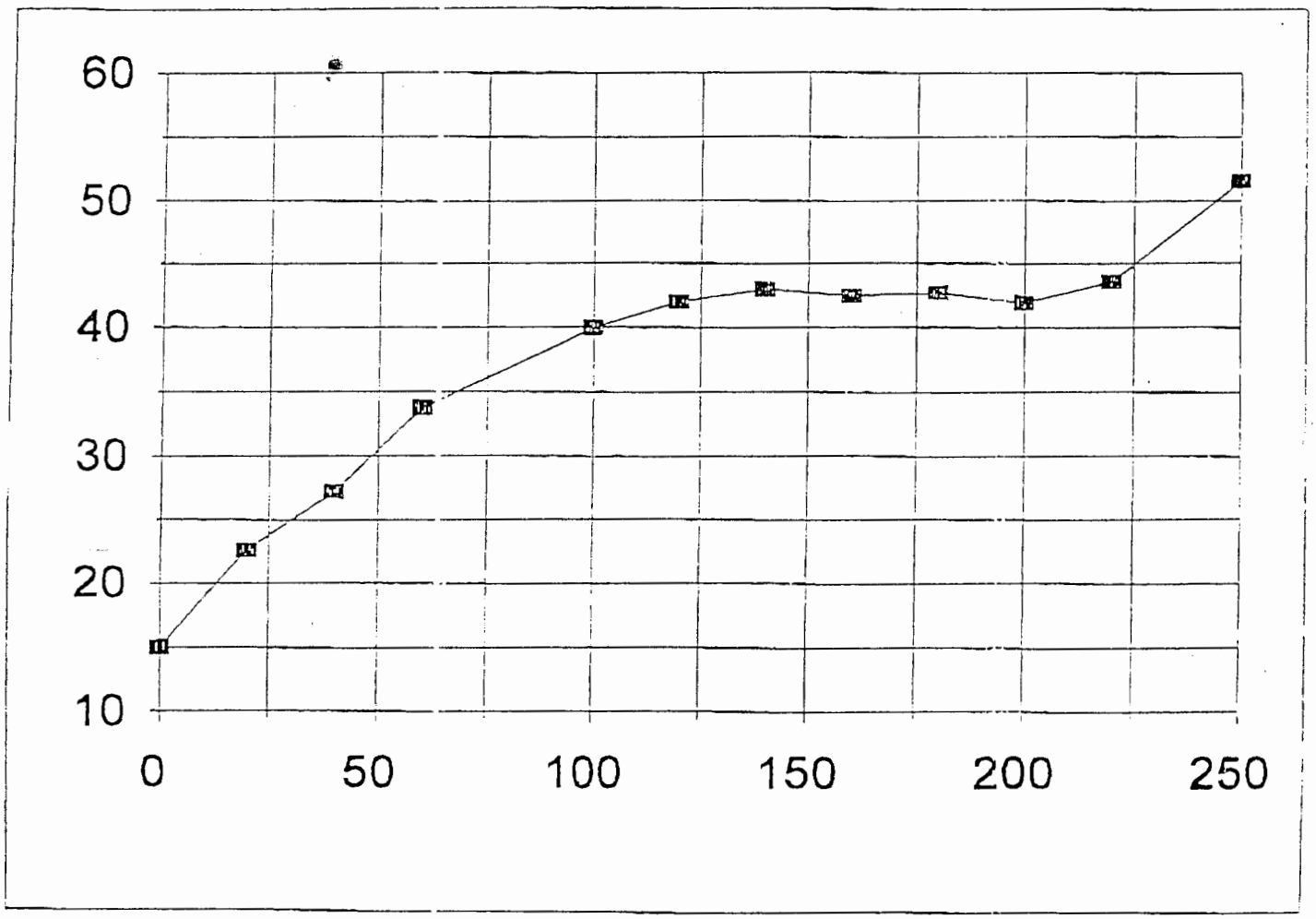


Figure 8 Temperature in the sifter during treatment. Time in minutes=X axis, temperature in degrees Celsius = Y axis. The low trace was in the sifter where the sifter trays had not been removed, and the high traces were in the sifter with trays removed.

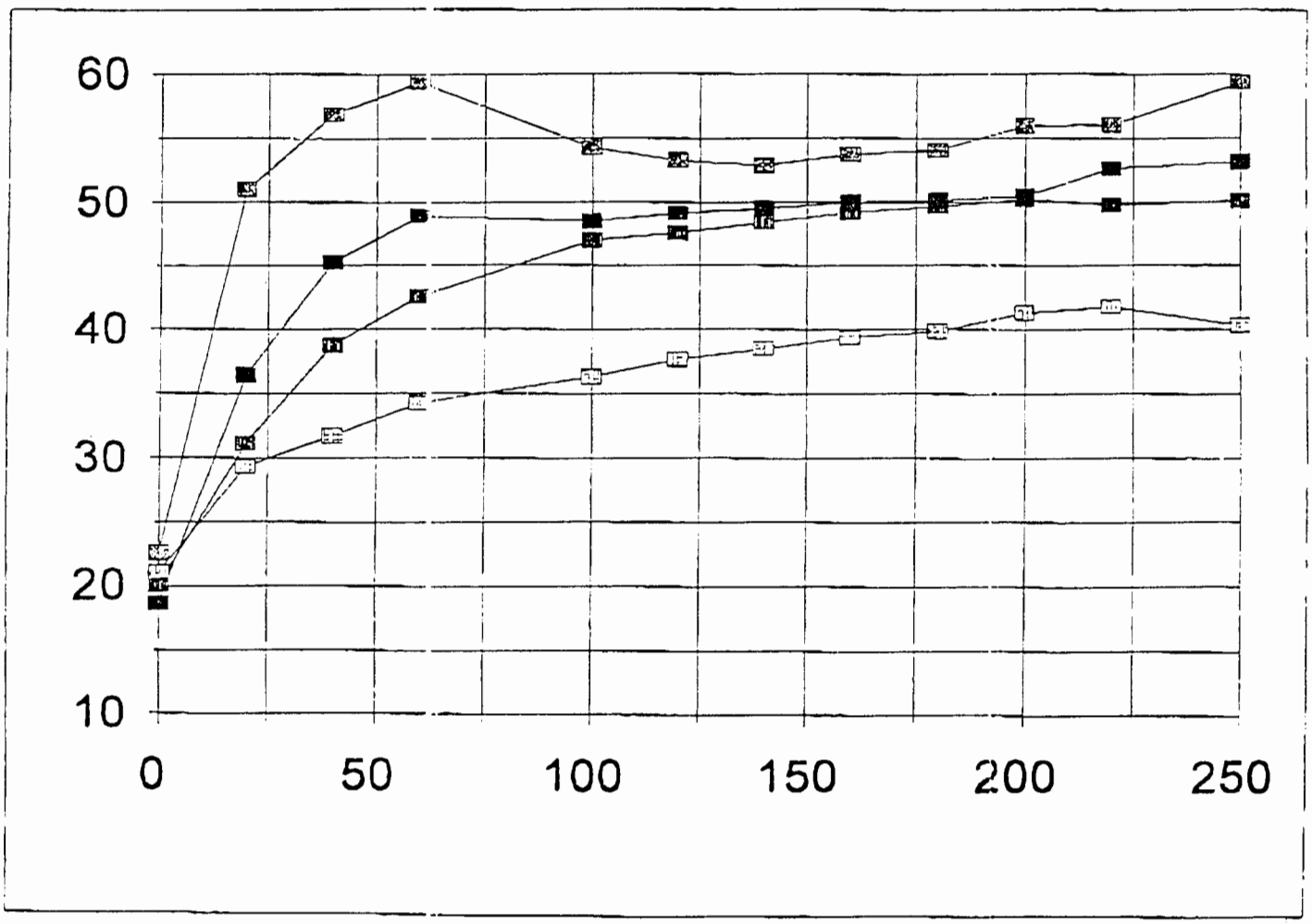
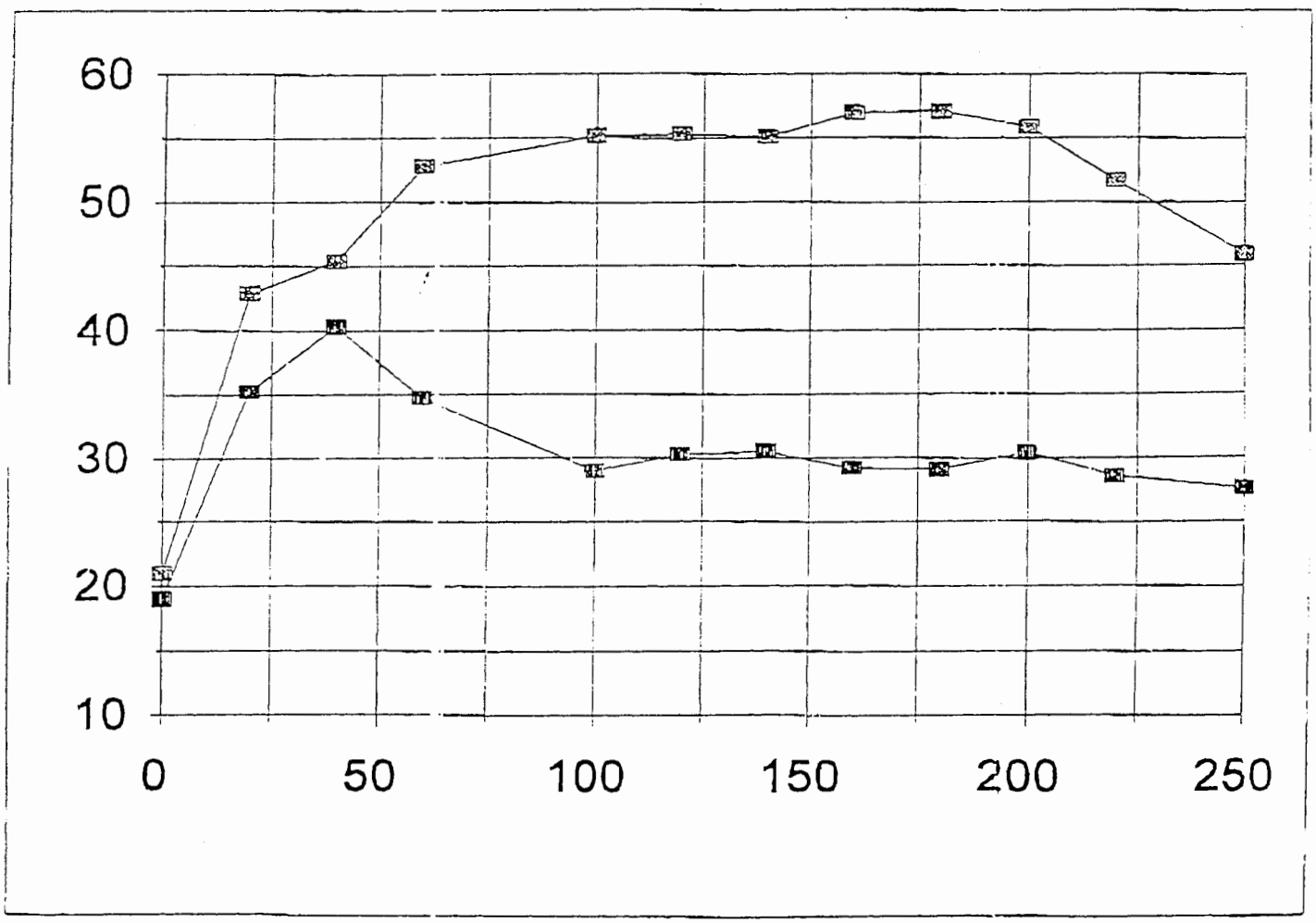


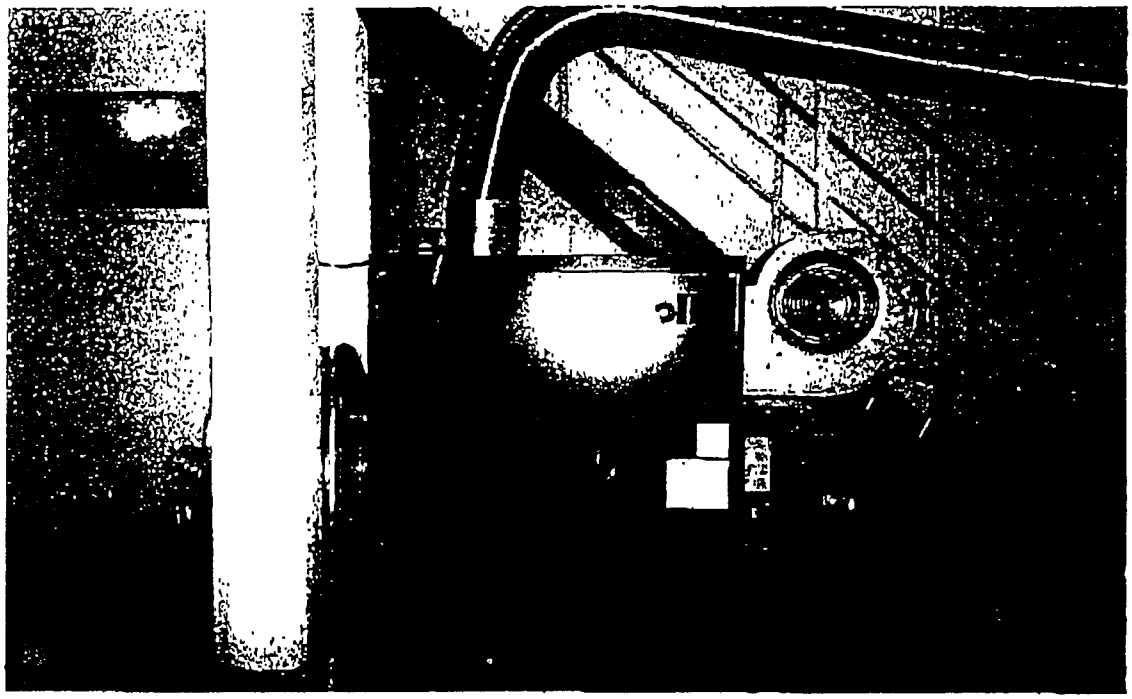
Figure 9 Temperature in sifter spouts during treatment. Time in minutes=X axis, temperature in degrees Celsius = Y axis. The low trace was in a spout under the sifter and the high trace in a spout above the sifter.



04/08 '99 WED 14:13 FAX 64 6 351 7050 CROP & FOOD

Flour mill heat treatment
17/18 July 1999

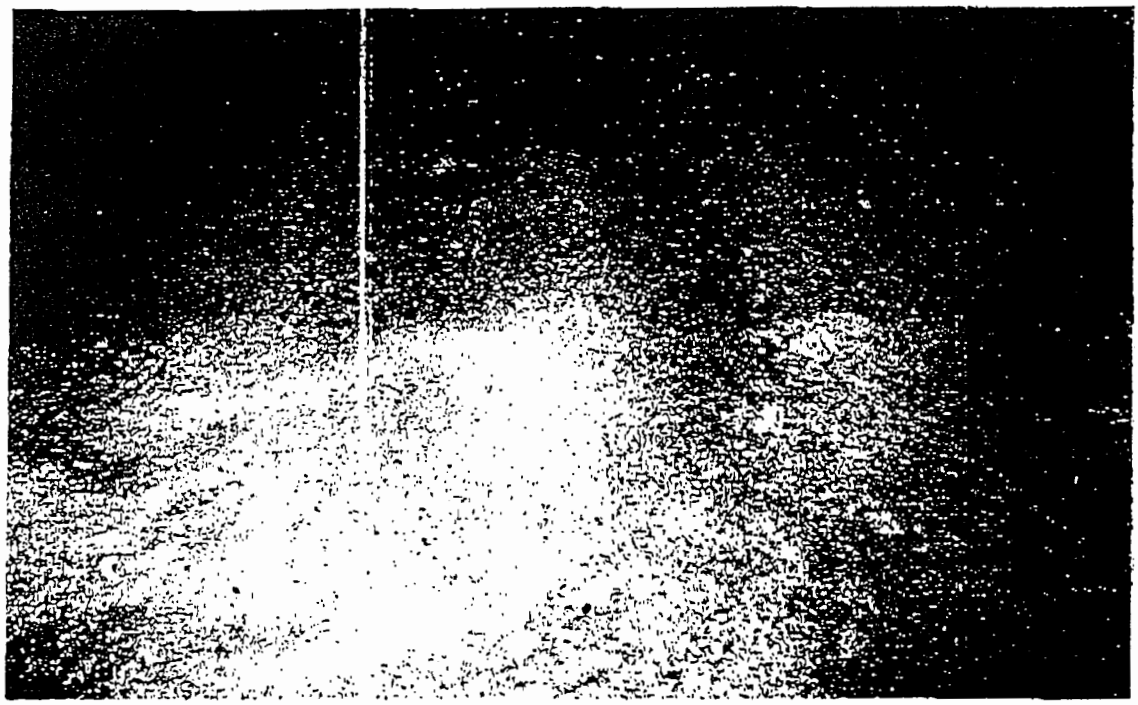
The heater from Germany



Rollstands covered in plastic

Flour mill heat treatment
17/18 July 1999

Insects that dropped out & lived

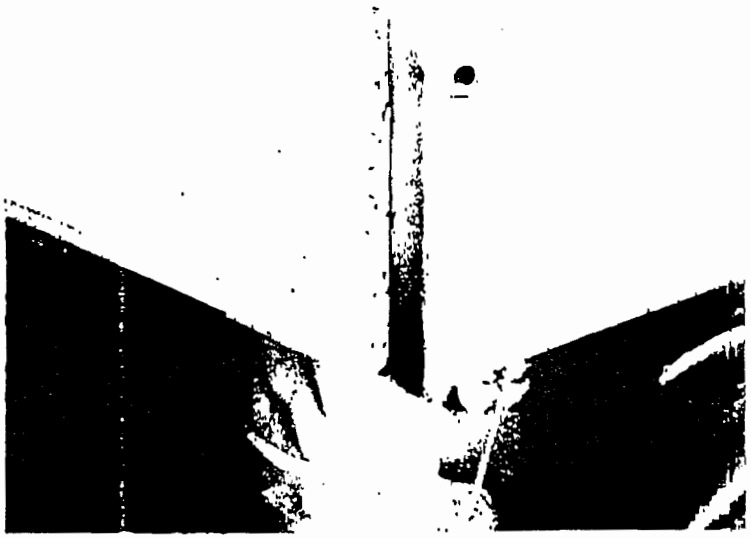


Insects leaving flour cake

Flour mill heat treatment
17/18 July 1999

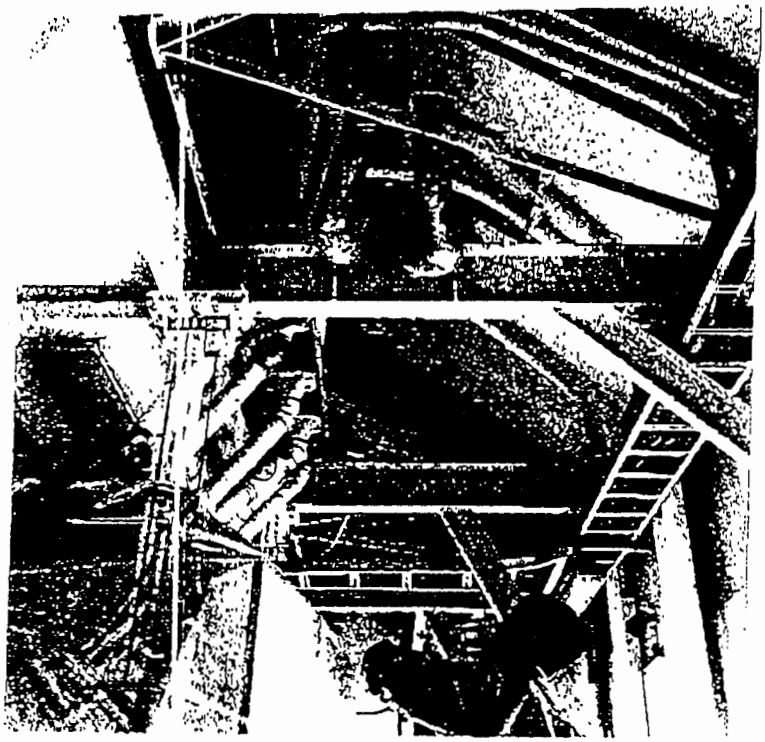
Plansifter all covered up

Insects migrating away from hot metal



Flour mill heat treatment
17/18 July 1999

Sealing takes a bit of effort



Insects that fell out of the top

04/08 '99 WED 14:15 FAX 64 6 351 7050 CROP & FOOD 001

Jeff Weier has been instrumental in developing new programs for Sprague since 1983, including the development of urban IPM strategies. Jeff is a registered sanitarian and his areas of expertise include stored product pests and sanitation in food processing plants.

Using Heat to Control Insects

By Jeffrey A. Weier, Technical Director

Insects are adapted to life in a very narrow range of temperatures. As the temperature varies outside of this range, insects slow their development and eventually die. Table 1 illustrates the temperature responses of typical stored product insects. By manipulating the temperature of an insect's environment, we can gain control of their activity and by using extreme temperatures, we can eliminate insect populations.

Zone	Temp. (F)	Effect
Lethal	122-140	Death in minutes
	113	Death in hours
Suboptimum	95	Development stops
	91-95	Development slows
Optimum	77-91	Maximum rate of development
Suboptimum	54-77	Development slows
	41-54	Development stops
Lethal	14-41	Death in days (unacclimated) movement stops
	-13-5	Death in minutes, insects freeze

Table 1

Adapted from Paul G. Fields, Journal of Product Research, 1992

Extreme cold temperatures can be used to eliminate insect populations, however, insects have developed many physiological and behavioral mechanisms to survive cold temperatures in their natural environments. These defenses make it difficult to achieve the cold temperatures needed to kill most insects. High heat provides a more effective alternative because it is relatively easy to achieve temperatures in excess of what the insects would naturally encounter. This can even be accomplished in large structures.

Insect's Response to Heat

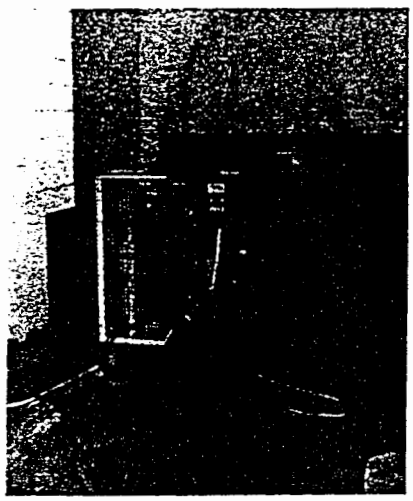
Two basic mechanisms are responsible for death in insects exposed to extreme heat, dessication or dehydration and protein coagulation. Dessication occurs at lower temperatures while protein coagulation occurs at higher temperatures.

Insects, being small animals, are very susceptible to water loss and dehydration. At normal ambient temperatures, the insect cuticle prevents water loss at a thin mono-molecular wax layer in the epicuticle. Excessive heat accelerates the loss of water by causing a change in the structure of the wax layer that reduces its waterproofing ability. The wet inner surfaces of the tracheae where gas exchange takes place in the respiratory system is another source of water loss in insects. Heat increases the insect's respiratory rate, thereby accelerating water loss.

As temperature increases, proteins that are necessary for the proper functioning of insect cells, break down and some coagulate. Coagulation of proteins is what happens to egg whites when eggs are cooked. At these higher temperatures, the insect is literally cooked.

Heat for Insect Control

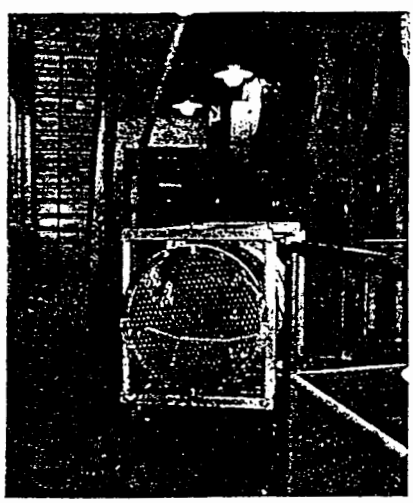
Heating buildings to control insects is not new. Heat was used to control insects in flour mills as early as 1901. Most early heat treatments used steam from the food plant's steam plant to provide the needed heat. Modern heat treatments can use plant steam or heating units from outside the plant. External heating units can use either electricity or natural gas as their energy source.



Gas fired heating unit with duct to inject heat into the structure.

Gas fired heating units operate outside the building and duct hot air into the structure. Injecting hot air into the structure from the outside creates a positive pressure which forces the air into cracks and crevices. This type of unit is suited to leaky structures where positive pressure is needed to prevent the infiltration of cool air from the outside.

Electric heaters operate inside the structure and do not introduce outside air. Because no outside air is used, less positive pressure is created. Electric heat is also easier to control and precise temperatures can be maintained.



Electrical heating unit in flour mill.

The temperature and time of exposure are critical for a successful heat treatment. Numerous studies have been performed to determine what combination is needed to kill various life stages of different insects. Table 2 is a compilation of the time and temperature required to obtain 50% or greater mortality in various insects. By examining the trends, a minimum standard has been developed to kill a wide variety of insects under field conditions. A temperature of 130 degrees for 36 hours has proven to be the appropriate standard to perform a successful treatment.

A critical factor in the success of a heat treatment is to raise the temperature of all areas of the b g to the 130 degree level. Air c ation is the only way to insure t appens. Fans are used to circulate the hot air to cooler areas of a building. Unlike fumigations, heat treatments allow people to enter the heated space to measure temperatures, monitor test insects and identify cool areas. Fans can be moved during the treatment if cool areas are detected.

Questions have been raised about the effects of heat on electronic equipment inside a structure. Every piece of electronic equipment needs to be evaluated by plant engineers to determine if it can tolerate the heat stress in a particular facility. However, during a demonstration at Kansas State University, several computers were placed in the heated area where the temperature was over 140 degrees with no apparent damage to the machines.

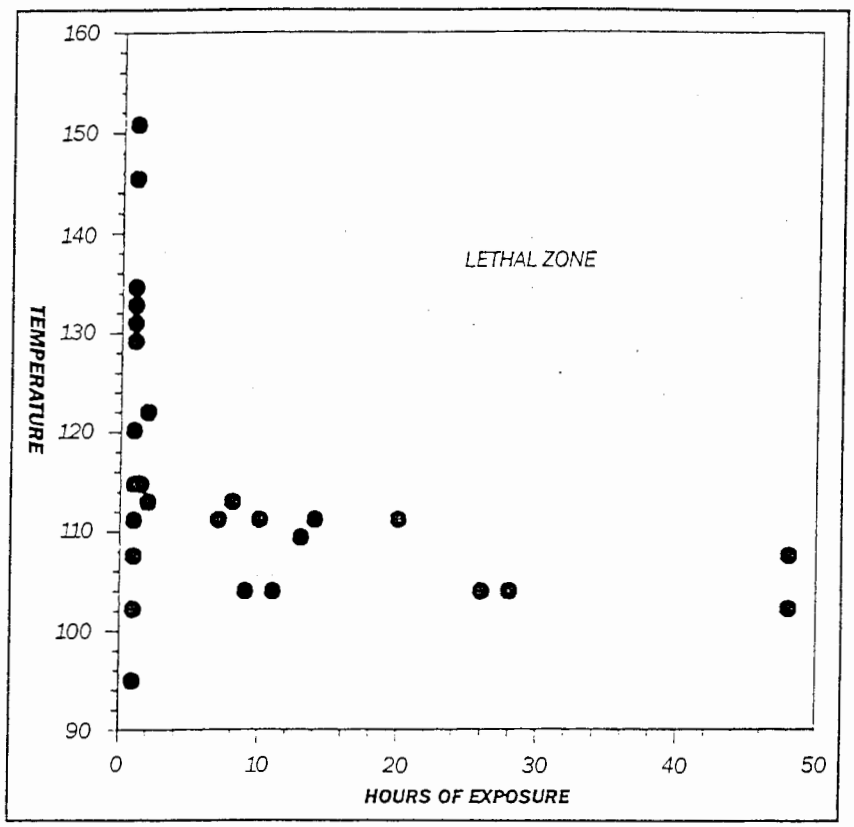


Table 2

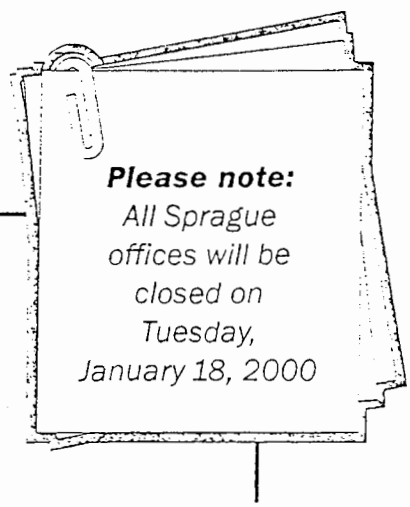
Heat treatments can be effective for structures, but disinfesting commodities is more problematic. The insulating properties of a commodity can make heat treatments of commodities difficult. During a recent heat treatment, temperature probes were placed in bags of flour. Although the temperature surrounding the bags was over 140 degrees, the temperature inside the bag did not exceed 95 degrees after 24 hours.

Phosphine and methyl bromide continue to be the most effective means of addressing pest issues in commodities. Although not a fit for every situation, heat treatments have proven to be an environmentally sound and sometimes even more effective alternative to fumigations for many situations.

rague 2000 Technical Conference

January 17, 18, 19, 2000

This annual event is dedicated to the professional and personal development of the Sprague Team.



Meetings & Presentations

October 8
Archivists Meeting
Bellevue, WA
Jeff Weier,
"Integrated Pest Management"

November 3
NWFP Sanitation Workshop
Portland, OR
Jeff Weier,
"Rodent & Bird Control in Food Processing"

November 20
Oregon Pest Control Association
Roseburg, OR
Jeff Wei
"Stored Product P

November 23
Snake River GEAPS Meeting
Colfax, WA
Jeff Weier,
"21st Century Pest Control for Grain"

December 12-16
Entomologists Society of America
Atlanta, GA
Jeff Weier,
"Precision Targeting"

January 17-19, 2000
Sprague Technical Conference
Seattle, WA

Jan. 26-27
Copesan Marketing Committee Meeting
Clearwater Beach, FL

Jan. 28-29
Copesan National Sales Meeting
Clearwater Beach, FL

March 2
Copesan Marke
Committee Meeting
Phoenix, AZ

March 24-25
Copesan National Conference
Phoenix, AZ

Insect Populations Before and After Heat Treatment of Mills

Bh. Subramanyam, R. Roesli, D. Eustace, and K. Behnke
Department of Grain Science and Industry
201 Shellenberger Hall
Kansas State University
Manhattan, KS 66506

Stored Products Symposium, March 28, 2000

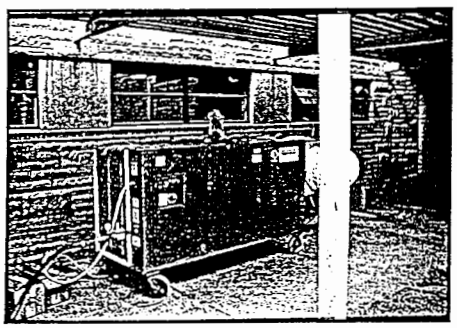
Use of High Temperatures to Control Insects

- 15-40°C or 59-104°F
- Old technology
- Renewed interest
- Very effective
- Little quantitative data
- Viable alternative to methyl bromide

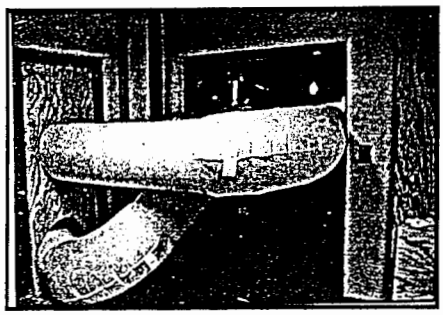
Heat Treatment or Heat Sterilization

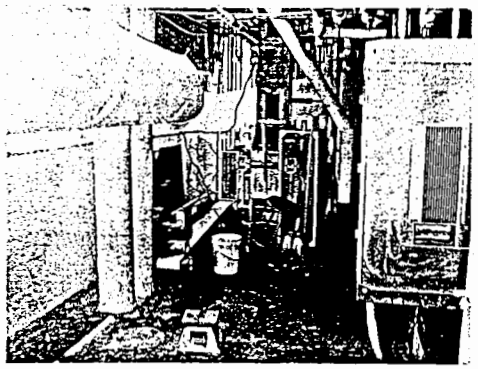
- Heat a facility to ≥50°C (122°F) for 24-36 hours

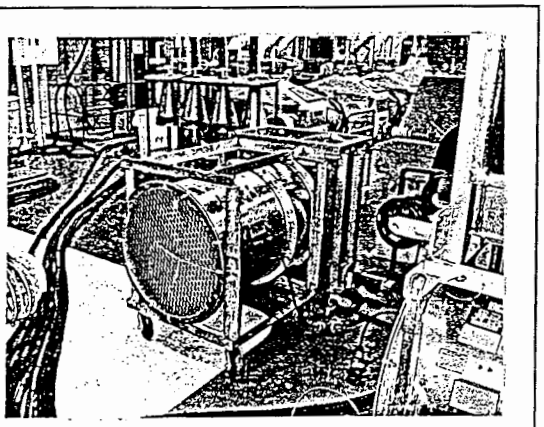
Natural Gas Heater

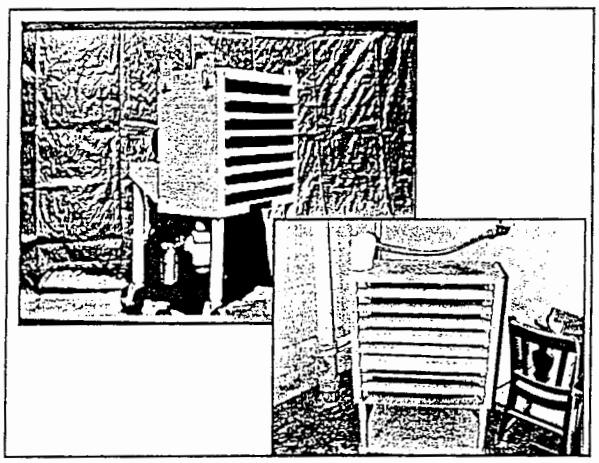


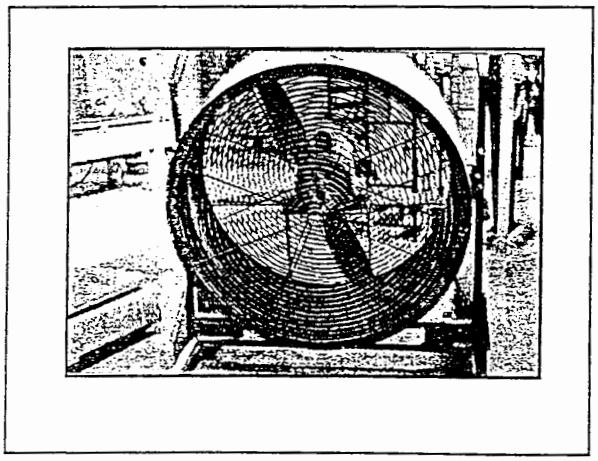
Ductwork During Heat Treatment

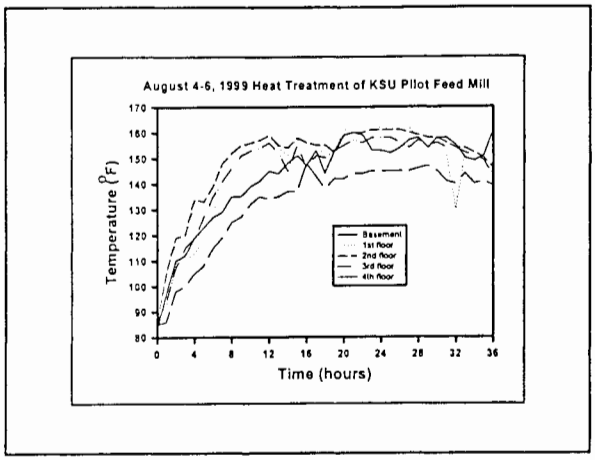


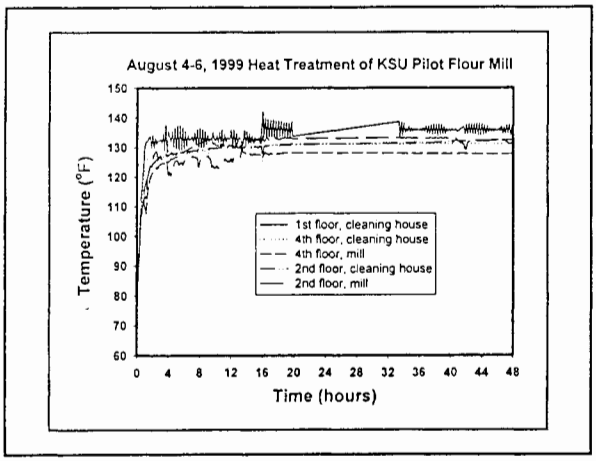


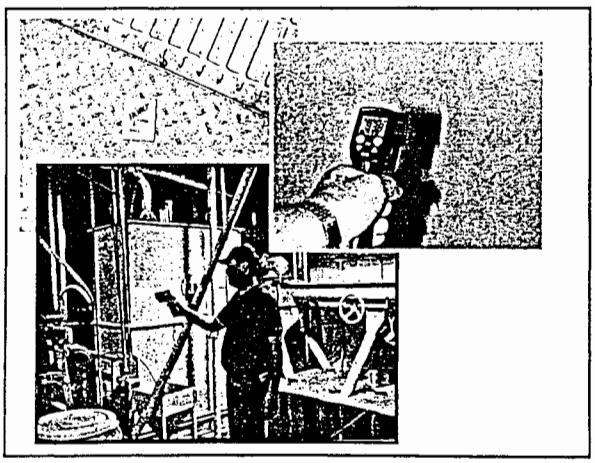







August 4-6, 1999 Heat Treatment of KSU Pilot Feed Mill
Temperature (°F)
Time (hours)
Basement
1st floor
2nd floor
3rd floor
4th floor


August 4-6, 1999 Heat Treatment of KSU Pilot Flour Mill
Temperature (°F)
Time (hours)
1st floor, cleaning house
4th floor, cleaning house
4th floor, mill
2nd floor, cleaning house
2nd floor, mill



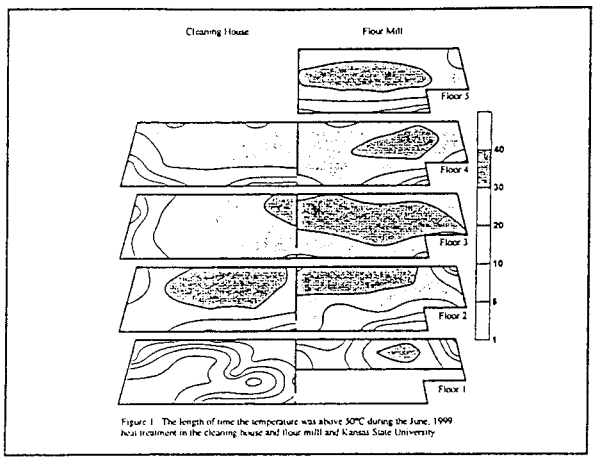


Figure 1. The length of time the temperature was above 50°C during the June, 1999 heat treatment in the cleaning house and flour mill and Kansas State University

Why 50°C for 24-36 hours?

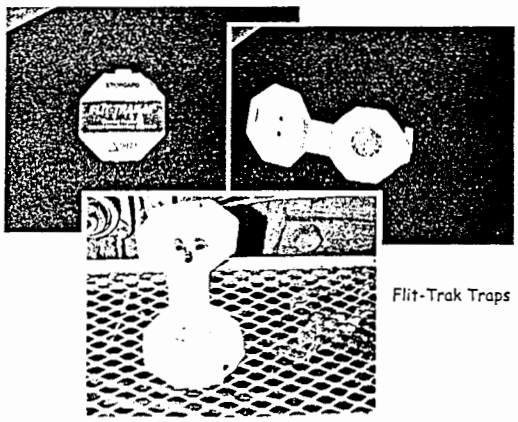
- Data exist on temperature profiles
- Very little empirical evidence on effectiveness against insects during actual heat-up

Heat Treatment Experiments at K-State

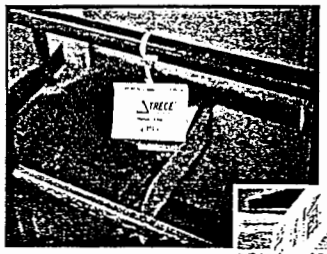
- Pilot flour mill
  - 4 floors of cleaning house (50,000 cu ft)
  - 4 floors of flour mill (50,000 cu ft)
  - Since 1995 has been heat-treated a dozen times
  - Since 1999 May:
    - June 25-27 - Gas heaters
    - August 4-6 - Electric heaters
    - November 23-28 - Steam heaters
- Pilot feed mill
  - 4 floors (100,00 cu ft)
  - August 4-6 - Gas heaters

Research Objectives

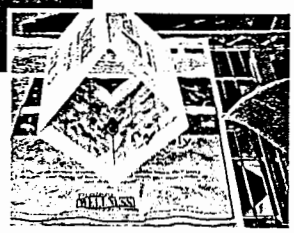
- 2 issues:
  - Degree of suppression
  - Duration of suppression



Flit-Trak Traps



For almond moths and Indianmeal moths



Phercon 1C traps

Sampling Insect Populations

- Pilot Feed Mill
  - 10 Flit Trak traps/floor
  - 10 Phercon 1C traps w/ almond moth lure
- Pilot Flour Mill
  - 10 Flit Trak traps/floor
  - 10 Phercon 1C traps w/ almond moth lure
  - 10 Phercon 1C traps w/ Indianmeal moth lure

Sampling Insect Populations

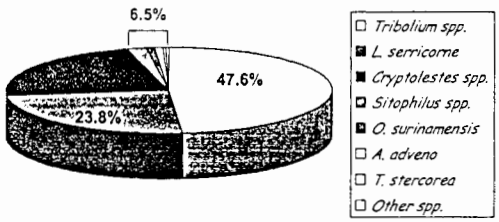
- Lures replaced every month
- Trap counts taken every week
- Unreplicated trial
- Data presented as total number of insects captured in traps

Insect Sampling

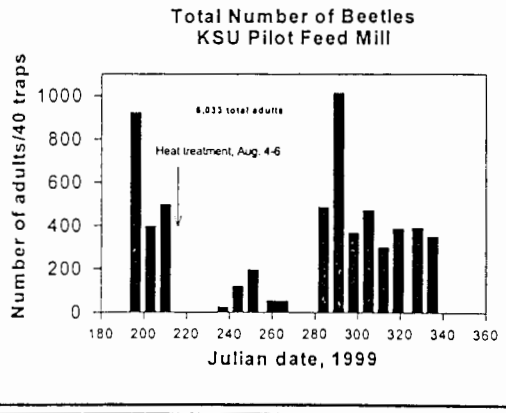
- Feed Mill
  - July 8 - December 10, 1999
  - 16 sampling occasions for beetles
  - 14 sampling occasions for moths
  - Only almond traps were used
- Flour Mill
  - June 23 - December 23, 1999
  - 18 sampling occasions for beetles
  - 17 sampling occasions for moths
  - Both Indianmeal moth and almond traps were used

Feed Mill Data

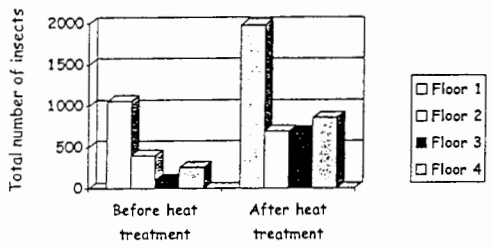
Species of Beetles Captured in Flit-Trak Traps in the KSU Pilot Feed Mill, July 8 - December 1, 1999



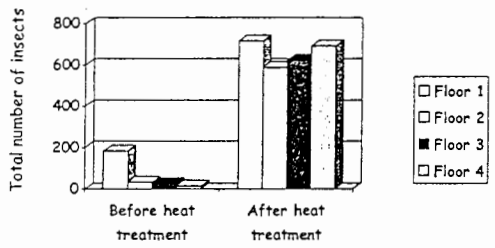
T. castaneum, 98.9% of total *Tribolium* spp.
S. oryzae, 91.1% of total *Sitophilus* spp.



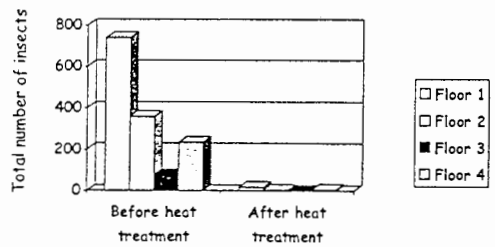
Total Number of Beetles in the Feed Mill Before and After Heat Treatment



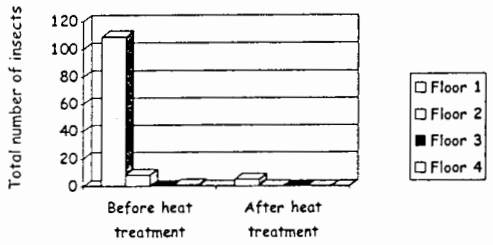
Total Number of *Tribolium* spp. in the Feed Mill Before and After Heat Treatment



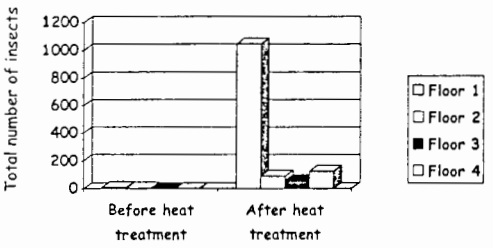
Total Number of Cigarette Beetles in the Feed Mill Before and After Heat Treatment



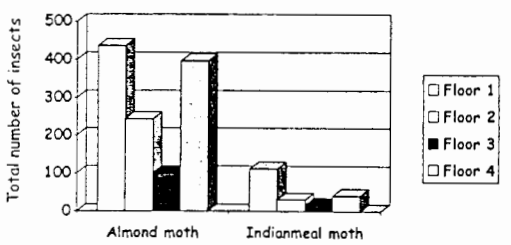
Total Number of *Sitophilus* spp. in the Feed Mill Before and After Heat Treatment



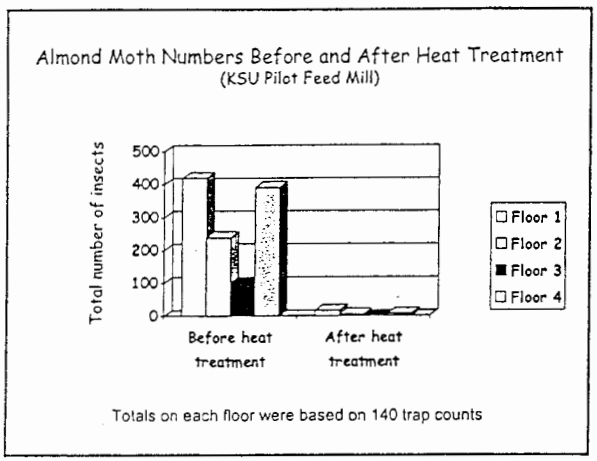
Total Number of *Cryptolestes* spp. in the Feed Mill Before and After Heat Treatment

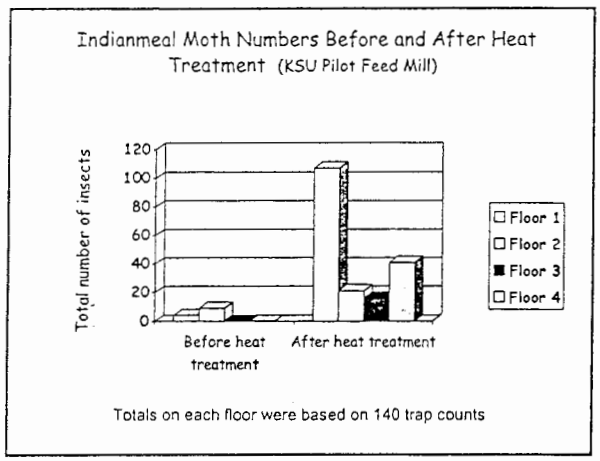


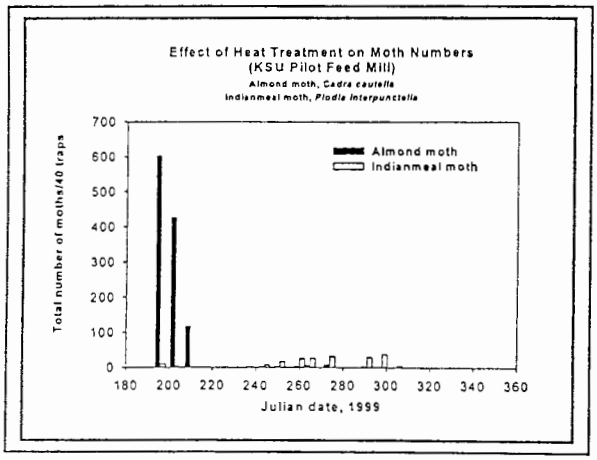
Distribution of Moths Among the Feed Mill Floors



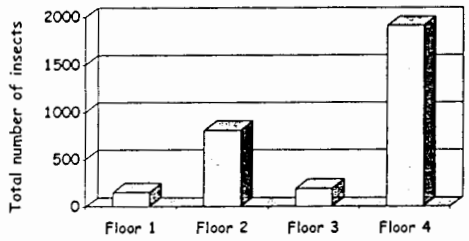
Totals on each floor were based on 140 trap counts


Almond Moth Numbers Before and After Heat Treatment
(KSU Pilot Feed Mill)
Total number of insects
500
400
300
200
100
0
Before heat treatment
After heat treatment
Floor 1
Floor 2
Floor 3
Floor 4
Totals on each floor were based on 140 trap counts

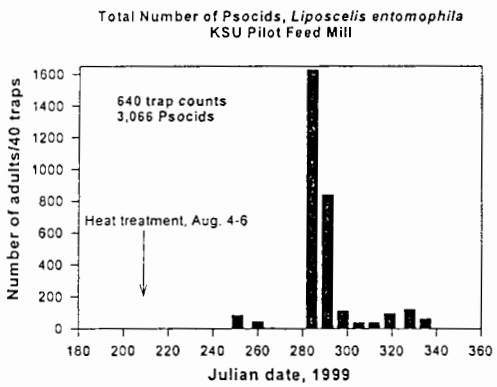

Indianmeal Moth Numbers Before and After Heat Treatment (KSU Pilot Feed Mill)
Total number of insects
120
100
80
60
40
20
0
Before heat treatment
After heat treatment
Floor 1
Floor 2
Floor 3
Floor 4
Totals on each floor were based on 140 trap counts


Effect of Heat Treatment on Moth Numbers
(KSU Pilot Feed Mill)
Almond moth, Cadra cautella
Indianmeal moth, Plodia interpunctella
Total number of moths/40 traps
700
600
500
400
300
200
100
0
180 200 220 240 260 280 300 320 340 360
Julian date, 1999
Almond moth
Indianmeal moth

Distribution of Psocids Among Floors (KSU Pilot Feed Mill)



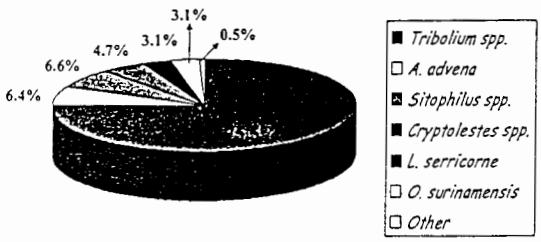
Totals based on 130 trap counts/floor



Flour Mill Data

Relative Abundance of Beetles in the Cleaning House

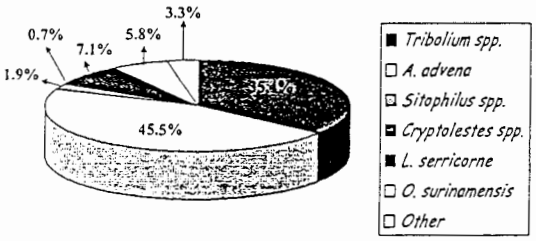
(KSU Pilot Flour Mill, June 23-December 23, 1999)



Total number of adults counted from 640 trap catches = 1,144

Relative Abundance of Beetles in the Flour Mill

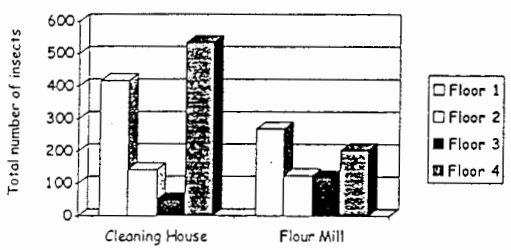
(KSU Pilot Flour Mill, June 23-December 23, 1999)



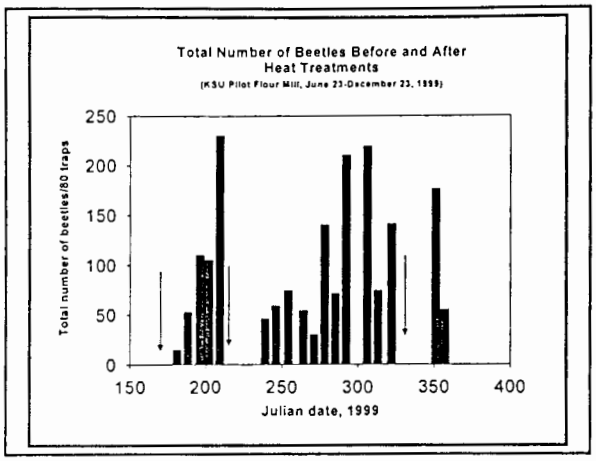
Total number of adults counted from 640 trap catches = 718

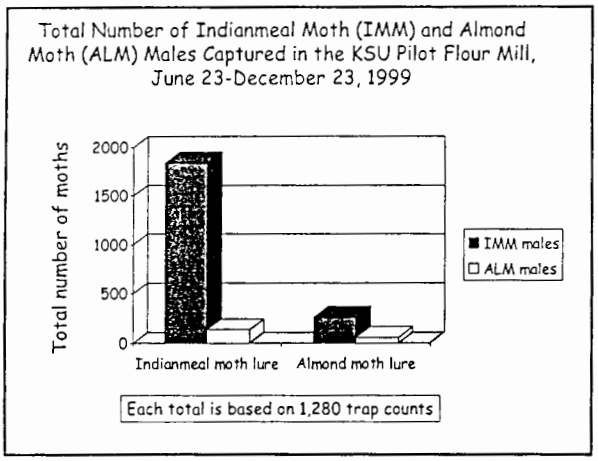
Distribution of Beetles Among the Four Floors of the Cleaning House and Flour Mill

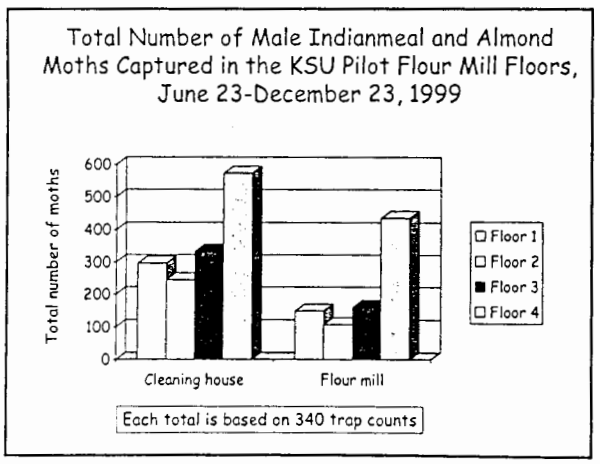
(KSU Pilot Flour Mill, June 23-December 23, 1999)

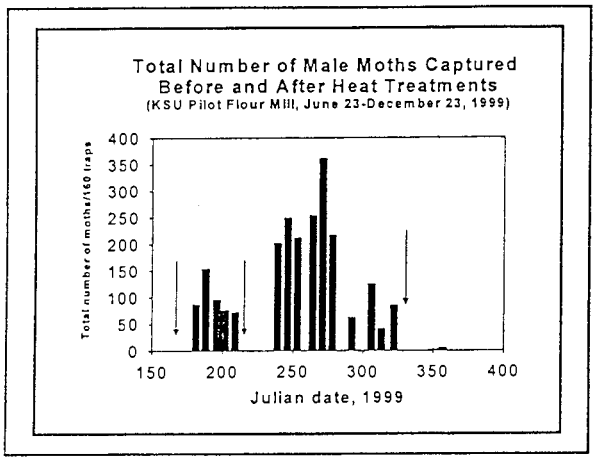


Data for each floor based on 160 trap counts


Total Number of Beetles Before and After Heat Treatments
(KSU Pilot Flour Mill, June 23-December 23, 1999)
Total number of beetles/80 traps
250
200
150
100
50
0
150
200
250
300
350
400
Julian date, 1999

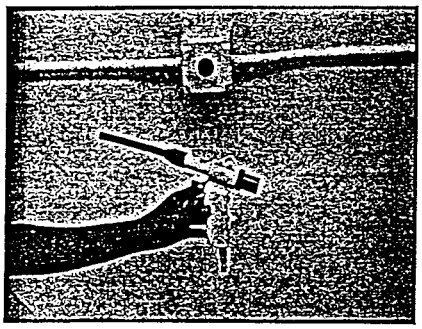

Total Number of Indianmeal Moth (IMM) and Almond Moth (ALM) Males Captured in the KSU Pilot Flour Mill, June 23-December 23, 1999
Total number of moths
2000
1500
1000
500
0
IMM males
ALM males
Indianmeal moth lure
Almond moth lure
Each total is based on 1,280 trap counts


Total Number of Male Indianmeal and Almond Moths Captured in the KSU Pilot Flour Mill Floors, June 23-December 23, 1999
Total number of moths
600
500
400
300
200
100
0
Floor 1
Floor 2
Floor 3
Floor 4
Cleaning house
Flour mill
Each total is based on 340 trap counts



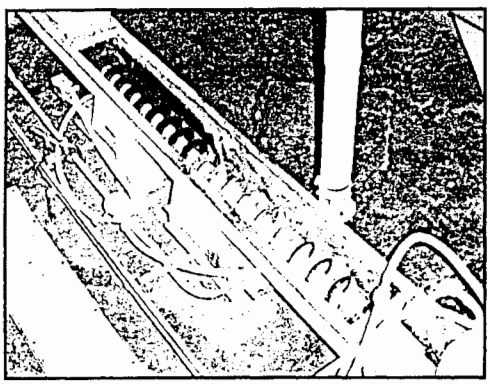
Can Traps Indicate Treatment Effectiveness?

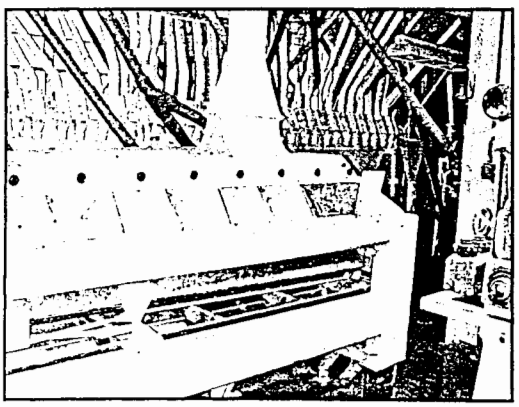
- Insect populations were detected 2-4 weeks after a heat treatment
- Traps alone are unreliable
- Source of insects
- Ingredient sampling is important
- Absolute estimates??

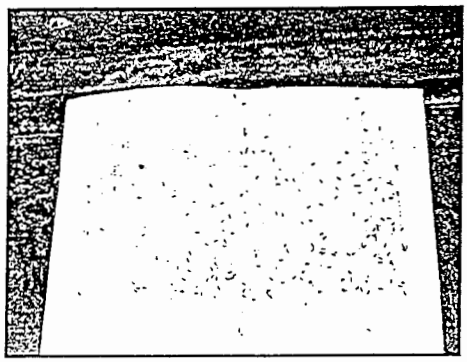


Number of Dead Insects in a Square Grid

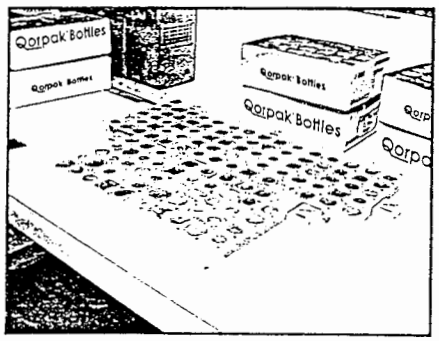
Room	Floor	No. Adults/Sq ft (No. samples)
Cleaning house	1	72. 4 (9)
Cleaning house	2	92.7 (3)
Cleaning house	3	23.3 (3)
Cleaning house	4	16.3 (5)
Mill	1	12.0 (2)
Mill	2	6.6 (5)
Mill	3	0.6 (5)
Mill	4	0.5 (4)





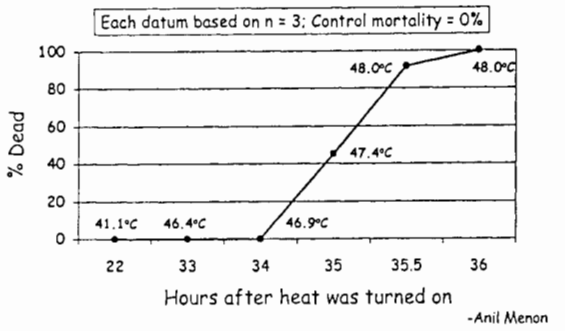


Mortality of Red Flour Beetles
During an Actual Heat-up



Mortality of Confined Red Flour Beetles During a Heat Treatment

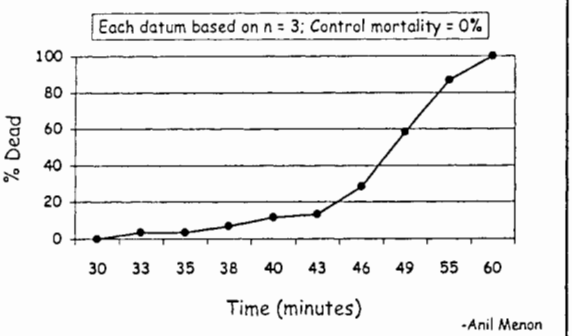
(KSU Pilot Flour Mill Steam Heat Treatment, March 17-20, 2000)



-Anil Menon

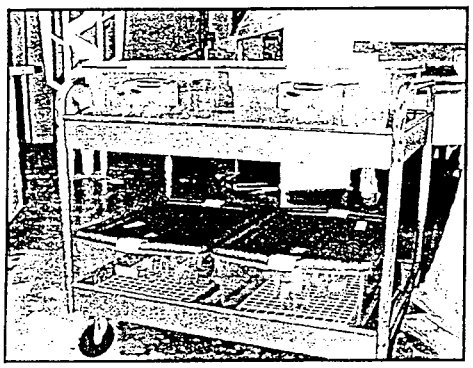
Mortality of Confined Red Flour Beetles at 50°C

(KSU Pilot Flour Mill Steam Heat Treatment, March 17-20, 2000)



-Anil Menon

Does Humidity Influence Mortality of Red Flour Beetles?



Effect of Humidity on Mortality of Red Flour Beetle Adults
(KSU Pilot Flour Mill, Steam Heat Treatment, March 17-20, 2000)

Temperature = 50.1-52.4°C; Growth chamber = 27.5°C

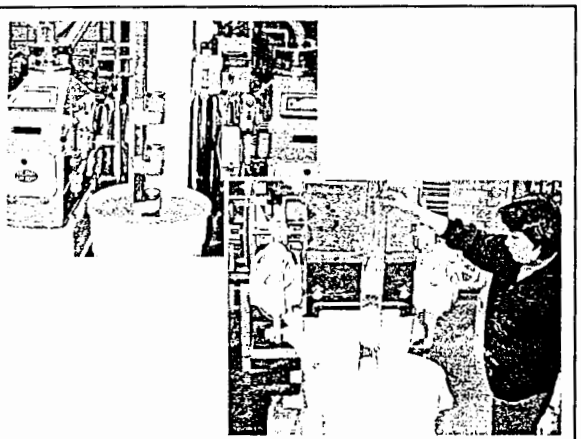
% RH, Range	20 Minutes	30 Minutes	50 Minutes
53.6-63.1	0.0	29.0 b	100.0
46.1-49.3	0.0	93.8 a	100.0
31.6-48.1	0.0	97.5 a	100.0
20.4-20.5 No Glycerol	0.0	95.0 a	100.0
32.4-38.1 Chamber	0.0	0.0 c	0.0

For each time and treatment combination, n = 3.

Effect of Humidity on Mortality of Red Flour Beetle Adults
(KSU Pilot Flour Mill, Steam Heat Treatment, March 17-20, 2000)

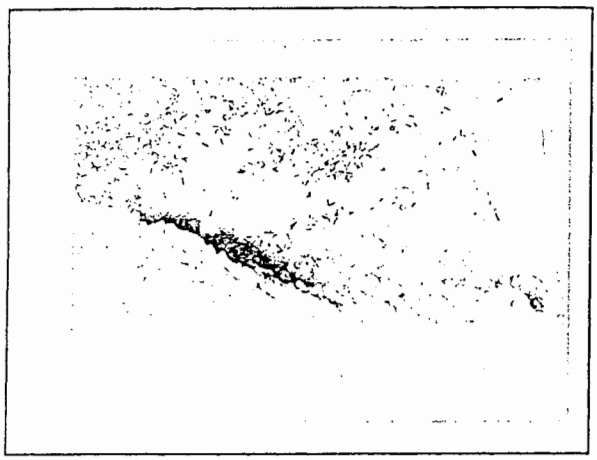
Exposure time (hours)	Temp. range (°C)	Hours to reach 50°C	Hours above 50°C	% RH	% Mortality
24	22.1-42.0	0.0	0.0	71.7	0.0
	22.1-42.0	0.0	0.0	58.6	0.0
	22.1-41.5	0.0	0.0	50.6	0.0
No Glycerol	22.1-41.5	0.0	0.0	30.7	1.7
G. Chamber	27.5-28.3	0.0	0.0	36.2	1.7
47	22.1-51.8	43.0	4.0	70.5	100.0
	22.1-51.8	43.0	4.0	57.5	100.0
	22.1-50.7	44.5	2.5	49.3	100.0
No Glycerol	22.1-51.2	44.0	3.0	26.2	100.0
G. Chamber	27.5-28.7	0.0	0.0	37.1	0.0

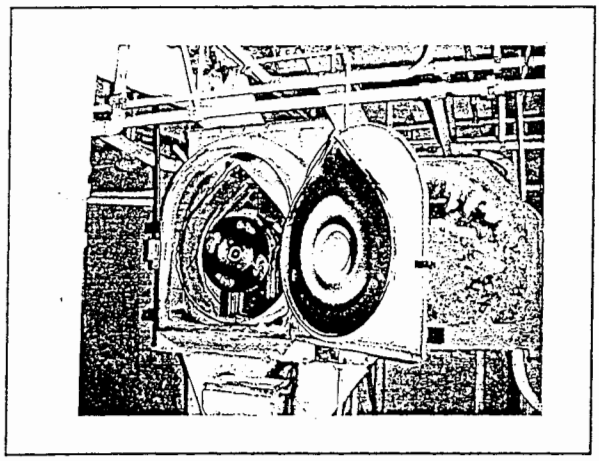
Can Insects in Grain and Flour Survive a Heat Treatment?

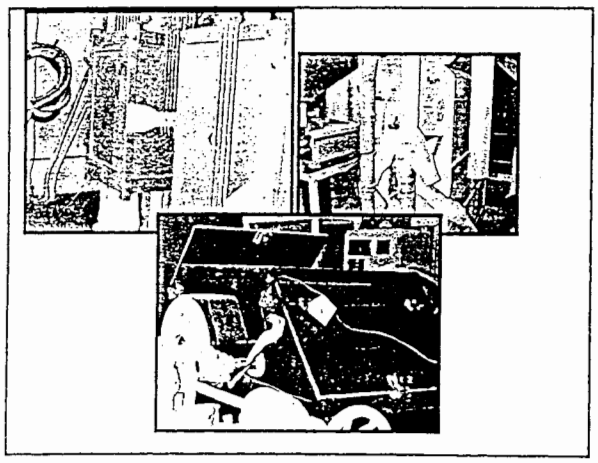


Mortality of Red Flour Beetles Insulated by Whole Wheat Kernels and Flour
(KSU Pilot Flour Mill, Steam Heat Treatment, November 23-28, 1999)

Commodity	Location	Temp. range (°C)	% RH, range	% Mortality
Wheat	Top, 4"	21.7 - 40.1	32.2 - 81.4	9.5
	Middle, 14"	22.9 - 40.1	26.2 - 79.5	40.0
	Bottom, 23"	22.9 - 39.7	26.1 - 80.2	25.0
Flour	Top, 6"	19.4 - 38.8	27.9 - 76.4	4.8
	Middle, 14"	19.4 - 38.9	27.6 - 75.5	0.0
	Bottom, 22"	19.8 - 37.9	28.3 - 70.6	0.0







Conclusions

- Temperature-time-mortality relationships
- Minimum temperature for 100% kill
- Quantifying population suppression
- Integration with other control tactics

Acknowledgments

Financial Support

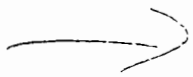
Rupp Industries, Inc.
Burnsville, MN

Arne Menon SHE 47

96:02 E

Heat treatment in the Scandinavian Milling Industry

Heat treatment as an alternative to Methyl Bromide



SFT

Norwegian Pollution Control Authority (SFT) is a subordinate agency of the Ministry of Environment, and plays an important role in efforts to combat pollution, waste disposal problems and noise.

SFT is responsible for measures to combat industrial pollution, supervision of the national oil pollution emergency services and administration of the Product Control Act. SFT acts as technical advisory agency for the Ministry of Environment and has the overall responsibility for monitoring atmospheric and aquatic pollution.

SFT is also responsible for issuing guidelines for county departments of environmental affairs with regard to agriculture, municipal waste, fish farming and hazardous waste.

SFT Norwegian Pollution Control Authority

P.O. Box 8100 Dep, N-0032 Oslo, Norway
Office address: Strømsveien 96
Telephone: +47 22 57 34 00 *Telefax:* +47 22 67 67 06
Telex: 76 684 sft n *Telegrams:* "Forurensning"

ENVIRONMENTAL TECHNOLOGY 96:02E

Norwegian Pollution Control Authority

SFT

P.O. Box 8100 Dep, N-0032 OSLO, Norway
Office address: Strømsveien 96
Telephone: +47 22 57 34 00 *Telefax:* +47 22 67 67 06
Telex: 76 684 sft n *Telegrams:* "Forurensning"

Executing research institution	SFT contact person		ISBN-number
Anticimex	Einar Modahl		82-7655-356-7
	SFT Department of Chemicals and Hazardous Waste		TA-number 1339/1996
Project responsible Anne Mari Opheim	Year 1996	No. of pages 38	Contract-number - SFT 95/261
Publisher Norwegian Pollution Control Authority	Project financed by Norwegian Pollution Control Authority Anticimex Norwegian Milling Association		

(Author(s))
Cand. Scient. Stein Norstein

(Title)

Heat treatment in the Scandinavian Milling Industry - Heat treatment as an altenative to Methyl Bromide

Summary

Three Scandinavian mills were treated with heat to control insects. Temperature and other measurements were made.

A review of the literature indicated that the necessary heat exposure time for 100% heat killing effect (mortality) ranges from 22 hours at 45 °C to 14 minutes at 54 °C. Allowing for inaccuracy and adding a safety margin shows that a temperature of 50 °C to 55 °C should be achieved during practical heat treatment.

At Nordmills, Uppsala, a spot treatment of roller stands was carried out. Temperature measurements showed that lethal temperatures were reached and that all insects in the roller stands should have been killed.

At Regal Mill, Moss, a ground floor and a wooden container were heated. The effect of the heat treatment was calculated.

It is concluded that heat treatment can be an efficient method of eradicating insect pests both in smaller, confined areas, and in larger buildings, and will in many cases be a good alternative to methyl bromide. Supplementary treatment using other methods may be needed in certain areas where the necessary temperature is difficult to achieve.

4 subject words
Environmental Technlogy
Methyl Bromide
Heat Treatment
Milling Industry

Preface

According to the Montreal Protocol, the consumption of methyl bromide is to be gradually phased out. With this obligation in mind, the Norwegian Pollution Control Authority (Statens forurensningstilsyn - SFT) has supported the development of feasible technology to substitute methyl bromide.

This report presents the results from three case studies in the Scandinavian milling industry. Approximately 80 % of the Norwegian consumption of methyl bromide is used for insect pest control in mills.

When phasing out methyl bromide, the Norwegian Pollution Control Authority wants to promote alternative technologies which do not involve chemicals that may be harmful to health and environment. The method used in these mills is heat treatment.

The project has been funded by the Norwegian Pollution Control Authority and the Norwegian Milling Association. The project has been carried out by Anticimex.

Oslo, June 1996

Anne Mari Opheim
Head of Department

Content

ABSTRACT 5

1 INTRODUCTION 6

2 THE PROJECT 7

3 MATERIAL AND METHODS 8

3.1 Review of the literature 8

3.2 Heating method and heating equipment 8

3.3 Temperature and data logger 8

3.4 Temperature measurements 9

3.5 Gas measurements 9

3.6 Other measurements 9

4 LITERATURE AND RESULTS OF PRACTICAL TESTS 10

4.1 Temperature tolerance of buildings and equipment 10

4.2 Temperature tolerance of insects 10
4.2.1 Temperature tolerance of different species 10
4.2.2 Heat tolerance of the different development stages 13
4.2.3 Influence of humidity on heat tolerance in insects 16

4.3 Our first trial - Berte Qvarn 16
4.3.1 The test area and the aim of the test 16
4.3.2 Preparations and set-up 17
4.3.3 The treatment 18
4.3.4 Results 18

4.4 Second trial - Nordmills Uppsala 19
4.4.1 The test area and the aim of the test 19
4.4.2 Preparations and set-up 19
4.4.3 The treatment 20
4.4.4 Results 20
4.4.5 Late effects 21

4.5 Last time - Regal Mill, Division Moss 22
4.5.1 The test area and our aim with the test 22
4.5.2 Preparations and set-up 23
4.5.3 The treatment 24

4.5.4.1 Conditions during the test 24
4.5.4.2 Result of the sealing of the test area 24
4.5.4.3 The heat treatment 25
4.5.4.4 Gas measurements 25
4.5.4.5 Air humidity 25
4.5.4.6 How hot was it? 25
4.5.4.7 Temperatures in products and under articles 26
4.5.4.8 Cooling down 26
4.5.5 Insect populations 27

5 DISCUSSION 28

5.1 Temperature tolerance of building and equipment 28

5.2 Temperature tolerance of insects 29

5.3 The heating equipment 30

5.4 Temperature measurements 30

5.5 Was the temperature high enough? 31

5.6 Spot treatment 32

5.7 Air distribution 33

5.8 What should be done about low temperature areas 33

5.9 Regal Mill, Moss - treating the whole building? 33

5.10 Economy 34

5.11 Hygiene 35

6 CONCLUSION 36

6.1 Maximum input air temperature 36

6.2 Minimum heat exposure time 36

6.3 Scope and cost of treatment 37

6.4 Other comments 37

List of Appendices

1 List of pests mentioned in the report
2 Technical documentation
3 Techno Consult: Heating strategy
4 Berte Qvarn
- 4.1 Temperature of air from heater
- 4.2 Air temperature inside
- 4.3 Temperature inside equipment
- 4.4 Temperature inside constructions
- 4.5 Temperature of electrical equipment
- 4.6 All temperatures

5 Nordmills
- 5.1 Heater ducting to the roller stands at Nordmills
- 5.2 The tent and heater ducts at each pair of roller stands
- 5.3 All temperatures

6 Regal Mill, Moss
- 6.1 Outline of the treated area in Moss
- 6.2 Number, position and function of sensors
- 6.3 Hourly temperatures during heat treatment
- 6.4 Key temperatures
- 6.5 Air temperatures inside during treatment
- 6.6 Temperature in construction
- 6.7 Air temperature inside equipment
- 6.8 Temperature in wooden container
- 6.9 Effects of products in the heating process
- 6.10 Volume and temperature of input air
- 6.11 Cooling of input air
- 6.12 Humidity measurements
- 6,13 Carbon monoxide measurements
- 6.14 Input air temperature versus Carbon dioxide
- 6.15 Oxygen measurements
- 6.16 Cooling down
- 6.17 Comparison between leak tube temperatures and outside and inside temperatures

Abstract

Three Scandinavian mills were treated with heat to control insects. Temperature and other measurements were made.

A review of the literature indicated that the necessary heat exposure time for 100% heat killing effect (mortality) ranges from 22 hours at 45 °C to 14 minutes at 54 °C. Allowing for inaccuracy and adding a safety margin shows that a temperature of 50 °C to 55 °C should be achieved during practical heat treatment.

At Nordmills, Uppsala, a spot treatment of roller stands was carried out. Temperature measurements showed that lethal temperatures were reached and that all insects in the roller stands should have been killed.

At Regal Mill, Moss, a ground floor and a wooden container were heated. The effect of the heat treatment was calculated and ranged from 0% at some places to 13 000% at others.

Details are given on how to maximize input air temperatures and thereby minimize the time needed without exceeding the limit of 70 °C that is imposed by electrical PVC conductors.

The cost of a heat treatment is calculated.

Important experiences are notified.

It is concluded that heat treatment can be an efficient method of eradicating insect pests both in smaller, confined areas, and in larger buildings, and will in many cases be a good alternative to methyl bromide. Supplementary treatment using other methods may be needed in certain areas where the necessary temperature is difficult to achieve.

1 Introduction

F or several decades, the milling industry has depended on gassing with methyl bromide to keep the level of insect pests down. In Norway, gassing is carried out every or every second year. Without such regular treatment the insect pest situation would get out of hand in most places. Hygiene in a mill today is based mainly on methyl bromide.

However methyl bromide also has disadvantages. The gas contributes to the breakdown of the ozone layer, and its use is therefore undesirable from an environmental point of view. Most industrialised countries now accept this, so the use of methyl bromide is restricted, and will ultimately be prohibited.

As a consequence of this, there is now renewed interest in heat treatment as a method of killing insect pests in the milling industry. In recent years (since the mid-1980s), several articles have been produced on this topic. Sheppard (1984) gives a short but thorough introduction to earlier debates and emphasises important aspects of heat treatment. Heating has been tried out in recent years, particularly in the USA, but also in Germany and the Netherlands (Forbes & Ebeling 1987, Heaps 1988, Heaps & Black 1994, Heiss 1994, Teich 1994).

Heat treatment was also debated and tested in the USA from 1910 to the mid 1930s. This is well documented by Dean 1913, Goodwin 1922, Grossman 1931, Mellanby 1932, Pepper & Strand 1935 and Gunn & Notley 1936.

At this time methyl bromide came into use and the interest in heating diminished.

2 The project

In March 1995, Anticimex AS in Norway started a project to test heat treatment in practice. The project was called: **Heat treatment at the closed fodder factory at Moss, Norway.**

Anticimex AS in Norway has for a number of years been using methyl bromide in the Norwegian milling industry. A meeting held in Copenhagen 21 November 1994 to discuss alternatives to methyl bromide, under the auspices of the Nordic Council of Ministers (1995) gave us the necessary impetus to start working on the use of heat to control insects.

Regal Mill, Division Moss was interested in participating in the development of heat treatment as an alternative to methyl bromide gassing, and the firm had already been discussing this for some months.

Anticimex AB in Sweden had also been looking at heat treatment as an alternative to methyl bromide for several months.

The local Anticimex office in Fredrikstad, Norway, which was working on pest control at the fodder factory in Moss, was also very interested in the project.

The members of the project were as follows:

Development Manager Stein Norstein, Anticimex AS, Norway (project leader)
Technical Manager Jan Jungerstam, Anticimex AB, Sweden
Division Manager Kjell Utvik, Anticimex Fredrikstad, Norway
Technical Manager Olav J. Thorkelsen, Regal Mill Division Moss
Operating Manager Ole Sommerstad, Regal Mill Division Moss

The project was supported financially by the Norwegian Pollution Control Authority (SFT) and the Norwegian Milling Association.

I am grateful for all the help and support we have received during the project. I would particularly like to mention the staff at the mills Berte Quam, NordMills and Regal Mill, Moss who have all been interested and supportive. Likewise I wish to express my thanks to the Anticimex offices in Fredrikstad and Halmstad for their interest and the work they have put into the project. I would also like to thank the Anticimex Headquarters in Stockholm and Oslo for giving this project the priority and resources needed to it carry out. Last but not least, I am grateful to the Norwegian Pollution Control Authority and the Norwegian Milling Association for their financial support and their interest in the project.

I would like to express my thanks to the rest of the project group for their hard work and enthusiasm.

3 Material and methods

3.1 Review of the literature

At the beginning of the project, earlier literature was reviewed to collect information about earlier experiments involving heat treatment, the equipment and methods used, the temperatures achieved and temperature tolerance in insects.

3.2 Heating method and heating equipment

Various techniques have previously been used to heat buildings. Steam radiation using high-pressure steam has been tried (Goodwin 1922) with success. More recently, electricity (Heaps & Black 1994) and gas (Ebeling 1994) have been used in heat treatment.

A central question is whether the building should be heated from both inside and outside. Heating from outside as well warms the exterior walls through in a much shorter time. This is done in heat treatment against termites and other structural pests (Ebeling 1994). However, heating the outside requires wrapping a tarpaulin around a mill building , which is an expensive and cumbersome procedure.

Even if the building is heated only from the inside external insulation would be a great help. But again, this is expensive for a large mill building.

We chose to heat the building from inside only, without using extra insulation outside.

We chose a small oil burner for our project. According to the supplier, it had an air capacity of 10 000 m^3/hour, and delivered 375 000 kcal/h (=427 kW). It weighed 350 kg and measured 2500x1000x1800 mm (LxBxH). See appendix 2.1.

The heater produced hot air as a mixture of exhaust from the oil burner and fresh air.

We equipped the oil burner with smooth piping of 380 mm diameter.

3.3 Temperature and data logger

For measurement logging, we chose an analogue data logger. It was equipped with 50 analogue entries, each of them could be used for different analogue inputs and thus store the measurement we wanted. The logger could be programmed beforehand, and all measurements were stored in the logger for later reading. The logger also had a built-in printer and alarm output. When the measurements were completed, the data were transferred to a computer for further processing. See appendix 2.2.

3.4 Temperature measurements

We used copper/constantan (type T) thermocouples for most temperature measurements. These were connected directly to the data logger.

In addition, we used glass thermometers for some measurements at Berte Qvarn, some temperature strips (Thermoscan strips 40-71 °C) at Nordmills and Moss, and an infra-red radiation meter at Moss.

3.5 Gas measurements

The following gases were measured continuously at Moss: carbon monoxide, carbon dioxide and oxygen. Air was extracted from the heated room and measured in the control room by means of a Dräger Multiwarn, and the results fed to the logger continuously. The Multiwarn was programmed to give an alarm if the levels of carbon monoxide or carbon dioxide were too high or if the oxygen level was too low.

3.6 Other measurements

Relative humidity (RH) and the air flow from the heater into the building were measured at Moss and fed to the logger.

4 Literature and results of the practical tests

4.1 Temperature tolerance of buildings and equipment

Teich (1994) reports several problems due to high temperatures and low humidity; sifters burst, wooden floors warped, and a stand of rollers moved out of position as a result of high tension in the driving belts. These problems, he said, would be solved by using a lower temperature, that is 69 °C.

Heaps & Black (1994) report that two computer cards were broken when they heated a dry mix area in a food plant.

The PVC-insulated cables for mains electricity are approved for temperatures up to 70 °C. Above this temperature the cables soften, and if they are under pressure, this can cause disposition of the conductors and possibly short-circuiting. Short-term exposure to higher temperatures does not usually cause damage, but under high mechanical pressure there is a greater risk of damage. If heat treatment is carried out at higher temperatures, one may be held responsible for later damage and fires caused by short circuits.

In conclusion, 70 °C should be the natural upper limit for standard equipment and buildings during heat treatment. If higher temperatures are to be applied, a written declaration of responsibility and documentation of heat tolerance should be provided.

The AOM Food Protection Committee (1990) has issued a checklist for heat treatments that should be consulted.

4.2 Temperature tolerance of insects.

4.2.1 Temperature tolerance of different species

Grossman (1931) made thorough studies of three insects, *Tribolium castaneum*, *Sitophilus oryzae* and *Cathartus quadricollis* (all adults). He ran series of tests on insects in test-tubes in water baths using different exposure times, and provided data on the maximum temperature/time exposures these insects can tolerate.

From his results it can be seen that the hardiest insect of the three is *T. castaneum*, except at 51 °C where *S. oryzae* survived for a few minutes longer. For *T. castaneum*, 5 minutes at 51 °C killed all insects. At 50 °C, they were dead after 15 minutes. The following table gives the time needed to kill the different insects:

	43 °C	44 °C	45 °C	46 °C	47 °C	48 °C	49 °C	50 °C	51 °C
T. castaneum	62 hrs	50 hrs	11 hrs	6 hrs	4 hrs	60 min	30 min	15 min	5 min
S. oryzae	16 hrs	5 hrs	3 hrs	2 hrs	90 min	30 min	30 min	10 min	10 min
C. quadricollis	5 hrs	2 hrs	60 min	30 min	10 min	5 min	-	-	-

Table 1:
Temperature tolerances of *T. castaneum* , *S. oryzae* and *C. quadricollis*. At the specified times and temperatures, all test insects were dead. After Grossman (1931).

Forbes & Ebeling (1987) tested four other insects, *Blattella germanica* (adult male), *Tribolium confusum* (adult), *Incisitermes minor* (nymphs) and *Iridomyrmex humilis* (adult). Their results were quite similar to Grossman's, see table 2.

	46 °C	48 °C	51 °C	54 °C
B. germanica	58 min	27 min	16 min	7 min
T. confusum	123 min	16 min	9 min	4 min
I. minor	265 min	33 min	10 min	6 min
I. humilis	8 min	4 min	2.5 min	1 min

Table 2:
Temperature tolerances of *Blattella germanica*, *Tribolium confusum*, *Incisitermes minor* and *Iridomyrmex humilis*. At the specified times and temperatures, all test insects were dead. After Forbes & Ebeling (1987).

Oosthuizen (1935) investigated heat resistance in *Tribolium confusum*. In contrast to Grossman, Oosthuizen worked with LD_{50} values. LD_{50} values give the temperature and time needed to kill half the insects present. As there is often extreme variability of the tolerance in living organisms, LD_{50} values are more satisfactory for comparison between different insects and heat treatment regimes.

Oosthuizen made a thorough study of several parameters, and obtained results quite similar to those of Grossman and Forbes & Ebeling. Extracts of his results are presented in table 3.

	44 °C	46 °C	48 °C	50 °C	52 °C	54 °C	56 °C	58 °C	60 °C
Time (LD_{50})	7.4 hrs	64 min	29 min	290 sec	175 sec	137 sec	112 sec	92 sec	59 sec

Table 3.
Temperature tolerance of *Tribolium confusum*. The times specified are those needed to kill 50% of the insects. After Oosthuizen (1935).

In figure 1 we have combined the results of Grossman and Forbes & Ebeling. By plotting the natural logarithms of exposure times against temperature, we obtained curves of the maximum exposure time required to kill all individuals of each species that were close to straight lines. In this diagram, we also see that *T. castaneum* and *B. germanica* are the most heat-resistant insects in this temperature interval.

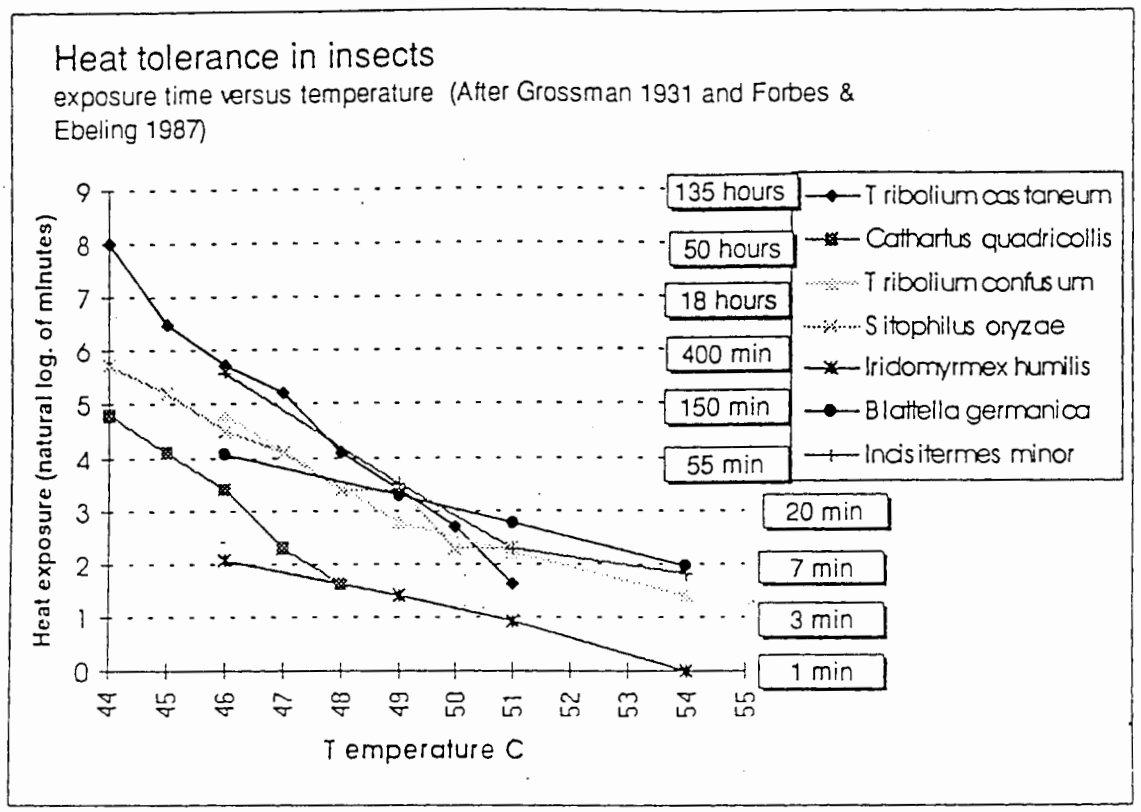


Figure 1.
Heat tolerance of insects according to the findings of Grossman and Forbes & Ebeling. The X-axis shows the temperature in °C, while the Y-axis shows the natural logarithm of the exposure time in minutes.

Fields (1992) reviews earlier work on extreme temperatures. According to him, Kirkpatrick & Tilton (1972) ranked the insects in the following groups according to their heat resistance at 49 °C:

Most resistant — Least resistant

Lasioderma serricorne
Cryptolestes pusillus
Rhyzopertha dominica
Sitophilus oryzae
Tribolium castaneum
Trogoderma variable
Sitophilus granarius
Gibbium psylloides
Cathartus quadricollis
Oryzaeophilus mercator
Tribolium confusum
Oryzaeophilus surinamensis

Oosthuizen (1935) ranked insects as follows, from the most heat-resistant to the least:

Most resistant — least resistant

Rhyzopertha dominica
Tribolium castaneum
Tribolium confusum
Tenebrio obscurus
Tenebrio molitor
Sitophilus granarius
Sitophilus oryzae
Cathartus quadricollis

From this we can see that at least three insects are ranked as more heat-resistant than *Tribolium castaneum*, i.e. *Lasioderma serricorne, Cryptolestes pusillus* and *Rhyzopertha dominica*. Fields states that temperatures used to control immature *R. dominica* will control virtually all other species. However, in the literature cited by Fields, the methods and temperature intervals are not easily compared with those used by Grossman and Forbes & Ebeling. Kirkpatrick & Tilton state that *R. dominica* dies after 96 hrs at 43 °C, which is 1.5 times the exposure time for *T. castaneum* at the same temperature.

4.2.2 Heat tolerance of different development stages

The above results are based on adults.

Grossman also tested heat resistance in different development stages of *T. castaneum* at 49 °C. He showed that eggs and adults were both killed in 30 minutes, whereas larvae could stand the heat for 45 minutes and pupae for 180 minutes. His results are shown in figure 2. Grossman also stated that none of the pupae heated for an hour or more developed into vigorous adults.

Similar results, he says, were obtained from a comparative test done at 45 °C.

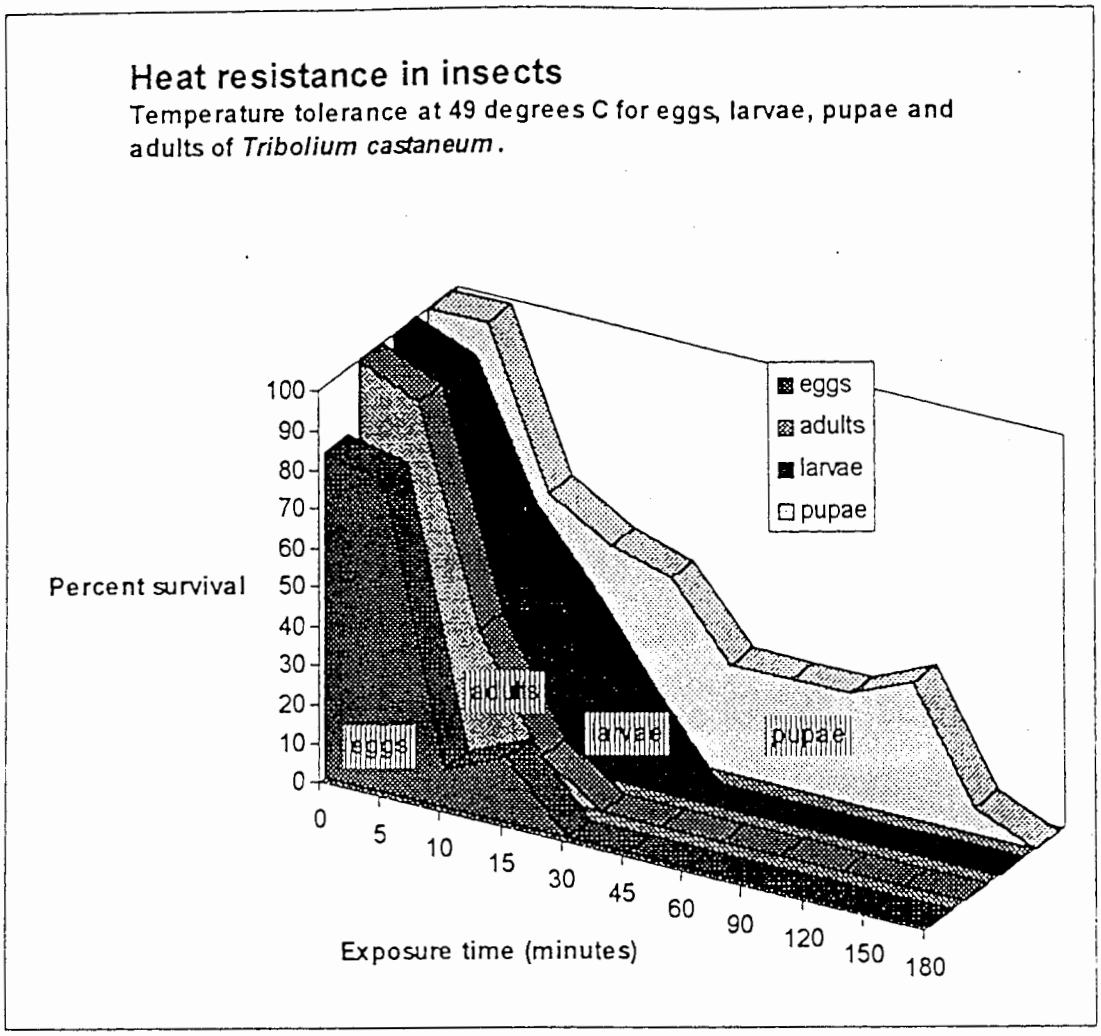


Figure 2.
Heat resistance of different developmental stages of *Tribolium castaneum*. Percentage survival is plotted as a function of time (minutes). After Grossman (1931).

Oosthuizen (1935) also found that pupae were the most resistant developmented stage at 44 and 46 °C, but that adults were most heat-resistant at temperatures of 48 and 50 °C, see table 4:

	Eggs	Larvae	Pupae	Adults
44 °C	14 hours	10 hours	20 hours	7 hours
46 °C	72 min	60 min	90 min	72 min
48 °C	-	8 min	12 min	26 min
50 °C	-	4.7 min	4.5 min	4.9 min

Table 4
Heat resistance of eggs, larvae, pupae and adults of *Tribolium confusum*. LD_{50}-values. After Oosthuizen (1935).

As there are some differences of opinion between Oosthuizen and Grossman, I find it safer to follow Grossman, who says that the pupae are more heat-resistant than adults. According to his results, twice the time needed to kill adults should be used to kill pupae as well. See figure 3.

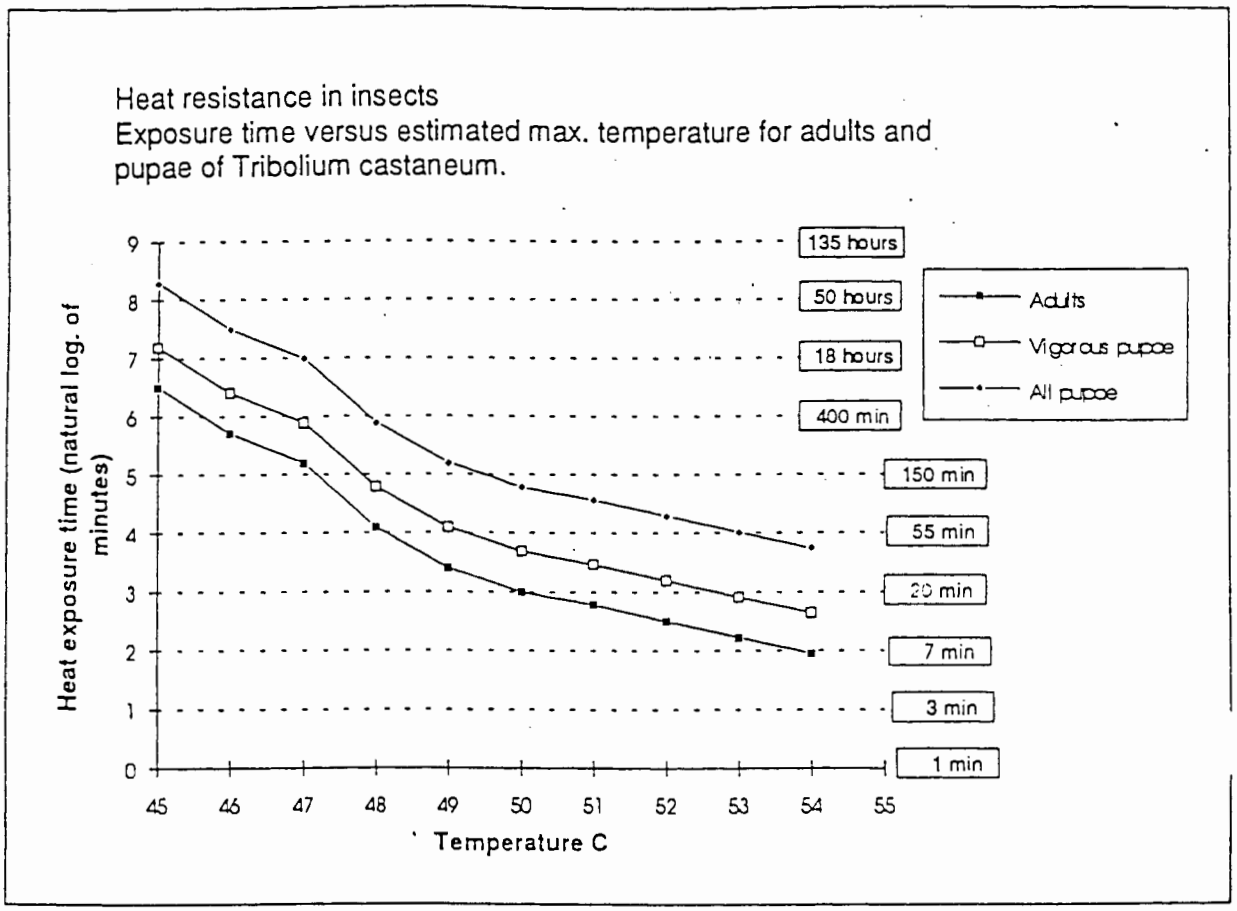


Figure 3:
Heat resistance in adults and pupae of *Tribolium castaneum* according to Grossman and in adults of *Blattella germanica* according to Forbes & Ebeling. For explanation, see table below.

	43 °C	44 °C	45°C	46 °C	47 °C	48 °C
Adults	62 hrs	50 hrs	11 hrs	6 hrs	4 hrs	1 hrs
Vigorous pupae	124 hrs	100 hrs	22 hrs	12 hrs	8 hrs	2 hrs
All pupae	372 hrs	300 hrs	66 hrs	36 hrs	24 hrs	6 hrs
	49 °C	50 °C	51 °C	52 °C	53 °C	54 °C
Adults	30 min	20 min	16 min	12 min	9 min	7 min
Vigorous pupae	60 min	40 min	32 min	24 min	18 min	14 min
All pupae	180 min	120 min	96 min	73 min	55 min	42 min

Table 5:
Heat exposure times. The row termed **adults** indicates the maximum exposure time needed to kill all adult insects in the experiments of Grossman (1931) and Forbes & Ebeling (1987). The row **vigorous pupae** indicates the time needed to enfeeble pupae of *T. castaneum* in the experiments of Grossman, interpolated over the whole temperature range. The row **all pupae** indicates the time needed to kill all pupae (after Grossman), also interpolated.

4.2.3 Influence of humidity on heat tolerance in insects

There has been some discussion of the influence of humidity on heat tolerance in insects, and the results obtained by different authors have varied.

Mellanby (1932) investigated four different insects, among them *Tenebrio molitor*. He found that on long-term exposure (24 hrs), some (small) insects died at lower temperatures in dry air than in humid air. In contrast, after one-hour exposure he found that other (larger) insects died at lower temperatures in humid air. Some insects were not affected by the humidity at all. Mellanby explained this by evaporation of water from the insects. Larger insects can lower their body temperature by evaporation in dry air for short periods (one hour). During long-term exposure (24 hrs), evaporation results in the loss of so much water, especially from smaller insects, that they die primarily of desiccation in dry air.

Gunn & Notley (1936), working on cockroaches, confirmed the results and conclusions reached by Mellanby.

Thus, if the heat treatment involves long-term exposure, drier air will lower the heat tolerance of some insects. However, as some insects, like *Tenebrio molitor*, are not affected by humidity during long-term exposure, there seems to be little to be gained by manipulating the humidity. The humidity will also differ from place to place depending on local moisture content of the surroundings.

I therefore view air humidity as an minor parameter with respect to the heat tolerance of insects in a practical heat treatment.

4.3 Our first trial - Berte Qvarn

Berte Qvarn is one of the oldest mills in Sweden, dating back to at least 1569. It is situated in southern Sweden in a rich farming area. Berte is a small mill, with an annual production of 19 000 tons flour. The owner, Anders Stenström, has for some years avoided the use of methyl bromide for environmental reasons. Berte Qvarn was therefore a suitable place to start testing heat treatment.

4.3.1 The test area and the aim of the test.

The test area chosen was the ground floor and first floor of the mill, containing roller stands, belts and machinery. This is a commonly infested area, and difficult to control without the use of methyl bromide. The two floors had a volume of about 1000 m^3, and the area of the concrete outer walls was 630 m^2.

The main aims of the test were as follows:

To familiarise ourselves with the equipment.
To test the temperature equipment before selecting a particular type.
To reveal practical problems we could not foresee.
To familiarise ourselves with the heating process.
To document the process.

4.3.2 Preparations and set-up

Prior to the heat treatment, the roller stands and remainder of the test areas were thoroughly cleaned. The test area was sealed off with plastic and tape in the same way as for a methyl bromide treatment.

The heater was placed outside, with a duct leading into the first floor. Here the duct split in two branches, one covering the first floor and one pointing downwards to the ground floor. These floors were not completely separated, so air could pass between them.

Teich (1994) reported problems with belts etc. when using high input temperatures at the Meneba mill in the Netherlands in 1994, and recommended that the temperature of the input air should not exceed 69 °C. We therefore agreed with the owner on a maximum input temperature of 70 °C.

There was no further air distribution other than the fan in the heater.

Twenty sites were selected for temperature measurements. There were thermocouples connected to the data logger at 10 of these, and glass thermometers at the other 10..

Sensors for the data logger were located as shown in table 6.

Sensor no.	Location
1	1m in front of duct where the hot air entered the room
2	Inside stand of rolls. Sensor placed in crevice beside roller, in contact with roller (metal temperature).
3	Air temperature, inside screw conveyor under flour container
4	Concrete temperature, 2 cm into crevice between concrete beam and concrete floor between ground and first floor.
5	Air temperature 1st floor, first 50 cm above floor , after 21:30 hours 150 cm above floor
6	Air temperature 1st floor, 0.2 cm above floor.
7	Air temperature in pneumatic transport tube above stand of rolls (above sensor 2)
8	Air temperature in crevice between basement of motor and concrete floor, ground floor
9	Air temperature inside electrical cupboard in corner, 1st floor
10	Temperature on electrical cables hanging 50 cm down from roof, 1st floor

Table 6:
Location of sensors at Berte Qvarn.

Glass thermometers were placed in wooden beams, on sacks of flour etc. However, during the heat treatment one of the glass thermometers on a roller stand was broken, and it was decided to remove all glass thermometers to avoid further contamination with glass. All readings from glass thermometers are therefore omitted.

Live insects in plastic boxes were placed around the test area to check the effect of the treatment. There were five samples of adult *Ephestia kuehniella*, one sample of larvae *Ephestia kuehniella*, one sample of larvae *Tribolium destructor* and one sample of adult *Tribolium destructor*. The samples were placed close to temperature sensors.

4.3.3 The treatment

The treatment started at 06:30 hours on 21 June. The heat was turned off at 09:00 hours on 22 June, as the mill was to start production again later that day. Temperatures were measured until 10:30 hours.

The starting temperatures in the test area varied from 16 to 20 °C.

The input air temperature very soon rose to above 100 °C, and we had problems in keeping it low enough. At 21:30 hours we had to move the heater further away from the mill, thus increasing the heat loss from the duct before it entered the test area. This solved the problem for some time. At 05:00 hours the temperature rose above the 70 °C limit and varied between 68 and 78 °C.

During the test, we observed a considerable loss of hot air through the ceiling of the 1st floor. We also observed cold air entering through crevices near the door on the ground floor.

4.3.4 Results

Air temperatures, 1st floor:
Air temperatures were measured in two places on the first floor (upper floor). Sensor 5 was located 1 m above the floor and sensor 6 0.2 cm above the floor. The temperature curve is shown in appendix 4.2. From 22:00 hours till 9:00 hours, the temperature rose by 1.2 °C and 1.1 °C per hour at sensors 5 and 6 respectively. As can be seen from the curve, the temperature would have continued to rise for some time if the test had been continued.

Temperature inside equipment:
Sensors 2, 3 and 7 were placed inside equipment. The temperatures achieved varied by 17 °C (see appendix 4.3), entirely as a result of uneven distribution of the hot air.

Temperature in constructions:
Sensor 4 was placed between a concrete beam and a concrete floor that were heated from both sides. A temperature of 42 °C was achieved here, and the curve (appendix 4.4) indicates that lethal temperatures would probably be reached. The temperature was rising by 1.4 °C per hour at the end of the test. Sensor 8 was placed on the ground floor, in a corner away from the air stream from the duct, and positioned in a crevice between a motor and the concrete floor. The temperature rose by 1.1 °C per hour, and would have reached 50 °C in a further 14 hours.

The eight samples of insects distributed around the test area were examined. The sample of adult *Tribolium destructor* reached a temperature of 60 °C and all the insects were dead. The larvae of *Tribolium destructor* were all alive at 35 °C. One box contained larvae of *Ephestia kuehniella*, which were still alive at 35 °C. The other 5 boxes all contained adults of *Ephestia kuehniella*, and the results for those are shown in table 7:

Max. temperature	Number of insects	Dead insects	Percentage dead
35 °C	6	1	17 %
40 °C	6	3	50 %
42 °C	5	2	40 %
45 °C	4	4	100 %
47 °C	4	4	100 %

Table 7:
Five samples of adult *Ephestia kuehniella* at different places during heat treatment at Berte Qvarn. Only maximum temperatures were noted.

4.4 Second trial - Nordmills Uppsala

The mill Nordmill in Uppsala, Sweden, produces wheat and rye flour. Annual production appr. 115 ooo tons flour. The mill has not been using methyl bromide for some years, and has a splendid hygiene.

4.4.1 The test area and the aim of the test

The mill has experienced insect problems in roller stands of older models which are difficult to clean properly.

One row of six of these roller stands was chosen for treatment. This row was on the first floor and easy to reach from the ground.

The aim of the test was to see if it was possible to carry out a spot treatment with heat by building a tent around the roller stands and heating this up to the necessary temperature in a short time.

4.4.2 Preparations and set-up

The roller stands were carefully cleaned by employees at the mill.

The duct from the heater was led to the roller stands where it split into two. One duct ran along each side of the row, with a side branch to each roller stand blowing air directly into the stand. See appendix 5.1.

A tent of heat-resistant tarpaulin was erected around the row of roller stands and the ducts. All the incoming hot air blown into the stands of rollers leaked out wherever possible, either into the tent or through conveyor spouts out of the tent. See appendix 5.2.

The tent measured approximately 16x3x2 m = 96 m^3.

The temperature sensors were located as shown in table 8:

Sensor no.	Location
1	In the hot air where it enters the tent
2	Roll stand no 1, in the rolls
3	Roll stand no 1, in spout
4	Roll stand no 1, base
5	Roll stand no 1, hole for light
6	Roll stand no 4, hole for light
7	Roll stand no 6, entrance of electrical wire
8	Roll stand no 6, in the rolls
9	Roll stand no 6, in spout
10	Roll stand no 6, in hole for light

Table 8:
The positions of temperature sensors at Nordmills.

17 temperature strips were placed at all levels from the basement to the 6th floor and outside the tent on the 1st floor, but in contact with the stands of rollers via spouts, conveyors etc., see table 9.

19 plastic boxes containing *Tribolium destructor*, *Trogoderma sp.* and *Oryzaephilus surinamensis* in rolled oats were marked with irreversible Thermoscan strips and placed as shown in tables 10, 11 and 12.

4.4.3 The treatment

The heater was started at 15:00 hours on 4 August 1995 and shut off 4 hours later, at 19:05 hours. The input air had an average temperature of 92 °C during this time, see appendix 5.3.

4.4.4 Results

During the four hours all the sensors showed that temperatures above 60 °C were achieved for more than an hour, see appendix 5.3.

Table 9 shows the temperatures recorded by Thermoscan strips in different parts of the mill.

Fl	Location	temp	fl	Location	temp	fl.	Location	temp
6	Filter 3	40	2	Spout C4	54	1	Roll stand C9	71
4	Sifter C 13	40	2	Spout B5 gr	-	1	Roll stand C12	71
4	Sifter C6	40	1	Roll stand C4	71	bas	Spout B5 gr	-
4	Sifter C12	40	1	Roll stand B5	71	bas	Spout B4 f	46
4	Sifter C7	46	1	Roll stand C7	71	bas	Spout C8	40
4	Sifter C4	46	1	Roll stand C8	71			

Table 9:
Temperature shown by thermo strips on equipment outside the heated tent, but in contact with heated equipment. Fl = floor, temp = temperature, bas = basement.

Tables 10, 11 and 12 shows the results for insects placed in the heated area. The maximum temperature for each sample of insects is also indicated.

Tribolium destructor larvae			*Tribolium destructor* adults		
location	temperature	dead/total	location	temperature	dead/total
Roll stand 1, floor	54	5/5	Roll stand 2, floor	54	5/5
Roll stand 5, floor	60	5/5	Roll stand 1, rolls	60	5/5
Rolls	65	5/5	Rolls	65	5/5
Roll stand 4, air inlet	65	5/5	Roll stand 1, air inlet	71	5/5
Roll stand 5, air inlet	71	5/5	Roll stand 2, air inlet	71	5/5
Roll stand 6, air inlet	71	5/5			
Control		0/5	Control		0/5

Table 10:
Effect of heating on larvae and adults of *Tribolium destructor*. Temperatures measured with temperature strips. The control groups were placed in an adjacent room at ca. 20 °C. All insects dead except for control groups.

Trogoderma sp.	larvae	
location	temperature	dead/total
Roll stand 3, floor	60	5/5
Roll stand 6, floor	65	5/5
Rolls	65	5/5
Rolls	65	5/5
Roll stand 3, air inlet	71	5/5
Control		0/5

Table 11:
Effect of heating on larvae of *Trogoderma sp.* Temperatures measured with temperature strips. All insects dead except for control groups.

Oryzaephilus surinamensis larvae			*Oryzaephilus surinamensis* adults		
location	temperature	dead/total	location	temperature	dead/total
Roll stand 4, floor	65	3/3	Roll stand 4, floor	65	3/3
			Floor	54	5/5
			Rolls	71	5/5
Control		0/5	Control		0/5

Table 12:
Effect of heating on larvae and adults of *Oryzaephilus surinamensis*. Temperatures measured with temperature strips. All insects dead except for control groups.

4.4.5 Delayed effects

After four months, the mill has not detected technical problems in the row of roller stands heated, in [illegible] of the high temperatures used.

Insects have been much less of a problem than in another, unheated row of roller stands of the same type.

Thus the mill is highly satisfied with the treatment.

4.5 Third trial - Regal Mill, Division Moss

Regal Mill, Division Moss in Norway mainly produces oats (annual production 10 000 tons), cereal products (müsli) (2000 tons), rice (2000 tons) and wheat/barley (2000 tons). The mill formerly produced considerable amounts of animal fodder as well.

4.5.1 The test area and the aim of the test.

Fodder production discontinued in 1990, and since then the fodder production buildings have been left unused. Product remains have resulted in considerable insect problems in parts of these buildings. This was a suitable area for heat treatment, and since there was no production, we were free to chose the time and day for our experiment. As this is a production site, we expected to meet many problems that are common for the whole industry. A lot of insects were present, but we were not dependent on the success of the treatment.

The fodder factory consists of two buildings, with stairs serving both buildings in the middle. The older building measures 19x14m and is 32 m high (volume 8200 m^3), and consists 25 wooden containers, together with machinery, elevators, spouts, conveyor bands etc. The newer building measures 19x19m and is 37 m high (volume 12 000 m^3) and contains a storage system for sacks, in addition to some other containers and machinery.

The numbers of insects in the buildings were counted in the period June-August. This was done by setting delta traps for meal moths and traps for crawling insects in addition to making visual inspections.

The following insects were registered prior to the heat treatment:

Dermestes lardarius
Ephestia kuehniella
Fannia canicularis (?)
Hofmannophila pseudosprettella
Ichneumonidae
Nitidinea fuscipunctella
Ptinus tectus
Stegobium paniceum
Tenebrio molitor
Tineola bisselliella
Tribolium castaneum
Tribolium confusum

In addition dead house sparrows (*Passer domesticus*) and dead great tits (*Parus major*) were found.

In choosing the size of the test area, we had to consider the capacity of the heater, which delivered 10 000 m^3 air/hour. The same amount of air has to leave the building, now cooled to 70 °C (this is in the steady state phase). This represents an energy loss of 210 kW. In addition, 8 kW would be lost through the 4 m piping outside the target area, given the diameter used and a temperature of 140 °C. Since the heater delivered 427 kW, this leaves 209 kW. The fodder factory had concrete outer walls and floors 150 mm thick. This gives a heat loss of 240 W/m^2. This means that our heater had the capacity to heat 870 m^2 of outer walls and floors in the steady state phase.

We chose to heat the basement of the older building, which measured 19x14x4 m (LxBxH), giving us 796 m^2 outer walls , floor and ceiling. In addition we chose an empty wooden container. This was one of the central containers, and was 2x2 m square and 14 m high. The containers were separated by 2.5 inch thick wooden planks. The container was partly divided into two by an internal wooden wall

Typical insects in this part of the building were *Ptinus tectus, Tenebrio molitor, Ephestia kuehniella, Tineola bisselliella* and *Tribolium castaneum.*

The aim with the final test at Moss was to:

1 Try out the equipment in a larger scale real life situation

2 Reach killing temperatures in the selected area

3 With as little preparation as possible, collect experience of the precautions that should normally be taken beforehand.

4. By choosing the ground floor, see what maximum temperatures could be expected here.

5. Count insects before and after the heat treatment to evaluate the effect.

6. Collect a range of technical information on the heating process for later review.

4.5.2 Preparations and set-up

Together with employees at the mill we sealed off the test area. Windows were covered with plastic on the outside to lower the thermal loss. The wooden containers were all sealed off at the top and bottom, except the one we wanted to heat. Screw conveyors leading out of the test area were dismantled and sealed. Most elevators and spouts leading out of the test area were closed at the bottom. For the rest, openings at floor level were left open and tested with a smoke generator during heating to confirm that the hot air went into the equipment. Holes in the ceiling were covered with plastic weighed down with sand.

The heater was placed just outside the test area, and ducts were taken in through a window. Inside the building the duct branched in two. One branch pointed straight ahead with 12 m free space in front to let the input air cool down when mixing with the air of the room. The other branch was directed into the wooden container from the underside, leading the hot air upwards.

Four fans were used to distribute the hot air around the room, each with a capacity of 2050 m^3/hour.

Temperature measurements were made with thermocouples and Thermoscan paper.

31 channels of the logger were temperature sensors used to document the result. Temperatures were logged every 10 minutes: (For more accurate positions and numbers, see appendix 6.2.)

* 10 sensors were placed on/inside/under equipment on the ground floor.
* 4 sensors were positioned to measure air temperatures, three as far away as possible from the incoming air, 30 cm under ceiling, 5 cm above the floor and 150 cm above the floor. The fourth was chosen as air reference temperature inside. 1 sensor was placed in the middle of the room, by the humidity sensor.

* 7 sensors were placed to monitor construction temperatures on the floor, outside walls, internal walls and ceiling.
* 9 sensors were placed in the wooden container, at the top, middle and bottom, in air and wood.
* 1 sensor was placed 20 cm inside a sack of flour, which was placed on the floor in the coldest area (farthest away from the incoming air).

14 of the logger's channels were used to monitor and document the process:

* 4 channels (temperature sensors) were used to control the mixing of the input air with the room air, ensuring that the air in contact with equipment did not rise above 70 ° C.
* 2 channels (temperature and air volume) were used to calculate the effect of the heater and the amount of energy entering the building.
* 3 channels (temperature sensors) were used to monitor the direction of air leakage, and were placed at the bottom, middle and top of the ground floor. The sensors measured temperature in the middle of a narrow tube going through the outer wall. The temperature in this leak tube showed whether cold air was entering the building or warm air was leaving it.
* 1 sensor monitored the outside air temperature
* 3 channels measured gases inside the building, CO_2, CO and O_2.
* 1 channel measured the relative humidity in the room.

4.5.3 The treatment

We started up the heater on Tuesday 20 September about 12:30 hours. At first, we set the temperature of the heater at 120 °C. This gave us a working air temperature (sensor 36) of around 40 °C in the beginning. The rise in temperature was 2.6 °C per hour (sensor 12 = reference air temperature). These temperatures are well below the working air temperature of 70 °C and the maximum temperature rise per hour of 6 °C which is recommended as a maximum (Teich 1994). The heater temperature was then raised to the maximum, and was about 140 °C from 16:00 hours.

After the heater was started, we spent some time in checking the sealing of the test area. There were leakages especially into wooden containers other than the one being treated, and into the elevators. The wooden container that was heated was also difficult to seal at the top. Leaks were detected with smoke bulbs and tablets, and by an air velocimeter.

4.5.4 Results

4.5.4.1 Conditions during the test

As it was the second half of September , the weather was cool. The temperature ranged from 5 °C at night to 16 °C in the daytime, which is ten degrees lower than on a warm summer's day. The average outdoor temperature during the heating period was 11.5 °C.

4.5.4.2 Result of the sealing of the test area.

The crucial factor when sealing the heated area is to ensure that the volume of air leaking out is equal to that of the input air from the heater. If the air leakage is greater than the hot air input, additional air has

to enter the area, and this will be cold, outside air. This air will enter at the bottom, making it impossible to heat up the lower part of the test area.

From appendix 6.17, we see that for the first few hours, air flowed out of the lowest leak tube (37). After 7 hours it seems that the air pressure dropped, and the leak temperature settled midway between the indoor and outdoor temperatures. It stayed in this intermediate position for the rest of the treatment period, following both indoor and outdoor temperatures. We conclude that the sealing worked fairly well.

4.5.4.3 The heat treatment
The actual heat treatment ran smoothly.

The heater supplied input air with an average temperature of 138 °C, that is 126 °C above the outside temperature. The input air volume was 6500 m³/hour on average. The average indoor temperature (sensor 12) was 55 °C (averages are based on a 29-hour period).

Total energy used during the heat treatment was 9400 kWh.

4.5.4.4 Gas measurements
Carbon monoxide, carbon dioxide and oxygen levels were measured. All three gas measurements were linked to an audible alarm that sounded if the gas concentrations reached hazardous levels. As it was the heater that could cause deviations from normal gas concentrations, the gas sensors were placed approximately 6 m in front of the hot air inlet, where the highest concentrations would be found.

Most crucial was carbon monoxide. In a process where exhaust is led into a working area there will always be a possibility of dangerous levels of this highly toxic gas. The results show a slight rise in CO values, from 2 to 5 ppm, see appendix 6.13.

The carbon dioxide concentration is also interesting, since high levels can be fatiguing, and even toxic. Insects will also be affected, so that a rise in the carbon dioxide level is not entirely undesirable. The level reached was the same as calculated beforehand, 0.7 per cent by volume (See appendix 6.14)

Oxygen was also measured. The results here showed very little deviation from normal, more than 21 per cent. (Appendix 6.15)

4.5.4.5 Air humidity
Relative humidity in the inside air was not recorded during the first 10 hours due to wiring problems. After this stage, the relative humidity was down to 10% and fell further to 5%, see appendix 6.12. After the treatment the humidity increased to 25% during the next 12 hours.

The building was cold, unheated and located near the harbour, and the relative humidity would therefore be expected to lie between 70 and 80% at the beginning of the heat treatment. Given a starting temperature of 12 °C, this corresponds to 7 g water/kg air. The figures for humidity and temperature 10 hours after start indicate that the air contained 10 g water/kg air. The extra 3 g/kg air water comes from exhaust gases from the heater. In addition, a large amount of water was transported out of the walls during the heating (and drying) process.

4.5.4.6 How hot was it?
[illegible] showed very different maximum temperatures. Appendix 6.3 shows the hourly

The temperature curves for sensors in concrete constructions are shown in appendix 6.6. They follow each other fairly closely, but with small differences in the rate of increase, from 0.6 °C/hour for sensor 14 to 1.2 °C/hour for sensor 15. Sensor 15 reached 54 °C and sensor 14 reached 41 °C.

Temperatures in equipment were monitored in several places. The results show that metal equipment readily absorbs heat and becomes very hot inside. The sensors in equipment showed maximum temperatures from 56 °C to 73 °C, see appendix 6.7. The highest temperature rise was 7.7 °C/hour.

In the empty container that was heated, the highest temperature in the wood varied from more than 80 °C in an internal partition heated from both sides (21) to 46 °C in an exterior wall 4 m above the bottom (22). See appendix 6.8.

4.5.4.7 Temperatures in products and under articles.
Temperatures were compared in an empty conveyor belt and in a conveyor belt filled with products (see appendix 6.9). While the empty conveyor (4) reached a temperature of more than 60 °C, the temperature in the filled conveyor (3) never rose above 47 °C.

The sensor in a sack of flour (30) never showed a temperature above 30 °C.

An infra-red temperature meter was also used for some measurements of surface temperatures.

On the floor in uncovered culverts, the temperature was as low as 32 - 34 °C in the least exposed spots, and the concrete was quite humid. The same temperature was recorded in parts of a culvert with an earthern floor. In such places, there were active *Tenebrio molitor* that did not appear to be affected by the temperature.

The temperature in open areas of the concrete floor of the basement was 44 to 49 °C at the end of the treatment, and no live insects were found in such areas then.

However, a number of insects, particularly *Ptinus tectus* and *Tenebrio molitor*, were found under different types of rubbish, equipment etc. on the floor, where temperature of 39 to 41 °C were recorded. The insects here were obviously bothered by the heat, and had gathered in the coolest place they could find. When the rubbish they were hiding under was removed, they all started wandering around looking for another shelter.

A few measurements gave the following insulation values:

The temperature was 7 °C lower on the floor under a plank of wood than on the floor next to it. Similarly, the temperature was 4-5 °C lower on the floor under a cardboard sheet and 2-4 °C lower under a metal sheet.

In some crevices in the exterior walls at floor level, hundreds of *Ptinus tectus* were gathered. The insects looked quiet, but appeared to be hiding from the heat. The temperature was not measured here, but was probably quite low.

4.5.4.8 Cooling down
After 33 hours, the heater and its fan were turned off. The fans in the building were left working. The doors were kept shut, but outside air entered the building through the duct at a rate of 3000 m^3/hour. Temperatures were logged for a further 12 hours.

The measurements from sensors 2, 12, 15 and 27 are used to illustrate the cooling process (see appendix 6.16). During the 12 hours of cooling, the temperature drop recorded by these four sensors averaged 19.7 °C, or 1.6 °C/hour. During the last hour, the reduction in temperature ranged from 0.5 to 0.9 °C/hour. At this rate of cooling, the air inside (sensor 12) would have taken an additional 2.8 hours (14.8 hours in total) to cool down to 30 °C and 8.3 hours (20.3 hours in total) to reach 25 °C. In fact, the curves were levelling off, so that even more time would be needed. On the other hand, more ventilation could have been arranged for a faster cooling process.

4.5.5 Insect populations

Counting insects before and after treatment gives an indication of the result. Insects were counted by trapping them in the treated area and on the ground floor of the newer building that was not treated.

Days before/after treatment	Treated area *E. kuehniella*	Treated area crawling beetles	Untreated area *E. kuehniella*	Untreated area crawling beetles
72 days before	11	0	73	0
51 days before	7	6	> 300 **	4
29 days before	60	10	> 300 **	14
10 days after	1*	0	70	0
16 days after	0	0	37	1

Table 13
Result of insect catches before and after treatment. The first column shows catches of *E. kuehniella* in pheromone traps in the treated area. The second column shows crawling beetles caught in sticky traps, also from the treated area. The third column shows catches of *E. kuehniella* in pheromone traps on the ground floor outside the treated area (new building). The fourth column shows crawling beetles caught in the untreated area. The catch marked * was classified as from the untreated area because the doors between the treated and the untreated areas was open.

From the table it can be seen that the numbers of moths drop to almost zero after treatment. However, at this time of the year, low temperature restricts the growth of the moths, and the number of moths in the untreated area also dropped. On the other hand, if the lethal temperatures for *E. kuehniella* were not reached during treatment, the extra warmth should speed up its development for several days, accelerating pupae hatching etc. No contingency table test was performed on the material, as we do not know the exact numbers in the catches marked **.

In conclusion, the heat treatment had a good effect on moths in the treated area. For beetles, no effect could be seen from the catches. The results, however, are disturbed by the oncoming cold season.

As mentioned earlier, many beetles were observed in the treated area after the treatment but they were not caught in the traps.

5 Discussion

5.1 Temperature tolerance of building and equipment.

Generally, most equipment is made to withstand 70 °C. As 70 °C is the limit for many electrical conductors, it would be difficult to raise this limit. The trial at Moss showed that this should not normally be necessary.

However, in special situations it can be feasible to use higher temperatures, as we did at Nordmills.

After heat treatment at Meneba Mill in the Netherlands, Teich (1994) recommended that the temperature should lie between 65 and 69 °C.

Nevertheless, as shown at Moss, the input air can be much warmer than 70 °C if there is a sufficient cooling area in front of the duct, and the process is monitored to ensure that the air is cooled to 70 °C. At Moss, the input air had a temperature of 140 °C.

If the duct hangs freely in the room, the hot air will cool as it is blended with the cooler air in the room. Roughly we can say that Δt is halved at a distance of 5d in front of the duct, where Δt is the temperature difference between the input air and the air in the room, and d is the diameter of the duct. In our case, the diameter of the duct was 38 cm, the input temperature was 130 °C and the room temperature started at 20 °C. This gives us an air temperature of 75 °C 1.9 m from the outlet of the duct. Later, when the room temperature is 50 °C, the temperature of the air from the duct will be reduced to 90 °C at 1.9 m from the outlet of the duct. This is in accordance with our results in appendix 6.11.

If the heating process is carried out with an input air temperature in the range 70 - 80 °C, the amount of input air must be increased, thus increasing the air leakage. This means a greater energy loss, and reduces the effect of the heater. This in turn raises the cost of fuel and prolongs the time needed for the treatment.

Various items of equipment can not withstand 70 °C, for instance CO_2 fire extinguishers, sensitive computer parts, some automatic sprinkler heads etc. A thorough investigation should be made beforehand to locate these problems and find a way to deal with them.

When in doubt, the manufacturer should be asked about the heat tolerance of the equipment in question.

Some sensitive equipment can be sealed off, either with normal plastic or with insulating fabrics. As we have seen, very little cover is needed to lower the temperature. Sensors should be placed in such sensitive equipment to monitor the temperature.

The AOM Food Protection Committee (1990) has drawn up a "Heat sterilisation checklist" for practical use in heat treatments that should be consulted.

5.2 Temperature tolerance of insects

According to the literature cited in chapter 4.2, the following should be the minimum exposure times for a heat treatment (table 14):

	45 °C	46 °C	47 °C	48 °C	49 °C	50 °C	51 °C	52 °C	53 °C	54 °C
Min. exposure	22 hrs	12 hrs	8 hrs	2 hrs	60 min	40 min	32 min	24 min	18 min	14 min

Table 14: **Minimum exposure values**
Calculated minimum heat exposure time. Min. exposure means the minimum exposure time at the specified temperature needed to kill all adult insects in the experiments of Grossman (1931) and Forbes & Ebeling (1987) and to enfeeble pupae of *T. castaneum* in the experiments of Grossman.

The values are interpolated over the temperature range, based on the results of the experiments at 49 °C. In practice, temperatures below 45 °C make almost no contribution to mortality in a plant heating process, because of the length of time needed. Exposures above 54 °C should be treated as exposure to 54 °C.

I assume that the exposure times at each temperature can be added to give the total effect. Thus, as pupae are enfeebled by 60 min at 49 °C or by 24 min at 52 °C, I assume that they would also be enfeebled by being exposed to 30 min at 49 °C followed by 12 min at 52 °C, giving an effect of 100%. Thus, we can make a table of various temperatures and exposure times that can be combined to give 100 % mortality.

	45 °C	46 °C	47 °C	48 °C	49 °C	50 °C	51 °C	52 °C	53 °C	54 °C
Effect of 10 min	0.76%	1.4%	2.1%	8.3%	17%	25%	31%	42%	56%	71%

Table 15: **Effect of 10-minute dosage at different temperatures**
This table shows the killing effect of 10 minutes exposure at different temperatures, using the min. exposure values.

Table 15 shows the mortality caused by 10 minutes exposure to different temperatures. The lowest temperature in the time period should be used for the whole period. Adding killing effects presupposes that there has not been a period of cooling in between. The representativity of the sensor temperatures is crucial in this computation, and should be evaluated very carefully.

The minimum exposure values are based on experiments with *Tribolium castaneum* and *Blattella germanica*. A few insect are ranked as more heat resistant than *T. castaneum* and *B. germanica*, i.e. *Lasioderma serricorne*, *Cryptolestes pusillus* and *Rhyzopertha dominica*. However, I have not been able to find experiments on these insects in the relevant temperature range that could be used to improve the accuracy of the exposure values in table 14. The minimum exposure values could be altered if more information on these insects or additional information on heat tolerance on insects in general becomes available.

A safety margin should therefore be added to the minimum exposure values if they are to be used in practice. The inaccuracy of the measuring equipment should also be taken into account. The temperature logger we used had a maximum inaccuracy of 1.6 °C, which should be incorporated into

table 15. Adding a safety margin of 1 °C gives us the results shown in table 16, which I shall use as our ndard :

	47.6 °C	48.6 °C	49.6 °C	50.6 °C	51.6 °C	52.6 °C	53.6 °C	54.6 °C	55.6 °C	56.6 °C
Exposure time	22 hrs	12 hrs	8 hrs	2 hrs	60 min	40 min	32 min	24 min	18 min	14 min
10 min effect	0.76%	1.4%	2.1%	8.3%	17%	25%	31%	42%	56%	71%

Table 16: **Heat exposure times for practical use, and effect of 10-minute dosages.**
Proposed heat exposure times to be used in practice and necessary doses at different temperatures.

5.3 The heating equipment

One of the main investments in the heating method is the heating equipment. Several alternatives are available, e.g. gas or oil burners and electrical equipment. The burner can heat the air directly, by releasing the exhaust into the are to be heated, or indirectly, by heating up cold air and releasing the exhaust outside the heated area.

Our choice worked very well. The choice of an oil burner that heated directly meant that we had to control the exhaust entering the building. The exhaust should not be allowed to contaminate the factory or pose a hazard to the personnel involved in the heating process.

Chemicals that may be a problem in exhaust are sulphur, chlorine, vanadium, carbon monoxide, carbon dioxide, unburned hydrocarbons and ashes. It is therefore important to use a high quality fuel. Our choice of a low aromatic white spirit (Shellsol D 70) met these requirements.

The amount of carbon monoxide in the exhaust depends on the quality of the burner and how it is maintained. As this can be difficult to foresee, and the burning process can change suddenly, a carbon monoxide alarm is necessary if people are meant to enter the heating area during the process.

The heater was stated by the producer to have a capacity of 427 kW and 10 000 m^3air/hour. The results at Moss showed that we only obtained 300 kW and 7000 m^3air/hour from the heater. The reason for this will be investigated.

5.4 Temperature measurements

Temperature measurements are important to:

* monitor the heat treatment
* document the effect of the heat treatment

The data logger equipped with thermocouples worked very well, and provided excellent monitoring capacity. Alarms coupled to the incoming air, sensitive equipment etc. make monitoring easier.

The automatic logger is also effective for documenting the process, and allows far more temperatures to be read. The personnel inspecting the process can concentrate on other tasks than noting temperatures.

Temperature strips are cheap and convenient to use in many cases. However, they give no information on how long a temperature is maintained, thus limiting their usefulness.

An infra-red radiation meter is very useful during the heating process. It is easily used to measure the surface temperature, which is an important parameter. It was used to check the sensors during the process, to measure temperatures in places that were difficult to reach, to monitor over areas, and to add extra measurements. At the end of the process, it can be used to check critical areas and to define temperature boundaries.

Glass thermometers should be avoided due to the risk of glass pollution in the factory.

The most important element in a programme of documentation and quality assurance for the heating process is a sufficiently large number of temperature monitoring sites. If the same area is heated several times, it will be possible to learn where the cold areas are, and to monitor only those. But every change in setting, such as changes in the positions of heater, ducts, fans, target area or sealing can alter the temperature distribution and create new cold areas. Temperature monitoring should therefore never be reduced to routine measurements, but should be specially planned before every heat treatment and checked during the process.

5.5 Was the temperature high enough ?

By adding the effect of 10-minutes doses as set out in table 16, we can calculate the effect of the heat treatment at Moss.

Using this method gives the following results :

Location of sensor	Killing effect
15: 5 cm inside concrete pillar, 2 m above floor	720 %
18: 3 cm inside exterior concrete wall, 2 m above floor	12 %
20: between electrical cable and ceiling	0 %
10: between concrete floor and base of motor	0 %
17: 1 cm into concrete floor	0 %
14: on concrete floor in ditch 1 m below floor.	0 %

Table 17: Heat killing effect in concrete constructions

We see that the internal pillar (15) received 7 times as much heat as necessary, whereas the exterior wall (18) received only 12% of what was necessary. The sensor in the ceiling (20) recorded no killing effect. This was because a concrete beam in front of the sensor sheltered it from the hot air. The sensors in the floor and ditch showed areas where there had been no killing effect. As can be seen from the curves (appendix 6.6), killing effects could have been achieved at some of the sites (18, 20) if the heating had been prolonged. Nevertheless, the results show that the floor at the ground level and exterior walls can be difficult to heat sufficiently.

·ion of sensor	Killing effect
.ir inside elevator	10 583 %
1: air inside conveyor belt	9 838 %
4: air inside conveyor belt	6 242 %
16: air inside switch box	2 761 %
7: air inside empty product tank	1 555 %
9: air inside empty product tank	1 159 %
6: air inside elevator	583 %
3: inside conveyor full of products , sensor 20 cm into product	0 %

Table 18: Heat killing effect inside equipment

All sensors inside empty equipment showed that the temperatures climbed high enough (table 18). The exposure was from 5 times to 100 times what was necessary, giving us a good margin. However, for the sensor 20 cm deep into products (3) the temperature would have to be 4 °C higher to cause any mortality. (Appendix 6.7 and 6.9).

Location of sensor	Heat killing effect
28: air, 12 m above bottom (top of container)	13 377 %
21: in wood, partition wall inside container, 6 m above bottom	11 024 %
27: in wood, exterior wall 12 m above bottom (top)	9 363 %
23: in wood, exterior wall, 6 m above bottom	1 946 %
22: in wood, exterior wall, 4 m above bottom	0 %

Table 19: Heat killing effect in wooden container

In the wooden container, the effect was good nearer the top, but between 4 and 6 m above the bottom the effect was drastically reduced. Thus the upper two thirds of the container was satisfactorily treated whereas the heating had no effect on the bottom third. This is probably because colder air leaked through the wooden container walls from the neighbouring container. Even in the upper part, the temperature on the other side of the wooden wall was probably quite low (it was not measured). The solution to these problems is to treat all the containers at the same time. (Appendix 6.8).

5.6 Spot treatment

At Nordmills we performed a spot treatment ; in other words, we chose some machinery, covered it with tarpaulin and heated as necessary. In this way, small, infested areas can be treated for a few hours, and then put back into production. At Nordmills, this could possibly have been done during the night, or during two shifts.

The result at Nordmills was easy to assess. All 9 temperature sensors were hotter than 60 °C for more than 60 minutes (appendix 5.3), which would totally eradicate all insects in the target area, assuming that the sensors were correctly placed.

In this way, spot treatment can be a powerful tool in machinery and areas where chemical methods are impossible or inappropriate.

5.7 Air distribution

Hot air always rises. The results from Moss show that the effect can be very good in one place, whereas one or two metres below there is no effect at all. This can be solved partly with a good air distribution system.

There should be a system of fans, all blowing the same direction (clockwise or counter clockwise) and at the same time blowing the air downwards. In some cases, more fans are better than more heat. If only one part of a building is to be heated, the floors to be heated should be sealed off horizontally. It is far more difficult to heat a building satisfactorily if air can pass freely between the floors..

5.8 What should be done about low temperature areas?

Even if heat treatment is successful there will be areas where the temperature remains too low:

Heating the building from the inside without insulating the exterior walls means that it is difficult to heat the walls sufficiently. Even if the temperature is high enough on the inside of an exterior wall, small cracks and crevices can lead to areas in the wall which are cooler. Such cracks are the normal habitat of the insects.

Around windows and frames there can be considerable problems, especially if the windows are not sealed on the outside, as was done at Moss.

It is always difficult to heat the floor of the ground floor sufficiently.

There are often culverts on the ground floor, and electrical cables leave the building into the ground, harbouring insects around them.

Wet areas need much longer heating periods, and it can be difficult to reach killing temperatures in the time available.

Heat-sensitive areas cannot be heated.

Such areas must be treated in other ways. Normal chemical treatment can be quite acceptable in some of these areas, such as walls, floors, windows, culverts etc.

Machinery and food handling equipment cannot be treated with residual pesticides. Such places also frequently harbour insects. They are therefore the main target of the heat treatment. On the other hand, these are the first areas to be heated, and a successful heat treatment will solve the pest problem here. See chapter 5.6 Spot treatment.

5.9 Regal Mill, Moss - treating the whole building?

TechnoConsult has calculated the capacity and energy needed to heat up the whole building in the old fodder production unit. See appendix 3.

Treating the oldest part of it would require a heating capacity of at least 750 kW for at least 30 hours. The total amount of energy needed would be at least 22 000 kWh.

iting both the old and new part of the fodder factory would require a capacity of 1400 kW for a period of 50 hours. The required energy would be 70 000 kWh.

5.10 Economy

In the following table we have calculated the cost of the heat treatment at Moss, together with other alternatives.

	Our treatment	Old building, Moss	Whole building Moss	Heaps & Black 1994
Average outside temp.	11,5	11,5	11,5	17,5
Volume of building (m^3)	1500	8200	20000	10000
Heating time (hours)	30	30	50	24
Heater capacity (kW)	300	750	1400	500
Labour costs (hours)	130	180	240	208
Cost of goods (S 1995)	2300*	4000*	9000*	12000**

Table 20:
Comparison between the three alternatives at Moss and the heat treatment by Heaps & Black (1994). Labour costs include sealing, rigging, monitoring, guarding, unrigging and documentation. Cleaning and preparation done by mill staff is not included. Cost of goods includes fuel, thermocouple wire, equipment etc. For the figures marked *, the cost of heating equipment, fans and measuring devices is not included. The figure from Heaps & Black (marked **) includes rental of heating equipment.

The cost of a heat treatment will depend on several factors. The old building at Moss was easy to seal, as it was built with concrete poured on site. Other mill buildings could be constructed in ways that are far more difficult to seal.

On the other hand, the building in Moss was cold and humid, with no heating of its own. A mill that is in normal use will be dry, thus lowering the amount of energy needed. It will also be warmer to start with, and if it has some extra heating capacity, the need for external heating can be reduced.

This treatment was carried out in September, with an average outdoor temperature of 11.5 °C. A higher average temperature would reduce the energy needed.

Several authors state that heat treatment should be carried out several times a year. Sheppard (1984) suggests 6 times a year, Heaps (1988) says 6 to 7 times a year in a temperate climate. Although this advice may be based on experience, in theory there should be no need to use heat treatment more frequently than methyl bromide gassing. In heat treatment, all stages of insects are killed, and if care is taken to clean and empty the equipment, the heat penetration should be as effective as gassing. We should therefore aim to apply heat treatment as often as gassing, for which the normal frequency in Norway is once a year. On the other hand, heat treatment may be less efficient than gassing to start with, as a new method has to be learned and introduced.

5.11 Hygiene

Methyl bromide has a fair penetration ability. It probably penetrates several centimetres into products. Heat, on the other hand, does not penetrate easily into flour. There are two main reasons for this:

1 Flour is a good insulator.

2 When flour is heated, the heat first vaporise water in the flour, thus drying it out, before the temperature rises.

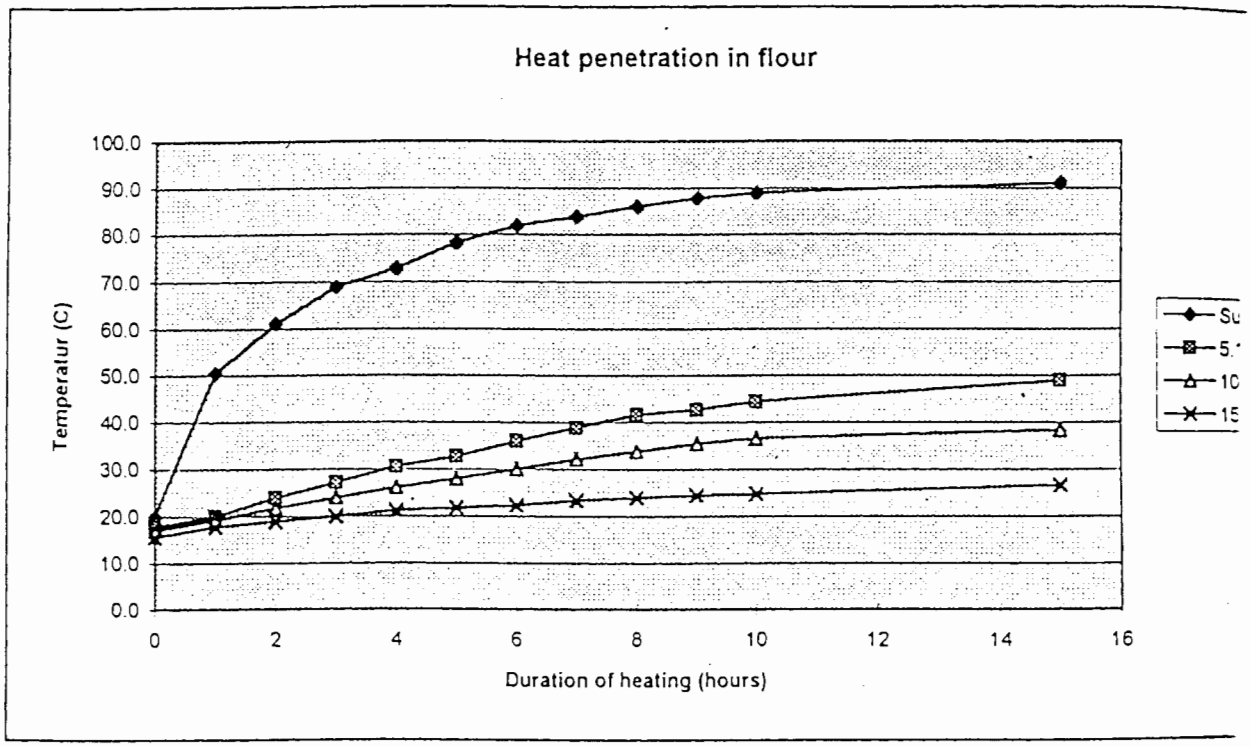


Fig 4:
The figure shows the time needed to raise the temperature in flour. The flour is spread on the floor, and thermocouples are placed on surface and at depths of 5.1 cm, 10.2 cm and 15.2 cm. The temperatures are recorded every hour. It can be seen that heat penetration in flour is extremely slow. After Pepper & Strand 1935.

Good hygiene is therefore an important aspect of heat treatment. All kinds of rubbish and product spills should be removed and areas cleaned. Sacks of flour etc. must also be removed. Silos, containers and tanks should be emptied and cleaned, as should elevators, conveyors and spouts.

6 Conclusions

6.1 Maximum input air temperature

The temperature of air that comes into contact with constructions and equipment should not exceed 70 °C . Above 70 °C there is a possibility of destroying electrical PVC cables, sifters, computer cards etc., and roller stands could be forced out of position by their belts. The AOM Food Protection Committee «Heat Sterilization Checklist» should be consulted.

Nevertheless, the temperature of the input air can be considerably higher than 70 °C if it is allowed to cool before it reaches any surfaces. Thus it was possible to work with an input temperature of 130 °C.

In addition, insulating tarpaulins etc. can be used to protect installations.

6.2 Minimum heat exposure time

A review of the literature showed that all stages of insects die after 22 hours at 45°C, 12 hours at 46 °C, 8 hours at 47 °C, 2 hours at 48 °C, 60 minutes at 49 °C, 40 minutes at 50 °C, 32 minutes at 51 °C, 24 minutes at 52 °C, 18 minutes at 53 °C or 14 minutes at 54 °C.

Allowing for an inaccuracy of 1.6 °C and adding a safety margin of 1 °C limit gives the following table:

	49.6 °C	50.6 °C	51.6 °C	52.6 °C	53.6 °C	54.6 °C	55.6 °C
Exposure time	8 hrs	2 hrs	60 min	40 min	32 min	24 min	18 min
10 min effect	2.1%	8.3%	17%	25%	31%	42%	56%

Table 21: **Heat exposure times for practical use, and effect of 10-minutes dosage.**
Proposed heat exposure times to be used in practice and necessary doses at different temperatures.

6.3 Scope and cost of the treatment

A spot treatment, i.e. building a tent around certain equipment and treating this area with heat can be carried out in a few hours with very good results.

With the right preparations and sufficient heating capacity, it is feasible to treat a whole building.

To start with, heat treatment will probably cost at least twice as much a methyl bromide treatment. The cost can probably be reduced once the method has been used several times, as it can be adapted to the premises and the equipment present, and there will be improvements of the technique.

6.4 Other comments

Hygiene is of great importance in heat treatment.

A good temperature registration system should be used to monitor the heating process and for later documentation.

Care must be taken to ensure that equipment and constructions can withstand the necessary temperature of 70 °C.

Necessary fire precautions should be taken.

Insurance companies should be contacted to assure the validity of fire and other insurances.

REFERENCES

AOM Food Protection Committee 1990: Heat Sterilization Checklist. In: R. Mills and J. Pedersen (edit): Flour Mill Sanitation Manual, Appendix D; 157-159.

Dean, G.A., 1913: Mill and stored-grain insects. *Kans. Agr. Expt. Sta. Bull. 189:* 140-236.

Forbes, C.F. and W. Ebeling. 1987: Update: use of heat for elimination of structural pests. *IPM Practioner 9(8):* 1-5.

Ebeling, W., C.F. Forbes and S.C. Ebeling. 1989: Heat treatment for powderpost beetles. *IPM Practitioner 11(9):*1-4.

Ebeling, W., 1994: The Thermal Pest Eradication System for Structural Pest Control. *The IPM Practioner 16(2):*1-7.

Fields, P.G., 1992: The control of stored-product insects and mites with extreme temperatures. *J. stored Prod. 28(2):* 89-118.

Grossman, E.F. 1931: Heat Treatment for Controlling the Insect Pests of Stored Corn. *Fla. Agr. Expt. Sta. Bull. 239:*3-24.

Goodwin, W.H., 1922: Heat treatment of cereal insects. *Ohio Agr. Sta. Bull. 354.* 1-18.

Gunn, D.L. and F.B. Notley. 1936: The temperature and humidity relation of the cockroach. IV Thermal deathpoint. *J. Exptl. Biology 13*:28-34.

Heaps, J.W., 1988: Turn on the Heat to Control Insects. *Dairy and Food Sanitation 8(8):*416-418.

Heaps, J.W. and Black, T., 1994: Using portable rented electric heaters to generate heat and control stored product insects. *Bull. Association of Operative Millers July:* 6408-6411.

Heiss, D., 1994: Einsatz von Heissluft zur Schädlingsbekämpfung in Mühlenbetrieben. *Die Mühle 10(März):* 122-123.

Imholte, T.J. 1984: Engineering for Food Safety and Sanitation. 219-226.

Madsen, B. 1994: Heat Treatment an alternative to Methyl Bromide Fumigation of Mills. In Alternatives to Methyl Bromide: TemaNord 1995(574):51-55.

Mellanby, K. 1932: The influence of atmospheric humidity in the thermal death point of a number of insects. *J. Exptl. Biology 9:* 222-231.

Mueller, D.K., 1994: Phospine, heat and carbon dioxide deliver death punch to insects. *Pest Control 62(3):* 42-48.

Nordic Council of Ministers, 1995: Alternatives to Methyl Bromide. *TemaNord 1995:574*, 1-67

Oosthuizen, M.J., 1935: The effect of high temperature on the confused flour beetle. *Minn. Agr. Expt. Sta. Bull. 107:* 1-45.

Pepper, J.H. and Strand, A.L., 1935: Superheating as a control for cereal-mill insects. Bull. Montana Agricultural Experiment Station no. 297, 26p

Sheppard, K.O., 1983: Heat Sterilization (Superheating) as a Control for Stored-Grain Pests in a Foodplant. *Insect Management for Food Storage and Processing 1983:* 193-200.

Teich, J.H., 1994: Hetluftsbehandling av lagerutrymmen som alternativ till användning av metylbromid. Translation of a speech?

Appendix 1

List of pests mentioned in the report

Scientific name	English name	Norwegian name
Blattella germanica	German cockroach	tysk kakerlakk
Cathartus quadricollis	Square-necked grain beetle	
Cryptolestes pusillus	Flat grain beetle	liten kornbille
Dermestes lardarius	Larder beetle	fleskeklanner
Ephestia kuehniella	Mediterranean flour moth	melmøll
Fannia canicularis	Little house fly	liten husflue
Gibbium psylloides	Hump spider beetle	rund tyvbille
Hofmannophila pseudosprettella	Brown house moth	frømøll
Incisitermes minor	Western drywood termite	
Iridomyrmex humilis	Argentine ant	argentinamaur
Lasioderma serricorne	Cigarette beetle	tobakksbille
Nitidinea fuscipunctella	Brown-dotted clothes moth	hønsehusmøll
Oryzaephilus mercator	Merchant grain beetle	sagtannet melbille
Oryzaephilus surinamensis	Saw-toothed grain beetle	sagtannet nøttebille
Parus major	Great tit	kjøttmeis
Passer domesticus	House sparrow	gråspurv
Ptinus tectus	Australian spider beetle	australsk tyvbille
Rhyzopertha dominica	Lesser grain borer	kornborebille
Sitophilus granarius	Granary weevil	kornsnutebille
Sitophilus oryzae	Rice weevil	rissnutebille
Stegobium paniceum	Drugstore beetle	brødbille
Tenebrio molitor	Yellow meal worm	stor melbille
Tenebrio obscurus	Dark meal worm	
Tineola bisselliella	Webbing clothes moth	klesmøll
Tribolium castaneum	Red flour beetle	kastanjebrun melbille
Tribolium confusum	Confused flour beetle	rismelbille
Tribolium destructor	False black flour beetle	brunsvart melbille
Trogoderma variabile		

Appendix 2.1

Technical documentation for heater

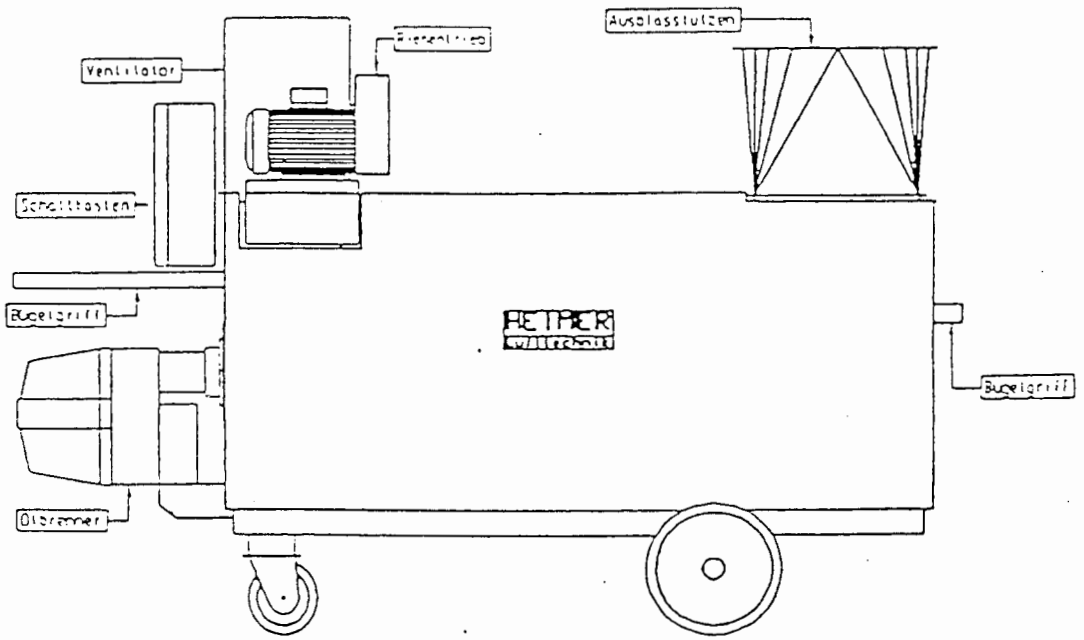
AHRENS
BAUTECHNOLOGIE

heimer
Lufttechnik

HEISSLUFTERZEUGER HHE750 und HHE375

"DACHSTUHLSANIERUNG"

aufgebaut auf PKW-Hänger

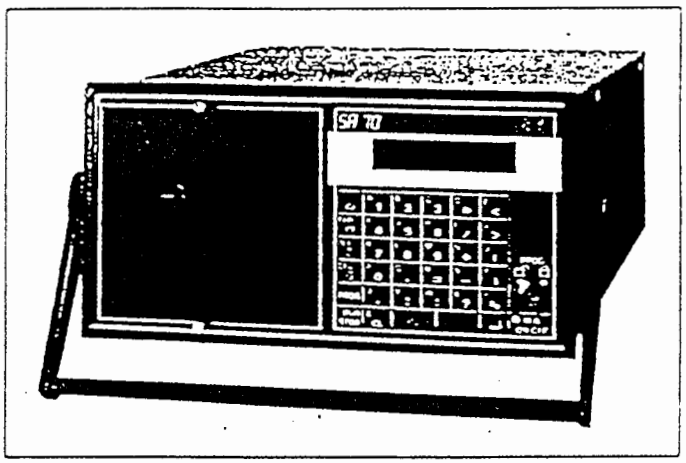


Technische Daten:	HHE375
Heizleistung:	375 000 kcal/h
Luftleistung:	10 000 m³/h
max. Ausblastemperatur:	180°C
Ventilatorantriebsleistung:	.. kW

Technical documentation for temperature and data logger

data acquisition systems
PréciTec SA 20/SA 70

- Universal I/O boards
- Up to 100 channels
- 300 000 count measurement accuracy
- Powerful algorithmic signal processing and statistical functions
- RS232C, RS485 and MODBUS-RTU networking
- On-board bulk data storage memory
- Optional battery-pack for portable operation
- P.C. software for easy programming and data analysis



SA 20/70 series data acquisition systems measure, process, monitor and record analogue and digital parameters from all common types of sensor. According to user requirements, the system is sold in various configurations which share a common central processing module providing a wide range of statistical and signal processing capabilities. Networking support is standard, offering wide possibilities for building extensive measu- together

applications

- for measurement acquisition and display on any compatible VDU terminal;
- pre-processing sensor data for presentation to computer-based measurement systems;
- as a distributed intelligence data acquisition node integrated via a network into larger industrial process installations;
- as a self-contained, multiple-sensor data logger with large capacity on-board bulk storage;
- as a portable, flexible on-site data logger and analyser.

functions

Each module can address 100 channels. These can be real channels measuring ... computing a result, or virtual mic calculations without degrading measurement scanning rate. Each channel is identified by a unit label (4 characters) and a mnemonic (8 characters) and supports the following functions:

monitoring
4 thresholds per channel, with hysteresis, alarm counter, an alarm label and, if required, activation of an output relay; all these functions can be programmed individually per channel. Additionally, SA 20/70 series systems have a common relay output covering all alarm thresholds.

mathematical operations
Calculations on or between channels involving the following operators are available:
+,-,/,x, raising to the nth power, OR, AND, NOT, <, =>, square root, decimal LOG, absolute value, time-based functions and statistical operations such as minimum, maximum, average and standard

REPORT

TECHNO CONSULT

Client : Anticimex
Project: 530630, Heat treatment

Date : 27.11.95

HEATING STRATEGY

The heater

The heater produces hot air as a mixture of exhaust from the oil burner and fresh air. Capacity 300 kW, 6500 Nm^3/h. The exit temperature was 137°C or 126°C above intake temperature. The actual fuel for the tests at Moss was Shellsol D-70. The CO_2 content of the hot air was in the region of 0.5%-1.0%. The total amount of energy used was 9400 kWh.

The heat loss from the hot air ducting (diam. 380 mm) is 2 kW per metre. The ducting should be insulated if unauthorised people can come in contact with it or the outdoor length exceeds around 10 metres. Actual length was 4 metres with a heat loss of 8 kW.

During the treatment process, the inside air temperature is kept at 70°C. All the air from the heater has to leave the building at this temperature, representing a heat loss of 155 kW. That leaves 137 kW for the steady state phase.

Inside high pressure

When heating a building, we create a high pressure at the top and low pressure at the bottom. The result is that air leaks out of the top of the building, and normally into it at the bottom. This allows cold outside air to cool the bottom of the building.

It is therefore important to seal all leakages as well as possible. Enough hot air must be blown into the building to force leaking air out of the very bottom of the building.

Regal Mølle in Moss is made of concrete, poured on site, with walls and floors of 150 mm thickness. This gives a relatively airtight construction.

The windows were sealed with one layer of plastic foil, and openings between the floors were sealed in the same way. Dampers in the production lines were closed and small openings in the building sealed with plastic foam. The result was a well-sealed building, and the inside high pressure was steady.

Temperatures

The temperature to be achieved on the surface is estimated to be 50°C. This is no problem on inside walls, floors and equipment. On the outside walls and ground floor it may be difficult and a forced air flow is necessary. The construction may incorporate "cold bridges" that leads the heat out too fast to achieve 50°C on the inside surface. Different wall constructions might give problems. Steel or wooden walls usually have sheet clothing inside, giving a lot of openings through which the insects can escape and find a safe place in the insulation inside the wall. Concrete elements present a similar problem.

Concrete that is poured on site like Regal Mølle in Moss, is less of a problem in this respect. However, there are always some cracks in the construction, and they do not need to be very deep to provide safe places for insects.

Outer walls have to be heated from both sides to guarantee killing of insects. For a ground floor this is very difficult. The hot air treatment therefore has its limitations here.

Time needed

The time needed for a heat treatment is a question of how "heavy" the building is and the effect of the heat source. A third factor is the humidity in the constructions or products stored inside. To heat "wet" materials, the humidity has to be dried out, a process that needs large quantities of energy. Products like flour are good insulators and if the humidity is high, they may be safe places for insects during the heat treatment period. High humidity can double the heat treatment time.
For heat treatment to be successful the place must be clean and dry.

At Regal Mølle the total heating time was 32 hours. After 30 hours of heating most places had reached a constant temperature, but in closed volumes and inside constructions the temperatures were still rising.

Necessary energy

The heat source must have a capacity at least equal to the heat loss from the building at the inside temperature achieved.

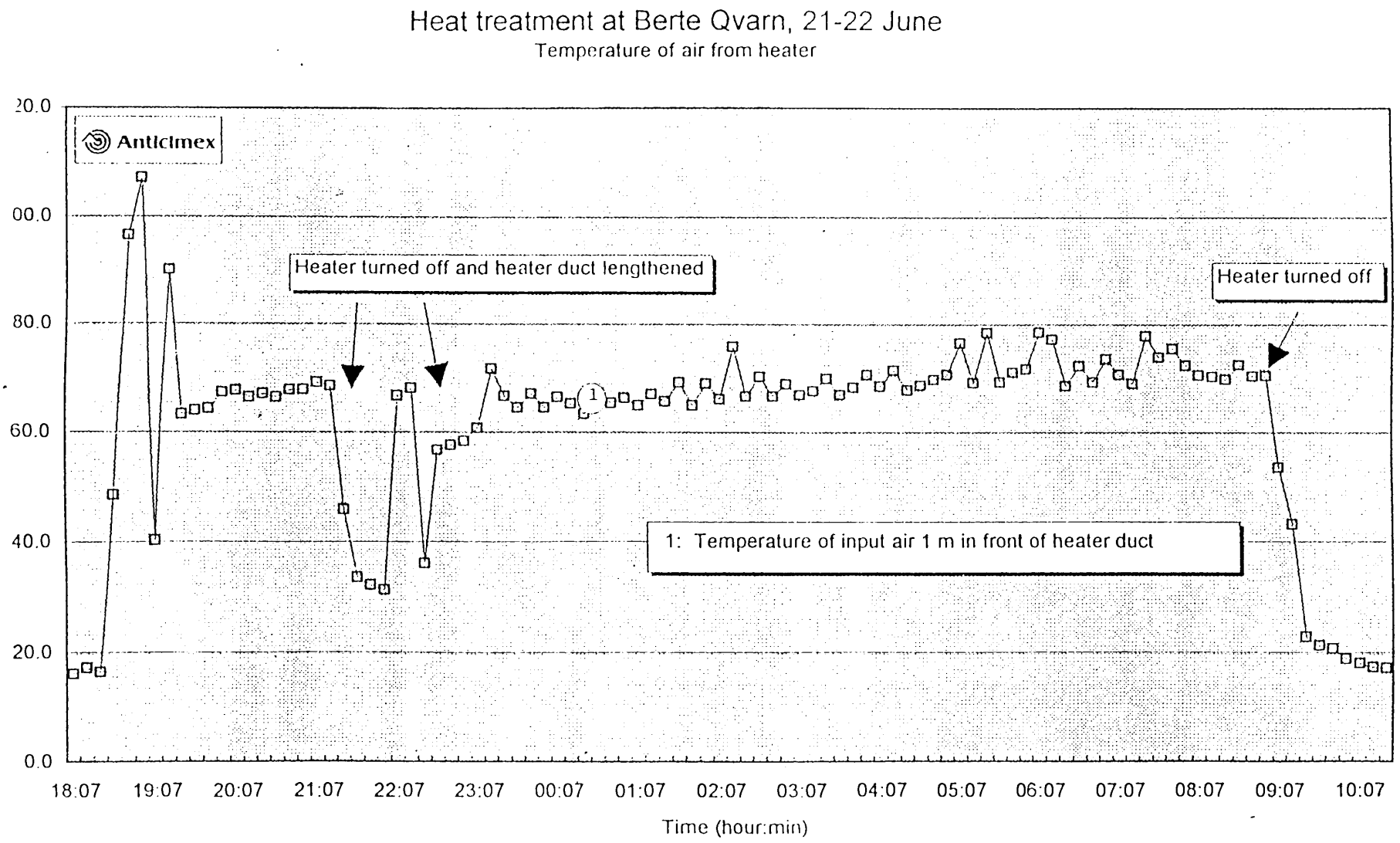
All inside constructions and machinery will be heated to the required temperature and the surrounding walls and floors to the same temperature on the inside surface.

The necessary amount of energy, the capacity of the heater and maximum part of the building to be heat treated in one operation must be calculated for each case.

The heat loss from the Regal Mølle building is 200 W/m². This makes it possible to treat a building or a part of it with a surrounding surface of about 700 m² with the heater used.

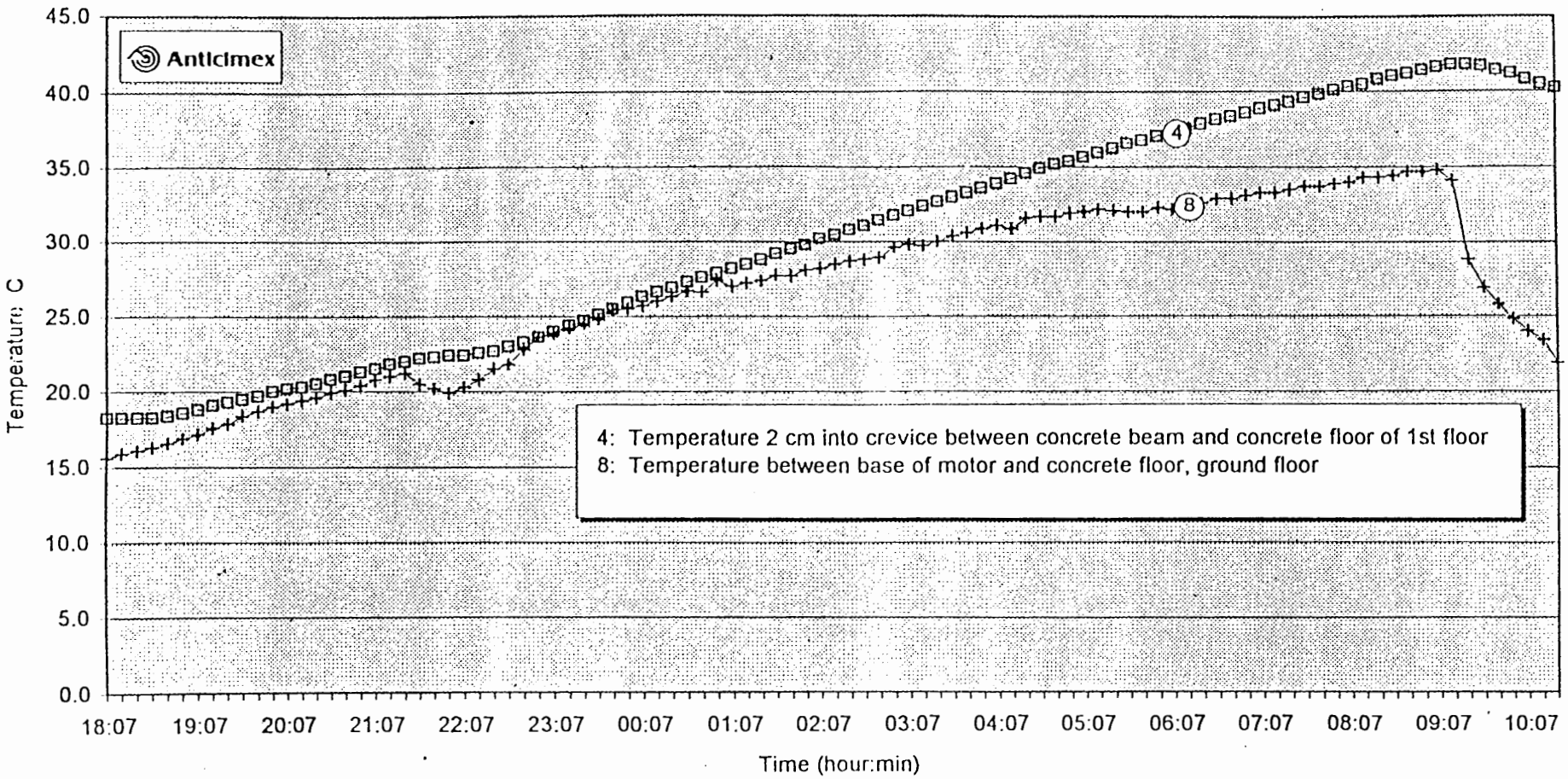
Regal Mølle consists of an old and a new building with one wall in common. To heat the old part in one operation, the heater capacity must be at least 750 kW. Heating time 30 hours.

To treat the whole building in one operation, the heater must give 1400 kW and the heating time required is 50 hours.


Heat treatment at Berte Qvarn, 21-22 June
Temperature of air from heater
Anticimex
Heater turned off and heater duct lengthened
Heater turned off
1: Temperature of input air 1 m in front of heater duct
20.0
00.0
80.0
60.0
40.0
20.0
0.0
18:07
19:07
20:07
21:07
22:07
23:07
00:07
01:07
02:07
03:07
04:07
05:07
06:07
07:07
08:07
09:07
10:07
Time (hour:min)

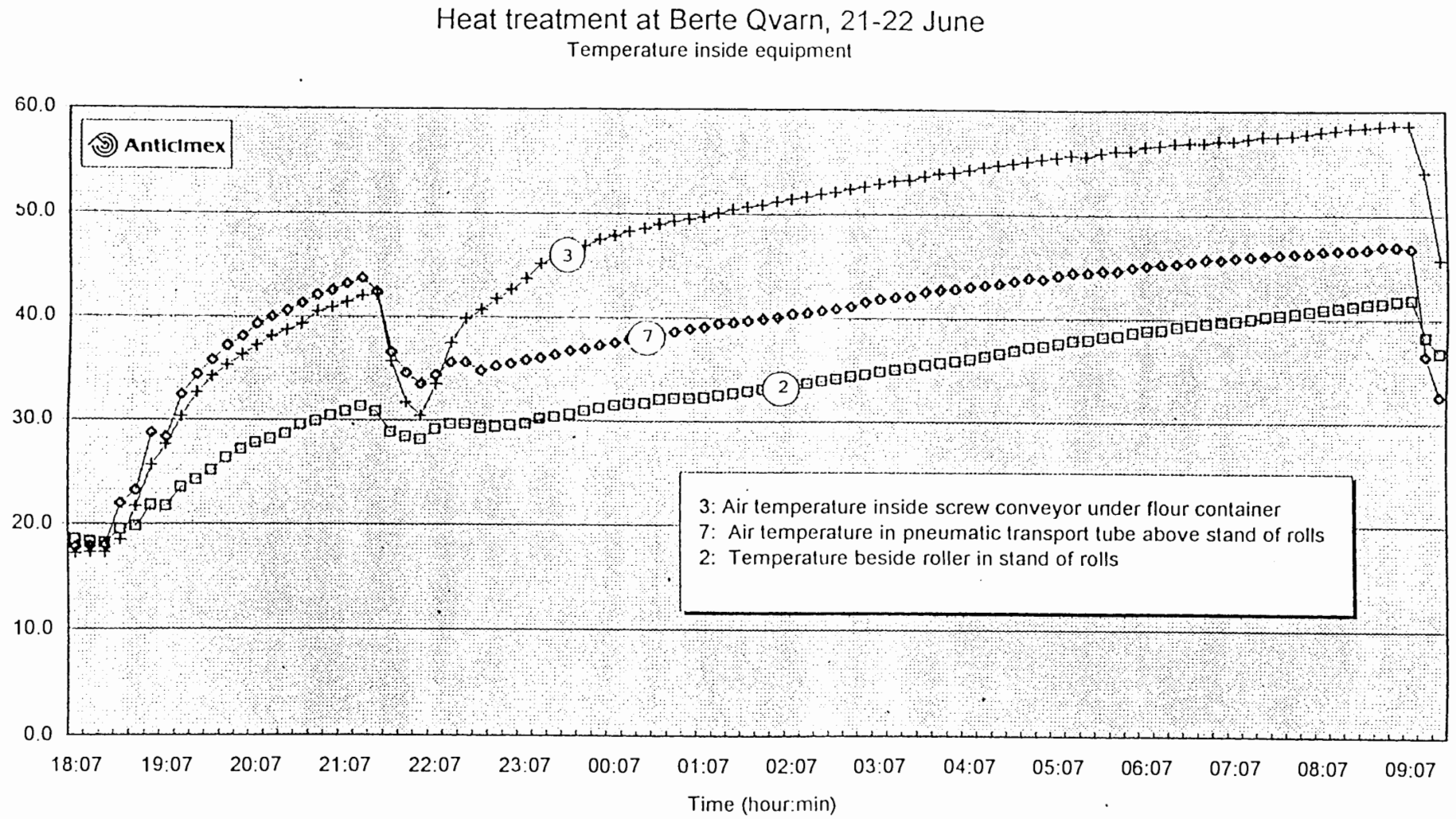
Heat treatment at Berte Qvarn, 21-22 June

Temperature inside constructions



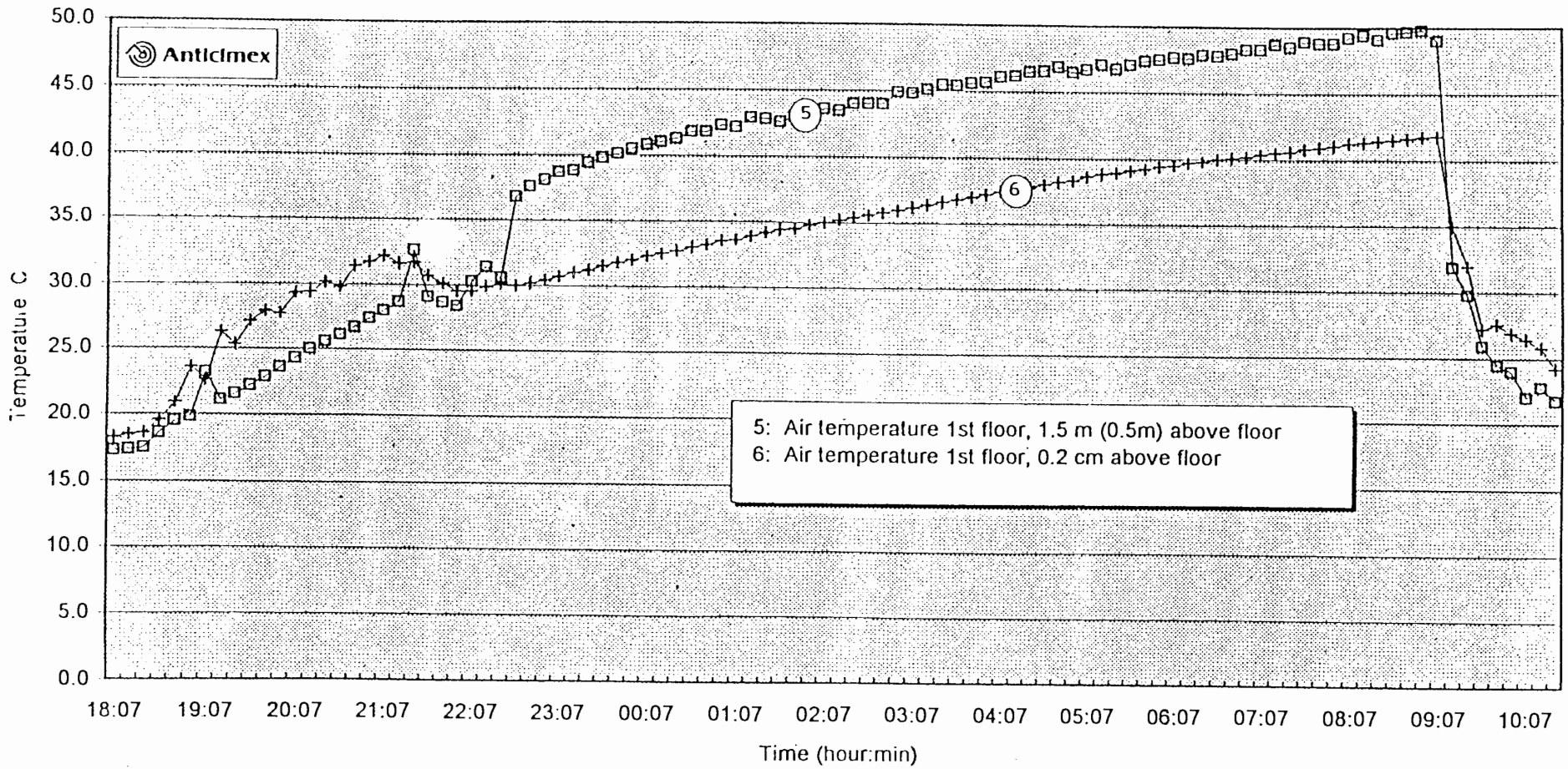
Side 1

Appendix 4.4


Heat treatment at Berte Qvarn, 21-22 June
Temperature inside equipment
Anticimex
60.0
50.0
40.0
30.0
20.0
10.0
0.0
18:07
19:07
20:07
21:07
22:07
23:07
00:07
01:07
02:07
03:07
04:07
05:07
06:07
07:07
08:07
09:07
Time (hour:min)
3
7
2
3: Air temperature inside screw conveyor under flour container
7: Air temperature in pneumatic transport tube above stand of rolls
2: Temperature beside roller in stand of rolls

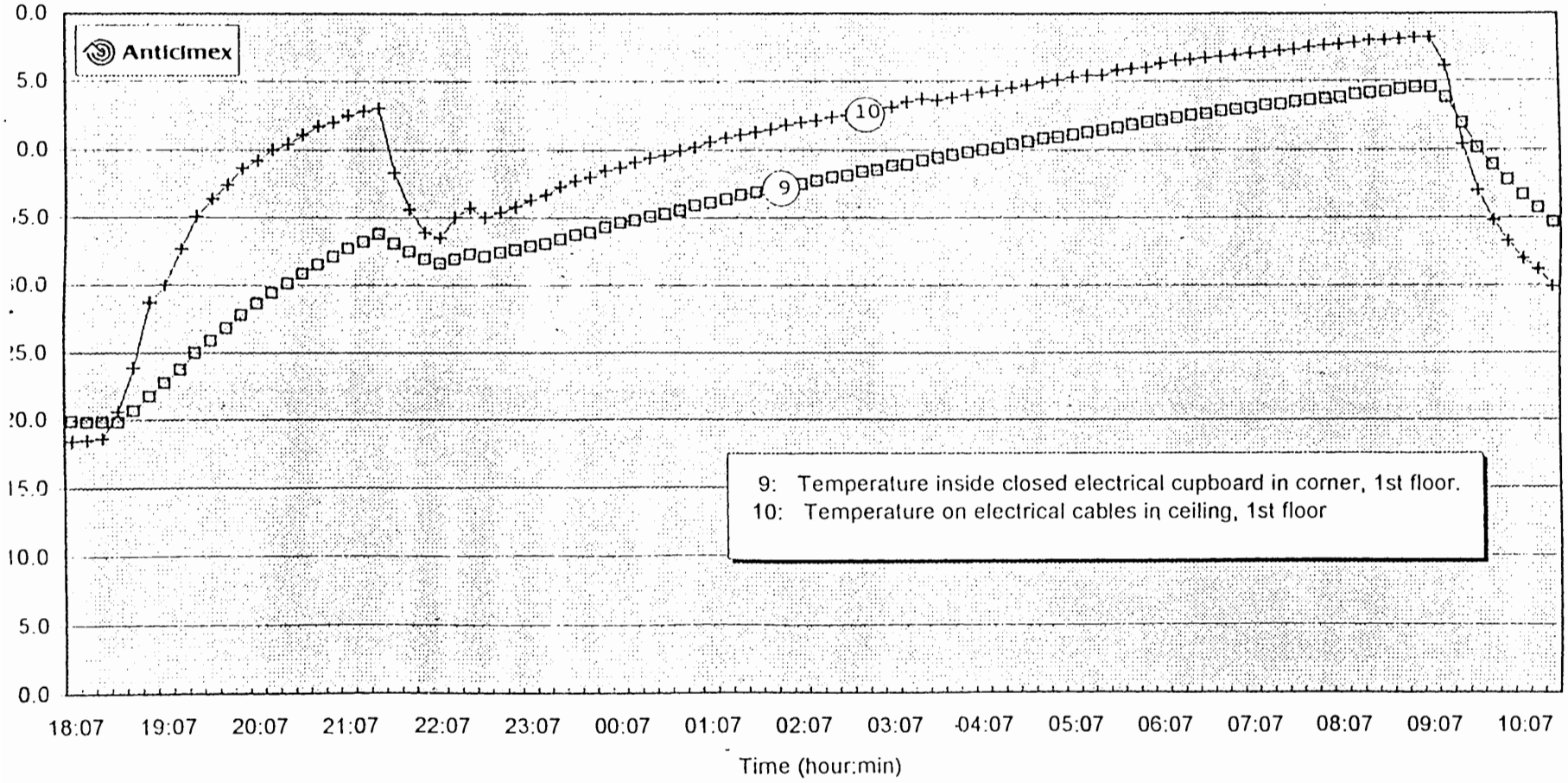
Heat treatment at Berte Qvarn, 21-22 June

Air temperature inside



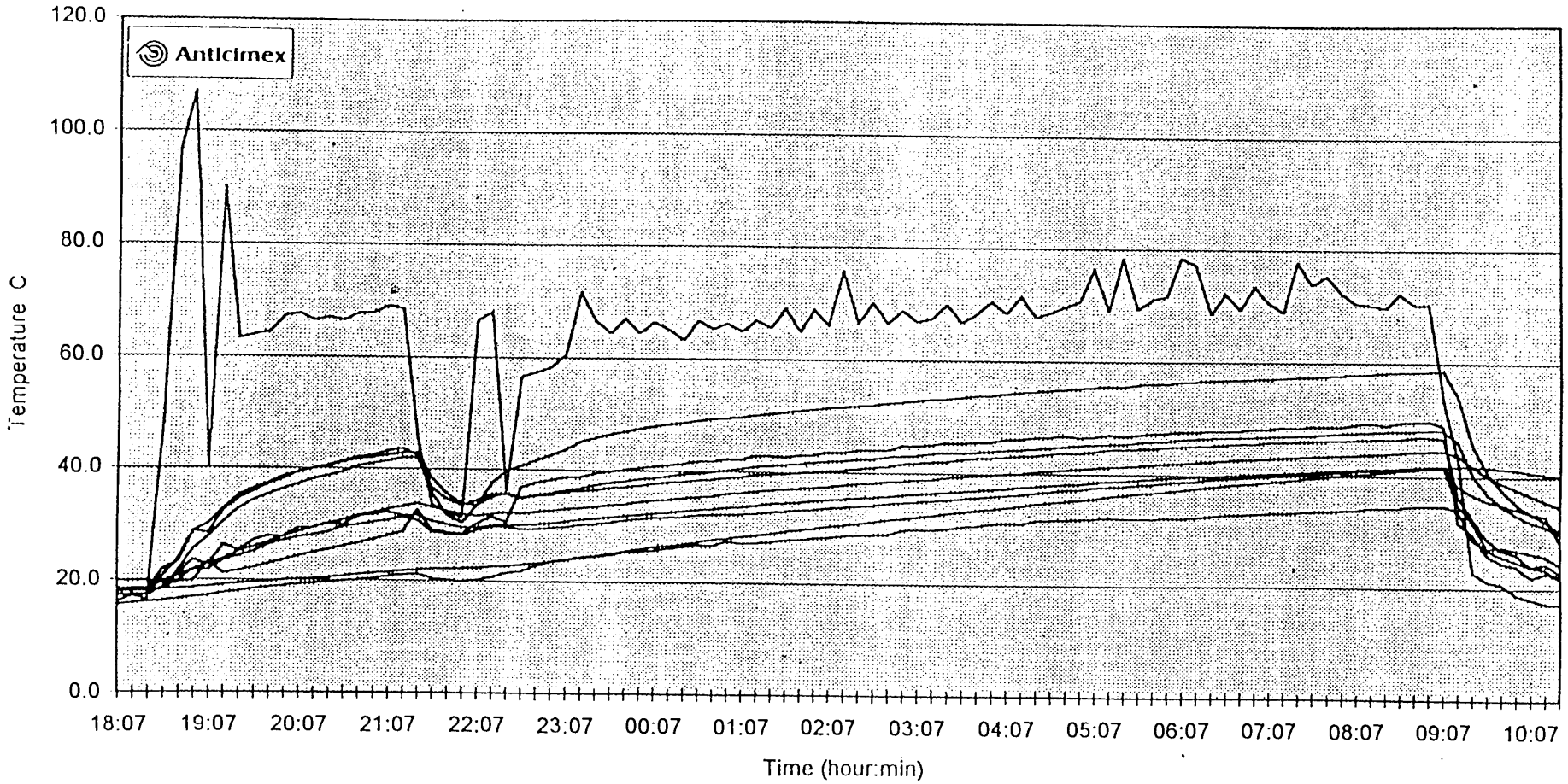
Heat treatment at Berte Qvarn, 21-22 June

Temperature of electrical equipment



Heat treatment at Berte Qvarn, 21-22 June

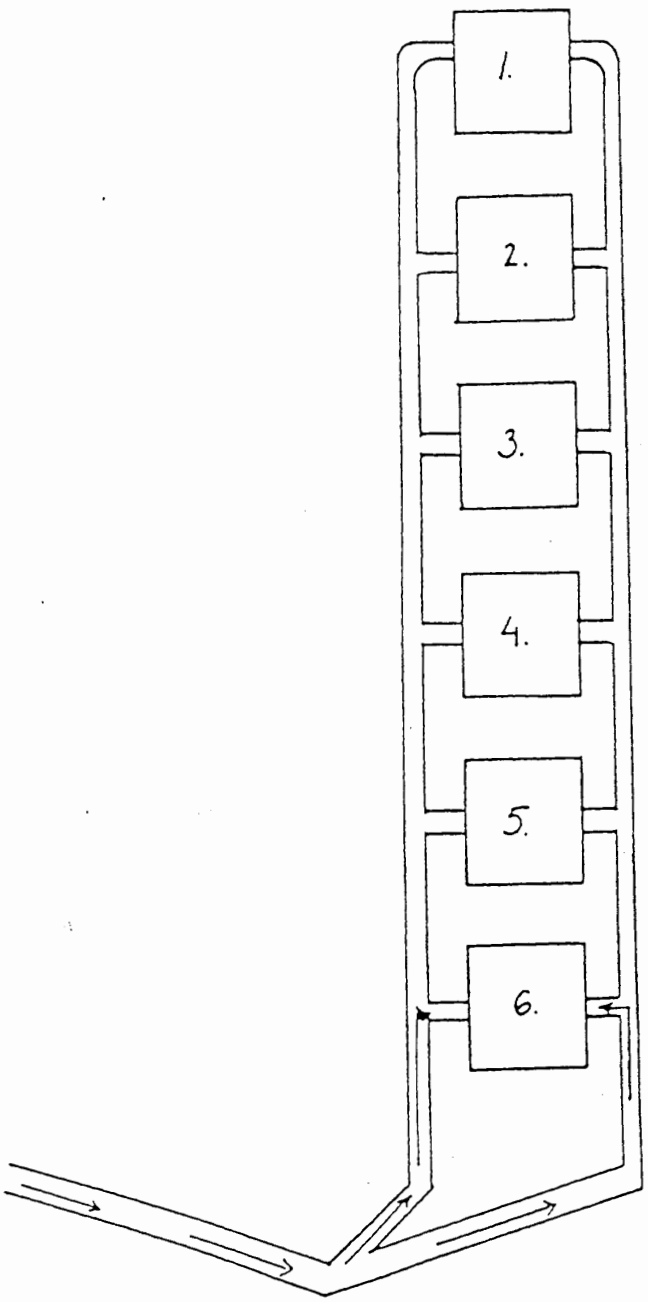
All temperatures



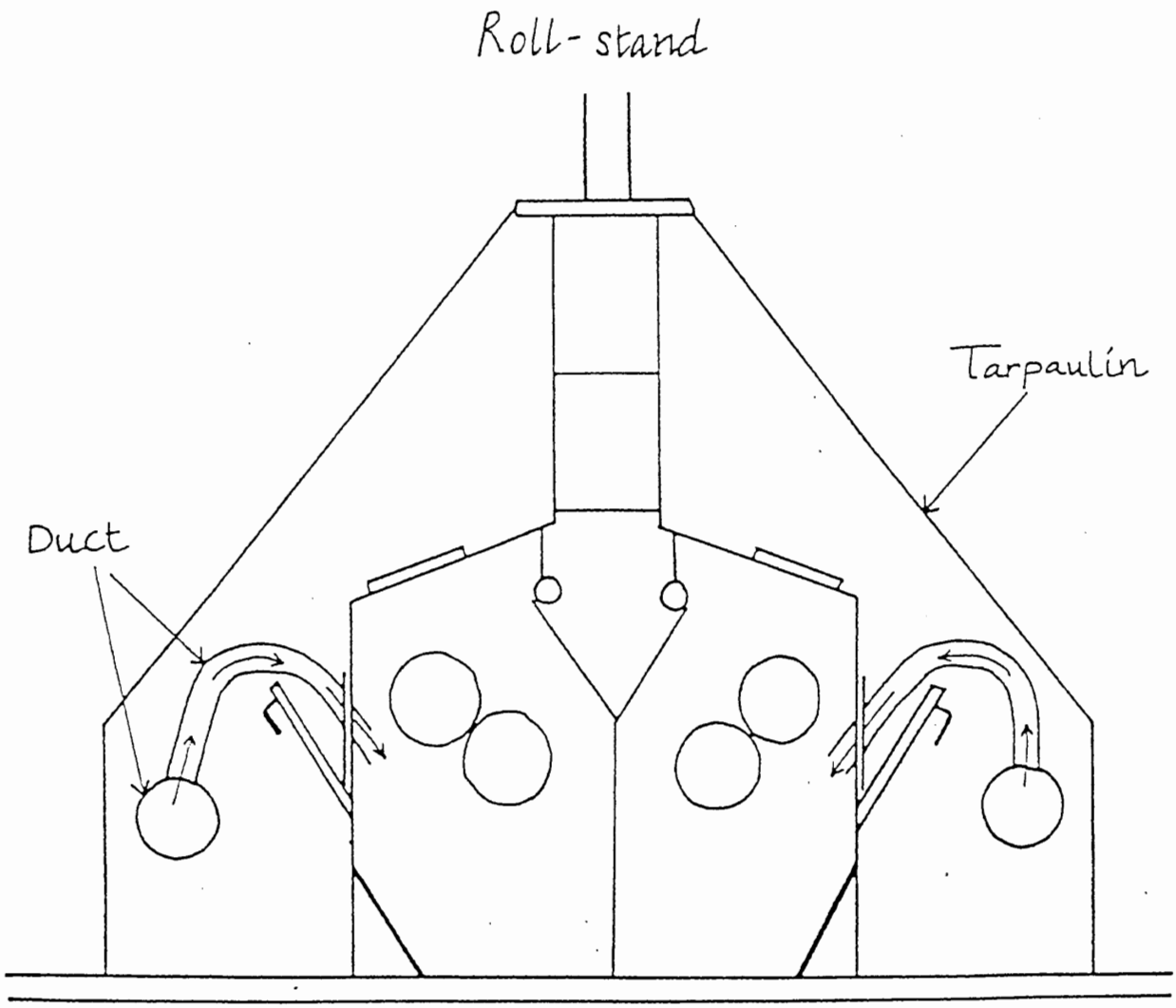
Appendix 4.6

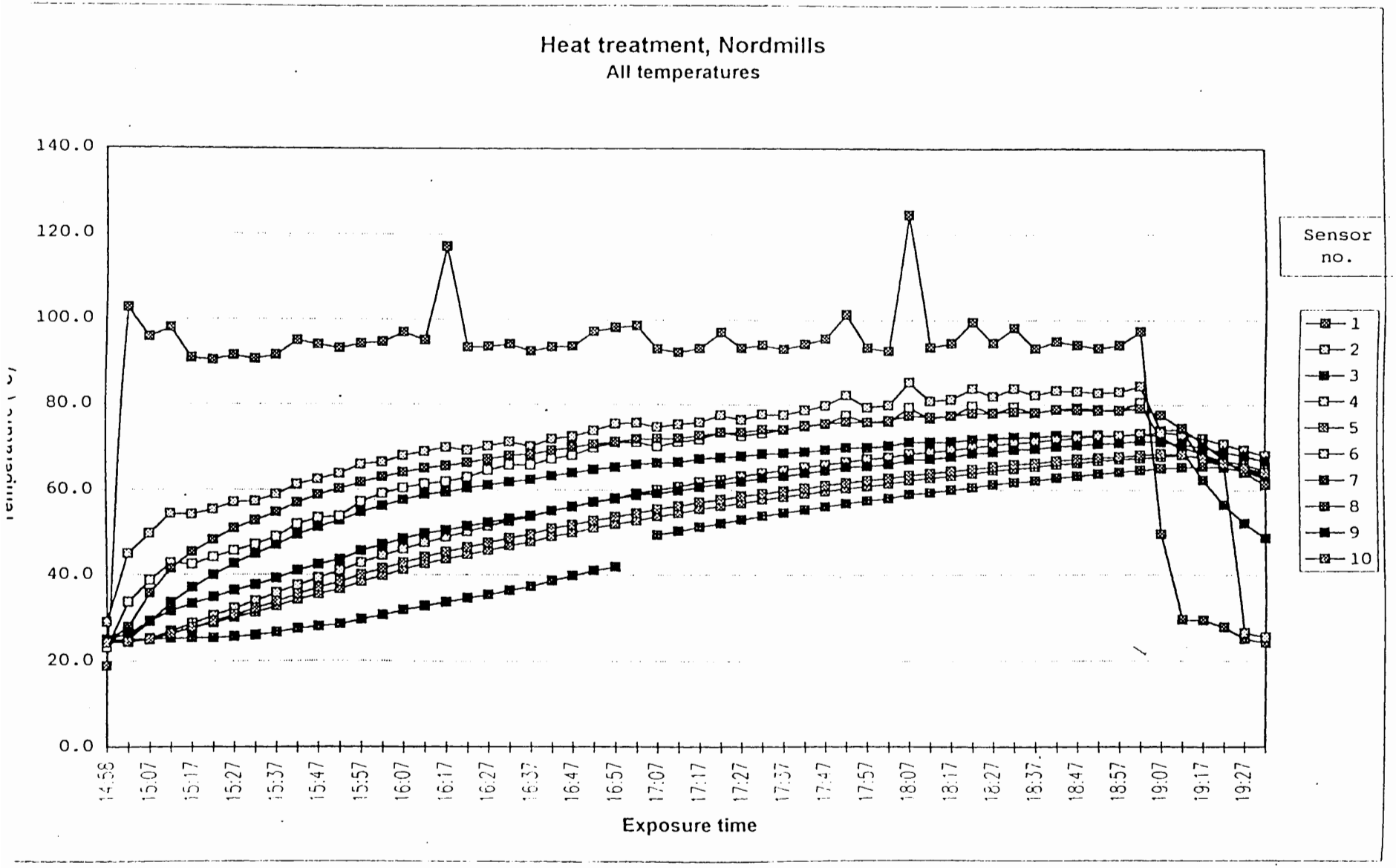
Heater ducting to the roller stands at Nordmills

Top view



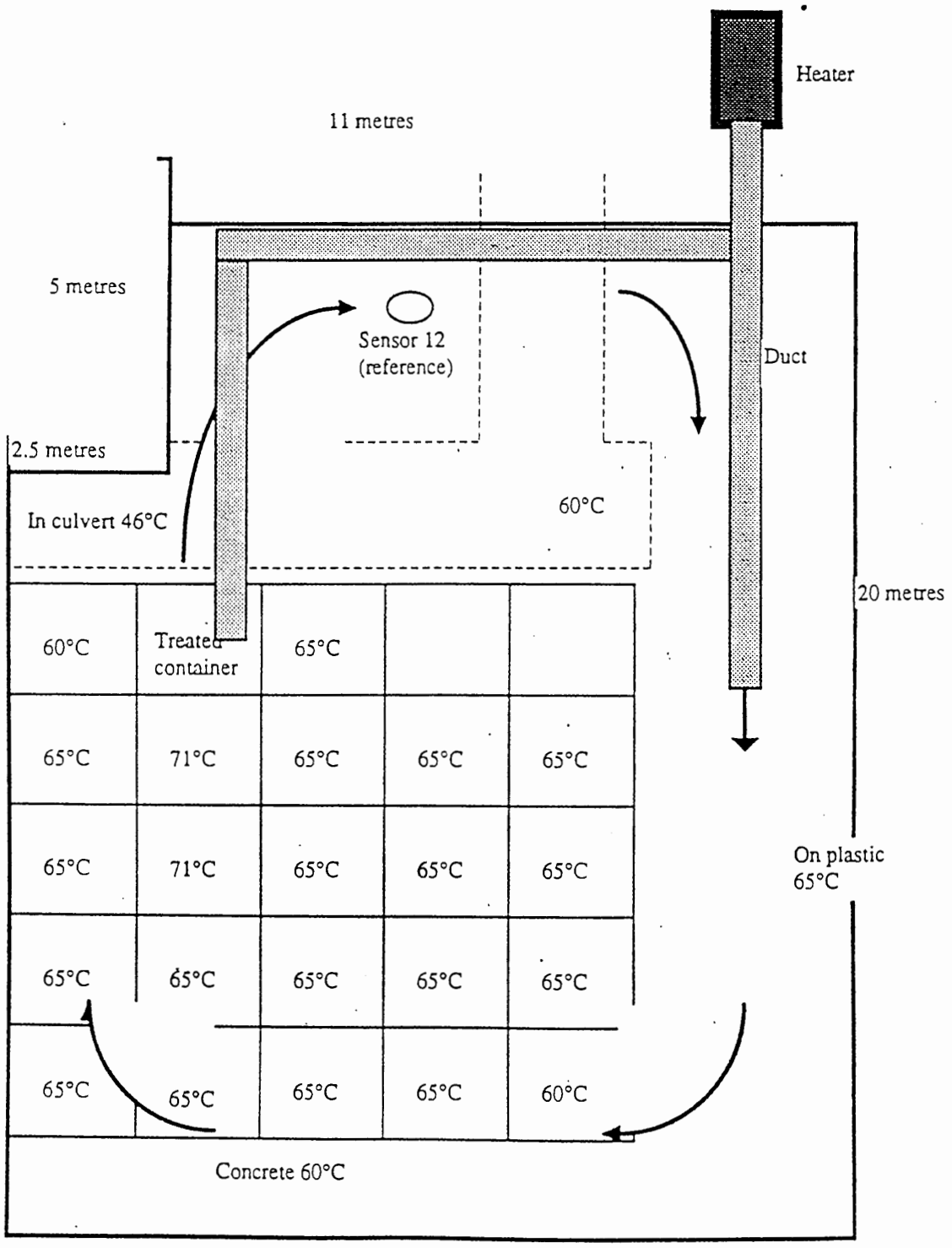
The tent and heater ducts at each pair of roller stands




Heat treatment, Nordmills
All temperatures
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Exposure time
Sensor no.
1
2
3
4
5
6
7
8
9
10

Outline of the treated area at Moss

Treated area at Moss. Temperatures are measured with strips on containers, conveyor covers and spouts, all measured at 1 m height on metal. Measurements not on metal are explained. Measurement in culvert is below floor level.



Number, position and function of sensors

No:	Position	Function
1	In conveyor belt	air temp
2	Inside elevator	air temp
3	Inside conveyor belt with products	temp. in products
4	Inside conveyor belt	air temp
5	Inside conveyor belt in ditch	air temp
6	Inside elevator	air temp
7	Inside empty product tank	air temp
8	Inside bottom of untreated container	metal temp
9	Inside untreated container, lower part	air temp
10	Concrete floor, between floor and basement of motor	temp. of concrete
11	Hanging 30 cm under ceiling	air temp.
12	Hanging 1.5 m above floor	air temp. (reference)
13	5 cm above floor	air temp.
14	Concrete ditch floor, 1 m below floor	temp of air/concrete
15	Concrete pillar, 2 m above floor, 5 cm into pillar	temp. of concrete
16	Inside electrical switch box	air temp
17	Concrete floor, 1 cm into floor	temp of concrete
18	Exterior wall, 2 m above floor, 3 cm into wall	temp. of concrete
19	Inside insulation on water pipe under ceiling	air temp
20	Cealing, between electrical cable and ceiling	temp. of concrete
21	Wooden container, partition wall 6 m above bottom	temp. of wood
22	Wooden container, exterior wall, 4 m above bottom	temp. of wood
23	Wooden container, exterior wall, 6 m above bottom	temp. of wood
24	Wooden container, lower part	air temp
25	Wooden container, middle, other side of interior wall	air temp
26	Wooden container, top of interior wall	temp. of wood
27	Wooden container, exterior wall 12 m above bottom	temp. of wood
28	Wooden container, top of container	air temp.
29	Opening of wooden container at bottom	air temp
30	Sack of flour lying on the floor, 20 cm inside	temp. of product
31	Not used	
32	Not used	
33	End of heater duct	temp of air
34	1.5 m from end of heater duct	temp. of air
35	3.6 m from end of heater duct	temp. of air
36	5.7 m from end of heater duct	temp. of air
37	Leak tube through exterior wall 50 cm above floor	air temp
38	Leak tube through exterior wall, 1.6 m above floor	air temp
39	Leak tube through ext. wall, 0.3 m under ceiling	air temp

40	Outside, 1.5 m above ground	temp. of air
41	Inside guard room, by data logger	temp. of air
42	In heater duct 1 m in front of heater	volume of air passing
43	In heater duct 1 m in front of heater	temp. of air
44	By wall, 2 m above floor, 6 m from end of heater duct	ppm of carbon monoxide
45	By wall, 2 m above floor, 6 m from end of heater duct	% by vol. of carbon dioxide
46	By wall, 2 m above floor, 6 m from end of heater duct	% by vol. of oxygen
47	Copper coil for gas cooling i guard room	temp. of copper coil
48	Hanging freely, 2 m above floor	relative humidity in percent
49	Hanging freely, 2 m above floor, near humidity sensor	temp. of air

APPENDIX 6.3

Hourly temperatures and other measurements during heat treatment at Moss 20 - 22 Sep 95. Column numbers refer to sensor numbers, see appendix 6.2.

0.0	1	2	3	4	5	6	7	
12:02	12.9		12.1	13.1	11.7	11.0		
13:02	22.1		17.2	18.9	20.8	17.2		
14:02	30.8		18.3	23.5	25.4	20.9		
15:02	35.1		21.3	26.8	28.6	24.7		
16:02	37.2		21.2	28.2	30.3	25.9		
17:02	43.0		21.4	35.9	36.9	24.2		
18:02	47.8	48.4	24.0	41.8	41.2	26.5		
19:02	49.3	51.4	24.1	42.2	42.0	25.2	30.9	3
20:02	51.3	54.4	25.7	44.8	44.1	30.5	33.3	4
21:02	52.8	56.2	26.8	46.6	45.6	32.2	35.3	4
22:11	55.0	58.5	29.1	48.7	46.8	34.4	37.8	4
23:01	55.6	59.1	29.7	49.4	48.1	35.3	38.9	4
00:01	56.5	59.8	30.4	50.1	49.0	36.6	39.9	4
01:01	57.1	60.4	31.6	50.7	49.4	36.6	41.5	4
02:01	57.7	61.1	32.2	51.5	50.2	37.5	42.4	4
03:01	58.2	61.5	32.9	51.9	50.7	38.2	43.3	4
04:01	59.0	62.4	33.6	53.1	53.0	41.1	43.9	5
05:01	59.9	62.7	34.1	53.7	54.3	42.3	45.1	5
06:01	60.4	63.1	34.8	54.3	54.9	43.0	45.4	5
07:01	60.9	63.8	36.1	55.0	55.5	44.0	46.3	5
08:01	60.6	63.2	36.5	54.8	55.6	44.8	46.8	5
09:01	62.2	64.8	37.3	56.0	53.9	44.0	46.7	5
10:01	63.6	66.6	38.1	57.1	46.4	38.9	46.4	5
11:01	64.7	67.8	39.0	59.2	44.4	38.5	53.2	5
12:01	64.9	67.8	38.5	59.3	42.9	37.4	53.8	5
13:01	66.7	69.7	40.4	61.7	44.0	39.3	55.6	5
14:01	67.2	70.1	40.8	62.0	44.0	39.2	56.0	5
15:01	65.9	68.9	40.1	56.6	55.2	46.2	41.6	5
16:01	65.8	69.3	40.5	56.1	56.1	49.4	40.3	5
17:01	67.4	70.3	42.8	58.2	58.2	50.6	47.3	5
18:01	70.1	72.9	45.1	61.2	60.8	53.0	50.6	5
19:01	70.9	73.6	46.5	62.0	61.2	53.5	53.5	5
20:01	70.8	73.1	45.4	61.1	61.0	52.8	55.0	5
21:01	61.4	67.2	43.0	55.8	52.2	50.4	44.6	5
22:01	50.6	53.2	40.3	50.2	45.9	45.2	42.2	4
23:01	45.7	46.3	38.6	46.5	42.9	41.8	39.8	4
00:01	42.8	42.6	37.3	44.2	40.8	39.7	38.1	4
01:01	40.9	40.3	36.2	42.5	39.3	38.2	36.5	4
02:01	39.4	38.8	35.5	41.1	38.1	37.0	35.5	3
03:01	38.3	37.7	35.1	40.0	37.4	36.4	34.7	3
04:01	37.5	36.8	34.6	39.1	36.7	35.7	34.0	
05:01	36.6	35.9	34.0	38.1	35.9	34.9	33.5	
06:01	35.8	35.2	33.5	37.3	35.3	34.3	32.9	
07:01	35.2	34.5	33.1	36.6	34.7	33.7	32.3	
08:01	34.5	33.9	32.6	35.9	34.1	33.2	31.9	
09:01	33.9	33.4	32.2	35.3	33.5	32.7	31.4	

APPENDIX 6.3

Hourly temperatures and other measurements during heat treatment at Moss 20 - 22 Sep 95. Column numbers refer to sensor numbers, see appendix 6.2.

0.0	9	10	11	12	13	14	15	16
12:02	12.7	12.0	12.6	11.7	9.7	11.5	11.5	10.6
13:02	17.1	14.7	21.9	25.3	17.6	14.3	14.0	16.1
14:02	21.7	15.1	26.7	28.2	18.4	13.1	14.1	18.3
15:02	24.2	18.1	30.0	31.6	22.1	15.6	17.7	22.6
16:02	26.1	19.0	31.8	33.1	23.5	15.5	18.6	23.6
17:02	31.2	19.0	49.4	41.6	27.3	14.7	19.2	25.6
18:02	34.7	22.4	50.6	45.5	30.6	17.9	23.8	31.4
19:02	36.4	22.5	51.5	45.4	30.9	15.4	22.8	30.4
20:02	39.8	24.8	54.0	47.2	33.1	22.0	26.1	34.1
21:02	40.9	26.4	55.3	48.9	34.3	23.0	28.0	36.0
22:11	42.8	27.9	57.9	50.4	35.5	25.0	30.9	38.5
23:01	44.1	28.7	58.2	51.6	38.9	27.5	32.3	40.1
00:01	41.5	29.6	57.8	51.9	39.0	26.4	33.5	40.9
01:01	44.2	30.7	59.2	53.0	40.2	26.6	34.8	41.9
02:01	43.5	31.7	60.5	53.3	40.3	27.4	36.3	43.3
03:01	47.0	32.4	60.3	53.6	42.3	26.6	37.0	43.8
04:01	45.7	33.3	61.6	54.9	42.7	28.1	38.7	45.2
05:01	44.4	34.1	61.4	55.2	42.4	29.8	39.9	46.3
06:01	46.7	34.6	62.1	55.7	43.3	29.2	41.0	47.1
07:01	48.6	35.3	62.5	56.0	42.4	30.2	42.1	48.0
08:01	46.8	36.0	62.8	56.6	43.2	30.8	43.1	48.5
09:01	48.3	36.7	65.0	58.1	45.2	30.1	43.8	49.3
10:01	47.8	37.7	68.9	60.0	48.0	33.5	45.7	51.2
11:01	52.5	38.8	65.3	60.6	48.8	32.4	46.8	52.3
12:01	49.9	39.3	65.1	60.4	47.2	31.9	46.3	51.5
13:01	55.9	40.9	68.2	62.8	50.5	33.8	49.5	54.8
14:01	51.7	41.3	67.7	62.6	49.9	33.3	49.9	54.9
15:01	51.3	42.3	61.2	59.2	45.3	50.6	48.5	52.7
16:01	49.5	43.8	61.0	59.7	46.2	36.0	50.2	53.9
17:01	50.7	43.3	62.2	62.1	47.6	37.9	51.2	54.9
18:01	52.8	44.0	63.9	64.3	50.0	40.3	53.2	57.3
19:01	50.5	44.3	64.5	64.8	50.2	40.7	53.9	57.5
20:01	53.8	43.9	63.5	63.7	49.3	39.3	52.7	55.9
21:01	52.3	44.8	57.2	51.1	44.9	37.7	53.6	54.5
22:01	45.8	43.3	52.0	46.3	41.9	36.4	52.9	51.7
23:01	44.8	41.5	48.0	43.0	39.3	34.7	50.9	49.0
00:01	43.0	40.1	45.5	40.4	37.5	33.5	49.3	47.1
01:01	42.2	39.0	43.9	39.1	36.4	32.6	47.9	45.6
02:01	41.2	38.1	42.5	37.8	35.4	31.9	46.6	44.2
03:01	39.2	37.3	41.5	37.3	34.9	31.5	45.6	43.4
04:01	39.1	36.6	40.3	36.4	34.1	31.1	44.6	42.4
05:01	38.6	36.0	39.5	35.5	33.5	30.5	43.7	41.4
06:01	37.7	35.4	38.8	34.9	33.0	30.2	42.8	40.6
07:01	37.0	34.9	37.9	34.2	32.3	29.7	41.9	39.8
08:01	36.5	34.4	37.3	33.2	31.9	29.3	41.1	39.0
09:01	36.2	33.9	36.8	33.1	31.4	29.0	40.4	38.2

APPENDIX 6.3

Hourly temperatures and other measurements during heat treatment at Moss 20 - 22 Sep 95. Column numbers refer to sensor numbers, see appendix 6.2.

0.0	17	18	19	20	21	22	23	
12:02	10.8	9.7	11.4	12.0	12.3	12.0	12.5	1
13:02	13.4	13.2	20.8	15.5	22.1	16.4	16.9	3
14:02	12.8	13.8	24.1	15.5	38.9	20.5	22.5	4
15:02	15.7	17.6	28.3	18.2	50.4	22.7	30.8	4
16:02	16.2	18.5	29.8	18.6	55.9	24.8	35.7	4
17:02	16.9	19.7	35.3	19.9	54.0	25.2	37.0	5
18:02	21.4	25.0	40.7	24.0	54.1	28.9	40.2	5
19:02	20.2	23.9	41.2	23.1	51.9	28.6	38.0	5
20:02	23.1	27.3	44.1	25.8	53.0	30.6	40.0	5
21:02	24.5	29.1	45.7	27.1	53.9	31.9	41.0	5
22:11	26.2	31.5	47.0	28.8	55.8	34.2	43.1	6
23:01	27.2	32.7	48.1	29.9	56.5	34.9	43.9	6
00:01	27.8	33.6	48.9	30.8	57.0	35.4	44.3	6
01:01	28.5	34.6	49.8	31.9	57.6	36.0	44.9	6
02:01	29.3	35.8	50.6	33.1	58.3	36.9	45.9	6
03:01	29.5	36.1	50.8	33.7	58.2	37.0	45.7	6
04:01	30.5	37.5	51.8	35.1	59.2	38.1	46.7	6
05:01	31.2	38.2	52.2	35.9	59.6	38.6	47.1	6
06:01	31.7	38.8	52.7	36.7	60.2	39.1	47.7	6
07:01	32.4	39.7	53.3	37.6	60.8	39.7	48.2	6
08:01	32.7	40.0	53.4	38.2	60.9	40.0	48.5	6
09:01	33.0	40.5	54.1	38.9	61.4	40.2	48.8	6
10:01	34.2	41.9	55.0	40.3	62.7	41.0	50.3	6
11:01	35.0	42.7	56.6	41.3	61.3	41.7	49.7	6
12:01	34.3	42.1	56.4	41.3	59.3	40.6	47.7	6
13:01	36.9	45.0	58.3	43.5	60.7	42.3	49.8	6
14:01	37.0	45.1	58.6	43.8	60.2	41.9	49.0	6
15:01	35.9	43.3	56.3	42.4	63.8	41.0	48.7	7
16:01	39.0	44.8	57.3	44.0	74.7	43.0	55.6	7
17:01	41.1	45.7	58.9	45.0	78.6	44.8	60.9	6
18:01	43.5	47.8	61.1	46.7	72.1	45.5	60.1	6
19:01	44.0	48.0	61.3	47.1	67.1	44.8	57.3	6
20:01	42.7	46.7	60.3	46.1	63.2	43.3	53.6	6
21:01	42.0	46.9	54.8	46.1	61.0	42.4	54.3	5
22:01	38.5	45.2	49.6	45.1	57.7	42.5	52.4	5
23:01	35.7	42.4	45.6	44.0	53.4	41.0	49.9	4
00:01	34.0	40.4	43.2	43.2	49.9	39.7	47.9	4
01:01	32.8	38.8	41.3	42.7	47.2	38.5	46.0	4
02:01	31.9	37.5	39.9	42.2	45.0	37.5	44.4	4
03:01	31.4	36.5	38.8	41.8	43.4	36.6	43.0	4
04:01	30.8	35.6	37.8	41.3	41.9	35.8	41.7	4
05:01	30.3	34.8	36.9	40.8	40.6	35.1	40.5	4
06:01	29.9	34.0	36.1	40.2	39.6	34.4	39.5	4
07:01	29.5	33.3	35.4	39.7	38.6	33.8	38.5	4
08:01	29.2	32.6	34.7	39.2	37.7	33.2	37.6	4
09:01	28.9	32.0	34.0	38.7	36.9	32.8	36.8	4

APPENDIX 6.3

Hourly temperatures and other measurements during heat treatment at Moss 20 - 22 Sep 95. Column numbers refer to sensor numbers, see appendix 6.2.

0.0	*25*	*26*	*27*	*28*	*29*	*30*	*33*	*34*
12:02	11.4	12.3	12.1	11.7	11.5	17.2		10.9
13:02	51.8	51.4	28.4	58.2	26.2	19.1		68.8
14:02	60.0	58.5	43.9	63.2	29.5	17.0		55.9
15:02	65.0	64.3	53.0	69.6	33.2	18.1		72.3
16:02	66.5	66.0	57.1	70.4	34.4	17.4		72.5
17:02	52.9	52.8	51.2	54.8	55.9	16.1	140.5	78.7
18:02	57.0	56.4	51.4	58.8	60.2	18.0	138	82.8
19:02	55.2	54.6	48.1	57.1	61.4	15.6	135.7	80.9
20:02	58.0	55.6	50.2	59.1	61.8	16.7	124.6	86.1
21:02	59.4	57.7	51.3	59.3	62.4	16.8	138.3	84.0
22:11	61.1	59.3	52.9	61.2	65.0	17.2	137.9	83.4
23:01	62.1	60.1	53.7	62.1	62.9	17.4	137.5	84.4
00:01	62.0	59.8	54.2	62.6	64.5	17.4	134.5	86.5
01:01	62.9	60.4	54.8	62.9	62.5	17.7	135.9	85.0
02:01	63.8	62.0	55.5	63.3	64.8	18.2	133	85.5
03:01	63.3	62.0	55.5	63.3	63.4	18.1	133.7	84.4
04:01	64.2	62.1	56.5	65.0	66.2	18.9	134.3	85.5
05:01	64.8	63.1	56.7	64.3	66.8	19.4	133.8	86.3
06:01	65.2	63.0	57.4	66.1	66.6	19.9	131.6	86.7
07:01	65.8	64.1	58.2	66.2	69.2	20.5	133.1	85.0
08:01	65.6	64.2	58.1	66.6	67.7	21.0	134.2	86.0
09:01	66.5	64.7	58.7	66.6	67.8	21.2	133.5	88.7
10:01	68.3	66.8	59.9	68.6	73.8	22.3	136.6	90.0
11:01	62.6	61.9	58.6	63.6	68.7	22.8	138.3	91.4
12:01	60.9	60.2	56.5	62.3	69.5	22.5	140	91.1
13:01	63.8	63.0	58.7	64.9	70.4	24.4	142.1	93.0
14:01	63.5	62.5	58.2	64.6	70.2	24.4	142	92.7
15:01	85.1	83.6	68.0	89.0	62.4	23.2	144.4	94.6
16:01	90.6	89.2	79.2	93.9	62.6	24.9	146.1	96.9
17:01	69.1	70.6	78.8	67.8	65.9	25.7	145.4	97.8
18:01	67.3	65.1	69.7	66.0	68.2	27.2	145.7	100.6
19:01	65.4	63.8	64.7	64.7	68.3	27.3	146.6	99.6
20:01	62.6	61.2	60.3	62.3	66.9	26.2	144.3	97.8
21:01	55.9	56.4	59.4	56.4	52.4	27.6	31.5	49.6
22:01	51.2	52.5	57.2	52.6	46.9	29.3	22.5	44.5
23:01	47.5	49.3	53.4	49.0	43.4	29.6	21.1	41.2
00:01	45.1	46.6	50.4	46.3	41.5	30.1	19	39.4
01:01	43.1	44.7	47.8	44.3	40.1	30.5	18.6	37.9
02:01	41.7	42.8	45.7	42.6	38.8	30.9	18.2	36.8
03:01	40.6	41.5	44.0	41.4	38.0	31.3	19.6	36.3
04:01	39.6	40.3	42.5	40.2	37.3	31.6	19.5	35.2
05:01	38.6	39.3	41.1	39.2	36.5	31.7	18.5	34.6
06:01	37.8	38.5	39.9	38.2	35.9	31.8	18.3	33.9
07:01	37.0	37.6	38.8	37.4	35.5	31.9	18.1	33.3
08:01	36.3	36.7	37.9	36.7	34.8	31.9	18.5	32.6
09:01	35.7	35.9	37.0	36.0	34.3	31.9	18.1	32.1

APPENDIX 6.3

Hourly temperatures and other measurements during heat treatment at Moss 20 - 22 Sep 95. Column numbers refer to sensor numbers, see appendix 6.2.

0.0	*35*	*36*	*37*	*38*	*39*	*40*	*41*	
12:02	10.3		7.6		8.6	7.4	13.6	8
13:02	50.2	32.4	14.9	23.5	16.6	10.7	17.3	
14:02	46.4	37.2	16.8	26.7	19.8	10.3	16.0	
15:02	54.8	39.3	21.1	30.5	24.1	13.0	21.9	
16:02	56.2	41.6	21.9	31.7	25.4	13.3	23.3	6
17:02	60.8	48.0	24.6	39.3	30.1	13.1	19.0	7
18:02	65.4	56.3	29.6	44.7	35.0	14.6	24.0	7
19:02	65.5	54.6	28.4	44.0	34.5	11.8	17.5	7
20:02	68.2	58.7	29.3	46.2	37.0	13.7	16.2	7
21:02	68.5	59.5	24.6	47.6	38.2	12.1	15.2	7
22:11	70.1	61.4	26.1	49.1	39.4	11.0	20.0	2
23:01	70.9	62.8	26.9	49.9	40.1	10.4	21.9	7
00:01	71.3	62.7	27.3	50.3	40.4	9.7	22.3	7
01:01	72.1	64.3	27.9	51.1	40.7	8.9	22.4	7
02:01	71.3	64.3	28.4	51.6	40.9	7.8	23.2	7
03:01	71.8	64.8	28.0	51.4	40.8	7.2	21.7	7
04:01	72.4	65.5	28.6	52.2	41.2	7.4	21.2	7
05:01	72.7	65.8	28.7	52.6	41.5	7.1	22.0	7
06:01	74.3	65.9	28.9	53.1	41.8	7.2	22.3	7
07:01	73.8	67.8	29.4	53.7	42.1	6.2	22.7	7
08:01	74.5	67.2	29.5	53.4	41.8	7.3	23.0	7
09:01	75.8	69.3	29.6	54.3	42.7	8.5	22.5	7
10:01	78.7	71.1	31.0	56.4	43.5	10.8	24.4	7
11:01	79.6	72.7	31.8	57.5	44.4	12.1	25.2	7
12:01	78.5	71.6	31.2	57.2	44.3	12.6	17.2	7
13:01	80.6	74.8	34.1	59.6	46.3	14.0	23.4	7
14:01	81.3	74.2	34.1	59.6	46.4	14.4	24.3	7
15:01	81.5	69.7	32.6	54.7	43.0	13.4	19.1	6
16:01	81.5	70.6	34.3	55.4	43.6	15.1	17.1	6
17:01	84.4	74.0	35.2	57.8	44.8	14.4	17.3	6
18:01	86.6	76.5	37.2	60.4	46.7	16.5	23.2	6
19:01	86.9	76.7	37.3	60.5	46.1	14.9	24.9	6
20:01	85.3	74.7	35.6	59.1	45.1	13.5	19.3	6
21:01	48.9	50.8	36.2	28.1	27.9	12.6	16.6	3
22:01	42.6	45.2	35.3	22.5	27.5	13.7	21.8	3
23:01	39.5	42.0	33.4	20.3	26.7	11.9	23.0	3
00:01	37.4	39.9	31.8	16.0	23.4	10.7	23.7	3
01:01	35.9	38.7	23.7	16.7	23.6	11.4	24.1	3
02:01	34.5	37.4	22.8	16.8	23.4	11.1	24.5	3
03:01	34.0	36.6	23.5	18.2	23.3	13.4	25.0	3
04:01	33.3	35.6	22.9	17.7	22.5	13.1	25.5	3
05:01	32.6	34.9	22.0	16.5	22.0	11.7	25.7	3
06:01	31.9	34.3	21.9	16.9	22.1	12.0	26.0	3
07:01	31.3	33.7	21.6	17.0	21.8	12.9	26.2	3
08:01	31.0	33.0	21.4	17.2	21.2	13.1	26.3	2
09:01	30.5	32.4	20.9	16.4	20.4	12.7	26.5	3

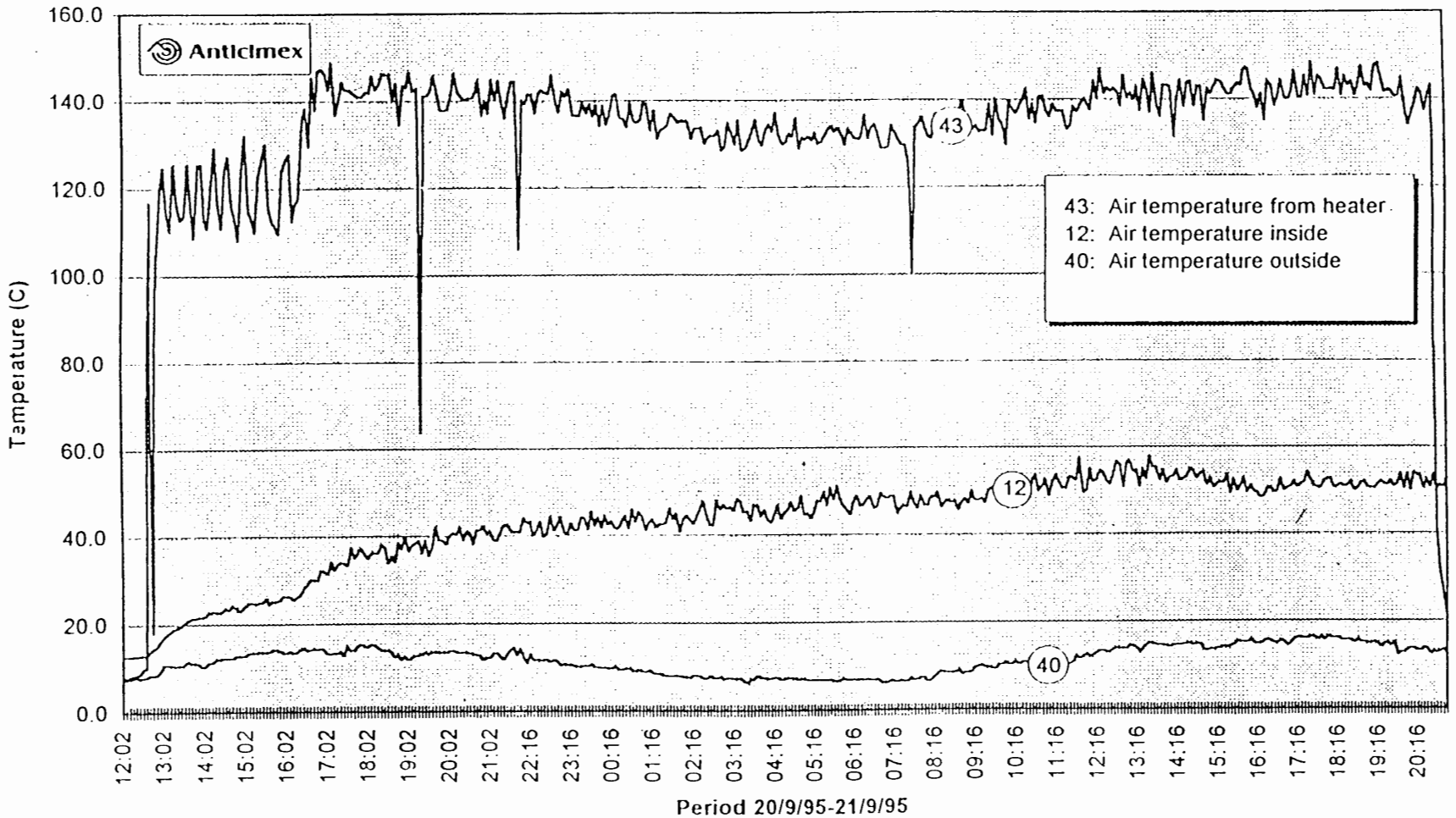
APPENDIX 6.3

Hourly temperatures and other measurements during heat treatment at Moss 20 - 22 Sep 95. Column numbers refer to sensor numbers, see appendix 6.2.

0.0	*43*	*44*	*45*	*46*	*47*	*48*	*49*
12:02	8.1	1	0.06	21.5	10.5		Err.01
13:02	124.5	2	0.37	21.2	13.9		Err.01
14:02	112.9	3	0.51	20.7	13.1		Err.01
15:02	132.1	3	0.48	20.7	17.2		Err.01
16:02	126.2	2	0.48	20.8	18.6		Err.01
17:02	146.5	3	0.66	20.5	15.0		Err.01
18:02	142.2	3	0.68	20.6	19.7		Err.01
19:02	143.1	3	0.69	20.6	13.8		Err.01
20:02	138.3	3	0.71	21.0	14.3		Err.01
21:02	137.1	3	0.71	21.1	13.4		Err.01
22:11	139.2	4	0.68	20.6	17.1		56.0
23:01	137.2	4	0.71	20.4	17.9	10.5	56.3
00:01	134.1	4	0.71	20.5	17.9	9.8	57.2
01:01	135.6	4	0.71	20.4	18.1	9.6	57.1
02:01	135.4	4	0.70	20.4	18.5	9.3	57.6
03:01	128.4				17.0	8.8	58.4
04:01	129.4				16.9	8.2	59.2
05:01	131.4	4	0.66	20.7	17.5	7.9	59.7
06:01	132.4	4	0.67	20.6	18.5	7.5	60.4
07:01	128.9	4	0.66	20.5	18.1	7.2	60.4
08:01	136.1	4	0.64	20.9	18.1	7.3	60.5
09:01	139.9	4	0.69	21.1	17.5	7.0	62.0
10:01	134.0	4	0.68	21.1	19.2	6.7	63.2
11:01	140.7				20.1	6.1	66.8
12:01	140.1				14.9	5.9	67.8
13:01	145.6				19.5	5.8	68.1
14:01	143.3	4	0.68	20.5	20.1	5.7	69.0
15:01	135.1	4	0.71	20.5	14.7	6.2	67.0
16:01	147.0	4	0.70	20.8	15.5	6.5	66.7
17:01	140.1	4	0.73	20.7	15.4	5.9	69.9
18:01	142.3	4	0.70	20.3	20.1	5.5	71.8
19:01	142.9	5	0.71	20.3	21.0	5.3	72.7
20:01	137.4	5	0.70	20.5	14.4	5.0	73.0
21:01	21.4		0.8		14.5	7.9	58.0
22:01	14.8				18.7	11.4	48.9
23:01	13.8				19.2	13.7	45.1
00:01	11.7				19.5	15.2	42.9
01:01	12.1				19.7	16.6	41.3
02:01	11.7				20.1	17.9	40.0
03:01	13.9				20.8	19.6	39.2
04:01	13.7				21.3	21.1	38.1
05:01	12.5				21.3	22.2	37.5
06:01	12.8				21.5	23.0	36.7
07:01	13.0				21.7	23.7	36.1
08:01	13.2				21.9	24.7	35.5
09:01	12.7				22.1	25.3	35.0

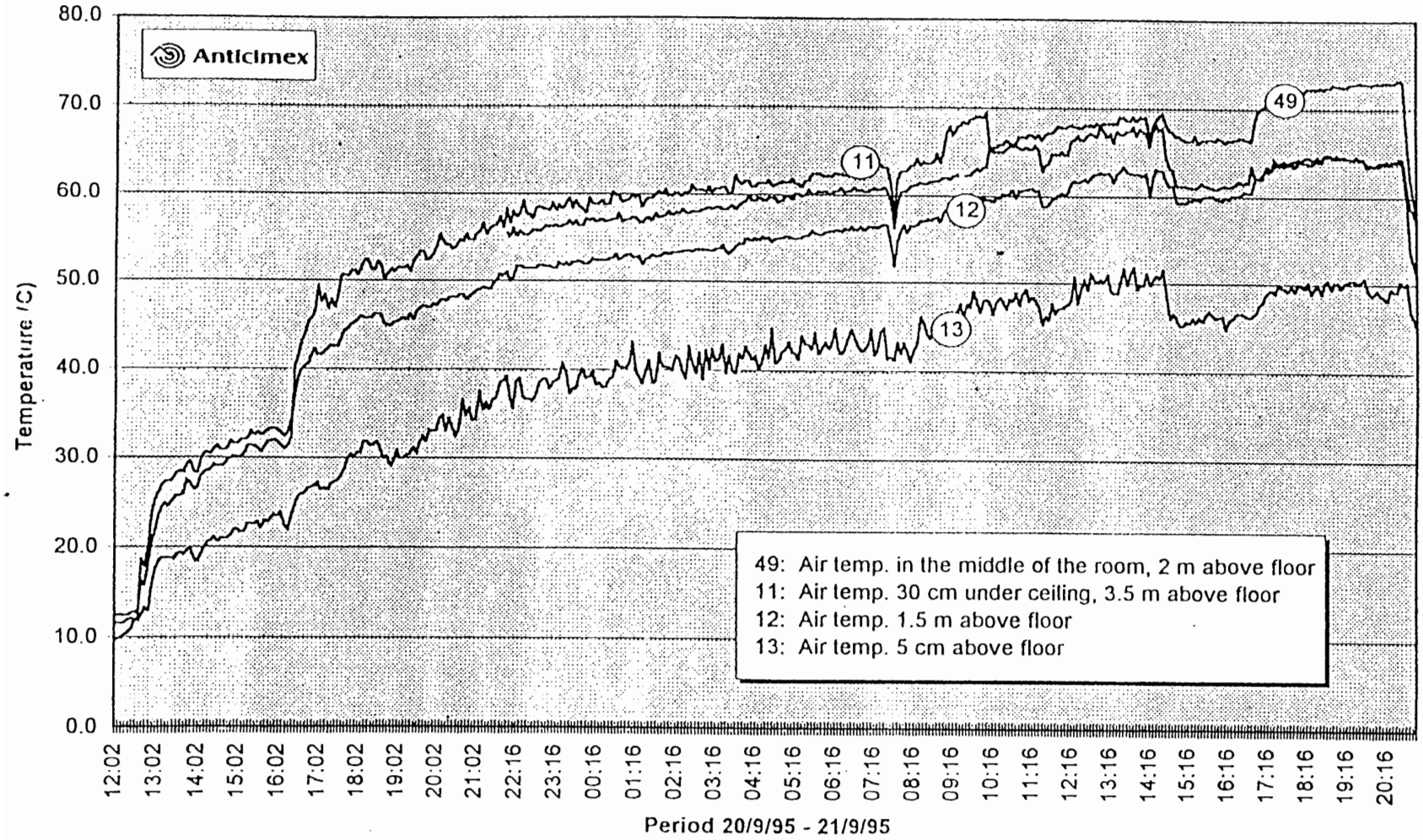
Heat treatment, Moss

Key temperatures



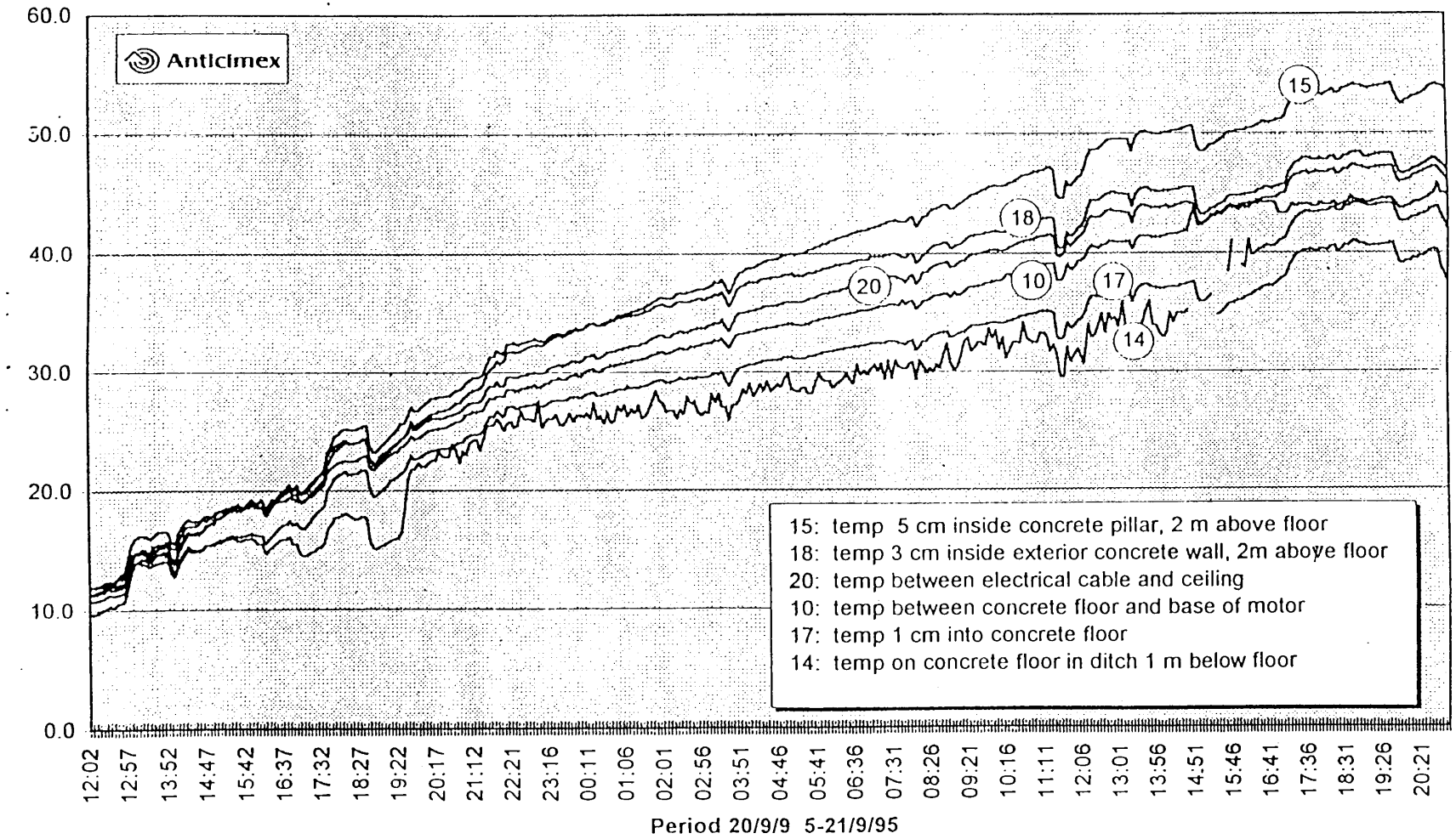
Heat treatment, Moss

Air temperatures inside during treatment



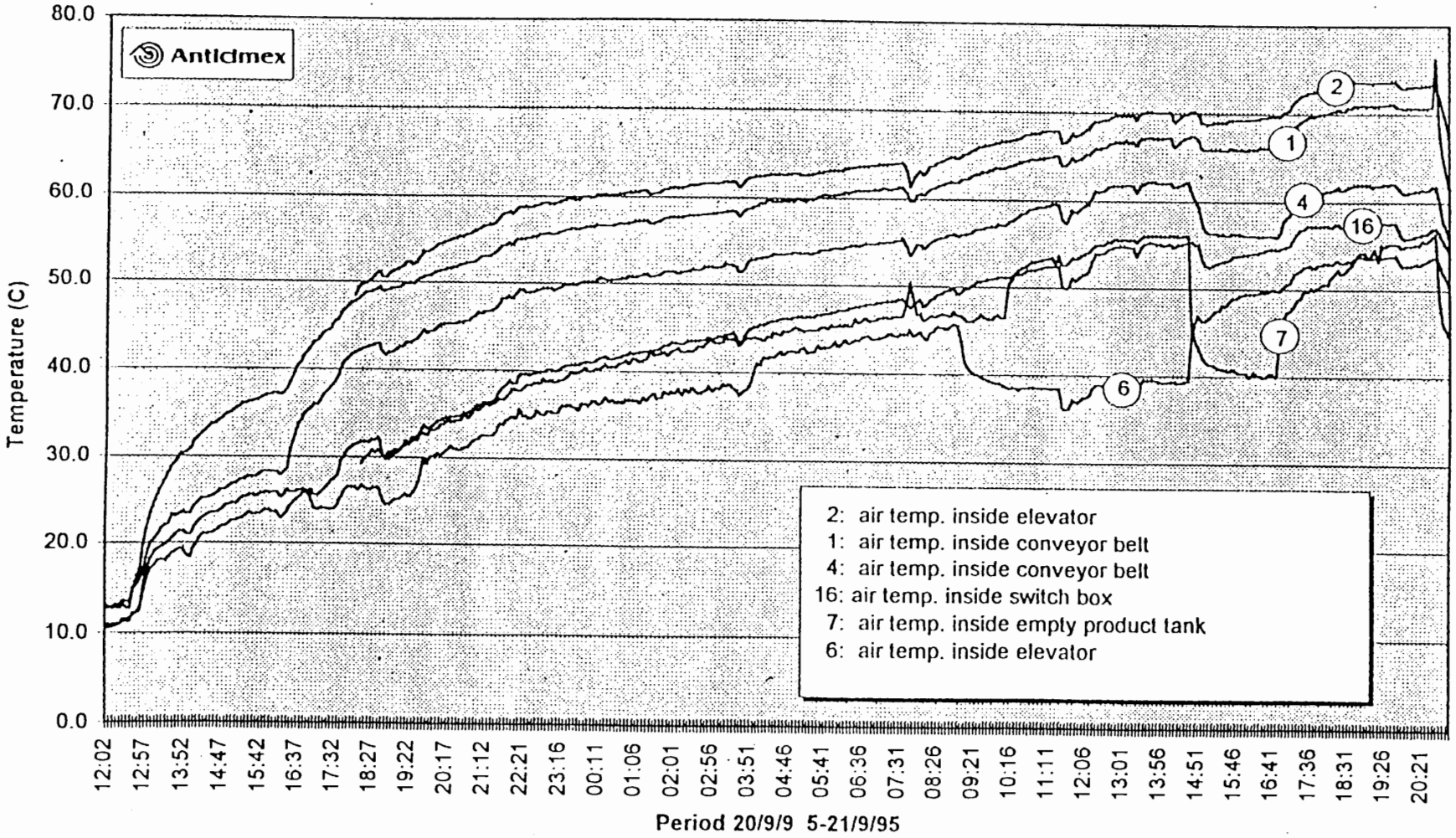
Heat treatment, Moss

Temperature in construction

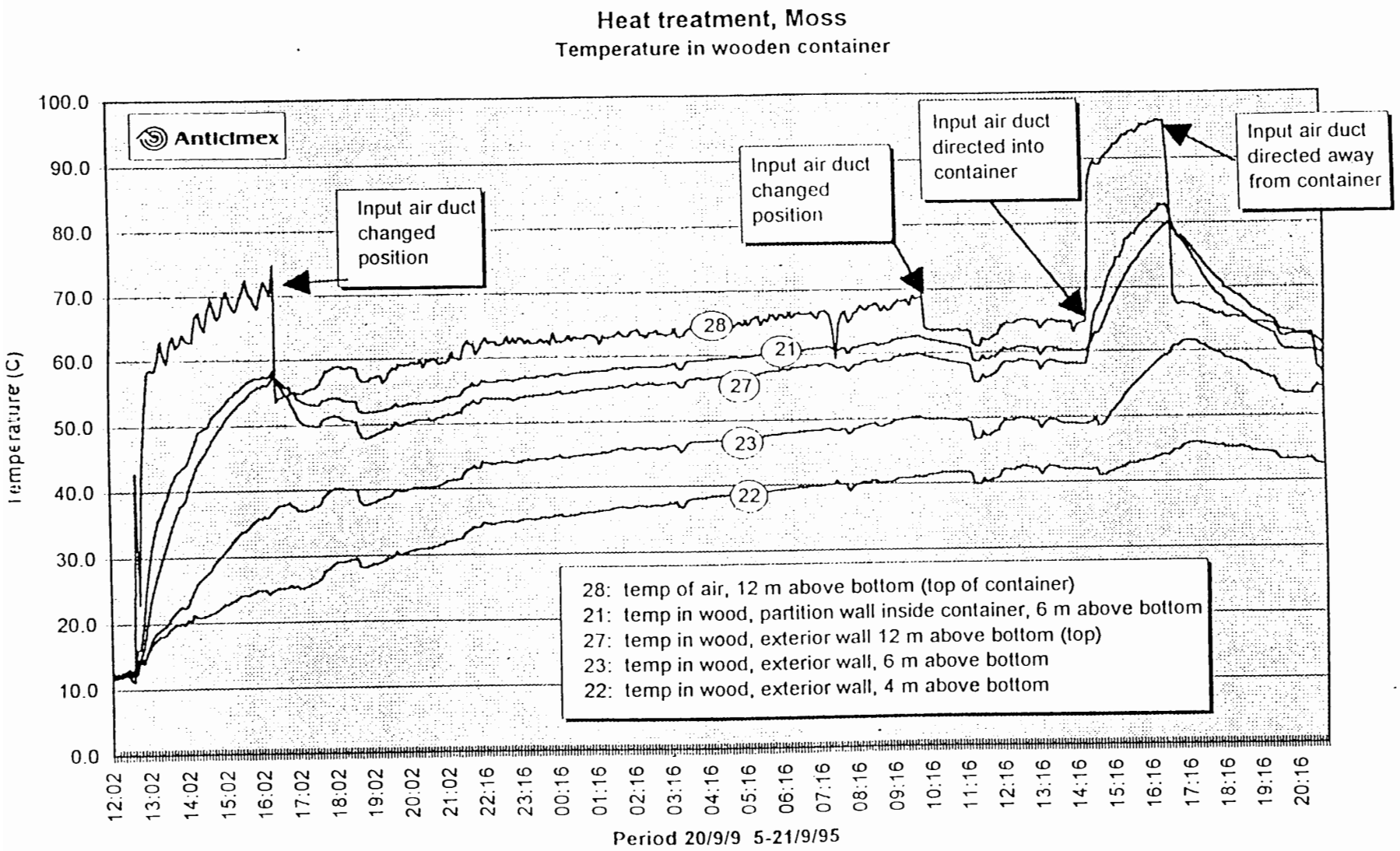


Heat treatment, Moss

Air temperature inside equipment

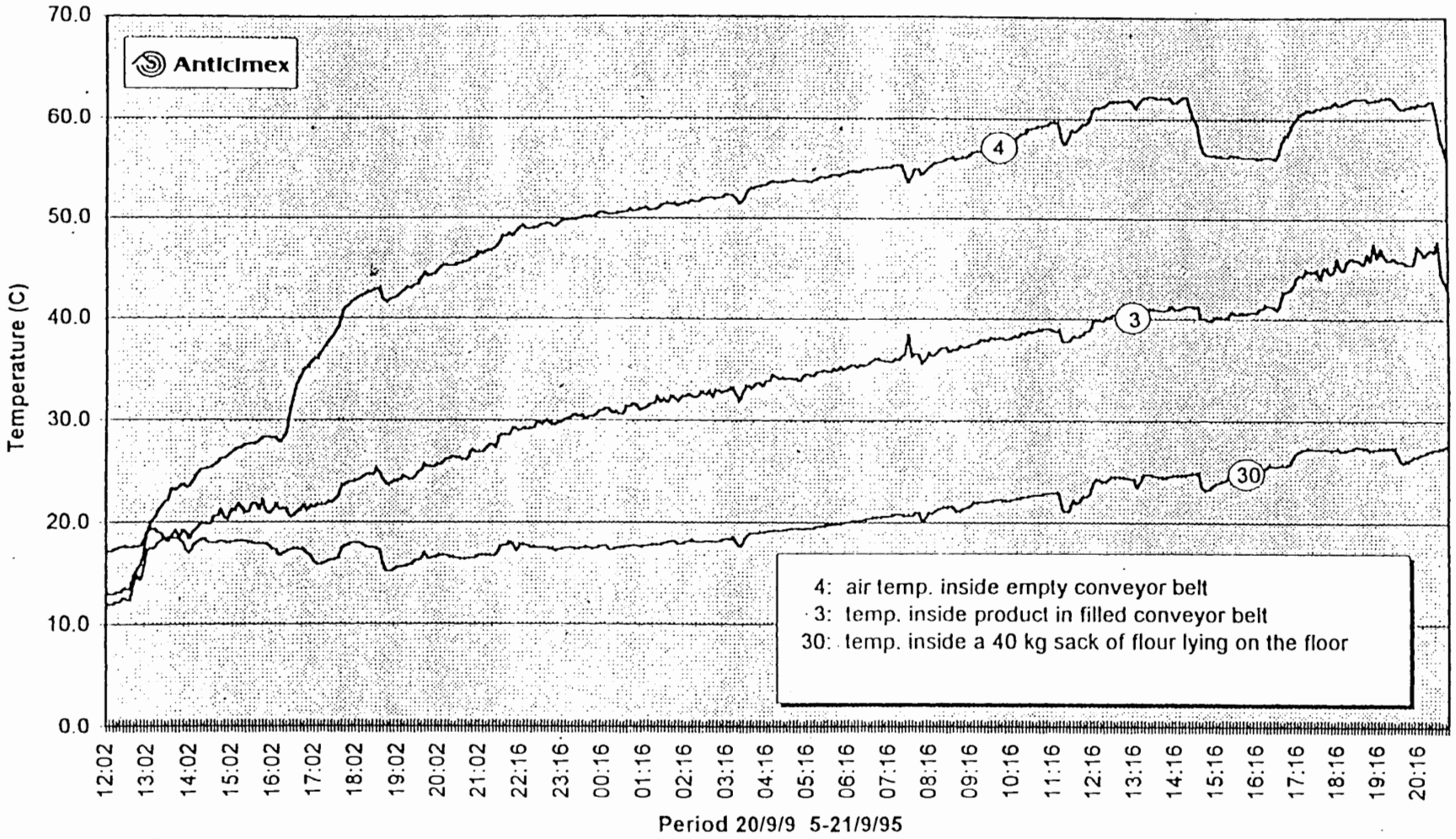


APPENDIX 6.8


Heat treatment, Moss
Temperature in wooden container
Anticimex
Input air duct changed position
Input air duct changed position
Input air duct directed into container
Input air duct directed away from container
28
21
27
23
22
28: temp of air, 12 m above bottom (top of container)
21: temp in wood, partition wall inside container, 6 m above bottom
27: temp in wood, exterior wall 12 m above bottom (top)
23: temp in wood, exterior wall, 6 m above bottom
22: temp in wood, exterior wall, 4 m above bottom
Temperature (C)
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
12:02
13:02
14:02
15:02
16:02
17:02
18:02
19:02
20:02
21:02
22:16
23:16
00:16
01:16
02:16
03:16
04:16
05:16
06:16
07:16
08:16
09:16
10:16
11:16
12:16
13:16
14:16
15:16
16:16
17:16
18:16
19:16
20:16
Period 20/9/9 5-21/9/95

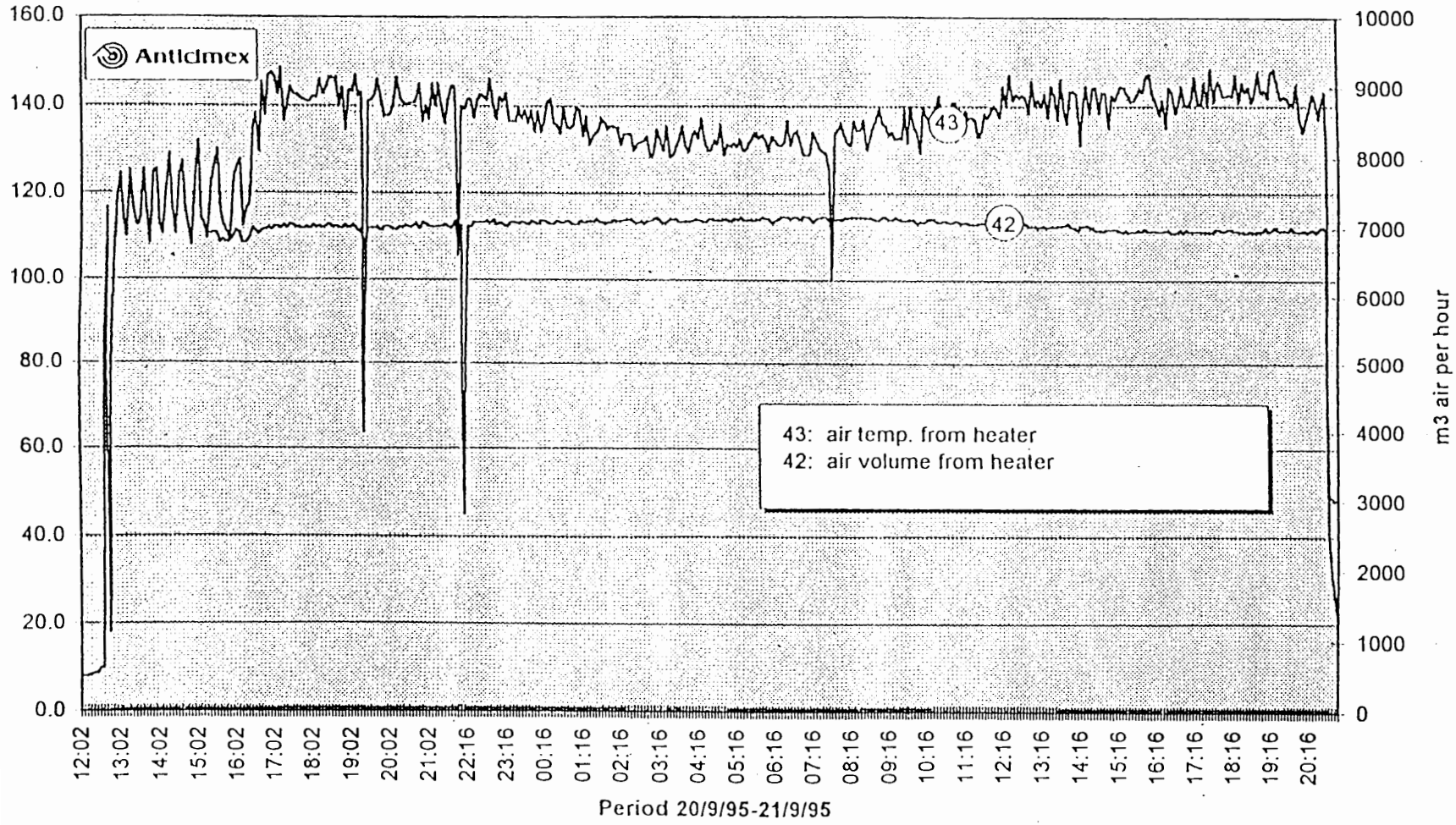
Heat treatment, Moss

Effect of products in the heating process



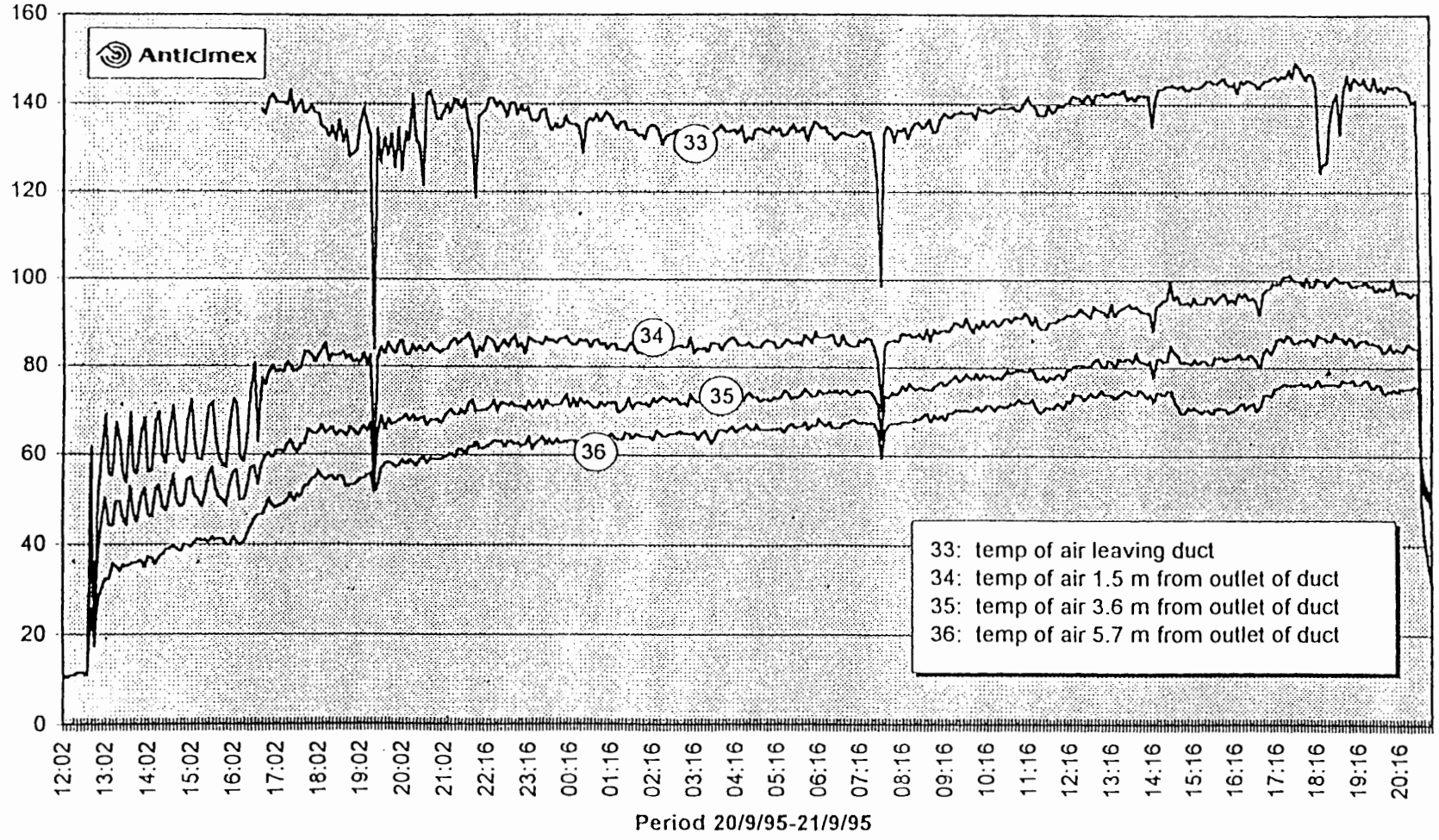
Heat treatment, Moss

Volume and temperature of input air



Heat treatment, Moss

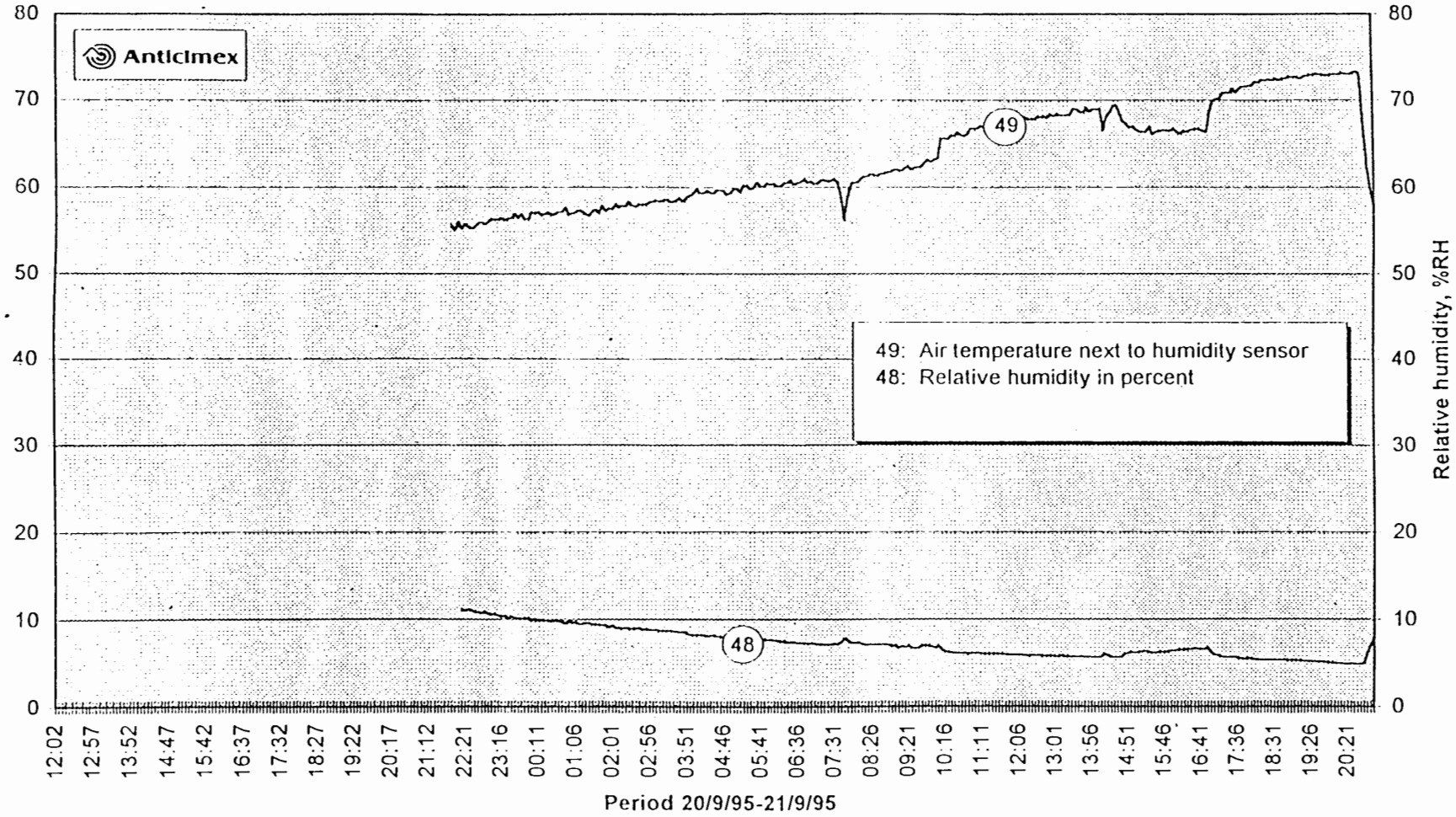
Cooling of input air



Appendix 6.11

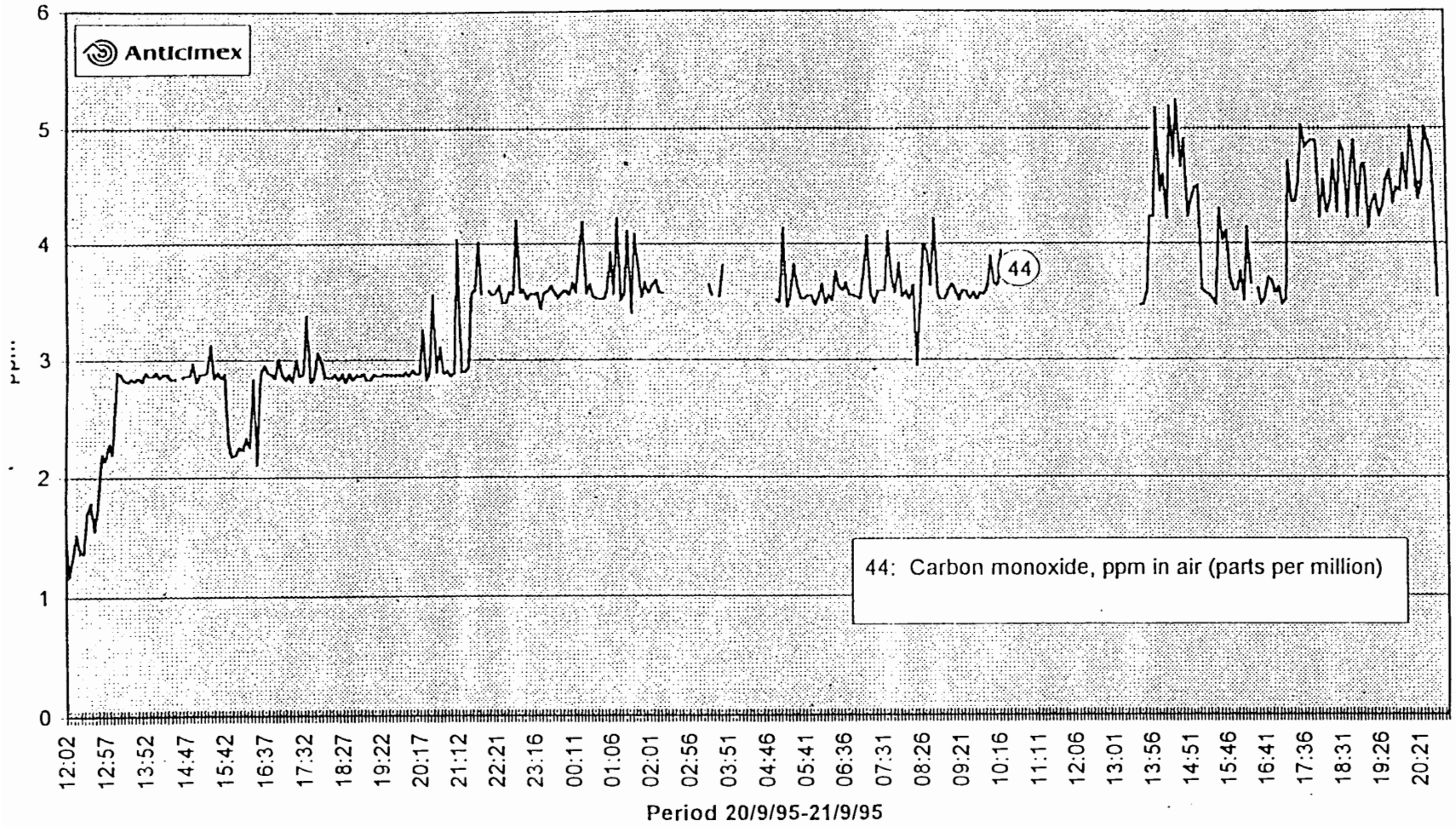
Heat treatment, Moss

Humidity measurements

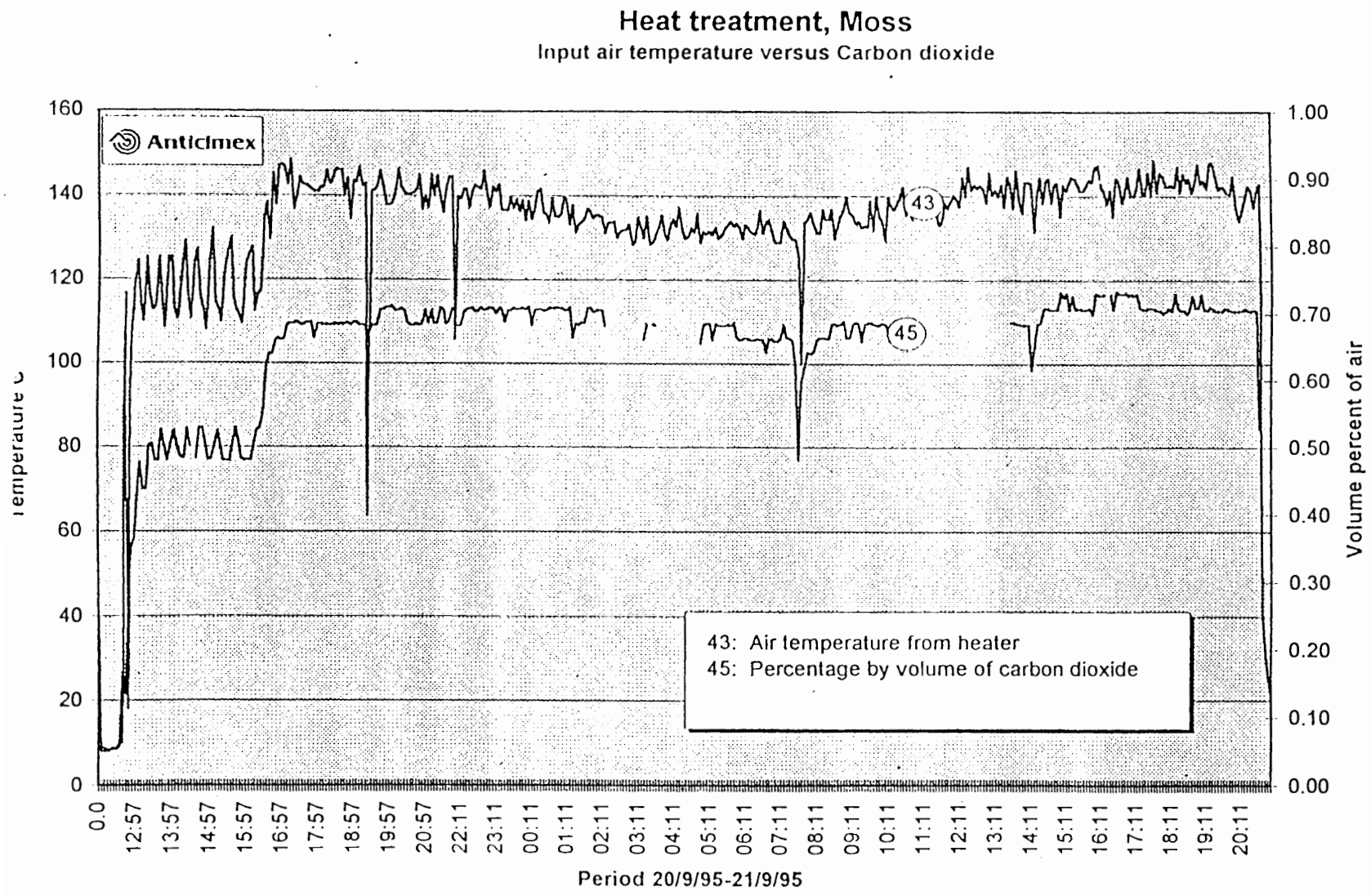


Heat treatment, Moss

Carbon monoxide measurements

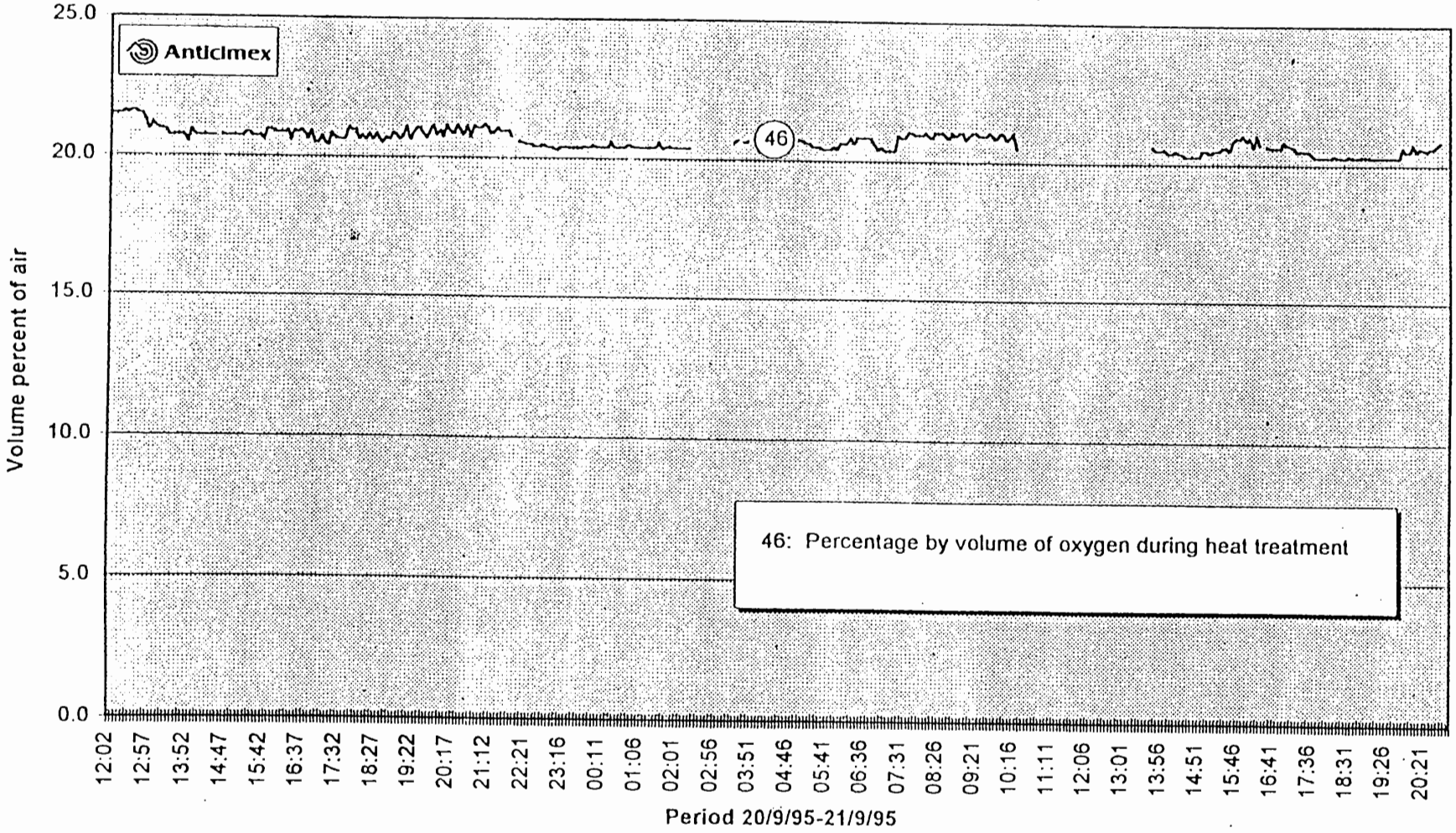


APPENDIX 6.14



Heat treatment, Moss

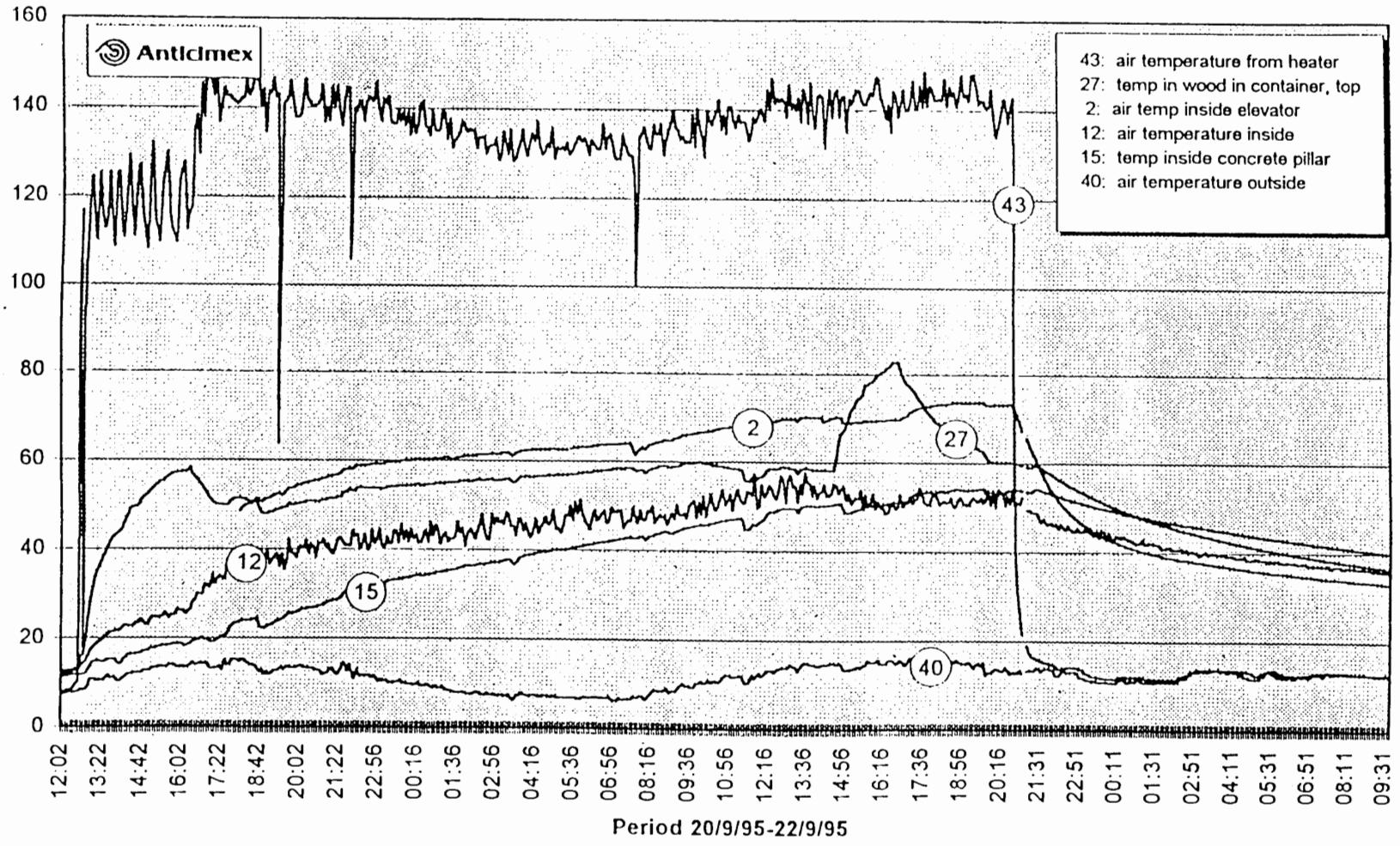
Oxygen measurement



APPENDIX 6.16

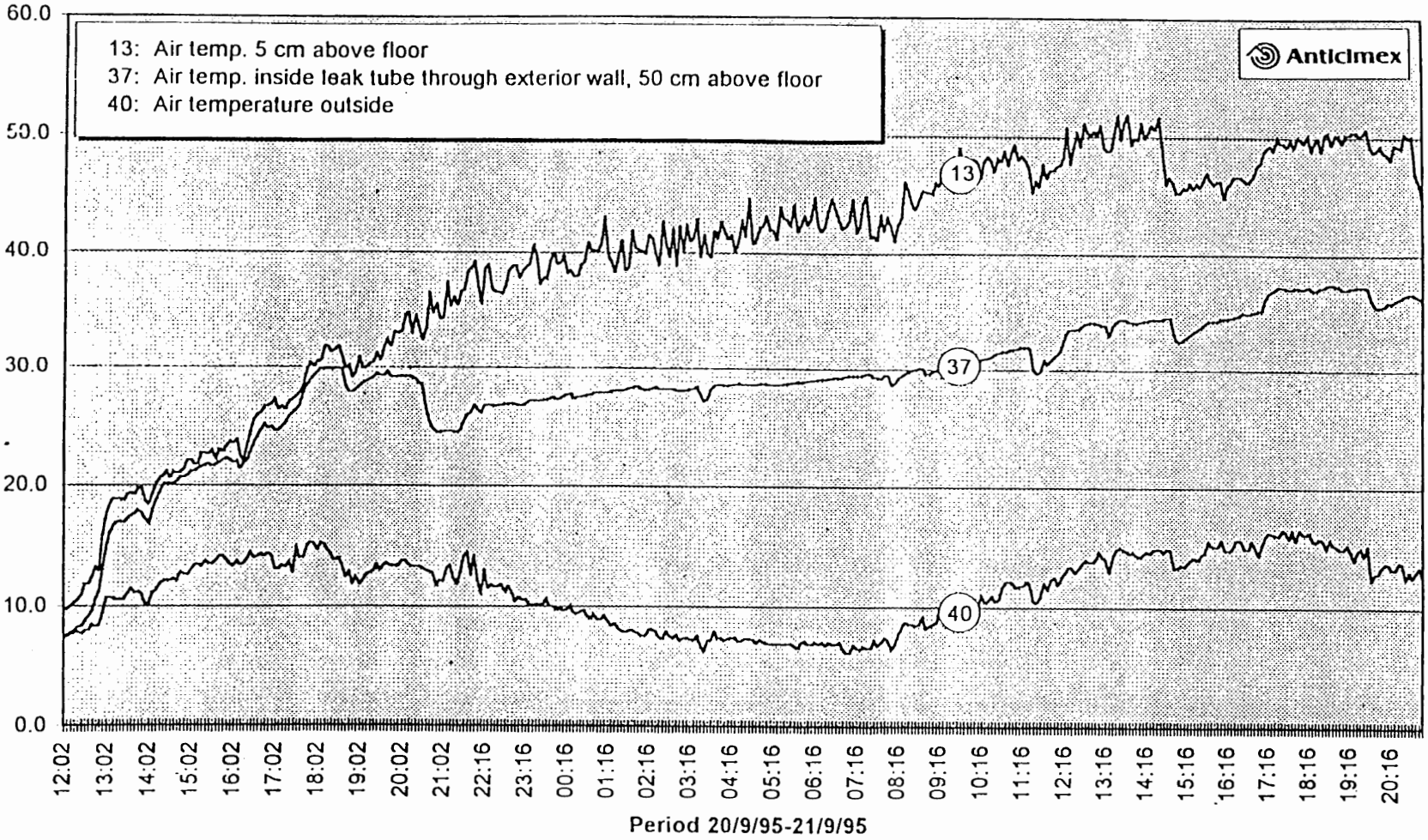
Heat treatment, Moss

Cooling down



Heat treatment, Moss

Comparison between leak tube temperatures and outside and inside temperatures



J. stored Prod. Res. Vol. 28, No. 2, pp. 89–118, 1992
Printed in Great Britain

0022-474X/92 $5.00 + 0.00
Pergamon Press Ltd

THE CONTROL OF STORED-PRODUCT INSECTS AND MITES WITH EXTREME TEMPERATURES*

PAUL G. FIELDS
Agriculture Canada Research Station, 195 Dafoe Road, Winnipeg, Manitoba, Canada R3T 2M9

Abstract—Heating or cooling is used extensively to control stored-product insect and mite pests. For most stored-product insects 25–33°C is optimal for growth and reproduction, at 13–25 or at 33–35°C insects are able to complete their development and produce offspring, but <13 or >35°C insects eventually die. The more extreme the temperature the more quickly insects die, with death occurring in a few minutes at −20 or 55°C. Lethal temperatures vary considerably and depend on species, stage of development, acclimation, and relative humidity. Extensive tables listing the survival of the major stored-product insects and mites at extreme temperatures from over 50 papers is presented. There are many ways to cool the commodity: turning, aeration or refrigerated aeration, or to heat the commodity: infrared, microwaves, high frequency irradiation, or hot air in fluidized-bed. Some of these processes are available commercially, while others have been tested only in the laboratory.

The proposed behavioral, physiological, and biochemical mechanisms that enable stored-product insects to survive extreme temperatures are reviewed. Possible synergists that might make stored-product insects more susceptible to extreme temperatures are suggested. One example is the use of ice-nucleating active bacteria to increase the supercooling points of insects, thereby making them less cold-hardy. The supercooling points of four beetles has been measured and compared to published data for other stored-product insects. A standard protocol for examining the survival of stored-product insects at extreme temperatures is outlined.

INTRODUCTION

In the last 50 yr the story of insect control has been written predominantly by chemists and toxicologists. The stunning successes of the organochlorines and organophosphates in the 1950s led to a dramatic increase in the number and quantity of insecticides used in agriculture (Ware, 1983). There has been a movement away from chemical control of insects in the last 15 yr because of two basic problems (Huffaker, 1980). One, insecticides are usually toxic to more species than those they are intended to control. Insecticides often kill predators and parasites that reduce insect pest populations. Also, insecticides can be toxic to fish, birds, or mammals. The deregistration in 1984 of the liquid fumigants for controlling stored-product insects in Canada and the U.S.A. is a recent example of society's concerns about toxic residues on food. Secondly, the continued use of a single insecticide or class of insecticides often leads to resistance within insect populations. In extreme cases the insecticide can no longer be used because it does not control the insect pest. This is the case for malathion and stored-product insects in Australia where widespread resistance to malathion required the replacement of this insecticide 16 yr after it was first introduced as a grain protectant (Collins and Wilson, 1986).

The challenge of controlling insect pests with a minimum of chemical insecticides has led to the development of integrated pest management strategies. There are several methods to reduce the amount of insecticide applied; baited insecticides, treatments synchronized with pest populations, resistant plants, biological control, mass trapping, insect growth regulators, cultural control or physical control, and many are currently being used against field crop pests (Huffaker, 1980). Several of these techniques have been used effectively to control stored-product pests (Evans, 1987a) and their implementation has been facilitated because the storage environment is largely determined by man.

One technique that is not readily applicable to field insect pests, but has been used successfully for many years against stored-product pests, is the use of extreme temperatures. As early as the 16th century high temperature was used as a means to control the moth *Sitotroga cerealella*

*Based on a paper presented at a symposium on "*Management of Postharvest Ecosystems: Current and Future Trends*" held at Winnipeg, Canada, in November 1990, at the annual meeting of the Entomological Society of Manitoba.
Copyright © for the Department of Agriculture, Government of Canada.

Table 1. The response of stored-product insects to temperature*

Zone	Temp. (°C)	Effect
Lethal	50–60	death in minutes
	45	death in hours
Suboptimum	35	development stops
	33–35	development slows
Optimum	25–33	maximum rate of development
Suboptimum	13–25	development slows
	13–20	development stops
Lethal	5	death in days (unacclimated), movement stops
	−10–5	death in weeks to months (acclimated)
	−25 to −15	death in minutes, insects freeze

*Species, stage of development and moisture content of food will influence the response to temperature.

(Oliver) in France (Oosthuizen, 1935). There are three temperature zones for any organism: optimum, where the species' fitness is greatest rate of development, number of offspring; suboptimum, where temperatures are above or below the optimum zone but where species can still complete their life cycle; lethal, where temperatures are above or below the suboptimum zone and kill the organism over time. Table 1 describes these zones for stored-product insects.

To describe situations that have fluctuating temperatures, Turnock *et al.* (1983) have further divided the cold lethal zone into three zones: cold-injury, where cold-injury occurs and cannot be repaired; neutral, where cold-injury does not occur and cannot be repaired; active, where cold-injury does not occur but can be repaired. This hypothesis has not been tested using stored-product insects, as most work with stored-product insects has used single temperature exposures rather than fluctuating temperatures.

The purpose of this paper is to (1) review the research on the use of extreme temperatures to control stored-product insects, (2) review the mechanisms by which insects survive extreme temperatures and suggest ways that insects could be made more susceptible to extreme temperatures, and (3) suggest standard protocols for examining the effects of extreme temperature on insects.

Low Temperature: Suboptimum

Lowering the grain temperature below the optimum will reduce damage caused by insects, mites, and molds (Longstaff, 1981; Flinn and Hagstrum, 1990). Howe (1965) did an extensive review of the minimum temperatures and humidities that insects needed to double their numbers annually. Grain held at 20°C will stop the development of most stored-product insects, the most important exception being *Sitophilus granarius* (Linnaeus) which can complete its development at 15°C. To prevent mites from developing on damp grain, temperatures must be lowered to 2°C. However, on grain at moisture contents of 13%, the minimum temperature is 6°C (Burges and Burrell, 1964). Low temperature can help to prevent grain from becoming moldy before it can be dried (Burrell and Laundon, 1967). However, temperatures as low as −23°C did not reduce mold populations in feed (Brown and Hill, 1984).

Low Temperature: Lethal

There are over 30 papers examining the survival of stored-product insects and mites at temperatures below their developmental thresholds (Tables 2–5). There are basically two types of studies, those that report laboratory experiments on low temperature survival (Tables 2–4), and those that report survival at low temperatures in the field (Table 5). The laboratory studies are easier to replicate and they can be used to examine single factors in isolation, but they can only approximate field conditions. Field experiments are a much better estimate of what is happening in the field, but they take much longer and require considerable resources. Since conditions vary from year to year and place to place, comparisons are often difficult.

Temperature, duration of exposure, species, stage of development, acclimation, relative humidity, and gender determine the survival of insects at low temperature. It is useful to know the general relationship between time and temperature to design experiments, to develop computer models and to suggest possible cold-injury mechanisms. The relationship between the time necessary to kill a given percentage of the population (y-axis) and temperature (x-axis) is usually a concave (j-shaped)

curve (Solomon and Adamson, 1955; Mullen and Arbogast, 1979; Evans, 1987c; Fig. 1). Occasionally, straight-line relationships are reported. In some cases this is probably due to the narrow range of temperatures used (e.g. Nowosielski-Slepowron *et al.*, 1968), and a wider range of temperatures would probably yield a concave curve. In other cases, data taken from a number of studies may produce a straight line because of significant differences in protocols [Fig. 1, *Cryptolestes ferrugineus* (Stephens), unacclimated]. Finally, there are a few species that the temperature–mortality relationships is neither a concave nor straight curve (Stratil and Reichmuth, 1984; data in Table 3).

The relationship between mortality (y-axis) and time (x-axis) at a given temperature is usually sigmoidal (Nagel and Shepard, 1934; Sømme, 1968a; Evans, 1983; Turnock *et al.*, 1983; Evans, 1987c). Probit analysis is often used to determine the lethal time for 50, 95, or 99% of the population, and produces variance estimates (fiducial limits) that can be used to compare tests. Unfortunately, these are rarely reported, perhaps because they often have wide ranges. Caution should be used when using probit analysis because all mortality vs time data are not sigmoidal (Robinson, 1926; Evans, 1983, 1987b). Also, extrapolating beyond the range of values that are actually covered by the experiment is tenuous.

Different species have different capacities to survive low temperatures (Tables 2–4). It is difficult to make comparisons between studies because of the differences in acclimation, temperatures, and durations used to test cold-survival. To avoid these problems several studies have examined the cold-tolerance of many species under the same conditions (Table 5). There is a general concurrence between these studies. The most cold-susceptible species are *Tribolium castaneum* (Herbst), *Tribolium confusum* Jacquelin du Val, and *Oryzaephilus mercator* (Fauvel). The most cold-tolerant insects are *Trogoderma granarium* (Everts), *S. granarius*, and the stored-product Lepidoptera, *Ephestia elutella* (Hübner), *E. kuehniella* (Zeller), and *Plodia interpunctella* (Hübner), with the rest of the species falling in between these extremes. With the correct tests and enough insects one could probably list all the species from most to least cold-susceptible with each species being significantly different from the other. However, that is not possible using data from Tables 2–4 because different studies rarely have used the same conditions, and often do not use probit analysis with fiducial limits.

These results also pose a dilemma for explaining the abundance of stored-product pests in the Canadian Prairies, the world's grain-growing area with the coldest winters. If cold plays a major role in the population dynamics in the Canadian Prairies, one would expect a preponderance of cold-hardy species. This is not the case. *Tribolium castaneum*, one of the most cold-susceptible stored-product insects, is the second most common species in grain stored on Canadian Prairie farms (Madrid *et al.*, 1990). The most common stored-product insect pest is *C. ferrugineus*, a relatively cold-hardy insect. Yet the other cold-hardy insects, such as *Trogoderma granarium*, *S. granarius*, *P. interpunctella*, *E. elutella*, and *E. kuehniella*, are generally absent. Although this is predictable for the Lepidoptera exposed to extremely low temperatures at the top surface of the grain (Bell, 1983), it does not explain the absence of the other cold-hardy species. Therefore, cold-tolerance alone is not a good predictor of stored-product species occurrence or abundance in cold temperate climates.

The stage of development is also an important factor in determining an individual insect's cold-tolerance (Nagel and Shepard, 1934; Howe and Hole, 1968; Smith, 1970; David *et al.*, 1977; Evans, 1983, 1987b; data in Tables 2 and 3). Temperate insects usually overwinter in diapause in one particular stage (Tauber *et al.*, 1985) that is more cold-hardy than the other stages (Danks, 1978). Since few stored-product insect pests have a diapausing stage that would be considered *a priori* the most cold-tolerant stage, all developmental stages must be tested to determine the most cold-hardy one. An exception is the Pyralidae which diapause as prepupae and diapause increases their cold-tolerance (Cox, 1987; data in Table 3). Eggs are usually the most cold-susceptible stage. Susceptibility varies greatly with the age of the egg, with young and old eggs being the least cold-hardy (Watters, 1966; Cline, 1970; Daumal *et al.*, 1974; Jacob and Flemming, 1986; Johnson and Wofford, 1991; data in Tables 2 and 3). The larva is the most cold-tolerant stage for *Rhyzopertha dominica* (Fabricius) and *Sitophilus oryzae* (Linnaeus) (David *et al.*, 1977). The adult is the most cold-tolerant stage for *C. ferrugineus* (Smith, 1970) and *Tribolium confusum* (Nagel and Sheppard, 1934). For *S. granarius*, certain larval stages are as cold-hardy as the adults (Howe and

Table 2. A review of the survival of stored-product beetles at low temperatures under laboratory conditions

Reference	Stage[1]	Strain[2]	Acclimation[3]	r.h.[4]	Temp.[5] (°C)	Percent survival (duration of exposure in days)[6]					
Callosobruchus maculatus (F.)											
Mullen and Arbogast (1979)[7]	e (12 h)	L	27°	?	5	50 (4.2)	5 (7.2)				
					0	50 (1.5)	5 (5.0)				
					−5	50 (0.6)	5 (1.7)				
					−10		5 (1.3)				
					−15		5 (0.2)				
Cryptolestes ferrugineus (Steph.)											
Mathlein (1961)	a	?	room°, 6°/7 d	?	0	3 (45)	0 (60)				
					−2	27 (25)					
					−4	26 (20)	10 (26)				
					−5	1 (28)	0 (30)				
Smith (1970)[7]	e	L	30°	70	2	50 (5.3)					
					−6	50 (0.6)					
					−12	50 (0.5)					
	l (1–2 d)	L	30°	70	2	50 (5.0)					
					−6	50 (1.4)					
					−12	50 (0.1)					
	l (10–17 d)	L	30°	70	2	50 (8.6)					
					−6	50 (2.7)					
					−12	50 (0.8)					
	p	L	30°	70	2	50 (8.8)					
					−6	50 (1.4)					
					−12	50 (0.3)					
	a (7–21 d)	L	30°	70	2	50 (15.3)					
					−6	50 (3.5)					
					−12	50 (0.6)					
			30°	70	−6	52 (3)	21 (5)	3 (9)			
			30°, 15°/1 d	70	−6	98 (3)	24 (5)				
			30°, 15°/3 d	70	−6	100 (3)	25 (5)				
			30°, 15°/7 d	70	−6	99 (3)	83 (5)	46 (9)	35 (14)		
			30°, 15°/14 d	70	−6	98 (3)	98 (5)	98 (9)	91 (14)	79 (21)	56 (28) 13 (35)
			30°, 15°/21 d	70	−6	100 (3)					
			30°	70	−12	0 (3)	0 (5)	0 (9)			
			30°, 15°/17 d	70	−12		33 (5)	31 (9)	19 (14)		
			30°, 15°/14 d	70	−12		80 (5)	41 (9)	41 (14)		
			30°, 15°/20 d	70	−12				76 (14)	77 (22)	51 (28)
			30°, 15°/28 d	70	−12				75 (14)	74 (22)	61 (28)
Evans (1983)[7]	a	?	32°	70	9	50 (7)	1 (33)				
				45	9	50 (11)	1 (24)				
			32° to 13.5°/28 d, (4.5°/7 d)	70	13.5	50 (265)	1 (>364)				
				45	13.5	50 (144)	1 (294)				
			32° to 9°/35 d, (4.5°/7 d)	70	9	50 (75)	1 (162)				
				45	9	50 (52)	1 (106)				
Barker (1990)[7]	l, p	L	30°	75	15	50 (18)	1 (245)				
					10	50 (12)	1 (335)				
					5	50 (12)	1 (43)				
					0	50 (10)	1 (30)				
					−5	5 (7)	0 (14)				

Kawamoto *et al.* (1990)	a (0–7 d)	L	30–[8]	70	15	100 (7)	100 (35)	100 (70)	99 (175)	97 (224)				
			30–[8]	70	10	100 (7)	99 (35)	98 (70)	97 (105)	95 (140)	91 (175)	87 (224)		
			30°, 15°/21 d	70	0	100 (7)	100 (14)	100 (21)	98 (28)	94 (42)	83 (49)	56 (77)		
			30°, 15°/21 d	70	−9	100 (7)	94 (14)	71 (21)	60 (28)	34 (42)	13 (49)			
Khan (1990)[8]	a (28 d)	?	30°	70	15	100 (7)	99 (14)	99 (21)	99 (28)	99 (35)	99 (42)			
					10	67 (7)	28 (14)	13 (21)	10 (28)	6 (35)	4 (42)			
					5	84 (7)	59 (14)	28 (21)	16 (28)	7 (35)	5 (42)			
					0	56 (7)	20 (14)	16 (21)	8 (28)	1 (35)	1 (42)			
			30°/7 d, 20°/7 d, 10°/7 d	70	0	95 (7)	94 (14)	91 (21)	50 (28)	38 (35)	31 (42)	28 (49)	26 (56)	
			30° to 5°/42 d, (5°/7 d)	70	0	94 (7)	91 (14)	86 (21)	85 (28)	84 (35)	79 (42)	44 (49)	42 (56)	42 (63)
						36 (70)	28 (77)							
			30°/7 d, 15°/7 d	70	0	96 (7)	95 (14)	94 (21)	53 (28)	44 (35)	39 (42)	34 (49)		
			30°/7 d, 15°/14 d	70	0	90 (7)	90 (14)	86 (21)	74 (28)	0 (35)	0 (42)	0 (49)	0 (56)	
			30°/7 d, 15°/21 d	70	0	94 (7)	94 (14)	92 (21)	54 (28)	0 (35)	0 (42)	0 (49)		
Fields (1990)[7]	a (7–28 d)	L	field 20 to 15°/Oct.–Nov.	16m	−10	50 (5)	5 (10)							
			field 20 to 15°/Oct.–Nov.	14m	−10	50 (6)	5 (11)							
			field 20 to 15°/Oct.–Nov.	12m	−10	50 (5)	5 (11)							
			field 20 to −2°/Oct.–Feb.	16m	−10	50 (40)	5 (73)							
			field 20 to −2°/Oct.–Feb.	14m	−10	50 (30)	5 (76)							
			field 20 to −2°/Oct.–Feb.	12m	−10	50 (24)	5 (38)							
Cryptolestes pusillus (Sch.)														
Williams (1954)	e	?	25°	35, 75 and 88	2	62 (1)	26 (2)	26 (2.5)	15 (3)	7 (4)				
	l (1)	?	25°	70	2			61 (2.5)						
	l (2)	?	25°	70	2			83 (2.5)						
	l (3)	?	25°	70	2			80 (2.5)						
	l (4)	?	25°	70	2			93 (2.5)						
	p	?	25°	70	2			98 (2.5)						
	a	?	25°	35, 75 and 88	2	95 (1)	80 (2)	67 (2.5)	39 (3)	13 (4)				
Lasioderma serricorne (F.)														
Childs *et al.* (1970)	l (3)	?	21.1°/1 d, 15.6°/4 d	75	4.4	100 (0)	60 (7)	20 (14)	0 (21)					
					7.2	90 (9)	90 (7)	20 (14)	0 (21)					
					10	100 (0)	70 (14)	60 (28)	20 (35)	40 (42)	70 (49)	30 (56)	70 (63)	
						70 (70)	40 (77)							
	l (4)	?	21.1°/1 d, 15.6°/4 d	75	4.4	100 (0)	100 (7)	50 (14)	0 (21)					
					7.2	100 (0)	100 (7)	90 (14)	20 (21)	0 (35)				
					10	100 (0)	100 (14)	100 (28)	100 (35)	90 (42)	100 (49)	80 (63)	80 (70)	80 (77)
Mullen and Arbogast (1979)[7]	e (12 h)	L	27°	?	5	50 (3.8)	5 (12.1)							
					0	50 (2.5)	5 (9.2)							
					−5	50 (1.0)	5 (4.4)							
					−10		5 (0.2)							
Oryzaephilus surinamensis (L.)														
Mathlein (1961)	a	?	room°, 6°/7 d	?	−2	5 (21)	0 (25)							
					−5	0 (20)								
					−5.5	3 (10)	0 (15)							
Mullen and Arbogast (1979)[7]	e (12 h)	L	27°	?	5	50 (1.0)	5 (2.9)							
					0	50 (0.3)	5 (0.6)							
					−5	50 (0.3)	5 (0.6)							
					−10		5 (0.6)							
Evans (1983)[7]	a (0–7)	?	32°	70	9	50 (19)	1 (72)							
				45	9	50 (11)	1 (48)							
			32° to 13.5°/28 d, (4.5°/7 d)	70	13.5	50 (221)	1 (> 350)							
				45	13.5	50 (117)	1 (278)							
			32° to 9°/35 d, (4.5°/7 d)	70	9	50 (99)	1 (209)							
				45	9	50 (55)	1 (101)							

continued overleaf

Table 2.—*continued*

Reference	Stage[1]	Strain[2]	Acclimation[3]	r.h.[4]	Temp.[5] (°C)	Percent survival (duration of exposure in days)[6]								
Jacob and Fleming (1986)	e (0–1 d)	L	25°	70	5	25 (1)	25 (2)	5 (3)	0 (4)					
					10	92 (1)	67 (2)	57 (3)	67 (4)	40 (5)	50 (6)	30 (7)	15 (8)	10 (9)
						2 (10)	2 (11)	2 (12)	0 (13)					
					15	93 (1)	88 (2)	93 (3)	90 (4)	88 (5)	48 (6)	67 (7)	52 (8)	46 (9)
						38 (10)	17 (11)	10 (12)	0 (13)	7 (14)	2 (15)	0 (16)		
	e (1–2 d)	L	25°	70	5	80 (1)	36 (2)	0 (3)						
					10	95 (1)	100 (2)	92 (3)	77 (4)	92 (5)	75 (6)	87 (7)	30 (8)	37 (9)
						23 (10)	5 (11)	5 (12)	0 (13)					
					15	95 (1)	90 (2)	95 (3)	79 (4)	83 (5)	60 (6)	52 (7)	26 (8)	12 (9)
						10 (10)	0 (11)							
	e (0–1 d)	L	25°	20	5	71 (1)	29 (2)	0 (3)						
					10	89 (1)	52 (2)	33 (3)	37 (4)	26 (5)	19 (6)	4 (7)	0 (8)	
					15	57 (1)	40 (2)	50 (3)	13 (4)	17 (5)	27 (6)	10 (7)	3 (8)	3 (9)
						0 (10)								
	e (1–2 d)	L	25°	20	5	35 (1)	0 (2)							
					10	100 (1)	81 (2)	89 (3)	70 (4)	56 (5)	44 (6)	19 (7)	12 (8)	0 (9)
					15	100 (1)	100 (2)	100 (3)	93 (4)	47 (5)	3 (6)	7 (7)	0 (8)	
Evans (1987b)	e, l, p	L	32° to 13.5°/28 d, (4.5°/7 d)	11m	13.5	1 (91)	0 (182)	1 (273)	1 (364)					
			32° to 9°/35 d, (4.5°/7 d)		9	0 (91)	0 (182)	0 (273)	0 (364)					
Rhyzopertha dominica (F.)														
Mathlein (1961)	a	F	room°, 13°/7 d	70	5	21 (21)								
			room°, 13°/7 d	70	1.2	0 (18)								
			room°, 13°/25 d	70	1.7	60 (5)								
			room°, 13°/35 d	70	−1.5	28 (10)								
Stojanovic (1965)	a	?	25°, 20 to 18°/20 d	12m	11	50 (47)	10 (68)							
				14m	11	50 (47)	10 (68)							
				17m	11	50 (47)	10 (68)							
				12m	0.5	50 (20)	10 (27)							
				14m	4.5	50 (20)	10 (27)							
				17m	4.5	50 (20)	10 (30)							
				12m	0.5	50 (6)	10 (8)							
				14m	0.5	50 (6)	10 (8)							
				17m	0.5	50 (7)	10 (11)							
Swain (1975)	a	?	?	?	−5		0 (0.40)							
					−10		0 (0.16)							
					−12		0 (0.13)							
					−18	50 (0.03)	0 (0.04)							
			?, starved for 48 h	?	−5		0 (0.11)							
					−10		0 (0.06)							
					−12		0 (0.04)							
					−18	50 (0.00)	0 (0.02)							
David *et al.* (1977)	e	F	27°	13.2m	4.4	1 (14)	0 (28)	0 (42)						
		L	27°	13.2m	4.4	1 (14)	0 (28)	0 (42)						
	l (7–10 d)	F	27°	13.2m	4.4	26 (14)	0 (28)	0 (42)						
		L	27°	13.2m	4.4	8 (14)	0 (28)	0 (42)						
	l (14–17 d)	F	27°	13.2m	4.4	3 (14)	0 (28)	0 (42)						
		L	27°	13.2m	4.4	1 (14)	0 (28)	0 (42)						
	l (21–24 d)	F	27°	13.2m	4.4	16 (14)	0 (28)	0 (42)						
		L	27°	13.2m	4.4	16 (14)	0 (28)	0 (42)						

	a (7–14 d)	F	27	13.2m	4.4	1 (14)	0 (28)	0 (42)					
		L	27	13.2m	4.4	2 (14)	0 (28)	0 (42)					
	e	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	0 (14)	0 (28)	0 (42)					
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	1 (14)	0 (28)	0 (42)					
	l (7–10 d)	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	38 (14)	7 (28)	0 (42)					
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	42 (14)	1 (28)	0 (42)					
	l (14–17 d)	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	15 (14)	2 (28)	0 (42)					
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	37 (14)	1 (28)	0 (42)					
	l (21–24 d)	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	56 (14)	9 (28)	0 (42)					
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	77 (14)	18 (28)	0 (42)					
	a (7–14 d)	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	54 (14)	6 (28)	0 (42)					
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	39 (14)	8 (28)	0 (42)					
Evans (1983)[7]	a	?	32°	70	9	50 (13)	1 (27)						
				45	9	50 (12)	1 (25)						
			32° to 13.5°/28 d, (4.5°/7 d)	70	13.5	50 (158)	1 (337)						
				45	13.5	50 (90)	1 (165)						
			32° to 9°/35 d, (4.5°/7 d)	70	9	50 (57)	1 (82)						
				45	9	50 (54)	1 (79)						
Jay (1984)	e, l, p	?	26.7°	60	15.4	75 (7)	46 (14)	30 (21)	24 (28)				
					10	83 (7)	26 (14)	9 (21)	11 (28)				
					4.4	36 (7)	5 (14)	0 (21)	0 (28)				
					1.7	27 (7)	1 (14)	0 (21)	0 (28)				
Evans (1987b)	e, l, p	L	32° to 13.5°/28 d, (4.5°/7 d)	11m	13.5	71 (91)	18 (182)	0 (273)	0 (364)				
			32° to 9°/35 d, (4.5°/7 d)		9	105 (91)	22 (182)	0 (273)	0 (364)				
Khan (1990)[8]	a (28 d)	?	30°	70	15	100 (7)	100 (14)	99 (21)	98 (28)	98 (35)	98 (42)		
					10	93 (7)	65 (14)	25 (21)	10 (28)	1 (35)	0 (42)		
					5	98 (7)	78 (14)	45 (21)	18 (28)	8 (35)	2 (42)		
					0	68 (7)	32 (14)	1 (21)	0 (28)	0 (35)	0 (42)		
			30°/7 d, 20°/7 d, 10°/7 d	70	0	98 (7)	98 (14)	98 (21)	90 (28)	28 (35)	0 (42)		
			30° to 5°/42 d, (5°/7 d)		0	99 (7)	97 (14)	97 (21)	97 (28)	97 (35)	97 (42)	70 (49)	41 (56) 13 (63)
			30°/7 d, 15°/7 d		0	90 (7)	80 (14)	70 (21)	53 (28)	0 (35)			
			30°/7 d, 15°/14 d		0	96 (7)	96 (14)	96 (12)	96 (28)	74 (35)	32 (42)		
			30°/7 d, 15°/21 d		0	100 (7)	100 (14)	100 (21)	100 (28)	96 (35)	86 (42)	54 (49)	
Sitophilus granarius (L.)													
Back and Cotton (1924)	a	?	?	?	12.8	0 (873)							
					5.8	0 (105)							
					3	0 (111)							
					0	0 (73)							
					−2.5	0 (46)							
					−5	0 (33)							
					−8	0 (14)							
					−15	0 (0.3)							
					−17.8	0 (0.2)							
Robinson (1926)[7]	a	?	27 to 18°	13.5m	1.6	50 (16)	0 (37)						
				13.5m	−1.1	50 (11)	0 (23)						
				13.5m	−6.6	50 (2)	0 (4)						
				13.5m	−12.2	50 (0.8)	0 (3)						
				17.2m	−12.2	50 (5)							
Mathlein (1961)	e	F	room°, 9°/2 d, 5°/2 d	13.5m	5	0 (60)							
					0	0 (40)							

continued overleaf

Table 2—*continued*

Reference	Stage[1]	Strain[2]	Acclimation[3]	r.h.[4]	Temp.[5] (°C)	Percent survival (duration of exposure in days)[6]			
					−2.5	0 (15)			
					−5.5	0 (10)			
	e, l, p,	F	room°, 9°/2 d, 5°/2 d	13.5m	5	11 (59)	3 (100)		
					0	1 (40)	0 (50)		
					−2.5	2 (20)	0 (30)		
					−5.5	0 (15)			
	a (7–42 d)	F	room°, 13°/7 d	13.5m	5	92 (18)			
			room°, 13°/7 d	13.5m	1.2	82 (10)			
			room°, 13°/25 d	13.5m	1.7	99 (5)			
			room°, 13°/35 d	13.5m	−1.5	99 (10)			
	a (7–42 d)	F	room°, 9°/2 d, 5°/2 d	13.5m	0	0 (85)			
					−2.5	17 (70)	2 (80)	2 (90)	
					−5	25 (30)	10 (35)	3 (40)	1 (45)
					−6.5	1 (28)	0 (30)		
Stojanovic (1965)	a	?	25°, 20 to 18°/20 d	12m	11	50 (32)	10 (60)		
				14m	11	50 (42)	35 (70)		
				17m	11	50 (52)	35 (70)		
				12m	4.5	50 (16)	10 (32)		
				14m	4.5	50 (34)	10 (50)		
				17m	4.5	50 (41)	10 (56)		
				12m	0.5	50 (18)	10 (26)		
				14m	0.5	50 (20)	10 (37)		
				17m	0.5	50 (29)	10 (40)		
Howe and Hole (1968)	e	L	25°	70	15	59 (42)	42 (56)		
	l (1)				15	90 (56)			
	l (2)				15	95 (56)			
	l (3)				15	72 (56)			
	l (4)				15	32 (56)			
	p				15	78 (56)			
	a				15	92 (56)			
	l (7–14 d)				15	86 (35)	95 (42)	92 (49)	96 (56)
	l (14–21 d)				15	88 (35)	90 (42)	75 (49)	65 (56)
	l (21–28 d)				15	60 (35)	42 (42)	26 (49)	29 (56)
	p (28–35 d)				15	77 (35)		77 (49)	87 (56)
David *et al.* (1977)	e	F	27°	13.2m	4.4	16 (14)	1 (28)	0 (42)	
		L	27°	13.2m	4.4	5 (14)	0 (28)	0 (42)	
	l (7–10 d)	F	27°	13.2m	4.4	4 (14)	0 (28)	0 (42)	
		L	27°	13.2m	4.4	0 (14)	0 (28)	0 (42)	
	l (14–17 d)	F	27°	13.2m	4.4	38 (14)	4 (28)	1 (42)	
		L	27°	13.2m	4.4	37 (14)	3 (28)	0 (42)	
	l (21–24 d)	F	27°	13.2m	4.4	64 (14)	25 (28)	10 (42)	
		L	27°	13.2m	4.4	53 (14)	11 (28)	5 (42)	
	a (7–14 d)	F	27°	13.2m	4.4	93 (14)	78 (28)	2 (42)	
		L	27°	13.2m	4.4	34 (14)	4 (28)	0 (42)	
	e	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	24 (14)	0 (28)	0 (42)	
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	6 (14)	0 (28)	0 (42)	
	l (7–10 d)	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	80 (14)	45 (28)	46 (42)	
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	68 (14)	33 (28)	28 (42)	

	l (14–17 d)	F	21 /3 d, 15 /7 d, 10 /7 d	13.2m	4.4	82 (14)	54 (28)	75 (42)	
		L	21 /3 d, 15 /7 d, 10 /7 d	13.2m	4.4	97 (14)	76 (28)	83 (42)	
	l (21–24 d)	F	21 /3 d, 15 /7 d, 10 /7 d	13.2m	4.4	38 (14)	16 (28)	14 (42)	
		L	21 /3 d, 15 /7 d, 10 /7 d	13.2m	4.4	37 (14)	17 (28)	12 (42)	
	a (7–14 d)	F	21 /3 d, 15 /7 d, 10 /7 d	13.2m	4.4	100 (14)	91 (28)	91 (42)	
		L	21 /3 d, 15 /7 d, 10 /7 d	13.2m	4.4	86 (14)	26 (28)	16 (42)	
Evans (1983)	a	?	30	70	9	50 (263)	1 (>385)		
				45	9	50 (36)	1 (195)		
			30 to 13.5 /28 d, (4.5 /7 d)	70	13.5	50 (281)	1 (>385)		
				45	13.5	50 (155)	1 (329)		
			30 to 9 /28 d, (4.5 /7 d)	70	9	50 (200)	1 (>385)		
				45	9	50 (52)	1 (165)		
Evans (1987b)	e, l, p	L	30 to 13.5 /28 d, (4.5 /7 d)	11m	13.5	19 (91)	5 (182)	3 (273)	0 (364)
			30 to 9 /35 d, (4.5 /7 d)	11m	9	24 (91)	3 (182)	0 (273)	0 (364)
Sitophilus oryzae (L.)									
Back and Cotton (1924)	a	?	?	?	12.8	0 (558)			
					5.8	0 (80)			
					3	0 (18)			
					0	0 (8)			
					−2.5	0 (8)			
					−5	0 (3)			
					−8	0 (3)			
					−15	0 (0.2)			
					−17.8	0 (0.2)			
Robinson (1926)[7]	a	?	27 to 18	13.5m	7.2	50 (10)	0 (15)		
				13.5m	1.6	50 (4)	0 (7)		
				8.4m	−1.1	50 (2.5)	0 (8.4)		
				13.5m	−1.1	50 (4)	0 (14)		
—				16.0m	−1.1	50 (5)	0 (16)		
				19.6m	−1.1	50 (6)	0 (20)		
				13.5m	−6.6	50 (0.4)	0 (0.6)		
				13.5m	−12.2	50 (0.1)	0 (0.1)		
Stojanovic (1965)	a	?	25 , 20 to 18 /20 d	12m	11	50 (20)	10 (35)		
				14m	11	50 (35)	10 (42)		
				17m	11	50 (37)	10 (42)		
				12m	4.5	50 (10)	10 (14)		
				14m	4.5	50 (11)	10 (21)		
				17m	4.5	50 (16)	10 (28)		
				12m	0.5	50 (3)	10 (4)		
				14m	0.5	50 (3)	10 (5)		
				17m	0.5	50 (4)	10 (6)		
David *et al.* (1977)	e	F	27	13.2m	4.4	0 (14)	0 (28)	0 (42)	
		L	27	13.2m	4.4	0 (14)	0 (28)	0 (42)	
	l (7–10 d)	F	27	13.2m	4.4	0 (14)	0 (28)	0 (42)	
		L	27	13.2m	4.4	0 (14)	0 (28)	0 (42)	
	l (14–17 d)	F	27	13.2m	4.4	2 (14)	0 (28)	0 (42)	
		L	27	13.2m	4.4	1 (14)	0 (28)	0 (42)	
	l (21–24 d)	F	27	13.2m	4.4	20 (14)	2 (28)	0 (42)	
		L	27	13.2m	4.4	26 (14)	1 (28)	0 (42)	
	a (7–10 d)	F	27	13.2m	4.4	1 (14)	0 (28)	0 (42)	
		L	27	13.2m	4.4	0 (14)	0 (28)	0 (42)	

continued overleaf

Table 2—*continued*

Reference	Stage[1]	Strain[2]	Acclimation[3]	r.h.[4]	Temp.[5] (°C)	Percent survival (duration of exposure in days)[6]			
	e	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	5 (14)	0 (28)	0 (42)	
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	1 (14)	0 (28)	0 (42)	
	l (7–10 d)	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	56 (14)	6 (28)	3 (42)	
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	35 (14)	2 (28)	1 (42)	
	l (14–17 d)	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	84 (14)	53 (28)	26 (42)	
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	83 (14)	48 (28)	37 (42)	
	l (21–24 d)	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	38 (14)	3 (28)	1 (42)	
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	27 (14)	2 (28)	1 (42)	
	a (7–14 d)	F	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	4 (14)	0 (28)	0 (42)	
		L	21°/3 d, 15°/7 d, 10°/7 d	13.2m	4.4	6 (14)	0 (28)	0 (42)	
Evans (1983)[7]	a	?	30°	70	9	50 (9)	1 (25)		
				45	9	50 (6)	1 (13)		
			30° to 13.5°/28 d, (4.5°/7 d)	70	13.5	50 (274)	1 (>364)		
				45	13.5	50 (74)	1 (371)		
			30° to 9°/35 d, (4.5°/7 d)	70	9	50 (62)	1 (111)		
				45	9	50 (39)	1 (61)		
Evans (1987b)	e, l, p	L	30° to 13.5°/28 d, (4.5°/7 d)	11m	13.5	22 (91)	5 (182)	0 (273)	0 (364)
			30° to 9°/35 d, (4.5°/7 d)	11m	9	8 (91)	3 (182)	0 (273)	0 (364)
Tribolium castaneum (Hbst.)									
Nowosielski *et al.* (1968)	a (14–21 d)	L	27°	70	−3.5	50 (0.5)			
					−5	50 (0.1)			
					−6.5	50 (0.1)			
Smith (1974)	l (late)	?	21 /7 d, 15.6 /7 d, 10 /7	?	3	34 (7)	2 (14)	0 (21)	
	a	?	21°/7 d, 15.6 /7 d, 10 /7 d	?	3	86 (7)	25 (14)	5 (21)	0 (28)
Mullen and Arbogast (1979)[7]	e (12 h)	L	27		5	50 (1.3)	5 (2.4)		
					0	50 (0.3)	5 (0.8)		
					−5	50 (0.3)	5 (0.8)		
Evans (1983)	a	?	32°	70	9	50 (6)	1 (7)		
				45	9	50 (5)	1 (14)		
			32° to 13.5°/28 d, (4.5°/7 d)	70	13.5	50 (115)	1 (194)		
				45	13.5	50 (8)	1 (140)		
			32° to 9°/35 d, (4.5°/7 d)	70	9	50 (49)	1 (74)		
				45	9	50 (43)	1 (62)		
Evans (1987)	e, l, p	L	32° to 13.5°/28 d, (4.5°/7 d)	11m	13.5	1 (91)	0 (182)	0 (273)	0 (364)
			32° to 9°/35 d, (4.5°/7 d)		9	0 (91)	0 (182)	0 (273)	0 (364)
Tribolium confusum Duv.									
Nagel and Shepard (1934)[7]	e (1 d)	?	27°	6 or 50 or 74	12	50 (5)	0 (12)		
					7	50 (2)	0 (9)		
					0	50 (0.2)	0 (0.5)		
					−4	50 (0.1)	0 (0.4)		
					−6		0 (0.3)		
					−12		0 (0.4)		
	e (3 d)	?	27°	6 or 50 or 74	12	50 (11)	0 (22)		
					7	50 (9)	0 (18)		
					−4	50 (0.1)	0 (0.3)		
					−6	50 (0.1)	0 (0.3)		
					−12	50 (0.1)	0 (0.5)		

	e (5.5 d)	?	27	6 or 50 or 74	12	50 (7)	0 (13)							
					7	50 (5)	0 (12)							
					−6	50 (0.2)	0 (0.5)							
					−12	50 (0.1)	0 (0.3)							
	l (1)	?	27	74	7	50 (6)	0 (12)							
					−6	50 (0.4)	0 (0.7)							
	l (3)	?	27	74	7	50 (6)	0 (10)							
					−6	50 (0.4)	0 (0.7)							
	l (6)	?	27	74	7	50 (8)	0 (22)							
					−6	50 (0.5)	0 (0.7)							
	p	?	27	74	7	50 (11)	0 (18)							
					−6		0 (0.4)							
	a (30–150 d)	?	27	74	7	50 (14)	0 (22)							
					−6	50 (0.3)	0 (1)							
					−12		0 (0.1)							
Edwards (1958)[7]	a (male)	L	38	75	−3	50 (2)								
	a (female)	L	38	75	−3	50 (1)								
	a (male)	L	30	75	−3	50 (2)								
	a (female)	L	30	75	−3	50 (1)								
	a (male)	L	18	75	−3	50 (4)								
	a (female)	L	18	75	−3	50 (4)								
Nowosielski *et al.* (1968)	a (14–21 d)	L	27	70	−3.5	50 (1.7)								
					−5	50 (0.3)								
Watters (1966)	e (1–2 h)	L	28	70	10	67 (0)	58 (1)	0 (5)	0 (10)	0 (15)				
					5	88 (0)	88 (1)	0 (5)	0 (10)	0 (15)				
	e (1 d)	L	28	70	10	83 (0)	79 (1)	58 (5)	0 (10)	0 (15)				
					5	96 (0)	100 (1)	67 (5)	0 (10)	0 (15)				
	e (3 d)	L	28	70	10	96 (0)	92 (1)	79 (5)	88 (10)	79 (15)				
					5	92 (0)	88 (1)	63 (5)	25 (10)	0 (15)				
Sømme (1968a)	a	L	27	?	0	98 (0)	85 (2)	49 (3)	18 (4)	5 (5)	1 (6)			
		L	27, 12/4 d		0	100 (0)	91 (3)		82 (4)		40 (6)	8 (8)	0 (9)	0 (10)
Trogoderma granarium (Everts)														
Mathlein (1961)	l	?	room, 10/4 d, 4/2 d	?	−2	99 (120)	55 (180)							
			room, 10/4 d, 4/2 d		−5	77 (90)								
	l	?	room, 4/2 d, −5/2 d	?	−10	2 (30)								
			room, 4/2 d, −5/2 d		−19	33 (5)	0 (10)	0 (15)						

[1] e = egg, l = larva with the instar given in parentheses, pp = prepupa, p = pupa, a = adult, age for a given stage in parentheses.
[2] L = strain that has been in the laboratory for > 2 yr, F = field strain.
[3] Temperature conditions before exposure to low temperature.
[4] Relative humidity in percent or if followed by an "m" the moisture content in percent.
[5] Low temperature that insects were exposed to.
[6] Usually, survival was estimated by hatching for eggs, movement for larvae or adults and emergence of adults for late instars or pupae, duration given in days except when followed by an "m" for minutes, or "h" for hours.
[7] Probit analysis.
[8] Same set of individuals used throughout the exposure period.

Table 3. A review of the survival of stored-product moths at low temperature, under laboratory conditions

Reference	Stage[1]	Strain[2]	Acclimation[3]	r.h.[4]	Temp.[5] (°C)	Percent survival (duration of exposure in days)[6]	
Ephestia cautella (Wlk.)							
Mullen and Arbogast (1979)[7]	e (12 h)	L	27	?	5	50 (4.6)	5 (8.0)
					0	50 (0.2)	5 (0.8)
					−5	50 (0.2)	5 (0.7)
					−10		5 (0.6)
					−15		5 (0.4)
Stratil and Reichmuth (1984)	e (1 d)	L	20	75	2	50 (0.2)	10 (3)
					5	50 (1.5)	10 (6)
					8	50 (4.5)	10 (8)
					11	50 (6.0)	10 (12)
					14	50 (8.0)	10 (15)
	e (2 d)	L	20	75	2	50 (0.5)	10 (5)
					5	50 (2.5)	10 (6)
					8	50 (4.0)	10 (8)
					11	50 (6.0)	10 (11)
					14	50 (8.0)	10 (15)
	e (3 d)	L	20	75	2	50 (0.5)	10 (6)
					5	50 (4.0)	10 (11)
					8	50 (5.0)	10 (11)
					11	50 (6.0)	10 (11)
					14	50 (7.0)	10 (12)
	e (4 d)	L	20	75	2	50 (0.5)	10 (4)
					5	50 (4.0)	10 (12)
					8	50 (5.0)	10 (8)
					11	50 (6.0)	10 (9)
	e (5 d)	L	20	75	2	50 (0.5)	10 (4)
					5	50 (3.0)	10 (7)
					8	50 (3.0)	10 (7)
					11	50 (3.0)	10 (6)
	e (6 d)	L	20	75	2	50 (0.5)	10 (3)
					5	50 (3.5)	10 (8)
					8	50 (5.0)	10 (12)
Ephesita elutella (Hüb.)							
Stratil and Reichmuth (1984)	e (1 d)	L	20	75	2	50 (3)	10 (11)
					5	50 (7)	10 (12)
					8	50 (12)	10 (28)
					11	50 (18)	10 (41)
	e (2 d)	L	20	75	2	50 (7)	10 (14)
					5	50 (11)	10 (18)
					8	50 (13)	10 (25)
					11	50 (17)	10 (36)
	e (3 d)	L	20	75	2	50 (2)	10 (8)
					5	50 (10)	10 (21)
					8	50 (14)	10 (25)
					11	50 (12)	10 (28)
	e (4 d)	L	20	75	2	50 (3)	10 (15)
					5	50 (12)	10 (28)
					8	50 (13)	10 (22)
					11	50 (11)	10 (24)

	e (5 d)	L	20	75	2	50 (7)	10 (20)						
					5	50 (12)	10 (27)						
					8	50 (8)	10 (17)						
					11	50 (13)	10 (24)						
	e (6 d)	L	20	75	2	50 (7)	10 (15)						
					5	50 (11)	10 (20)						
					8	50 (7)	10 (14)						
					11		10 (24)						
Ephestia kuehniella Zell.													
Mathlein (1961)	e	?	18 , 4 to 0 /3 d	?	11.5	10 (43)							
					10	0 (43)							
					−6	100 (2)	85 (5)	65 (7)					
					−7.5	25 (5)	1 (10)						
					−9.5	18 (2)	4 (5)	0 (7)					
					−18	0 (1)							
	l	?	18 , 4 to 0 /3 d	?	−7	48 (10)	30 (12)	1 (15)	0 (17)				
					−9.5	68 (5)	0 (6)						
					−19	0 (1)							
	p	?	18 , 4 to 0 /3 d	?	−7	43 (10)	32 (12)						
					−9.5	0 (5)	0 (6)						
Sømme (1968b)	l (last)		20 /4 d (no food)	?	−6	92 (0)	94 (2)	86 (4)	71 (6)	39 (8)			
					−10	92 (0)	83 (1)	78 (2)	24 (3)	0 (4)			
	l (last)	L	20 /4 d (no food), 6 /7 d	?	−6	86 (0)	82 (4)	78 (8)	80 (10)	70 (12)	17 (16)		
					−10	92 (0)	94 (1)	88 (2)	88 (3)	72 (4)	13 (6)		
Daumal *et al.* (1974)	e (0.1 d)	L	20	?	4.5	90 (2)	50 (1)						
					−1	90 (4)	50 (1)						
	e (1 d)	L	20	?	4.5	90 (10)	50 (16)	10 (22)					
					−1	90 (8)	50 (17)	10 (22)					
	e (4 d)	L	20	?	4.5	90 (17)	50 (24)	10 (28)					
					−1	90 (10)	50 (22)	10 (31)					
	e (7 d)	L	20	?	4.5	90 (5)	50 (8)	10 (11)					
					−1	90 (4)	50 (9)	10 (12)					
Le Torc'h (1977)	l (5, female)	L	25	80	2	88 (0)	22 (20)	28 (30)	32 (40)	2 (50)	0 (60)		
	l (5, male)	L	25	80	2	86 (0)	16 (20)	16 (30)	6 (40)	0 (50)	0 (60)		
	l (5, female)	L	25	60	2		18 (20)	12 (30)	4 (40)	2 (50)	0 (60)		
	l (5, male)	L	25	60	2		22 (20)	14 (30)	4 (40)	0 (50)	0 (60)		
Cox (1987)	l (pp)	L	25 to −2.5, (5 /d)	?	2.5	95 (0)	95 (28)	80 (56)					
	diapause				−2.5	95 (0)	80 (28)	0 (56)					
	l (pp)	L	25 to −2.5, (5 /d)	?	2.5	100 (0)	40 (28)	20 (56)					
	nondiapause				−2.5	100 (0)	10 (28)	0 (56)					
Plodia interpunctella (Hüb.)													
Cline (1970)	e (0–1.5 h)	L	27	85	2.4	69 (1 h)	39 (2 h)	12 (1)	15 (2)	5 (3)			
	e (3–3.5 h)	L	27	85	2.4		48 (2 h)	13 (1)	0 (2)	0 (3)	0 (4)		
	e (4–4.5 h)	L	27	85	2.4	67 (1 h)	45 (2 h)	29 (1)	11 (2)		1 (4)		
	e (5–5.5 h)	L	27	85	2.4		96 (2 h)	68 (1)	35 (2)		8 (4)	1 (5)	
	e (6–6.5 h)	L	27	85	2.4			99 (1)	84 (2)	48 (3)	12 (4)	0 (7)	0 (8)
	e (17.5–18 h)	L	27	85	2.4	100 (1 h)		95 (2)	93 (2)		54 (4)	23 (5)	11 (6)
	e (23–25 h)	L	27	85	2.4	97 (1 h)		94 (1)	89 (2)		54 (4)	40 (5)	23 (6)
	e (71–72 h)	L	27	85	2.4	94 (1 h)	94 (2 h)	90 (1)	86 (2)	74 (3)	55 (4)	28 (5)	10 (6)
Le Torc'h (1977)	l (5, female)	L	25	80	2	90 (0)	31 (20)	14 (30)	6 (40)				0 (8)
	l (5, male)	L	25	80	2	68 (0)	53 (20)	18 (30)	6 (40)				
	l (5, female)	L	25	80	2		11 (20)	14 (30)	2 (40)				
	l (5, male)	L	25	80	2		40 (20)	32 (30)	8 (40)				

continued overleaf

Table 3—*continued*

Reference	Stage[1]	Strain[2]	Acclimation[3]	r.h.[4]	Temp.[5] (°C)	Percent survival (duration of exposure in days)[6]					
Johnson and Wofford (1991)	e (33 h)	L	28°	60	−12	90 (10 m)	95 (20 m)	95 (30 m)	95 (40 m)	95 (50 m)	85 (60 m)
					−15	85 (10 m)	90 (20 m)	90 (30 m)	90 (40 m)	75 (50 m)	60 (60 m)
					−19	80 (10 m)	90 (20 m)	90 (30 m)	25 (40 m)	3 (50 m)	0 (60 m)
	e (55 h)	L	28°	60	−12	100 (10 m)	90 (20 m)	80 (30 m)	80 (40 m)	65 (50 m)	60 (60 m)
					−15	98 (10 m)	95 (20 m)	30 (30 m)	0 (40 m)		0 (60 m)
					−19	98 (10 m)	0 (20 m)				0 (60 m)
Sitotroga cerealella (Oliver) Vincent *et al.* (1980)	e	?	26.7°	60	16	100 (4 h)	100 (8 h)	97 (12 h)			
					10	100 (4 h)	89 (8 h)	100 (12 h)			
					4	85 (4 h)	90 (8 h)	94 (12 h)			
					−1	80 (4 h)	75 (8 h)	67 (12 h)			
					−7	12 (4 h)	18 (8 h)	9 (12 h)			
	e	?	26.7°	60	16	57 (4 h)	67 (8 h)	56 (12 h)			
					10	26 (4 h)	23 (8 h)	34 (12 h)			
					4	62 (4 h)	67 (8 h)	59 (12 h)			
					−1	23 (4 h)	30 (8 h)	31 (12 h)			
					−7	48 (4 h)	69 (8 h)	45 (12 h)			
	p	?	26.7°	60	16	71 (4 h)	65 (8 h)	60 (12 h)			
					10	27 (4 h)	8 (8 h)	37 (12 h)			
					4	73 (4 h)	64 (8 h)	61 (12 h)			
					−1	10 (4 h)	26 (8 h)	16 (12 h)			
					−7	48 (4 h)	62 (8 h)	24 (12 h)			
	a	?	26.7°	60	16	69 (4 h)	83 (8 h)	83 (12 h)			
					10	66 (4 h)	79 (8 h)	74 (12 h)			
					4	77 (4 h)	81 (8 h)	94 (12 h)			
					−1	88 (4 h)	88 (8 h)	79 (12 h)			
					−7	91 (4 h)	87 (8 h)	83 (12 h)			

[1] e = egg, l = larva with the instar given in parentheses, pp = prepupa, p = pupa, a = adult, age for a given stage in parentheses.
[2] L = strain that has been in the laboratory for >2 yr, F = field strain.
[3] Temperature conditions before exposure to low temperature.
[4] Relative humidity in percent or if followed by a "m" the moisture content in percent.
[5] Low temperature that insects were exposed to.
[6] Usually, survival was estimated by hatching for eggs, movement for larvae or adults and emergence of adults for late instars or pupae, duration given in days except when followed by an "m" for minutes, or "h" for hours.
[7] Probit analysis.
[8] Same set of individuals used throughout the exposure period.

Table 4. A review of the survival of stored-product mites at low temperatures under laboratory conditions

Reference	Stage[1]	Strain[2]	Acclimation[3]	r.h.[4]	Temp.[5] (°C)	Percent survival (duration of exposure in days)[6]								
Acarus siro L.														
Sinha (1964)	a, n, l	F	6°/730 d, 10°/1 d, 2°/1 h	50 to 85	−18	88 (0.04)	38 (1)	2 (3.5)	1 (7)					
	a, n, l	F	21°/365 d, 10°/1 d, 2°/1 h	50 to 85	−18	45 (0.04)	15 (1)	0 (3)						
Cunnington (1984)	e (1 d)	?	10°	20	0	80 (10)	60 (20)	75 (30)	20 (40)	5 (50)	1 (60)	1 (70)	0 (80)	
				90	0	78 (10)	80 (20)	55 (30)	45 (40)	80 (50)	60 (60)	50 (70)	70 (80)	50 (100)
						25 (120)	10 (140)	5 (150)						
				20 or 90	−5	90 (1)	80 (2)	60 (4)	53 (6)	50 (7)	35 (8)	50 (10)	15 (12)	10 (14)
						20 (16)	15 (18)	10 (20)						
				20 or 90	−10	70 (1)	55 (2)	30 (4)	35 (5)	28 (6)	10 (7)	9 (8)	10 (9)	5 (10)
						0 (11)	0 (12)							
	e (0.2 d)	?	10°	90	−10	68 (2)								
	e (1.8 d)	?	10°	90	−10	60 (2)								
	e (3.8 d)	?	10°	90	−10	20 (2)								
	e (5.8 d)	?	10°	90	−10	5 (2)								
	e (7.8 d)	?	10°	90	−10	1 (2)								
	e (9.5 d)	?	10°	90	−10	0 (2)								
	l (active)	?	10°	90	−10	28 (1)								
	l (resting)	?	10°	90	−10	7 (1)								
	n (active)	?	10°	90	−10	31 (1)								
	n (resting)	?	10°	90	−10	10 (1)								
	a	?	10°	90	−10	17 (1)								
Catoglyphus berlesei (Mich.) Sinha (1964)	a, n, l	F	21°/2 d, 10°/1 d, 2°/1 h	50 to 85	−18	0 (0.04)								
Cheyletus eruditus (Schr.) Sinha (1964)	a, n, l	F	10°/7 d, 10°/1 d, 2°/1 h	50 to 85	−18	65 (0.04)	0 (1)							
Glycyphagus destructor (Schr.) Sinha (1964)	a, n, l	F	10°/14 d, 10°/1 d, 2°/1 h	50 to 85	−18	20 (0.04)	18 (1)	3 (3)	3 (7)					
Haemogamasus pontiger (Berl.) Sinha (1964)	a, n, l	F	21°/6 d, 10°/1 d, 2°/1 h	50 to 85	−18	30 (0.04)	0 (1)							
Haemolaelaps casalis (Berl.) Sinha (1964)	a, n, l	F	10°/30 d, 10°/1 d, 2°/1 h	50 to 85	−18	55 (0.04)	50 (1)	15 (3)	0 (7)					
Haemolaelaps glasgowi (Ew.) Sinha (1964)	a, n, l	F	10°/3 d, 10°/1 d, 2°/1 h	50 to 85	−18	100 (0.04)	7 (1)	0 (3)						
Kleemania plumosus Oud. Sinha (1964)	a, n, l	F	21°/60 d, 10°/1 d, 2°/1 h	50 to 85	−18	0 (0.04)								
Leiodinychus krameri (Can.) Sinha (1964)	a, n, l	F	21°/7 d, 10°/1 d, 2°/1 h	50 to 85	−18	85 (0.04)	80 (1)	20 (3)	1 (7)					
Tydeus interruptus (Thor.) Sinha (1964)	a, n, l	F	10°/2 d, 10°/1 d, 2°/1 h	50 to 85	−18	98 (0.04)	98 (1)	15 (3)	20 (7)					

[1] e = egg, l = larva with the instar given in parentheses, pp = prepupa, p = pupa, a = adult, age for a given stage in parentheses.
[2] L = strain that has been in the laboratory for >2 yr, F = field strain.
[3] Temperature conditions before exposure to low temperature.
[4] Relative humidity in percent or if followed by a "m" the moisture content in percent.
[5] Low temperature that insects were exposed to.
[6] Usually, survival was estimated by hatching for eggs, movement for larvae or adults and emergence of adults for late instars or pupae, duration given in days except when followed by an "m" for minutes, or "h" for hours.
[7] Probit analysis.
[8] Same set of individuals used throughout the exposure period.

Table 5. The relative cold-hardiness of some stored-product insects

Reference	Site	Stage[2]	Most susceptible			Most tolerant
Mansbridge[1] (1936)	Field	l or a	*T. castaneum* *T. confusum*	*C. turcicus* *E. cautella* *L. serricorne* *R. dominica* *S. oryzae*	*O. surinamensis* *S. granarius*	*E. elutella* *E. keuhniella* *P. interpunctella* *T. granarium* *T. molitor*
Solomon and Adamson[1] (1955)	Field	e, l, p, a,	*O. mercator*	*E. cautella* *S. oryzae* *S. granarius* *T. castaneum* *T. confusum*	*S. cerealella*	*C. ferrugineus* *C. turcicus* *E. elutella* *E. kuehniella* *S. surinamensis* *P. interpunctella* *T. granarium* *T. molitor*
Mathlein (1961)	Field and Lab	l or a	*E. cautella* *O. surinamensis* *R. dominica* *S. oryzae*	*C. ferrugineus* *E. elutella* *E. kuehniella* *T. granarium* *S. granarius*		
David *et al.* (1977)	Lab	e, l, p, a	*R. dominica*	*S. oryzae*	*S. granarius*	
Bahr (1978)	Field	l, a	*C. pusillus* *O. mercator* *R. dominica* *T. castaneum* *T. confusum*	*S. cerealella* *S. oryzae* *S. zeamais*	*C. turcicus* *C. ferrugineus* *O. surinamensis* *S. granarius*	
Mullen and Agrobast (1979)	Lab	e	*E. cautella* *O. surinamensis* *T. castaneum*	*C. maculatus*	*L. serricorne*	
Evans (1983)	Lab	a	*T. castaneum*	*O. surinamensis* *C. ferrugineus* *S. oryzae* *R. dominica*	*S. granarius*	
Evans (1987)	Lab	l, p	*O. surinamensis* *T. castaneum*	*S. oryzae*	*S. granarius*	*R. dominica*
Wohlgemuth (1989)	Field	l, a	*T. confusum*	*C. turcicus* *O. surinamensis*	*T. granarium*	*S. granarius*

[1]Only a partial list of species studied.
[2]e = egg, l = larva, p = pupa, a = adult.
[3]Within a given study, species not separated by a space had similar cold-hardiness.

Hole, 1968; David *et al.*, 1977). Most studies do not incude the pupal stage as it is difficult to manipulate.

The criterion for cold-survival is different for the various stages and it is difficult to make direct comparisons of cold-tolerance within a species. For eggs and pupae, the criterion is usually transition to the next stage, for adults and larvae it is co-ordinated movement. The ultimate test

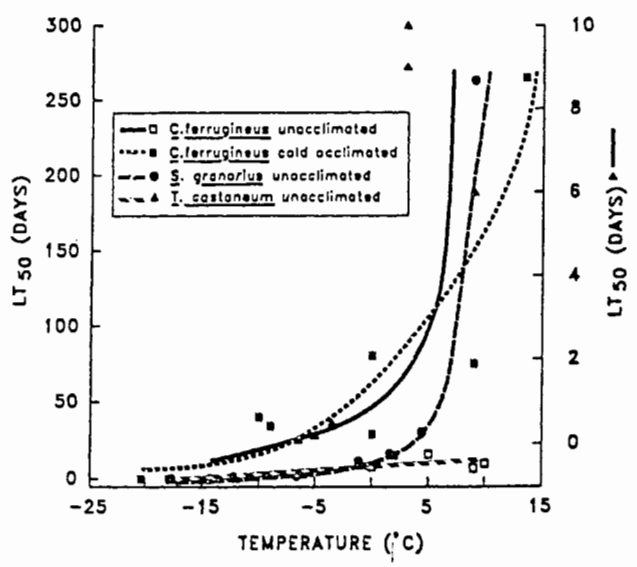


Fig. 1. The lethal time for 50% of the population for some stored-product insects at temperatures below their developmental thresholds. Data are from papers cited in Table 2.

for the effects of cold-stress would be to measure the effects of low temperature on fitness under field conditions. A few studies suggest that cold-stress, in addition to increasing mortality, reduces the fitness of surviving individuals (Howe and Hole, 1968; Kawamoto *et al.*, 1989).

Of all the factors that affect cold-survival, acclimation is the one most often ignored. Generally, exposing insects to cool temperatures (20–10°C) increases their survival by 2 to 10 times at lower temperatures (Tables 2–4). There are only two studies, both with *S. granarius*, in which acclimation did not increase cold-tolerance (Robinson, 1926; Evans, 1983). The practical application of results from studies that do not use cold-acclimated individuals is limited to situations where refrigeration is used to rapidly cool commodities. In all other field situations the temperature declines are gradual enough for the insects to cold-acclimate.

What is the best method to acclimate insects to cold? As a guide for his step-wise acclimation regime, Evans (1983) took the temperature declines that could be attained by refrigerated aeration in Australia. Smith (1970) chose 15°C because it was just below the development threshold for *C. ferrugineus*. Fields (1990) tried to approximate field acclimation by placing caged insects into 100-tonne grain bulks and removing them during the winter. Smith (1970) and Khan (1990) tested several different acclimation regimes and found that the longest and slowest temperature declines give the greatest cold-tolerance, suggesting that slower temperature declines would give even greater cold-tolerance. These studies also indicate that most of the acclimation regimes used in other studies are too brief for the insects to attain their maximum cold-tolerance. For the purpose of insect control, acclimation regimes that approximate those in the field are probably the best to use in cold-hardiness studies. A limitation of this approach is that these temperature declines are slow and vary according to storage facilities and climate.

Relative humidity affects many aspects of stored-product insect biology (Birch, 1953; Howe, 1965) and low relative humidity can shorten by half the time to kill 50% of the population at low temperature (Stojanovic, 1965; Le Torc'h, 1977; Evans, 1983, 1987b; Fields, 1990; data in Table 2). The cold-tolerance of eggs is not usually affected by relative humidity (Nagel and Shepard, 1934; Jacobs and Flemming, 1986; data in Table 2).

A few studies have examined the possibility that there could be differential mortality between the sexes, since this could greatly affect population dynamics. However, gender has only a minor, although significant, effect on survival at low temperatures. Edwards (1958; data in Table 2), working with *Tribolium castaneum* adults, showed that unacclimated males were twice as cold-hardy as females, but acclimated insects showed no differences. Williams (1954) reported that *Cryptolestes pusillus* (Schönherr) males died slightly sooner than females. Kawamoto *et al.* (1989) showed that *C. ferrugineus* females survived slightly better than males did on four of the seven sampling dates. Finally, Le Torc'h (1977; data in Table 3) working with fifth-instar larvae found no difference between the sexes for *E. kuehniella*, but did for *P. interpunctella*.

Low Temperature: Mechanisms

The differences in cold-tolerance outlined in Tables 2–5 are dependent on behavioral, physiological, or biochemical mechanisms used to avoid cold-injury. A better understanding of how insects survive the cold should make it easier to control them with low temperature.

Most temperate field insects overwinter in sheltered micro-habitats, such as under the bark on the southern exposure of the tree (Danks, 1978). Grain bulks are usually much warmer than ambient winter air temperatures. Considerable seasonal variation in temperature and moisture content exists within the grain bulk (Hagstrum, 1987; Fields, 1990). Intuitively, one would assume that stored-product insects would migrate to the warmest grain in the bin as the bulk slowly cooled during the winter. A few laboratory studies have shown that *Oryzaephilus surinamensis* (Linnaeus) (Amos, 1968), and *Tribolium castaneum* (Graham, 1958) aggregate where it is between 25 and 32°C. However, *Tribolium confusum* aggregates at 15°C, the lowest temperature available (Graham, 1958). These behaviors have not been rigorously tested in commercial-sized grain silos. Hagstrum (1987) showed that *C. ferrugineus* populations were more numerous in the warmer grain during the winter, but could not show that this was due to movement alone, rather than differences in mortality or emergence from the various locations within the grain bulk. Ability to move in grain varies between species (Surtees, 1965) and this may affect their ability to respond to a temperature

gradient. Finally, some species such as stored-product Lepidoptera larvae cannot move more than a few centimeters below the grain surface (Bell, 1983), and therefore would be exposed to the highest and lowest temperatures in the grain bulk. It is interesting to note that stored-product Lepidoptera are among the most cold-tolerant insects that attack grain (Table 5).

Although behavior may enable some insects to avoid cold temperatures and thereby minimize cold-injury, physiological and biological mechanisms determine if an insect can survive when low temperatures cannot be avoided. There are many theories; "frozen" lipids, rate imbalances, changes in ionic activity, and ice formation (Hochachka and Somero, 1984; Hazel, 1989; Storey and Storey, 1989) have been proposed to explain why organisms live or die at cold temperatures. These theories often have not been rigorously supported with experimental data nor are they mutually exclusive.

A convincing mechanism of cold-injury is the "frozen" lipid hypothesis. The phospholipid membrane is essential for the normal function of cells, organelles, and membrane-bound enzymes. These membranes must remain homeoviscous (maintain a stable viscosity) to carry out their various functions (Bretscher, 1985). As temperatures drop, membranes become less viscous or "freeze" (Hochachka and Somero, 1984; Hazel, 1989; Storey and Storey, 1989). There is some evidence that cold-acclimated plants (Lynch, 1990) and animals (Hazel, 1989) have less viscous membranes due to an increase in the proportion of unsaturated fatty acids. This hypothesis has not yet been tested on stored-product insects.

Imbalances in the rate of biochemical reactions have also been cited as a cause of cold-injury (Hochachka and Somero, 1984; Hazel, 1989; Storey and Storey, 1989). Like any chemical reaction, enzyme-catalyzed reactions are slower at lower temperatures. If reduced enzyme activity at low temperature was the only factor, poikilotherms would slow down but not die. However, the activity of some enzymes is reduced more than others, causing biochemical reactions to be uncoupled and physiological balances to be upset. One way that organisms acclimate to cold is to increase the quantity of enzyme present. The other option is to change the type of enzyme (isoenzyme) present under cold conditions. Isoenzymes occur in closely related species from different thermal habitats, but are not seen within species as a response to cold temperatures (Hochachka and Somero, 1984).

Another mechanism of cold-injury concerns the ionic activity of molecules as a function of temperature. For example, a temperature shift from 35 to 0°C increases the solubility of oxygen in water by two-fold, increases the concentration of hydrogen ions by 2.5-fold, but does not change the solubility of NaCl. Minor shifts in pH can radically change the activity of enzymes: digestive enzymes would be reduced by 20% solely due to pH changes occurring when the temperature drops by 20°C (equivalent to a 0.34 unit increase in pH) (Houseman and Downe, 1981).

Freezing is lethal for many insects (freeze-intolerant or freeze-susceptible), although some insects can tolerate extracellular freezing (freeze-tolerant). Freeze-susceptible species generally have lower supercooling points (temperature at which water in the insect begins to freeze) in the winter than in the summer. This reduction is thought to be adaptive because freezing is lethal. However, the supercooling point is not an absolute measure of cold-hardiness. Because one species freezes at −15°C does not mean it is less cold-hardy than one that freezes at −25°C. Temperatures above the supercooling point are often lethal, as observed for stored-product insects (Tables 2 and 6), and for other insects (Turnock *et al.*, 1983). The supercooling point is useful because it represents a temperature that causes death in a matter of minutes.

It is believed that freezing is lethal because ice crystals physically destroy cell structure, cause severe osmotic shocks as salt concentrations increase in the unfrozen cytoplasm during freezing and rapidly decrease during thawing, or prevent the movement of molecules within and between cells (Storey and Storey, 1989). Freeze-susceptible insects avoid freezing by many different mechanisms. One is to eliminate or mask ice nucleators. Small volumes of water cooled rapidly can attain −40°C before freezing, even larger bulks of water can remain supercooled at −5°C for long periods of time (Franks, 1985). However, if an ice crystal is placed in the water, no supercooling occurs and the water will freeze at 0°C. The ice crystal acts as a nucleator or template that enables the formation of ice. Ice causes nucleation at the highest temperatures, but many other compounds, such as dust, silver iodide, food, proteins, amino acids, or alcohols can act as ice nucleators (Lindow, 1983). Before the onset of winter, insects commonly empty their guts which often contain potent nucleators (Sømme, 1982). They also may eliminate nucleators within the cells (Baust and Zachariassen, 1983; Neven *et al.*, 1986). Another mechanism to lower the supercooling point is to

Table 6. The supercooling points of some stored-product insects

Reference	Stage[1]	Acclimation	Supercooling	Standard error of the mean	n
Cryptolestes ferrugineus					
Smith (1977)	a	30	−17.9		20
		30, 15 C/28 d	−20.2		20
Fields (1990)	a	30	−17.0	1.0	34
		30, nucleators[2]	−8.1	0.5	36
Cryptolestes pusillus					
This study[3]	a	30	−14.0	1.0	38
		30, nucleators[2]	−12.0	1.5	33
Ephestia kuehniella					
Sømme (1966)[4]	l	26, 20/2 d	−16.9	0.5	10–25
		26, 0/7 d	−20.3	0.3	10–25
		26, 6/14–42 d	−18.3	0.7	10–25
			−21.7	0.4	10–25
Gibbium psylloides					
Lee *et al.* (1992)	a	23	−10.7	0.9	11
		23, nucleators	−6.0	0.5	11
Oryzaephilus surinamensis					
This study[3]	a	30	−13.7	1.9	32
		30, nucleators[2]	−11.0	1.3	33
Plodia interpunctella					
Lee *et al.* (1992)	l	23	−10.3	0.4	54
		23, nucleators	−5.4	0.5	33
Rhyzopertha dominica					
Lee *et al.* (1992)	a	23	−15.2	0.8	23
		23, nucleators	−3.3	0.1	7
Sitophilus granarius					
This study[3]	a	30	−14.3	0.8	41
		30, nucleators[2]	−7.8	0.5	72
Lee *et al.* (1992)	a	23	−15.7	1.0	16
		23, nucleators	−8.0	0.6	18
Tenebrio molitor					
Patterson and Duman (1978)	l	20, long day, 90% r.h.	−7.7	1.0	7
		20, short day, 90% r.h.	−13.6	0.9	10
		20, short day, 15% r.h.	−12.8	1.5	8
		20, 5 C/1 d, 90% r.h.	−14.9	0.7	8
Constantinou and Cloudsley-Thompson (1986)	l	23	−10.3	0.4	39
		23, 6/5 d	−11.1	0.5	17
	p	23	−13.3	0.2	79
		23, 6/15 d	−13.7	0.3	42
	a	23	−7.1	0.4	28
Tribolium castaneum					
This study[3]	a	30	−12.3	1.0	41
		30, nucleators[2]	−5.8	0.3	77
Lee *et al.* (1992)	a	23	−13.9	0.8	23
		23, nucleators	−4.7	0.4	11

[1] a = adult, l = larva, p = pupa.
[2] Ice-nucleating active bacteria on grain at 1000 ppm.
[3] Same methods as Fields (1992).
[4] Standard deviation given instead of the standard error of the mean.

produce solutes, such as glycerol, mannitol, sorbitol, trehalose, fructose, or glucose, that lower the freezing point because of their colligative properties, the same way antifreeze in an automobile's radiator prevents freezing. These solutes may have other roles, such as stabilizing proteins (Storey and Storey, 1989). Finally, some insects produce thermal hysteresis proteins which lower the melting point of the insect by as much as 5°C (Duman, 1982). These proteins are thought to bind to ice nuclei to prevent them from causing freezing throughout the insect.

Most of the work on low temperature physiology has used arctic or temperate field insects, although there has been some work using stored-product insects. Smith (1970) found that supercooling points for *C. ferrugineus* adults decrease by only 2°C when they are held at 15°C for 4 weeks. In the same period, the lethal time for 50% of the population at −12°C went from 2 to 30 days, hence the supercooling point is a poor indicator of changes in cold-tolerance. Constantinou and Cloudsley-Thompson (1986) measured the supercooling points for *Tenebrio molitor* Linnaeus) adult (−7.1°C), pupae (−14.1°C) and larvae (−10.3°C), and concluded that the low supercooling point of the pupae was a pre-adaptation to survive low temperatures. They did not support this hypothesis with low temperature survival data. It is not unusual for pupae to have lower supercooling points than adults and larvae (Sømme, 1982), but it is probably a reflection of nucleators (food) rather than a measure of their cold-tolerance. Sømme (1968a) showed that glycerol injected into unacclimated *E. kuehniella* larvae increased their survival at −10°C beyond

that of cold-acclimated insects. He did not determine if cold-acclimation increased the levels of low molecular solutes as observed in other insects. Additional work suggested that cold acclimation or the injection of glycerol enables larvae to maintain a better balance of enzymes during cold exposure (Sømme, 1972). Insect thermal hysteresis proteins were first discovered in *Tenebrio molitor* (Ramsay, 1964) and have been shown to increase during cold-acclimation (Duman, 1982). They are present in unacclimated insects and may serve to reabsorb water in the hind gut.

Knowledge of cryobiology has been used to develop a new control method for stored-product insects by using ice-nucleating active bacteria to increase the supercooling point of insect pests (Fields, 1990; Lee *et al.*, 1992). After ice crystals, ice-nucleating active bacteria are the most potent nucleators. Many bacteria that live on the surface of leaves act as ice nucleators. The presence of these bacteria raises the freezing point of plants by several degrees. This is thought to be adaptive for the bacteria, since plant tissue damaged by freezing is better for their growth than unfrozen plant tissue (Lindow, 1983). Strong-Gunderson *et al.* (1990) suggested that the ingestion of ice-nucleating active bacteria could reduce the cold-hardiness of insects, because when adults of the Coccinellid beetle *Hippodamia convergens* Guérin were fed on ice-nucleating active bacteria their supercooling point rose by 11°C.

Ice-nucleating active bacteria have been reared commercially and used in snowmakers to increase the production of artificial snow. Fields (1990) found that the supercooling points of *C. ferrugineus* adults increase from −17 to −8°C when they are exposed to wheat that had been treated with commercial ice-nucleating active bacteria (Snomax Technologies Division of Genencor International, Rochester, N.Y., U.S.A.). Also, the mortality of insects held at −10°C for 1 day increased from 8 to 81% with the application of the nucleators. Other stored-product insects react in a similar way with their supercooling point and their mortality increasing at sub-zero temperatures and their supercooling point increasing when they are exposed to ice-nucleating active bacteria (Lee *et al.*, 1992; data in Table 6). Additional work is needed to determine if this technique works under field conditions.

High Temperature: Suboptimum

Temperatures for maximum rate of multiplication and development are only about 5°C below temperatures that stop development. For example, *S. oryzae* has a maximum multiplication rate at 29.1°C, but this drops to zero at 35°C. For *R. dominica* the maximum multiplication rate occurs at 34°C, and drops to zero at 38.6°C (Birch, 1953). High temperatures (37–42°C), in addition to causing some mortality, cause reduced fecundity (number of eggs laid) and fertility (percent hatch) (Oosthuizen, 1935; Kirkpatrick and Tilton, 1973; Vardell and Tilton, 1980; Arbogast, 1981). Diapausing larvae of *E. elutella* are more resistant to high temperatures than non-diapausing larvae in that they produced fertile adults, whereas the non-diapausing larvae did not (Bell, 1983).

High Temperature: Lethal

As with low temperature mortality, temperature, duration of exposure, species, stage of development, acclimation, and relative humidity can determine the survival of insects at high temperatures. The research on high temperature control has focused on using hot air in fluidized-beds, high frequency waves (10–100 MHz), microwaves (300–3000 MHz), or infrared (100–100,000 GHz) to heat (50–80°C) briefly the grain or flour before rapidly cooling the commodity. The temperatures are in constant flux and the rates of heating and cooling depend on the instruments used for heating, the product being treated, its moisture content, and packaging. All these factors make comparisons difficult. Most species will not survive more than 24 hr at 40°C, 12 hr at 45°C, 5 min at 50°C, 1 min at 55°C, and 30 sec at 60°C (Table 7). Different species have different susceptibilities to heat treatment. Kirkpatrick and Tilton (1972) tested the heat-tolerance of several species, and found that the survival at 49°C of adult *Lasioderma serricorne* (Fabricius) > *C. pusillus* = *R. dominica* > *S. oryzae* = *Tribolium castaneum* = *Trogoderma variable* Ballion > *S. granarius* = *Gibbium psylloides* (Czenpinski) > *Cathartus quadricollis* (Guérin-Méneville) = *O. mercator* > *Tribolium confusum* = *O. surinamensis*. Oosthuizen (1935) summarized the early literature on heat-tolerance ranking from highest to lowest; *R. dominica*, *Tribolium ferrugineum* (Fabricius), *Tribolium confusum*, *Tenebrio obscurus* (Fabricius), *Tenebrio molitor*, *S. granarius*, *S. oryzae*. Tests with high

frequency heating revealed two groups of insects, those that were killed at temperatures between 41 and 47°C (*S. granarius*, *S. oryzae*, and *O. surinamensis*) and those that were killed at temperatures between 48 and 57°C [*Tenebroides mauritanicus* (Linnaeus), *L. serricorne*, *Trogoderma glabrum* (Herbst), and *Trogoderma parabile* Beal] (Nelson and Kantack, 1966). *Rhyzopertha dominica* and *S. oryzae* have often been used to test the effectiveness of heat treatment because they tolerate heat better than other stored-product insects (Table 7). Temperatures used to control immature *R. dominica* will control virtually all other species (Evans and Dermott, 1981).

There have been few thorough tests of heat-tolerance of the different developmental stages of various species. Immature stages of the boring insects are believed to be more difficult to control with heat treatment because they are inside the seed, and experience lower temperatures than adults, which are often outside the seed (Dermott and Evans, 1978; Fleurat-Lessard, 1985). Working at lower temperatures than those used in fluidized-beds, Oosthuizen (1935) ranked pupae > eggs > larvae > adults of *Tribolium confusum* in order of heat-tolerance at 44°C. However, there were no significant differences at 50°C.

The lower the relative humidity or moisture content of the grain, the more susceptible insects are to heat treatment (Mellanby, 1932; Kirkpatrick and Tilton, 1973; Evans, 1981; Vardell and Tilton, 1981; data in Table 7). These differences are greatest between 40 and 45°C. At the higher temperatures used in fluidized-bed treatments, it takes less time to kill insects in dry grain than in wet grain, but this can be explained by the longer times needed to heat wet grain, as the grain temperature needed to kill 99.9% of the population is the same in both wet and dry grain (Evans, 1981).

Acclimation to high temperature has been examined in few stored-product insects. Gonen (1977; data in Table 7) found that acclimated *S. granarius* were three times more tolerant to 40°C than non-acclimated insects. However, *S. oryzae* had only marginal increases in heat-tolerance with acclimation. Using much higher temperatures (55°C), Evans (1981; data in Table 7) showed that acclimation did not increase tolerance of *R. dominica* or *S. oryzae*.

High Temperature: Mechanisms

Many of the mechanisms proposed to explain why insects die at high temperatures are the same as those proposed for low temperature mortality. Changes in lipids, rate imbalances, perturbation of ionic activities, as well as desiccation have been proposed as possible mechanisms of death due to high temperatures.

Phospholipid membranes become more fluid at higher temperatures. The nervous system, because it is so dependent upon membrane integrity, is thought to be especially sensitive to high temperatures. Warm-acclimated goldfish have higher heat coma temperatures than non-acclimated goldfish. This increased heat-tolerance is believed to be due to the higher melting temperatures of the lipids in synaptic membranes, which contain fewer saturated fats (Cossins and Prosser, 1978). Insects reared at high temperatures also have lipids with higher melting points (Fraenkel and Hopf, 1940; Cherry, 1959), which supports the hypothesis that high temperatures destabilize phospholipid membranes and are responsible for the death of animals.

The structure of proteins is affected adversely by high temperatures. There is a positive correlation between the temperature at which pyruvate kinase, a key enzyme in glycolysis, is inactivated and body temperature (Hochachka and Somero, 1984). This enzyme is inactivated by a 3 min exposure to temperatures from 56 to 60°C, the same conditions that kill most stored-product insects (Table 7). Enzymes will be affected adversely at temperatures below which there is gross denaturation, and this causes rate imbalances as discussed in the section on low temperature.

Ionic activity changes with temperature as previously mentioned. This hypothesis for mortality is supported by work on desert insects showing that insects that died because of heat-stress had a more acidic hemolymph than live insects (Cloudsley-Thompson, 1962).

Water-stress may also cause insects to die at high temperatures. In many cases low relative humidity makes insects more susceptible to heat (Table 7). Cloudsley-Thompson (1962), working with desert arthropods, found that the mean percent desiccation was greater in insects that died after 24 hr at high temperature and low relative humidity than those that survived. Dead insects do lose water at a faster rate than live insects, but not enough to account for the differences between

Table 7. A review of the survival of stored-product insects at high temperatures, under laboratory or field conditions

Reference	Stage[1]	Strain[2]	Acclimation[3]	r.h.[4]	Temp.[5] (°C)	Percent survival (duration of exposure)[6]			
Ephestia cautella									
Arbogast (1981)	p	L	27°, incubator	60	40	100 (2 h)	100 (4 h)		
					45	94 (2 h)	18 (4 h)		
					50	0 (2 h)			
Ephestia elutella									
Bell (1983)[7]	l, diapause	L	25°, incubator	60	40	50 (63 h)	0 (96 h)		
					43	50 (13 h)	0 (24 h)		
					45	50 (8 h)	0 (16 h)		
Lasioderma serricorne									
Kirkpatrick and Tilton (1972)	a	?	26°, infrared	13.5m	49	65 (20 s)			
					57	1 (32 s)			
					66	0 (40 s)			
Oryzaephilus surinamensis									
Nelson and Kantack (1966)	a	L	27°, high frequency	13m	35	50 (2.2 s)			
					44	10 (4.4 s)			
Kirkpatrick and Tilton (1972)	a	?	26°, infrared	13.5m	49	3 (20 s)			
					57	2 (32 s)			
					66	0 (40 s)			
Locatelli and Traversa (1989)	e	?	27°, microwaves and oven	?	81	1 (2 m)			
	l, p				80	1 (2 m)			
Plodia interpunctella									
Arbogast (1981)	p	L	27°, incubator	60	40	97 (2 h)	8 (4 h)		
					45	0 (2 h)			
					50	0 (2 h)			
Rhyzopertha dominica									
Tilton and Schroeder (1963)	e, l, p	?	27°, infrared	14m	55	50 (10 s)			
					63	10 (15 s)			
Kirkpatrick and Tilton (1972)	a	?	26°, infrared	13.5m	49	55 (20 s)			
					57	3 (32 s)			
					66	0 (40 s)			
Kirkpatrick and Tilton (1973)	e	L	27°, incubator	60	39	9 (31 d)			
	l			60	39	1 (17 d)			
	p			60	39	35 (7 d)			
	a			60	39	92 (4 d)			
	a			50	43	0.3 (4 d)			
Evans (1981)[7]	e, l, p	L	22°, fluidized-bed	11.3m	55	50 (2.4 m)	0.1 (3.3 m)		
			32°, fluidized-bed	11.3m	55	50 (2.4 m)	0.1 (3.3 m)		
			32°, fluidized-bed	14m	55	50 (3.1 m)	0.1 (4.0 m)		
Evans and Dermott (1981)	e, l, p	L	30°, fluidized-bed	11.3m	56	47 (2.4 m)	5 (6.4 m)	1 (10.4 m)	0.6 (18.4)
Vardell and Tilton (1981)	e, l, p, a	L	27°, fluidized-bed	12.3m	55	58 (?)			
					57	52 (?)			
					59	29 (?)			
					61	15 (?)			
					63	10 (?)			
					65	1 (?)			
					67	0 (4.8 m)			
Vardell and Tilton (1981)	a	L	27° incubator	40	40	76 (7 d)			
				40	42	2 (7 d)			

				50	42	56 (7 d)	
				60	42	41 (7 d)	
Tilton *et al.* (1983)	e, l, p, a	L	?, infrared	?	52	71 (30 s)	
					54	45 (38 s)	
					56	33 (45 s)	
			?, infrared and vacuum	?	52	38 (60 s)	
					54	24 (75 s)	
					56	22 (90 s)	
Sitophilus granarius							
Baker *et al.* (1956)	a	?	?, microwaves	?	32	60 (3 s)	
					42	45 (6 s)	
					57	2 (9 s)	
					72	0 (12 s)	
Nelson and Kantack (1966)	a	L	27°, high frequency	12.2m	39	50 (2.5 s)	
					52	10 (5 s)	
Kirkpatrick and Tilton (1972)	a	?	26°, infrared	13.5m	49	30 (20 s)	
					57	6 (32 s)	
					66	0 (40 s)	
Gonen (1977)[7]	a	?	27°, incubator	65	40	50 (9 h)	5 (15 h)
			27°, 32/14 d, incubator	65	40	50 (26 h)	5 (34 h)
Locatelli and Traversa (1989)	e	?	27°, microwaves and oven	?	83	1 (2 m)	
	l, p				80	0 (2 m)	
Sitophilus oryzae							
Tilton and Schroeder (1963)	e, l, p	?	27°, infrared	14m	45	50 (10 s)	
					58	5 (15 s)	
Nelson and Kantack (1966)	a	L	27°, high frequency	11.8m	38	50 (2.4 s)	
					47	10 (4 s)	
Kirkpatrick and Tilton (1972)	a	?	26°, infrared	13.5m	49	40 (20 s)	
					57	2 (32 s)	
					66	0 (40 s)	
Kirkpatrick and Tilton (1973)	e	L	27°, incubator	60	39	0 (31 d)	
	l			60	39	0 (17 d)	
	p			60	39	1 (7 d)	
	a			60	39	0 (4 d)	
	a			65	39	88 (4 d)	
	a			75	39	98 (2 d)	
Gonen (1977)	a	?	27°, incubator	65	40	50 (9 h)	5 (11 h)
			27°, 32/14 d, incubator	65	40	50 (11 h)	5 (15 h)
Evans (1981)[7]	e, l, p	L	15°/14 d, fluidized-bed	11.3 m	55	50 (1.9 m)	0.1 (2.9 m)
			30°/35 d, fluidized-bed	11.3m	55	50 (1.6 m)	0.1 (2.8 m)
Vardell and Tilton (1981b)	e, l, p, a	L	27°, fluidized-bed	12.3m	50	62 (1.8 m)	
					52	32 (?)	
					54	17 (?)	
					56	11 (?)	
					58	1 (?)	
					60	0 (?)	
Tilton *et al.* (1983)	e, l, p, a	L	?, infrared	?	52	33 (30 s)	
					54	20 (38 s)	
					56	21 (45 s)	
			?, infrared and vacuum	?	52	14 (60 s)	
					54	11 (75 s)	
					56	5 (90 s)	

continued overleaf

Table 7—*continued*

Reference	Stage[1]	Strain[2]	Acclimation[3]	r.h.[4]	Temp.[5] (°C)	Percent survival (duration of exposure)[6]	
Fleurat-Lessard (1985)	e, l, p	?	?, fluidized-bed	13m	54	0.1 (66 s)	
					64	0.1 (16 s)	
					72	0.1 (12 s)	
					80	0.1 (10 s)	
Locatelli and Traversa (1989)	e	?	27°, microwaves and oven	?	82	0 (2 m)	
	l, p				80	1 (2 m)	
Tribolium castaneum							
Kirkpatrick and Tilton (1972)	a	?	26°, infrared	13.5m	49	38 (20 s)	
					57	2 (32 s)	
					66	0 (40 s)	
Tribolium confusum							
Oostbuizen (1935)	e	?	?, incubator	75	44	50 (14 h)	5 (19 h)
					46	50 (1.2 h)	5 (2 h)
	l				44	50 (10 h)	5 (19 h)
					46	50 (1 h)	5 (1.5 h)
					48	50 (8 m)	
					50	50 (4.7 m)	
	p				44	50 (20 h)	5 (29 h)
					46	50 (1.5 h)	5 (2.7 h)
					48	50 (12 m)	
					50	50 (4.5 m)	
	a				44	50 (7 h)	5 (11 h)
					46	50 (1.2 h)	5 (2.2 h)
					48	50 (26 m)	
					50	50 (4.9 m)	
Edwards (1958)[7]	a	L	18°, incubator	75	40	50 (5.2 d)	
			30°, incubator	75	40	50 (4.0 d)	
			38°, incubator	75	40	50 (1.2 d)	
Kirkpatrick and Tilton (1972)	a	?	26°, infrared	13.5m	49	5 (20 s)	
					57	2 (32 s)	
					66	0 (40 s)	
Trogoderma granarium							
Fleurat-Lessard (1985)	l	?	?, fluidized-bed	14m	73	0.1 (14 s)	
					77	0.1 (9 s)	
					78	0.1 (5 s)	

[1]e = egg, l = larva with the instar given parentheses, pp = prepupa, p = pupa, a = adult, age for a given stage in parentheses.
[2]L = strain that has been in the laboratory for >2 yr, F = field strain.
[3]Temperature conditions before exposure to low temperature.
[4]Relative humidity in percent or if followed by an "m" the moisture content in percent.
[5]Highest temperature insects were exposed to.
[6]Duration of exposures; s = seconds, m = minutes, d = days.
[7]Probit analysis.

the two groups. At temperatures above 50°C, water-stress is unlikely to be the prime cause of death because the durations of exposure are too short to cause significant desiccation. Mellanby (1932) showed that there was no relationship between relative humidity and lethal temperature for 1 hr exposures, but there was a direct relationship for insects exposed to test temperatures for 24 hr.

Heat-shock proteins are found in insects, bacteria, mammals, and plants (Petersen and Mitchell, 1985). Most of the work has focused on the heat-shock proteins produced by *Drosophila*. These proteins are produced between 30 and 40°C, and are associated with increased survival at 40°C. Heat-shock proteins aggregate around mRNA, and may help to repair heat-damaged proteins and lipids (Nagao *et al.*, 1990). However, experimental data are not available to support this theory. The role that heat-shock proteins play in the ability of stored-product insects to survive high temperatures is unknown.

Engineering Solutions: Low Temperature

Once the duration and temperature needed to control an insect are determined, there are three ways to lower grain temperature. Turning or mixing the grain is a recommended practice to avoid grain spoilage. As there is little heat exchange when the grain is moved, the overall temperature of the grain bulk remains about the same, but "hot spots" are dispersed and cooled by coming in contact with cooler grain (Watters, 1963). Turning the grain causes breakage of kernels, particularly in maize, and grain temperature cannot be quickly reduced, factors which limit the usefulness of this method.

Ambient air ventilation is the most widely used means for cooling bulk grain. There are many types of ventilation systems, and care must be taken to insure that adequate and even air flow is maintained. To maximize cooling, systems have been designed to ventilate only when the ambient air temperatures are below the grain temperature (Metzger and Muir, 1983; Armitage and Llewellin, 1987; Epperly *et al.*, 1987; Lasseran and Fleurat-Lessard, 1990). Studies on full-sized commercial silos have shown that aeration reduces or even eliminates insect populations (Thorpe *et al.*, 1982; Cuperus *et al.*, 1986; Armitage and Llewellin, 1987), although this is not always the case (Armitage and Stables, 1984). Under certain conditions, ambient air ventilation will also cool grain through evaporative cooling and will dry grain to a limited extent (Desmarchelier, 1988; Sanderson *et al.*, 1988).

Ambient air cooling can be assisted by refrigerating air used to ventilate the grain. Tests have been conducted in Britain (Burrell, 1967; Burrell and Laundon, 1967), Israel (Donahaye *et al.*, 1974), and Australia (Hunter and Taylor, 1980; Thorpe and Elder, 1980). The primary goal is to cool grain enough to slow or even stop the development of molds (Burrell and Laundon, 1967) and insects (Evans, 1987a). Commercial units are available in Europe (Sulzer-Escher Wyss) and Australia (McBea Services), and over 60 million tonnes of grain are cooled via refrigeration in some 50 countries around the world. These units can be mobile, making it easy for one unit to service many granaries. Large permanent units are also used, and can cool up to 300,000-tonne grain bulks. The energy required to cool the grain varies from 3 kWh/tonne in insulated silos (Hunter and Taylor, 1980) to 12.0 kWh/tonne for uninsulated bins in tropical conditions. Condensation on the grain can be a problem if warm wet air comes in contact with cool dry grain (Navarro *et al.*, 1973), although this was not a problem encountered in other studies using refrigerated air (Donahaye *et al.*, 1974; Hunter and Taylor, 1980).

Engineering Solutions: High Temperature

There are two ways that grain can be heated to temperatures high enough to kill insects. Fluidized-beds use hot air (60–120°C) blown at rates high enough to lift and mix the grain. This raises the temperature of the grain to between 56 and 72°C in < 1 min. Small-scaled batch (Dermott and Evans, 1978) and continuous flow (Evans *et al.*, 1983; Fleurat-Lessard, 1985) fluidized-beds that can treat 150 tonnes/hr have been built and tested. Grain is rapidly cooled by spraying water on the grain (Evans *et al.*, 1983) or a fluidized-bed with ambient air (Fleurat-Lessard, 1985). Costs to operate fluidized-beds are similar to the cost of fumigation if large-scale treatment of grain is required (Fleurat-Lessard, 1987).

Non-ionizing electromagnetic energy has also been used to heat grain and other stored products to temperatures high enough to kill insects. High frequency or radio frequencies have been studied

over the last 50 yr as a means to disinfest grain (Ark and Parry, 1940; Nelson and Kantack, 1966; Fleurat-Lessard, 1987). Microwaves tend to remove the water from the product during heating which may be undesirable, but this has been used in conjunction with a vacuum to dry grain (Tilton *et al.*, 1983). Infrared irradiation has been used effectively in the laboratory (Tilton and Schroeder, 1963) but this work has not been followed by pilot-scale studies. One advantage of these methods is that they can easily be incorporated onto conveyor belts and in some instances can even be used on packaged products. Commercial units using high frequencies and microwaves are now available.

Heat sterilization of food processing plants has been used in the U.S.A. as early as 1901. Today a few plants use this method on a regular basis, heating the facility to 54°C for 30 hr. Some precautions, such as insuring the fire sprinklers will not be activated and removing material that will be adversely affected by these high temperatures, must be taken before the heat treatment (Sheppard, 1984).

FUTURE RESEARCH

There has been an immense amount of research on the ability of stored-product insects to survive extreme temperatures. The diversity of experimental protocols makes it difficult to compare studies. Also, many of the studies are inadequate to predict survival in field situations. To avoid these problems I suggest the following standard protocols for testing the effects of extremes of temperature on insects. (1) Populations that have been reared in the laboratory for <2 yr should be used. (2) The most temperature-resistant stage of development should be used. For insects with diapause, diapausing individuals should be used (Howe, 1962). (3) Insects should be acclimated before exposing them to the extreme temperatures. For low temperature studies, acclimation at 15°C for 3 weeks should give a moderate level of cold-hardiness for most species. However, this probably will not give the maximum level of cold-hardiness. An additional acclimation schedule that reflects temperature declines that are observed in the field should also be incorporated into a complete study of cold-hardiness. Acclimation to high temperatures does not seem to affect survival at the very high temperatures (55–80°C) used in fluidized-beds and irradiation heating. However, at lower temperatures (40–50°C) acclimation can affect survival. (4) A range of extreme temperatures should be used to facilitate the development of predictive models. (5) Probit analysis should be used to analyze the data. The lethal time for 50% (best for comparisons), and 99% (best for designing control programs) of the population should be given with the fiducial limits. Fiducial limits are often not reported, perhaps because the ranges are large. Not reporting the fiducial limits with the survival data is like not giving the standard deviation with the means, making comparisons very difficult. The survival of insects at extreme temperature is highly variable. Large fiducial limits are a reflection of this fact and should be accepted as part of the biological system. (6) The final phase of any study should be a validation of laboratory results under field conditions.

The use of synergists is common with chemical control systems, an example being the use of food baits to increase consumption of the pesticide, or the addition of chemicals that inhibit the enzymes that degrade the pesticide such as piperonyl butoxide (Ware, 1983). This concept has considerable potential to increase the effectiveness of extreme temperature controls. However, a thorough knowledge of the mechanisms that enable insects to deal with extremes in temperature is needed before procedures to synergize extreme temperature control can be implemented. There are several promising avenues of research that could disclose low temperature control synergists. Information on the physiological and biochemical control of cold-acclimation and methods to block this process would make insects 3–10 times more susceptible to cold treatments. It is possible that there is no unified control of cold-acclimation and the best way to make insects more susceptible is to block the biochemical changes that enable them to survive low temperature. Lipids and enzymes have been suggested as key molecules in the temperature adaptions of other organisms, but this has yet to be investigated in any depth with stored-product insects. Preliminary work on ice nucleators indicate that insects could be controlled at -5°C in a few hours (Fields, 1990; Lee *et al.*, 1992). The use of a synergist is also possible with high temperature control, but we know less about how organisms deal with high temperature than how they deal with low temperature. Lipids and enzymes have been suggested as the key molecules that break down at high temperatures, and the blocking of the mechanisms that protect these molecules (perhaps heat-shock proteins) would be the first step to uncover heat synergists.

Acknowledgements—I thank Drs Noel White and Robert Bodnaryk for critically reviewing this manuscript.

REFERENCES

Amos T. G. (1968) Some observations on *Oryzaephilus surinamensis* L. (Col., Silvanidae) in a temperature-moisture gradient. *Entomology* **101**, 67–70.

Arbogast R. L. (1981) Mortality and reproduction of *Ephestia cautella* and *Plodia interpunctella* exposed as pupae to high temperatures. *Environ. Ent.* **10**, 708–710.

Ark P. A. and Parry W. (1940) Application of high-frequency electrostatic fields in agriculture. *Qt Rev. Biol.* **15**, 172–191.

Armitage D. M. and Llewellin B. E. (1987) The survival of *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae) and *Sitophilus granarius* (L.) (Coleoptera: Curculionidae) in aerated bins of wheat during British winters. *Bull. ent. Res.* **77**, 457–466.

Armitage D. M. and Stables L. M. (1984) Effects of aeration on established insect infestations in bins of wheat. *Protect. Ecol.* **6**, 63–74.

Back E. A. and Cotton R. T. (1924) Relative resistance of the Rice Weevil *Sitophilus oryza* L., and the Granary Weevil, *S. granarius* L., to high and low temperatures. *J. agric. Res.* **28**, 1043–1044.

Bahr I. (1978) Uberwinterungsversuche mit Schadinsekten der Getreidevorräte in ungeheizten Räumen. *Nachr.-Bl. Pflanzenschutz Berl.* **32**, 224–230.

Baker V. H., Wiant D. E. and Taboada O. (1956) Some effects of microwaves on certain insects which infest wheat and flour. *J. econ. Ent.* **49**, 33–37.

Barker P. S. (1990) Note on the effect of low temperatures on the survival of immature stages of the rusty grain beetle, *Cryptolestes ferrugineus*. *Phytoprotection* **71**, 37–39.

Baust J. G. and Zachariassen K. E. (1983) Cell matrix associated nucleators in a high supercooling capacity beetle. *Cryo-letters* **4**, 65–71.

Bell C. H. (1983) Effect of high temperatures on larvae of *Ephestia elutella* (Lepidoptera: Pyralidae) in diapause. *J. stored Prod. Res.* **19**, 153–157.

Birch L. C. (1953) Experimental background to the study of the distribution and abundance of insects. I. The influence of temperature, moisture and food on the innate capacity for increase of three grain beetles. *Ecology* **34**, 698–711.

Bretscher M. S. (1985) The molecules of the cell membrane. *Sci. Am.* **253**, 100–109.

Brown C. W. and Hill S. T. (1984) Survival of micro-organisms in deep-frozen barley and pig feed. *J. stored Prod. Res.* **20**, 145–150.

Burges H. D. and Burrell N. J. (1964) Cooling bulk grain in the British climate to control storage insects and to improve keeping quality. *J. sci. Food Agric.* **15**, 32–50.

Burrell N. J. (1967) Grain Cooling Studies—II: effect of aeration on infested grain bulks. *J. stored Prod. Res.* **3**, 145–154.

Burrell N. J. and Laundon J. H. J. (1967) Grain Cooling Studies—I: observations during a large scale refrigeration test on damp grain. *J. stored Prod. Res.* **3**, 125–144.

Cherry L. (1959) Fat metabolism and temperature acclimatization in the fly *Phormia terraenovae* R.D. *Ent. exp. Appl.* **2**, 68–76.

Childs D. P., Overby J. E., Watkins B. J. and Niffenegger D. (1970) Low temperature effect upon third- and fourth-instar Cigarette Beetle larvae. *J. econ. Ent.* **63**, 1860–1864.

Cline D. L. (1970) Indian-meal moth egg hatch and subsequent larval survival after short exposures to low temperature. *J. econ. Ent.* **63**, 1081–1083.

Cloudsley-Thompson J. L. (1962) Lethal temperatures of some desert arthropods and the mechanism of heat death. *Ent. exp. Appl.* **5**, 270–280.

Collins P. J. and Wilson D. (1986) Insecticide resistance in the major coleopterous pests of stored grain in southern Queensland. *Queensl. J. agric. anim. Sci.* **43**, 107–114.

Constantinou C. and Cloudsley-Thompson J. L. (1986) Supercooling in the various instars of the mealworm beetle *Tenebrio molitor* L. *J. natn Hist.* **20**, 649–651.

Cossins A. R. and Prosser C. L. (1978) Evolutionary adaptation of membranes to temperature. *Proc. natn Acad. Sci. U.S.A.* **75**, 2040–2043.

Cox P. D. (1987) Cold tolerance and factors affecting the duration of diapause in *Ephestia kuehniella* Zeller (Lepidoptera: Pyralidae). *J. stored Prod. Res.* **23**, 163–168.

Cunnington A. M. (1984) Resistance of the grain mite *Acarus siro* L. (Acarina, Acaridae) to unfavorable physical conditions beyond the limits of its development. *Agric. Ecosyst. Environ.* **11**, 319–339.

Cuperus G. W., Prickett C. K., Bloome P. D. and Pitts J. T. (1986) Insect populations in aerated and unaerated stored wheat in Oklahoma. *J. Kans. ent. Soc.* **59**, 620–627.

Danks H. V. (1978) Modes of seasonal adaptation in the insects. I. Winter survival. *Can. Ent.* **110**, 1167–1206.

Daumal J., Jourdheuil P. and Tomassone R. (1974) Variabilité des effets létaux des basses températures en fonction du stade de développement embryonnaire chez la pyrale de la farine (*Anagasta kuhniella* Zell., Lepid., Pyralidae). *Ann. Zool.-Ecol. Anim.* **6**, 229–243.

David M. H., Mills R. B. and White G. D. (1977) Effects of low temperature acclimation on developmental stages of stored-product insects. *Environ. Ent.* **6**, 181–184.

Dermott T. and Evans D. E. (1978) An evaluation of fluidized-bed heating as a means of disinfesting wheat. *J. stored Prod. Res.* **14**, 1–12.

Desmarchelier J. M. (1988) The relationship between wet-bulb temperature and intrinsic rate of increase of eight species of stored-product Coleoptera. *J. stored Prod. Res.* **24**, 107–113.

Donahaye E., Navarro S. and Calderon M. (1974) Studies on aeration with refrigerated air—III. Chilling of wheat with a modified chilling unit. *J. stored Prod. Res.* **10**, 1–8.

Duman J. G. (1982) Insect antifreezes and ice-nucleating agents. *Cryobiology* **19**, 613–627.

Edwards D. K. (1958) Effects of acclimatization and sex on respiration and thermal resistance in *Tribolium* (Coleoptera: Tenebrionidae). *Can. J. Zool.* **36**, 363–382.

Epperly D. R., Noyes R. T., Cuperus G. W. and Clary B. L. (1987) Control of stored grain insects by grain temperature management. *Am. soc. agric. Eng.*, 21 pp. ASAE Paper No. 87-6035.

Evans D. E. (1981) The influence of some biological and physical factors on the heat tolerance relationships for *Rhyzopertha dominica* (F.) and *Sitophilus oryzae* (L.) (Coleoptera: Bostrychidae and Curculionidae). *J. stored Prod. Res.* **17**, 65–72.
Evans D. E. (1983) The influence of relative humidity and thermal acclimation on the survival of adult grain beetles in cooled grain. *J. stored Prod. Res.* **19**, 173–180.
Evans D. E. (1987a) Stored products. In *Integrated Pest Management* (Edited by Burn A. J., Coaker T. H. and Jepson P. C.), pp. 425–461. Academic Press, New York.
Evans D. E. (1987b) The survival of immature grain beetles at low temperatures. *J. stored Prod. Res.* **23**, 79–83.
Evans D. E. (1987c) Some biological and physical constraints to the use of heat and cold for disinfesting and preserving stored products. In *Proc. 4th Int. Work. Conf. Stored-Prod. Prot.* (Edited by Donahaye E. and Navarro S.), pp. 149–164. Tel Aviv.
Evans D. E. and Dermott T. (1981) Dosage–mortality relationships for *Rhyzopertha dominica* (F.) (Coleoptera: Bostrychidae) exposed to heat in a fluidized-bed. *J. stored Prod. Res.* **17**, 53–64.
Evans D. E., Thorpe G. R. and Dermott T. (1983) The disinfestation of wheat in a continuous-flow fluidized bed. *J. stored Prod. Res.* **19**, 125–137.
Fields P. G. (1990) The cold-hardiness of *Cryptolestes ferrugineus* and the use of ice-nucleation active bacteria as a cold-synergist. In *Proc. 5th Int. Work. Conf. Stored-Prod. Prot.* (Edited by Fleurat-Lessard F. and Ducom P.), pp. 1183–1191. Bordeaux.
Fleurat-Lessard F. (1985) Les traitements thermiques de désinfestation des céréales et des produits céréaliers: Possibilité d'utilisation pratique et domaine d'application. *Bull. OEPP* **15**, 109–118.
Fleurat-Lessard F. (1987) Control of storage insects by physical means and modified environmental conditions. Feasibility and application. In *Brit. Crop Prot. Coun. Mono.* (Edited by Lawson T. J.), pp. 209–218. London.
Flinn P. W. and Hagstrum D. W. (1990) Simulations comparing the effectiveness of various stored-product management practices used to control *Rhyzopertha dominica* (Coleoptera: Bostrichidae). *Environ. Ent.* **19**, 725–729.
Fraenkel G. S. and Hopf H. S. (1940) The physiological action of abnormally high temperatures on poikilothermic animals I. Temperature adaptation and the degree of saturation of the phosphatides. *Biochem. J.* **34**, 1085–1092.
Franks F. (1985) *Biophysics and Biochemistry at Low Temperatures*. Cambridge University Press, Cambridge.
Gonen M. (1977) Susceptibility of *Sitophilus granarius* and *S. oryzae* (Coleoptera: Curculionidae) to high temperature after exposure to supra-optimal temperature. *Ent. exp. Appl.* **21**, 243–348.
Graham W. M. (1958) Temperature preference determinations using *Tribolium*. *Anim. Behav.* **6**, 231–237.
Hagstrum D. W. (1987) Seasonal variation of stored wheat environment and insect populations. *Environ. Ent.* 16, 77–83.
Hazel J. R. (1989) Cold adaptation in ectotherms: regulation of membrane function and cellular metabolism. In *Advances in Comparative and Environmental Physiology* (Edited by Wang L. C. H.), Vol. 4, pp. 1–50. Springer, Berlin.
Hochachka P. W. and Somero G. N. (1984) *Biochemical Adaptation*. Princeton University Press, Princeton.
Houseman J. G. and Downe A. E. R. (1981) Identification and partial characterization of digestive proteinases from *Triatoma phyllosoma pallidipennis* Stal (Hemiptera: Reduviidae). *Comp. Biochem. Physiol.* **70B**, 713–717.
Howe R. W. (1962) The influence of diapause on the status as pests of insects found in houses and warehouses. *Proc. Assoc. appl. Biol.* **50**, 611–614.
Howe R. W. (1965) A summary of estimates of optimal and minimal conditions for population increase of some stored products insects. *J. stored Prod. Res.* **1**, 177–184.
Howe R. W. and Hole B. D. (1968) The susceptibility of developmental stages of *Sitophilus granarius* (L.) (Coleoptera, Curculionidae) to moderately low temperatures. *J. stored Prod. Res.* **4**, 147–156.
Huffaker C. B. (1980) *New Technologies of Pest Control*. Wiley, New York.
Hunter A. J. and Taylor P. A. (1980) Refrigerated aeration for the preservation of bulk grain. *J. stored Prod. Res.* 16, 123–131.
Jacob T. A. and Fleming D. A. (1986) The effect of temporary exposure to low temperature on the viability of eggs of *Oryzaephilus surinamensis* (L.) (Col., Silvanidae). *Ent. Month. Mag.* **122**, 117–120.
Jay E. (1984) Control of *Rhyzopertha dominica* with modified atmospheres at low temperatures. *J. agric. Ent.* **1**, 155–160.
Johnson J. A. and Wofford P. L. (1991) Effects of age on response of eggs of Indianmeal moth and Navel Orangeworm (Lepidoptera: Pyralidae) to subfreezing temperatures. *J. econ. Ent.* **84**, 202–205.
Kawamoto H., Sinha R. N. and Muir W. E. (1989) Effect of temperature on adult survival and potential fecundity of the Rusty Grain Beetle, *Cryptolestes ferrugineus*. *Ann. ent. Zool.* **24**, 418–423.
Khan N. I. (1990) The effects of various temperature regimes and cooling rates on the mortality and reproductive abilities of two stored grain insect species. M.Sc. thesis, Oklahoma State University.
Kirkpatrick R. L. and Tilton E. W. (1972) Infrared radiation to control adult stored-product Coleoptera. *J. Ga ent. Soc.* **7**, 73–75.
Kirkpatrick R. L. and Tilton E. W. (1973) Elevated temperatures to control insect infestations in wheat. *J. Ga ent. Soc.* **8**, 264–267.
Lasseran J. C. and Fleurat-Lessard F. (1990) Aeration of grain with ambient or artificially cooled air: a technique to control weevils in temperate climates. In *Proc. 5th Int. Work. Conf. Stored-Prod. Prot.* (Edited by Fleurat-Lessard F. and Ducom P.), pp. 1221–1230. Bordeaux.
Lee R. E. Jr. Strong-Gunderson J. M., Lee M. R. and Davidson E. C. (1992). Ice nucleating active bacteria decrease the cold-hardiness of stored grain insects. *J. econ. Ent.* In press.
Le Torc'h J. M. (1977) Le froid: moyen de protection contre les ravageurs des denrées stockées. Essais de laboratoire sur les insectes des Pruneaux. *Revue Zool. Agricole Path. Vég.* **76**, 109–117.
Lindow S. E. (1983) The role of bacterial ice nucleation in frost injury to plants. *Ann. Rev. Phytopathol.* **21**, 363–384.
Locatelli D. P. and Traversa S. (1989) Microwaves in the control of rice infestations. *Ital. J. Food Sci.* **2**, 53–62.
Longstaff B. C. (1981) The manipulation of the population growth of a pest species: an analytical approach. *J. appl. Ecol.* **18**, 727–736.
Lynch D. V. (1990) Chilling injury in plants: the relevance of membrane lipids. In *Environmental Injury to Plants* (Edited by Katterman F.), pp. 17–34. Academic Press, New York.
Madrid F. J., White N. D. G. and Loschiavo S. R. (1990) Insects in stored cereals, and their association with farmir practices in southern Manitoba. *Can. Ent.* **122**, 515–523.

Mansbridge G. H. (1936) A note on the resistance to prolonged cold of some insect pests of stored products. *Proc. R. ent. soc. Lond.* **11**, 83–86.
Mathlein R. (1961) Studies on some major storage pests in Sweden, with special reference to their cold resistance. *Meddn. St. Vaxtsk Anst.* **12:83**, 1–49.
Mellanby K. (1932) The influence of atmospheric humidity on the thermal death point of a number of insects. *J. exptl Biol.* **9**, 222–231.
Metzger J. F. and Muir W. E. (1983) Aeration of stored wheat in the Canadian Prairies. *Can. agric. Eng.* **25**, 127–137.
Mullen M. A. and Arbogast R. T. (1979) Time-temperature-mortality relationship for various stored-product insect eggs and chilling times for selected commodities. *J. econ. Ent.* **72**, 476–478.
Nagao R. T., Kimpel J. A. and Key J. L. (1990) Molecular and cellular biology of the heat-shock response. *Adv. Genet.* **28**, 235–275.
Nagel R. H. and Shepard H. H. (1934) The lethal effect of low temperatures on the various stages of the Confused Flour Beetle. *J. agric. Res* **48**, 1009–1016.
Navarro S., Donahaye E. and Calderon M. (1973) Studies on aeration with refrigerated air—1. Chilling of wheat in a concrete elevator. *J. stored Prod. Res.* **9**, 253–259.
Nelson S. O. and Kantack B. H. (1966) Stored-grain insect control studies with radio-frequency energy. *J. econ. Ent.* **59**, 588–594.
Neven L. G., Duman J. G., Beals J. M. and Castellino F. J. (1986) Overwintering adaptations of the stag beetle, *Ceruchus piceus*: removal of ice nucleators in the winter to promote supercooling. *J. comp. Physiol. B.* **156**, 707–716.
Nowosielski-Slepowron B. J. A., Waterhouse F. L. and Strevens D. E. A. (1968) Sub-zero mortality responses of *Tribolium confusum* Duval (two stocks) and *T. castaneum* (Herbst) (four stocks) analyzed by weighted regression lines based on individual temperature LD50's. *Physiol. Zool.* **41**, 440–446.
Oosthuizen M. J. (1935) The effect of high temperature on the confused flour beetle. *Minn. Tech. Bull.* **107**, 1–45.
Patterson J. L. and Duman J. G. (1978) The role of the thermal hysteresis factor in *Tenebrio molitor* larvae. *J. exp. Biol.* **74**, 37–45.
Petersen N. S. and Mitchell H. K. (1985) Heat shock proteins. In *Comparative Insect Physiology, Biochemistry and Pharmacology* (Edited by Kerkut G. A. and Gilbert L. I.), Vol. 10, pp. 347–365. Pergamon Press, New York.
Ramsay J. A. (1964) The rectal complex of the mealworm *Tenebrio molitor* L. (Coleoptera, Tenebrionidae). *Phil. Trans. R. Soc. B* **248**, 279–314.
Robinson W. (1926) Low temperature and moisture as factors in the ecology of Rice Weevil, *Sitophilus oryzae* L. and the Granary Weevil, *Sitophilus granarius* L. *Univ. Minn. Agric. exptl Stn* **41**, 40 pp.
Sanderson D. B., Muir W. E. and Sinha R. N. (1988) Intergranular air temperatures of ventilated bulks of wheat. *J. agric. Eng. Res.* **40**, 3–43.
Sheppard K. O. (1984) Heat sterilization (superheating) as a control for stored-grain pests in a food plant. In *Insect Management for Food Storage and Processing* (Edited by Baur F. J.), pp. 194–200. American Associates of Cereal Chemists, St Paul.
Sinha R. N. (1964) Effect of low temperature on the survival of some stored products mites *Acarologia* **2**, 336–341.
Smith L. B. (1970) Effects of cold-acclimation on supercooling and survival of the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae) at sub-zero temperatures. *Can. J. Zool.* **48**, 853–858.
Smith L. B. (1974) The role of low temperature to control stored product food pests. In *Proc. 1st Int. Work. Conf. Stored-Prod. Ent.* (Edited by Bradey E. U.), pp. 418–430. Savannah, Ga.
Solomon M. E. and Adamson B. E. (1955) The powers of survival of storage and domestic pests under winter conditions in Britain. *Bull. ent. Res.* **46**, 311–355.
Somme L. (1966) The effect of temperature, anoxia, or injection of various substances on haemolymph composition and supercooling in larvae of *Anagasta kuehniella* (Zell.). *J. Insect Physiol.* **12**, 1069–1083.
Somme L. (1968a) The effect of acclimation and glycerol injection on mortality and pupation in larvae of *Ephestia kuehniella* after exposures at low temperatures. *Ent. exp. Appl.* **11**, 143–148.
Somme L. (1968b) Acclimation to low temperatures in *Tribolium confusum* Duval (Col., Tenebrionidae). *Norsk. ent. Tidsskr.* **15**, 134–136.
Somme L. (1972) The effects of acclimation and low temperatures on enzyme activities in larvae of *Ephestia kuehniella* Zell. (Lep., Pyralidae). *Ent. Scand.* **3**, 12–18.
Somme L. (1982) Supercooling and winter survival in terrestrial arthropods. *Comp. Biochem. Physiol.* **73A**, 519–543.
Stratil H. H. and Reichmuth C. (1964) Überlebensdauer von eiern der vorratsschädlichen motten *Ephestia cautella* (Wlk.) und *Ephestia elutella* (Hüb.) (Lepidoptera, Pyralidae) bei temperaturen unterhalb ihres entwicklungsminimums. *Z. ang. Ent.* **97**, 63–70.
Stojanovic T. (1965) Uticaj vla nosti pšenice na otpornost i aka (*Calandra granaria* L. i *C. oryzae* L.) i itnog kukulji ara (*Rhyzopertha dominica* F.) prema niskm temperaturama. *Let. Nauch. Radova Poljopriv. Fakult. Novom Sadu* **9**, 80–90.
Storey K. B. and Storey J. M. (1989) Freeze tolerance and freeze avoidance in ectotherms. In *Advances in Comparative and Environmental Physiology* (Edited by Wang L. C. H.), Vol. 4, pp. 52–82. Springer, Berlin.
Strong-Gunderson J. M., Lee R. E., Lee M. R. and Riga T. J. (1990) Ingestion of ice-nucleating active bacteria increases the supercooling point of the lady beetle *Hippodamia convergens*. *J. Insect Physiol.* **36**, 153–157.
Surtees G. (1965) Ecological significance and practical implications of behavior patterns determining the spatial structure of insect populations in stored grain. *Bull. ent. Res.* **56**, 201–213.
Swain W. R. (1975) Cold tolerance in relation to starvation of adult *Rhyzopertha dominica* (Coleoptera: Bostrichidae). *Can. Ent.* **107**, 1057–1062.
Tauber M. J., Tauber C. A. and Masaki S. (1985) *Seasonal Adaptations of Insects*. Oxford University Press, Oxford.
Thorpe G. R. and Elder W. B. (1980) The use of mechanical refrigeration to improve the storage of pesticide treated grain. *Int. J. Refrig.* **3**, 99–106.
Thorpe G. R., Cuff W. R. and Longstaff B. C. (1982) Control of *Sitophilus oryzae* infestation of stored wheat: an ecosystem model of the use of aeration. *Ecol. Mod.* **15**, 331–351.
Tilton E. W. and Schroeder H. W. (1963) Some effects of infrared irradiation on the mortality of immature insects in kernels of rough rice. *J. econ. Ent.* **56**, 727–730.

Tilton E. W., Vardell H. H. and Jones R. D. (1983) Infrared heating with vacuum for control of the Lesser Grain Borer (*Rhyzopertha dominica* F.) and Rice Weevil (*Sitophilus oryzae* L.) infesting wheat. *J. Ga ent. Soc.* **18**, 61–64.

Turnock W. J., Lamb R. J. and Bodnaryk R. P. (1983) Effects of cold stress during pupal diapause on the survival and development of *Mamestra configurata* (Lepidoptera: Noctuidae). *Oecologia* **56**, 185–192.

Vardell H. H. and Tilton E. W. (1980) Heat sensitivity of the Lesser Grain Borer, *Rhyzopertha dominica* (F.). *J. Ga ent. Soc.* **16**, 117–121.

Vardell H. H. and Tilton E. W. (1981) Control of the Lesser Grain Borer, *Rhyzopertha dominica* (F.), and the Rice Weevil, *Sitophilus oryzae* (L.), in wheat with a heat fluidized bed. *J. Kans. ent. Soc.* **54**, 481–485.

Vincent L. E., Rust M. K. and Lindgren D. L. (1980) Methyl bromide toxicity at various low temperatures and exposure periods to Angoumois Grain moth and Indianmeal moth in popcorn. *J. econ. Ent.* **73**, 313–317.

Ware G. W. (1983) *Pesticides: Theory and Application.* Freeman, New York.

Watters F. L. (1963) The cooling of heated grain by transfer during cold weather. *J. econ. Ent.* **56**, 215–219.

Watters F. L. (1966) The effects of short exposures to sub-threshold temperatures on subsequent hatching and development of eggs of *Tribolium confusum* Duval (Coleoptera, Tenebrionidae). *J. stored Prod. Res.* **2**, 81–90.

Williams G. C. (1954) Observations of the effect of exposure to a low temperature on *Laemophloeus minutus* (Ol.) (Col., Cucujidae). *Bull. ent. Res.* **45**, 351–359.

Wohlgemuth V. R. (1989) Überlebensdauer vorratsschädlicher Insekten in Getreidekühllägern *Anz. Schädlingskde. Pflanzenschutz Umweltschutz* **62**, 114–119.

Mortality and Reproduction of *Ephestia cautella* and *Plodia interpunctella*[1] Exposed as Pupae to High Temperatures[2]

RICHARD T. ARBOGAST

Stored-Product Insects Research and Development Laboratory, Agricultural Research, Science and Education Administration U.S. Department of Agriculture, Savannah, Georgia 31403

ABSTRACT

Environ. Entomol. 10: 708–711 (1981)

Pupae of *Ephestia cautella* (Walker) and *Plodia interpunctella* (Hübner) were briefly exposed to temperatures of 40, 45, or 50° C, and the effects on adult eclosion, mating, fecundity, and fertility were determined. All males and females of both species were killed by a 2-h exposure to 50° C, but *E. cautella* was significantly more tolerant of exposure to 40 and 45° C than *P. interpunctella*. The median lethal time for exposure to 45° C was 7- to 8-fold longer in *E. cautella* than in *P. interpunctella*. Generally, exposure of male or female pupae of either species to high temperature caused some failure to mate and reduced the fecundity of mated females but did not reduce hatchability of the eggs laid. The percentage of mating failure depended to some extent on which sex was exposed and increased with temperature and length of exposure. Loss of fecundity was usually more severe when females rather than males were exposed.

The almond moth, *Ephestia cautella* (Walker), and the Indianmeal moth, *Plodia interpunctella* (Hübner), attack a wide variety of stored products throughout the world and are the two most important pests of stored farmer's stock peanuts in the southeastern United States. Peanuts in this region are stored in a wide variety of wooden and metal structures, but in all of them, temperatures that develop in the free space above the peanuts during the spring and summer are probably high enough to adversely affect most insects. The peanuts conduct heat poorly, however, and provide the insects with a refuge from the heat. The temperature in the bulk decreases rapidly with distance from the surface. For example, at Savannah, Ga., on a clear day in mid-July, the maximum outside temperature was 35° C and the temperature in the headspace of a 17.62-kl metal bin containing farmer's stock peanuts exceeded 45° C for 7 h and reached a high of 48° C, whereas the temperature 5 cm below the surface of the peanut bulk exceeded 40° C for 5 h and reached a maximum of 42° C, and the temperature 0.61 m below the surface remained at ca. 31° C throughout the day.

Adult moths in warehouses have been observed to take refuge in the cooler peanuts during the heat of the day. If such moths are disturbed, they fly for only a brief period and then quickly return to the peanuts. It is clear that larvae, as well as adults, could escape adversely high temperatures by moving downward to cooler layers as temperature increases during the day, whereas eggs and pupae at or near the surface would certainly be exposed. The purpose of the present study was to examine the effects of such exposure in the late pupal stage on mortality, wing malformation, mating, fecundity, and fertility in *E. cautella* and *P. interpunctella*.

Materials and Methods

The insects used in this study were reared on moth medium (Boles and Marzke 1966) at 27 ± 1° C and 60 ± 5% RH with a 12-h photoperiod. The cultures of *E. cautella* were established with moths collected from peanuts at Dothan, Ala. The cultures of *P. interpunctella* originated from stock collected in a peanut warehouse at Sylvania, Ga. Both species had been reared in the laboratory for about 3 years at the time the study began.

When the larvae in a culture jar had reached the wandering stage, the medium was broken up and the fine material was sieved off. The insects and medium were then returned to the jar, and a coil of corrugated paper was placed on top of the medium to provide pupation sites. The coil was removed 24 h later and held for an additional 7 days, after which the pupae were removed and sexed. Pupae were selected for experimentation based on pigmentation, and only those that were tan with brown eyes, dark brown eyes, or black eyes were used; these were estimated to be within 1 or 2 days of becoming pharate adults (Smithwick and Brady 1971).

The pupae were exposed for either 2 or 4 h to a temperature of 40, 45, or 50° C maintained in a water bath. For each treatment, 10 pupae of a given sex were placed in each of 10 3.7-ml snap cap bottles and submerged in the bath. Temperature was measured with a thermistor inserted in an identical snap cap bottle and placed in the bath at the same time as the pupae. Recordings of the temperature in this bottle indicated that it reached equilibrium with the bath in ≤5 min and that the temperature did not fluctuate noticeably during the course of the exposure. After exposure, each pupa was paired with an untreated pupa of the opposite sex and confined in a tapered plastic cup (55 mm high by 28 to 37 mm ID) covered with nylon screen fine enough to retain any eggs deposited. The cups were inverted over moth medium and held at 27° C and 60% RH for emergence, mating, and oviposition. Pairs of un-

[1] Lepidoptera: Pyralidae.

[2] Received for publication 1 October 1980.

Table 1.—Performance of moths held at 27°C throughout pupal development (controls)

Species	Mating frequency[a]		Fecundity		% Hatch	
	n	Mean ± SE	*n*	Mean ± SE	*n*	Mean ± SE
E. cautella	97	1.5 ± 0.1	94	368 ± 8.9	10	85 ± 6.6
P. interpunctella	99	1.9 ± 0.2	99	319 ± 10.4	10	99 ± 0.4

[a]Number of spermatophores in the bursa copulatrix of mated moths.

Table 2.—Effect of short exposures to high temperatures on pupal mortality of *E. cautella* and *P. interpunctella*

Temp. and duration of exposure	% Mortality[a]			
	E. cautella		*P. interpunctella*	
	♂♂	♀♀	♂♂	♀♀
40°C				
2 h	0	0	2	3
4 h	1	0	4*	14***
45°C				
2 h	9**	2	100***	100***
4 h	77***	88***		
50°C				
2 h	100***	100***	100***	

[a]Percentages with asterisks differ significantly from the controls (χ^2 test): *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

treated pupae held at the same conditions served as controls. The number of moths that emerged and the number with malformed wings were recorded, and eggs were counted twice weekly until the females died. Dead females were held in 70% ethanol for dissection to determine the number of spermatophores in the bursa copulatrix. A sample of 50 eggs was collected during days 3 and 4 of oviposition from each of 10 randomly selected females and held for determination of hatchability.

Pupal mortality, wing malformation, and mating were compared within species by means of a χ^2 one-sample test before the data were converted to percentages. Comparisons of fecundity and fertility (percent hatch) were made within species by means of analysis of variance and a Student-Newman-Keuls test.

For determination of the median lethal exposure (LT_{50}) to 45° C, groups of 100 pupae were exposed in the water bath as already described for various periods of time and then held at 27° C and 60% RH for emergence. Controls consisted of 100 pupae held at 27° C. Pupal mortality was recorded, and the LT_{50} was determined by probit analysis (Daum 1970).

Table 3.—LT_{50} for exposure of *E. cautella* and *P. interpunctella* pupae to 45°C

Species	LT_{50} (min)[a]	
	♂♂	♀♀
E. cautella	171 (160–191)	162 (152–174)
P. interpunctella	22 (17 – 26)	22 (21 – 23)

[a]Numbers in parentheses are 95% confidence limits.

Results and Discussion

Natural pupal mortality was 1% or less, and <3% of the emerging moths had malformed wings. All of the *P. interpunctella* and 97% of the *E. cautella* mated at least once. Observations of mating frequency, fecundity, and fertility are summarized in Table 1. Pairs of *E. cautella* mated one to six times: 60% once, 31% twice, 7% three times, and 2% four or more times. Pairs of *P. interpunctella* mated one to seven times: 50% once, 31% twice, 11% three times, and 8% four or more times. Oviposition by mated females was quite variable in both species. The number of eggs laid by each *E. cautella* female ranged from 9 to 530, and the number laid by each *P. interpunctella* female ranged from 9 to 524. Nearly all the eggs laid by *P. interpunctella* hatched, but for unknown reasons hatchability was lower in *E. cautella*.

Exposure to 40° C had no effect on pupal mortality of *E. cautella*, but a 4-h exposure produced a slight increase in mortality of *P. interpunctella* (Table 2). Both species were killed by a 2-h exposure to 50° C. The most interesting results were obtained at 45° C. All pupae of *P. interpunctella* were killed by a 2-h exposure to 45° C, whereas those of *E. cautella* suffered only slight mortality and, in fact, a few survived even a 4-h exposure to this temperature. The greater tolerance of *E. cautella* was confirmed by the median lethal time (LT_{50}) for exposure to 45° C (Table 3), which was 7- to 8-fold longer in *E. cautella* than in *P. interpunctella*.

Adults emerging from pupae that were exposed to high temperatures often had malformed wings, and the wings sometimes remained attached to the pupal case (Table 4). Here again, the greater tol-

Table 4.—Effect of short exposures of pupae to high temperatures on the incidence of wing malformation in *E. cautella* and *P. interpunctella*

Temp and duration of exposure	% of adults with malformed wings[a]			
	E. cautella		*P. interpunctella*	
	♂♂	♀♀	♂♂	♀♀
40°C				
2 h	2	1	4*	7
4 h	3	1	10**	23**
45°C				
2 h	56**	44**	—	—
4 h	100**	100**	—	—

[a]Percentages with asterisks differ significantly from the controls (χ^2 test): *$P < 0.05$; **$P < 0.001$.

Table 5.—Effect of short exposures of pupae to high temperatures on mating in *E. cautella* and *P. interpunctella*

Temp and duration of exposure	% of pairs that mated			
	E. cautella		*P. interpunctella*	
	♂♂ Exposed	♀♀ Exposed	♂♂ Exposed	♀♀ Exposed
40°C				
2 h	90*	98	94**	87***
4 h	90*	92	92**	79***
45°C				
2 h	20***	85**	—	—
4 h	0***	0***	—	—

*Percentages with asterisks differ significantly from the controls (χ^2 test): *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

erance of *E. cautella* for high temperatures was quite apparent. Exposure of pupae to 40° C produced a much higher incidence of malformation in *P. interpunctella* than in *E. cautella*. At this temperature, the incidence of malformation was slight in *E. cautella*, but exposure to 45° C for 2 h produced a high incidence of malformation, and all of the few adults that emerged after a 4 h exposure had malformed wings.

Exposure of either male or female pupae to high temperatures generally caused some reduction in the numbers of pairs that mated, although the ability of female *E. cautella* to mate was apparently not impaired by exposure to 40° C for as long as 4 h (Table 5). The degree of mating failure increased with temperature and length of exposure and depended to some extent on which sex was exposed. In *E. cautella*, exposure of male pupae seemed to have the greatest effect: differences between sexes were significant with exposures of 2 h to 40° C (χ^2 test, $P < 0.05$) and 2 h to 45° C ($P < 0.001$). The reverse was true in *P. interpunctella*, in which significantly fewer pairs mated when female pupae were exposed to 40° C for 4 h than when male pupae were exposed for the same period of time ($P < 0.01$). The reason for these differences is unknown, but they could, in part, reflect loss of mating ability in moths with malformed wings, since parallel differences between sexes occurred in the incidence of wing malformation (cf. Table 4). However, exposure of male *E. cautella* to 45° C for 2 h had a much greater impact on mating than it did on wing malformation; the reverse was true for females. This suggests that the mating ability of females may be less impaired by wing malformation than that of males, or that some factor other than wing malformation is involved in the loss of mating ability.

Table 6.—Fecundity[a] of female moths exposed as pupae to high temperature or mated with males that were so exposed

Temp and duration of exposure	*E. cautella*		*P. interpunctella*	
	♂♂ Exposed	♀♀ Exposed	♂♂ Exposed	♀♀ Exposed
40°C				
2 h	311 [a]	318[a]	(297)[a]	(302)[a]
4 h	(358)	305[a]	278 [a]	249
45°C				
2 h	304 [a]	153	—	—
4 h	—	—	—	—

[a]Mean number of eggs per female. Means in the same column followed by the same letter are not significantly different; means in parentheses are not significantly different from the control (Student-Newman-Keuls test, $P < 0.05$).

There was no indication in either species that exposure of pupae to high temperatures affected the frequency of mating in those moths that did mate. Thus, the proportions of females with various numbers of spermatophores in the bursa copulatrix did not differ significantly from the proportions observed in mated control females (χ^2 test, $P > 0.10$).

Generally, there was some loss of fecundity when either the male or female member of a pair was exposed in the pupal stage to high temperatures (Table 6). However, the loss was usually more severe when females rather than males were exposed. For example, exposure of *E. cautella* pupae to 40° C for 4 h or 45° C for 2 h had a significantly greater effect on fecundity when females were exposed than when males were exposed (F test, $P < 0.001$); the same was true when *P. interpunctella* pupae were exposed to 40° C for 4 h (F test, $P < 0.05$). Also, the loss of fecundity produced by exposure of females increased with temperature and length of exposure; this was not true when males were exposed.

Exposure of pupae to 40 or 45° C had little or no effect on fertility; that is, the hatchability of eggs laid by exposed females or females mated with exposed males was about equal to as that of eggs laid by control females. In *E. cautella*, the mean hatchability ranged from 74 to 93% and in *P. interpunctella* from 94 to 100%.

Burges and Haskins (1965) reported that the optimal conditions for rapid development of *E. cautella* are 30 to 32° C and 70 to 80% RH and that the upper temperature limit for development is ca. 36° C. Howe (1965) estimated that the optimal temperature range for population growth of both *P. interpunctella* and *E. cautella* is 28 to 32° C. A few authors have presented information concerning the effects of temperatures above optimum on survival and reproduction of these moths. Tuli et al. (1966), for example, recorded a considerable reduction in fecundity of *E. cautella* reared at 35° C compared with those reared at 15 to 30° C, and Abdel-Rahman (1971) noted that fewer *P. interpunctella* completed development at 35° C than at 30° C. However, the only detailed information available on the effects of high temperature was presented by Lum (1977). He found that pupae of *P. interpunctella* exposed to 36° C for 6 days (the entire pupal period) all died; some *E. cautella* pupae survived, although the adults were malformed and did not reproduce. Thus, his study lends support to the hypothesis that *E. cautella* is somewhat more tolerant of high temperatures than is *P. interpunctella*. He also found that exposure to 34 or 35° C for 6 days reduced the fecundity of both species. Fertility remained high (60 to 80%) after exposure to 34° C but was reduced to 5% after exposure to 35° C.

By crossing normal (held at 30° C) and treated (exposed to 35° C) moths, Lum showed that reduced fecundity and fertility resulted from heat injury to the males. He demonstrated further that this injury resulted from a selective interference of heat with production of eupyrene sperm. Thus, males treated for 3 days as prepupae or early pupae possessed few bundles of eupyrene sperm, whereas those treated as late pupae, after considerable spermatogenesis had already occurred, possessed normal numbers of eupyrene sperm.

In the present study, brief exposures (2 or 4 h) of late pupae to temperatures of 40 or 45° C produced injury in both males and females but failed to reduce fertility. Apparently, the eupyrene sperm already present in these pupae were not damaged by such exposures.

Acknowledgment

I thank Margaret Carthon, biological laboratory technician, for assistance in the collection of data for this study.

REFERENCES CITED

Abdel-Rahman, H. A. 1971. Some factors influencing the abundance of the Indian meal moth, *Plodia interpunctella* Hb., on stored shelled corn. Bull. Soc. Entomol. Egypte. 55: 321–330.

Boles, H. P., and F. O. Marzke. 1966. Lepidoptera infesting stored products, pp. 255–270. *In* C. N. Smith [ed.], Insect colonization and mass production. Academic Press, Inc. New York. 618 pp.

Burges, H. D., and K. P. F. Haskins. 1965. Life-cycle of the tropical warehouse moth, *Cadra cautella* (Wlk.), at controlled temperatures and humidities. Bull. Entomol. Res. 55: 775–789.

Daum, R. J. 1970. A revision of two computer programs for probit analysis. Bull. Entomol. Soc. Am. 16: 10–15.

Howe, R. W. 1965. A summary of estimates of optimal and minimal conditions for population increase of some stored product insects. J. Stored Prod. Res. 1: 177–184.

Lum, P. T. M. 1977. High temperature inhibition of development of eupyrene sperm and of reproduction in *Plodia interpunctella* and *Ephestia cautella*. J. Ga. Entomol. Soc. 12: 199–203.

Smithwick, E. B., and U. E. Brady. 1971. Integumentary pigmentation as an age index in Indian-meal moth pupae. J. Ga. Entomol. Soc. 6: 137–144.

Tuli, S., P. B. Mookerjee, and G. C. Sharma. 1966. Effect of temperature and humidity on the fecundity and development of *Cadra cautella* Wlk. in wheat. Indian J. Entomol. 28: 305–317.

J. stored Prod. Res. Vol. 28, No. 1, pp. 67–70, 1992
Printed in Great Britain. All rights reserved

0022-474X/92 $5.00 + 0.00
Copyright © 1992 Pergamon Press plc

TEMPERATURE INDUCED STERILIZATION FOR CONTROL OF THREE STORED GRAIN BEETLES

B. P. SAXENA, P. R. SHARMA, R. K. THAPPA and K. TIKKU
Division of Insect Physiology, Regional Research Laboratory, Jammu Tawi 180 001, India

(Received for publication 24 September 1991)

Abstract—Pupae (1, 2 and 3 days old) of three stored grain beetles, *Trogoderma granarium*, *Tribolium castaneum* and *Callosobruchus chinensis*, were subjected to temperatures of 30, 40 and 45°C with an exposure period of 24, 48 and 72 h for each age-group. Observations of adult emergence and their progeny revealed that though all the temperatures were effective in causing sterility, exposure to 45°C was particularly effective in suppressing adult formation. With *T. castaneum* and *C. chinensis*, adult emergence was totally prevented by 48 and 72 h exposures to 45°C. With *T. granarium*, the inhibitory effect was greater with male pupae and the resultant adults were completely sterile.

INTRODUCTION

A substantial loss of food grains takes place every year because of infestation by insects. The toxic nature of many pesticides limits their use in preventing such losses. Physical methods are not without inherent disadvantages, e.g. irradiation or high temperature may damage the treated grain. The application of vegetable oils is impractical in large-scale programmes (Tikku *et al.*, 1981).

The present study of populations of three very destructive stored grain insects, *Trogoderma granarium* Everts, *Tribolium castaneum* Herbst and *Callosobruchus chinensis* L., is based on the use of a slight increase of ambient temperature to levels that inhibit the production of progeny but are harmless for the infested medium. The investigations were undertaken against the backdrop of earlier work where a slightly elevated temperature had resulted into the sterilization of some insects such as the bug *Dysdercus koenigii* F. and the hopper *Poecilocerus pictus* F. (Tikku and Saxena, 1985, 1990). Increasing temperature by a few degrees disrupted spermeiogenesis and defective sperm production occurred because of the inability of the sperm to separate out due to ensheathment by a common plasma membrane. The observation that sterility might be readily induced was therefore exploited in view of the immense potential offered by such a simple procedure in providing protection to the foodgrain godowns.

The importance of the subject is being realized in developed countries too, where heat applications are increasingly being tried for disinfestation programmes of stored commodities (Evans, 1986).

MATERIALS AND METHODS

Cultures of *T. granarium*, *T. castaneum*, and *C. chinensis* were raised in the laboratory at 27 ± 2°C and 75% r.h. (Koul *et al.*, 1977; Saxena *et al.*, 1976; Tikku *et al.*, 1978). The pupae of *Trogoderma* and *Tribolium* were subjected at different stages of their development (i.e. at 1, 2 and 3 days of age) to 30, 40 and 45°C temperature with exposure periods of 24, 48 and 72 h for each age-group. After the separation of the sexes of pupae and adult emergence, 10 pairs of adults (in 12 replicates) formed from each of such exposures were released into a semi-crushed wheat medium for *Trogoderma* and into a wheat–flour medium for *Tribolium*. The adults were removed from their respective media after 15 days and their larval progeny counted after 1 month.

The precise age of the pupae of *Callosobruchus chinensis* was difficult to determine because of the protection given to them by the seed cover of *Phaseolus aureus* (the common variety of green gram used for rearing this culture). Therefore, the approximate age (±24 h after pupation) was estimated by breaking open some seeds at the operculum (i.e. the future opening made before

RRL Jammu contribution No. 2007.

pupation by the larva for escape of the adult) with forceps and assuming the pupal formation to have taken place in the rest of those seeds that contained the-ruptured egg-shell sticking over the outer cover. Such pupae (of approximately uniform age and undisturbed inside the seed) were exposed to heat treatments in a manner similar to that for the other two beetles. The emerged adults, after sexing, were introduced into their rearing medium from which they were removed after 72 h. The number of eggs laid by the heat-affected adults and their hatching (evident by the adults issuing from seeds having remanants of eggs) was tabulated.

RESULTS

The experiments revealed two effects of heating, i.e. a temperature-dependent inhibition of transformation from treated pupae to adults and a considerable reduction in the numbers of progeny developed from such adults (Tables 1–4). The specific observations recorded were:

(a) With *T. granarium* the male pupae were particularly sensitive to heating, especially at 45°C—the temperature at which there was a marked difference between the numbers of adults emerging from the 24 and 72 h exposures in all age groups (Table 1). Further, at this temperature, the adults obtained from the 48 and 72 h treatments were totally incapable of giving rise to a new generation. Even with a 24 h treatment, the larval number was highly reduced (Table 2). Pupae 1 day old were more susceptible to induction of sterility than those of greater age.

(b) In *T. castaneum* also, with the exception of 1 day old pupae exposed for 24 h, exposure to 45°C for any period at any age inhibited development and thereby adult formation (Table 1). At lower temperatures the adult emergence was almost unaffected. The effect of exposure to 40°C was far greater than that of exposure to 30°C in exercising a control over the population of larvae, with the youngest pupae (1 day) being most susceptible (Table 3). As was to be expected, the longest duration of treatment (72 h) provided greatest suppression in each age-group (Table 3).

(c) In *C. chinensis* the 45°C temperature was effective in preventing adult formation in all pupae heated for 48 and 72 h. The few adults found after 24 h exposure to 45°C (Table 1) displayed a very low fecundity and fertility (Table 4). This effect was not as prominent in 30 and 40°C treatments because the egg-laying and hatching was almost equal to that of the controls in the 30°C treatment, while in the 40°C treatment, longer periods of pupal treatments (48 and 72 h) yielded greater sterility (Table 4).

Table 1. Adult emergence (%) from heat-treated pupae of *T. castaneum*, *C. chinensis* and *T. granarium*

Age of pupae (days)	Duration of treatment (h)	Adult emergence (%)														
		30°C					40°C					45°C				
		T. castaneum		*C. chinensis*	*T. granarium*		*T. castaneum*		*C. chinensis*	*T. granarium*		*T. castaneum*		*C. chinensis*	*T. granarium*	
		♂	♀		♂	♀	♂	♀		♂	♀	♂	♀		♂	♀
Control	—	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	24	100	100	100	100	100	100	90	100	100	100	15	10	28	30	100
1	48	100	100	90	100	100	100	100	59	100	100	0	0	0	20	100
1	72	100	100	83	100	100	85	80	40	96	100	0	0	0	18	100
2	24	95	100	100	100	100	100	100	53	100	100	0	0	8	20	100
2	48	100	100	92	100	100	95	100	35	100	100	0	0	0	16	100
2	72	100	100	87	100	100	90	85	19	64	96	0	0	0	16	100
3	24	100	100	100	100	100	100	100	45	100	100	0	0	49	40	100
3	48	100	100	94	100	100	100	100	41	100	100	0	0	0	40	100
3	72	100	100	81	100	100	75	85	29	82	100	0	0	0	16	100

Control = at 27°C, separate control for each temperature.
*Pupae undisturbed within seed (unsexed).
Number of treated pupae (in 3 replicates) = 50 of each sex for *T. castaneum* and *T. granarium*, 100 for *C. chinensis*.

Table 2. The larval progeny of *T. granarium* developed from 10 pairs of heat-affected adults ($n = 12$)

Age of pupae (days)	Duration of treatment (h)	Number of larvae after 1 month*	
		40°C	45°C
Control	—	802 ± 45	781 ± 62
1	24	780 ± 95	71 ± 8
1	48	551 ± 65	0
1	72	301 ± 62	0
2	24	671 ± 59	125 ± 35
2	48	510 ± 70	0
2	72	291 ± 58	0
3	24	411 ± 64	230 ± 92
3	48	313 ± 69	0
3	72	253 ± 59	0

Control = at 27°C, separate control for each temperature.
*No significant effect at 30°C.

Table 3. The larval progeny of *T. castaneum* developed from 10 pairs of heat-affected adults ($n = 12$)

Age of pupae (days)	Duration of treatment (h)	Number of larvae after 1 month		
		30°C	40°C	45°C
Control	—	453 ± 76	355 ± 66	481 ± 71
1	24	448 ± 63	190 ± 51	40 ± 7
1	48	484 ± 79	60 ± 13	0*
1	72	291 ± 66	0	0*
2	24	382 ± 55	360 ± 49	0*
2	48	366 ± 59	61 ± 14	0*
2	72	291 ± 66	7.3 ± 3.5	0*
3	24	421 ± 59	640 ± 8	0*
3	48	361 ± 80	326 ± 79	0*
3	72	342 ± 70	4.2 ± 1.5	0*

Control = at 27°C, separate control for each temperature.
*No adults emerged from treated pupae.

DISCUSSION

Due to the adverse nature of some established methods, there is a constant search for new means of controlling insects in stored grains. A pollution-free, economical and easily applicable method which maintains its effectiveness for longer periods has become an urgent necessity in view of the low likelihood of success of even comparatively safe methods such as the use of hormone analogues and the pheromones. Keeping stored products pest free is particularly problematic because of the need to maintain the viability of the grains in some instances. Presently, fumigants are the answer for many pest problems but their main drawbacks are the requirement of users possessing expertise and the cost of the chemicals. Irradiation too has negative aspects, e.g. it causes a substantial loss of vitamins in the edible products. Trials with infrared radiation have been made with some success, e.g. twelve species of adult stored-product beetles suffered mortalities on raising the temperatures of wheat samples with infrared radiation to 49, 57 and 65°C (exposure periods: 20, 32 and 40 sec respectively) with kills reaching 100% at 57 and 65°C (Kirkpatrick and Tilton, 1972); 99% of *Sitophilus oryzae* and 93% of *Rhyzopertha dominica* died when temperature of their wheat medium was elevated by means of infrared radiation to 48.6°C (Kirkpatrick, 1975); wheat temperature increased to 55°C by infrared treatment killed natural infestations of stored-product insects (Kirkpatrick and Cagle, 1978). Similarly, Lindgren and Vincent (1959) have shown that increasing temperature to 55.6°C killed 95% of *T. granarium* eggs in 3 min.

In his exhaustive review, Evans (1986) has summarised the lethal limits of high temperatures which shows that the data in this field is fragmentary, e.g. adults of *S. oryzae* and *S. granarius* are killed in 180 and 30 min at 49 and 54°C respectively (Back and Cotton, 1924); *R. dominica* is killed in 15 min at 55°C (Pruthi, 1946); *Tribolium confusum* J. du V. adults are killed in 60 and 15 min at 50 and 55°C respectively (Knipling and Sullivan, 1958). Depending on the moisture content and the nature of the commodity to be heated, achieving the target thermal death points in this manner may be deleterious to the germination of the grain.

Table 4. Fecundity and fertility data of 10 pairs of heat-affected adults of *C. chinensis* ($n = 12$)

Age of pupae (days)	Duration of treatment (h)	Number of eggs laid and hatched					
		30°C		40°C		45°C	
		Laid ± SD	Hatched ± SD	Laid ± SD	Hatched ± SD	Laid ± SD	Hatched ± SD
Control	—	371 ± 34	369 ± 44	310 ± 49	305 ± 51	363 ± 40	361 ± 39
1	24	370 ± 47	369 ± 47	301 ± 51	265 ± 62	281 ± 40	188 ± 55
1	48	326 ± 46	322 ± 45	155 ± 58	136 ± 44	0*	0*
1	72	238 ± 46	211 ± 29	88 ± 19	24 ± 9	0*	0*
2	24	359 ± 42	351 ± 45	189 ± 58	182 ± 59	21.2 ± 6.8	12.0 ± 2.2
2	48	331 ± 43	309 ± 33	152 ± 41	147 ± 41	0*	0*
2	72	220 ± 31	204 ± 29	42 ± 12	31 ± 6	0*	0*
3	24	354 ± 29	352 ± 29	281 ± 50	218 ± 38	15.9 ± 4.2	2.0 ± 1.7
3	48	335 ± 38	334 ± 38	140 ± 52	122 ± 38	0*	0*
3	72	201 ± 50	171 ± 52	38 ± 9	4.6 ± 2.3	0*	0*

Control = at 27°C, separate control for each temperature.
*No adults emerged from treated pupae.

J. stored Prod. Res. V
Pergamon Press plc. Pr

Moderately elevated temperatures as a means of modifying population growth, however, have been tried, apparently without damage to the grain, by Kirkpatrick and Tilton (1973) who found that immature *S. oryzae* and *R. dominica* when exposed continuously to 39 or 43°C respectively yielded >99% mortality.

The data for all the three species studied here reveals the distinct temperature threshold of effective temperature within the range of 40–45°C. Such temperatures cause no harm to the infested commodity and can very easily be maintained in godowns for periods of 48–72 h needed to induce sterility. The study demonstrates the progeny reduction from treatment of 1 day old pupae due to heat stress in *T. granarium* and to some extent in *T. castaneum* with the best effective temperature for both these insects as well as for *C. chinensis* to be 45°C in exposures ranging between 48–72 h. In *T. granarium* the striking disparity of adult formation between the male and female pupae could serve as a long term gain in programmes for increasing the incidence of sterility in those individuals that are able to resist the 45°C temperature and give rise to a progeny (e.g. the adults obtained from 24 h treatment of pupae can produce a new generation).

The exploitation of the presently suggested temperature-range, which is within the benign limits for the germination of the grain, is desirable if complicated and expensive facilities are to be avoided. The summers of the tropical countries are often as hot as the maximum temperature applied in the present study but unfortunately the gains of such a temperature-range are often counteracted by percolating cool air through the granary in the belief that aeration will preserve the quality of the grains. In winter, temperatures could be artificially created by commonly available solar heating devices to reduce pest numbers to acceptable and justifiable limits.

REFERENCES

Back E. A. and Cotton R. T. (1924) Relative resistance of the rice weevil, *Sitophilus oryzae* L., and the granary weevil, *S. granarius* L., to high and low temperatures. *J. agric. Res.* **28**, 1043–1044.

Evans D. E. (1986) Some biological and physical constraints to the use of heat and cold for disinfesting and preserving stored products. *Proc. 4th Int. Wkg Conf. Stored Prod. Prot.*, pp. 149–164. Tel Aviv, Israel.

Kirkpatrick R. L. and Tilton E. W. (1972) Infrared radiation to control adult stored-product Coleoptera. *J. Ga ent. Soc.* **7**, 73–75.

Kirkpatrick R. L. and Tilton E. W. (1973) Elevated temperatures to control insect infestations in wheat. *J. Ga ent. Soc.* **8**, 264–268.

Kirkpatrick R. L. (1975) Infrared radiation for control of lesser grain borers and rice weevils in bulk wheat. *J. Kans. ent Soc.* **48**, 100–104.

Kirkpatrick R. L. and Cagle A. (1978) Controlling insects in bulk wheat with infrared radiation. *J. Kans. ent Soc.* **51**, 386–393.

Knipling E. B. and Sullivan W. N. (1958) Thermal death points of several species of insect. *J. econ. Ent.* **51**, 344–345.

Koul O., Tikku K. and Saxena B. P. (1977) Follicular regression in *Trogoderma granarium* due to sterilizing vapours of *Acorus calamus L.* oil. *Curr. Sci.* **46**, 724–725.

Lindgren D. L. and Vincent L. E. (1959) Biology and control of *Trogoderma granarium* Everts. *J. econ. Ent.* **52**, 312–319.

Pruthi H. S. (1946) Report of the Imperial Entomologist. *Abridg. sci. Rep. agric. Res. Inst.*, pp. 64–71. 1941–1944, New Dehli.

Saxena B. P., Koul O. and Tikku K. (1976) Non-toxic protectant against the stored grain insect pests. *Bull. Grain Technol.* **14**, 190–193.

Tikku K., Saxena B. P. and Koul O. (1978) Oogensis in *Callosobruchus chinensis* and induced sterility by *Acorus calamus* L. oil vapours. *Ann. Zool. Ecol. Anim.* **10**, 545–551.

Tikku K., Koul O. and Saxena B. P. (1981) Possible mode of action of vegetable oils to protect *Phaseolus aureus* Roxb. from bruchid attack. *Sci. Cult.* **47**, 103–105.

Tikku K. and Saxena B. P. (1985) Ultrastructure of sperms of heat sterilized *Dysdercus koenigii* F. *Curr. Sci.* **54**, 386–387.

Tikku K. and Saxena B. P. (1990) Ultrastructural spermatid and sperm morphology in *Poecilocerus pictus* (Fab.) with a reference to spermeiophagic cells in the testis and sperm duct. *Tiss. Cell* **22**, 71–80.

INTERN

This conference v
due to be held at t
January 1991).

Speakers may pre
atmosphere techni

The tentative titles

(1) Cun
(2) I
arth
(3) Pres
(4) Phy
(5) App
tech
(6) Inte
(7) Pote
resis

For further inform

The IPM Practitioner
Monitoring the Field of Pest Management

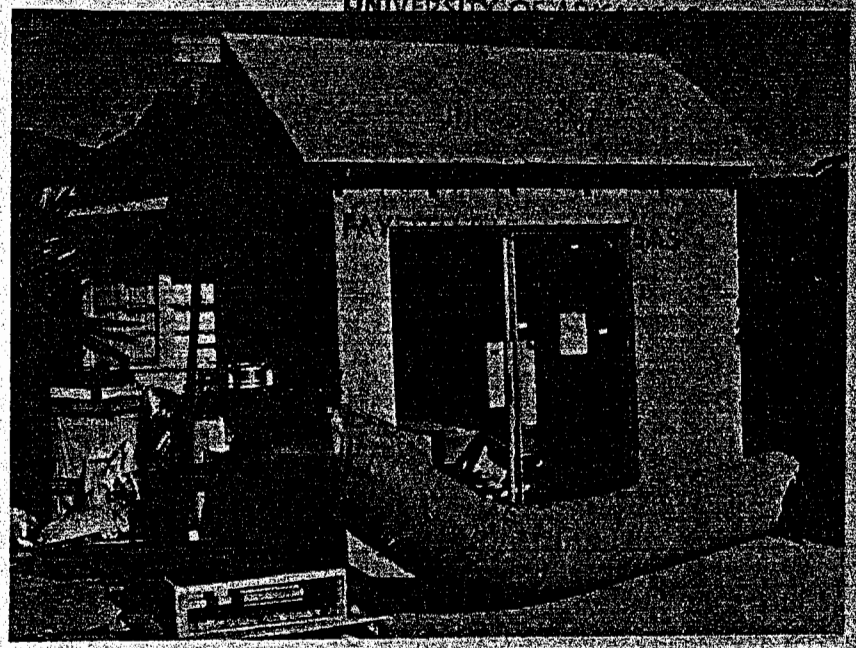
Update: Use Of Heat For Elimination Of Structural Pests

By Charles F. Forbes and Walter Ebeling

Over a period of three years the writers have conducted research on safe, practical methods of utilizing temperature control for the elimination of pests that inhabit buildings and other structures. Initial research was done with mock-up structures simulating those existing in conventional residential construction, such as mock-up walls and a small mock-up house. Then field experiments were conducted on houses in Florida and more houses and condominiums in the Los Angeles area. Our initial published report was on the use of liquid nitrogen to generate low temperature for the elimination of structural pests (Forbes and Ebeling 1986). The present report deals with the use of high temperature for the same purpose. In both cases our objective was the development of a pest-elimination methodology that is environmentally benign and acceptable to a public increasingly aware of health hazards that can accompany the use of toxic insecticides. In the case of some chemically sensitive persons, non-chemical methods may provide the only acceptable solution to their pest problems.

CRITICAL TEMPERATURES FOR INSECTS

Compared with most vertebrates, including humans, insects can tolerate only a very narrow range of temperatures. They are exceedingly vulnerable to either low or high temperatures, and they exercise very little control over their own body temperature. While at rest, they produce a temperature excess of no more than a degree or so centigrade by metabolic activity. Cooling by evaporation results in a temperature decrease →



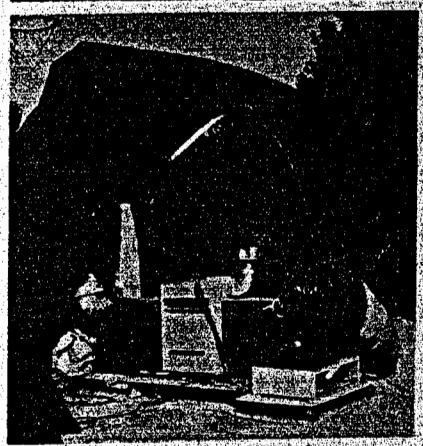


FIGURE 2. *Upper photo: An 8 x 10 foot mock-up house containing all the conventional features of residential construction. In front is a blower & heater with ducts used to raise temperatures in the building high enough to kill structural pests. Lower: a lightweight black tarp is used to contain hot air between house and tarp.*

In This Issue

UPDATE:
Using Heat Against Structural Pests 1
RESEARCH NOTE:
Whitefly Control in the Southwest 6
CONFERENCE NOTES:
Trichogramma Symposium in China 2
JOURNAL HIGHLIGHTS:
Mildew-Resistant Crape-myrtle 10
Citrus Whitefly Trap Crops 10
Natural Herbicides from Microbes 10
Biocontrol of Grapevine Crown Gall 11
Cucumber Mosaic Control for Tomato 11
Algae Products Control Nematodes 11
Biocontrol of Root Knot Nematodes 12
Solar Bait Container for Wireworms 12
Less Pesticide in Corn with IPM 12
Soil Practices Affect Soybean Pests 12
Fungus Foils Rice Mosquitoes 13
Grasshopper Growth Regulator 13
Nitrogen Fertilizer vs Stable Flies 13
Honeybee Foul Brood Test 13
Juvenile Hormone Affects Crustacae 13
PEST MANAGEMENT LIBRARY: 14
READERS' COLUMN:
Availability of Biocontrols 16
CALENDAR: 17
IPM MARKETPLACE: 17
CLASSIFIED ADS: 20

of about the same magnitude. Each species has a fairly well-defined range of critical temperatures, high or low (Bursell, 1964).

Working with 5 species of common insect pests, Mellanby (1932) determined the highest temperatures at which they could survive when exposed for 24-hour and 1-hour periods at controlled atmospheric humidities of 0, 30, 60, and 90 percent. The insects used were the body louse, *Pediculus humanus*, the green bottle fly, *Phaenicia sericata* [= *Lucilia*], the yellow mealworm, *Tenebrio molitor*, and adults and larvae of the oriental rat flea, *Xenopsylla cheopis*. Groups of 5 insects were placed in silk bags, with 3 to 5 bags at each temperature and relative humidity. In the 24-hour period the species not able to conserve their water died at lower temperatures in dry than in moist air because of desiccation. In dry air they died at temperatures ranging from 20°C [68°F] (flea larvae) to 38.6°C [101.5°F] (*Tenebrio*). In moist air (90% RH) the insects died between 36 and 38.6°C (97 and 102°F) and death was presumed to have been caused by heat.

The survival data for 1-hour exposures are of greatest interest in the present context and are shown in Figure 1. Temperatures for 100% mortality ranged from 39°C (103°F) for flea larvae to 46.6°C (116°F) for body lice. In the 1-hour exposures, relative humidities ranging from 0% to 90% had no discernible effect on the resistance of the small insects to high temperatures. However, for the largest *Tenebrio* larvae, weighing over 100 mg, the temperature for 100% mortality was 1°C higher in dry than in moist air. Mellanby believed these larvae were able to slightly reduce their body temperature by evaporating water and this was an advantage they possessed only in dry air.

Mellanby assumed that "large" insects such as cockroaches, by having relatively small surface areas, should be able to keep their bodies cool by evaporation longer than small insects when heated in dry air. This was shown to be the case in experiments conducted by Gunn and Notley (1936) in which American, *Periplaneta americana*, oriental, *Blatta orientalis*, and German, *Blattella germanica*, cockroaches were used as test insects. Again, in the 24-hour exposures, moist air (90% RH) was more favorable for survival than dry air (0% RH) because in dry air desiccation occurred even if the temperature itself was not fatal. However, in the 1-hour exposures, the temperatures for 100% mortality were higher in dry than in moist air: for *P. americana*, 45°C (113°F) and 42°C (108°F); for *B. orientalis*, 46°C (115°F) and 43°C (109°F); and for *B. germanica*, 45°C (113°F) and 43°C (109°F), respectively.

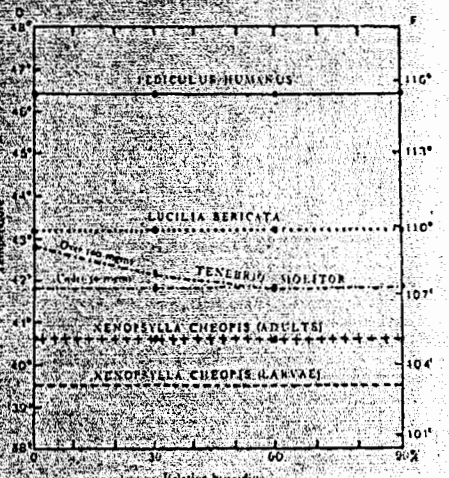


FIGURE 1. *Temperatures causing 100% mortality, in 1 hour, of 4 species of insects at 4 relative humidities. From Mellanby (1932).*

Gunn and Notley noted that earlier experiments had revealed that none of the 3 species of cockroaches would settle down at temperatures as high as 35°C (95°F), and higher temperatures caused a violent avoidance reaction. They concluded that their data on lethal temperatures had no great ecological importance since no individuals would settle at the higher temperatures. Yet it is obvious that heat can be utilized as an effective weapon against cockroaches if their escape is prevented.

Utilizing a thermostatically controlled temperature cabinet, the writers determined the time required to obtain 100% mortality of adult male German cockroaches, *Blattella germanica*, adult flour beetles, *Tribolium confusum*, and nymphs of the western drywood termite, *Incisitermes minor*, and adult Argentine ants, *Iridomyrmex humilis*, at 46, 48, 51, and 54°C (115, 120, 125, and 130°F) [Table 1]. The greatest decrease (82%) in time for 100% mortality was obtained by increasing the temperature from 46°C to 48°C

The IPM Practitioner
Monitoring the Field of Pest Management

The *IPM Practitioner* is published 10 times per year by the **Bio-Integral Resource Center (BIRC)**, a non-profit corporation undertaking research and education in resource management.

Editors: Sheila Daar
Helga Olkowski
William Olkowski

Editorial Associates: William Quarles
Rhoda Slanger

Contributing Editors: Joel Grossman
Judith Redmond

Design & Production: Joyce Hawley

Circulation: Kathy Spalding

Advisory Board:
George Bird, *Michigan State Univ.*; Sterling Bunnell, *Physician, Berkeley, CA*; Paul Catts, *Washington State Univ.*; Sharon Collman, *Coop Extn., Washington State Univ.*; David Davis, *No. Carolina State Univ., Emer.*; Walter Ebeling, *UCLA, Emer.*; Steve Frantz, *NY State Dept. Health*, Joseph Hancock, *Univ. Calif, Berkeley*, Manfred Mackauer, *Center for Pest Management, Simon Fraser Univ., Canada*; Robert Metcalf, *Univ. Illinois*; George Poinar, *Univ. Calif., Berkeley*; Ron Prokopy, *Univ. Massachusetts*; Ramesh Chandra Saxema, *The International Rice Institute, Manila, Philippines*; Ruth Troestschler, *Zoecon Corporation*; J. C. van Lenteren, *Agricultural University-Wageningen, The Netherlands*; Larry White, *Dir. Parks, Palo Alto, CA.*

The *IPMP* staff welcomes accounts of investigations germane to IPM for any pest situation. Write for details on manuscript format.

Citations: Unless otherwise noted, all text written by Sheila Daar, Helga Olkowski and William Olkowski. Reprint permission granted if source fully acknowledged and notified.

Subscriptions: $50/yr (institutions/libraries/businesses), $25/yr (personal or self-owned business check), $18/yr (registered student). Government purchase orders accepted. Canadian subscribers add $5.50 postage. All other foreign subscribers add postage at the following rates: $15/air or $5/surface. Memberships/subscriptions are tax deductible.

When writing to request a change of address, please send a copy of a recent address label.

©1987 BIRC, P.O. Box 7414, Berkeley, CA 94707; (415) 524-2567. All rights reserved.
ISSN #0738-968X.

(115°F to 120°F). It is evident that insects have suprisingly little tolerance for temperatures that are only marginally uncomfortable to humans.

In another experiment in the temperature cabinet, we determined the period required to reach temperatures of 48, 51, and 54°C (120, 125, and 130°F) in the center of a block of Douglas-fir lumber that was 3 1/4 x 1 1/2 inches in cross section and 4 inches long when the block was placed in the temperature cabinet at temperatures of 59, 65, 70, 76, and 81°C (140, 150, 160, 170, and 180°F). Temperatures were determined by means of thermocouple sensors placed in the centers of the wood block. Tests were also made with 10-inch blocks of wood that were 3 1/2 x 3 1/2 inches in cross section, but only at one cabinet temperature (70°C; 160°F). Drywood termite nymphs were placed in the centers of the blocks. This experiment demonstrated the feasibility of penetrating any structural wood member likely to be encountered in residential or commercial building construction with temperatures lethal to insects and within a practical time frame.

EXPERIMENTS IN THE MOCK-UP HOUSE

A small mock-up house was built with an inner dimension of 8x10 feet (see Figure 2 on the first page of this article). Despite its small size, the house contained the principal structural elements of conventional residential construction, ranging from 2x4-inch studs, plates, and joists, to 4x12-inch headers, and beams as large as 6x12 inches. Crawl space, attic, and wall voids with and without insulation and ceiling joists with and without insulation were featured in the model.

The object was to determine, at a given room temperature, how long it would take for temperatures inside various wood members, wall voids, etc., to reach the lethal temperatures found in the temperature cabinet experiments. The equipment used to obtain lethal temperatures with a large high-capacity heater is shown in Figure 2. Air from an electrically driven blower passes through a gas-fired heater and into the mock-up house through an 18-inch insulated flexible metal duct. The heated air was withdrawn from the opposite end of the house through the same type of duct and was recycled back into the blower. As will be shown later, recycling of hot air is not required in the treatment of houses.

Heating efficiency was increased by covering the roof with tar paper and was further increased by covering the entire house with a lightweight black plastic tarp. Hot air was allowed to escape from the house and caused the ballooning effect shown in Figure 2, bottom. The tarp ensured lethal temperatures in the eaves and the outer surface of the house.

Temperatures were monitored in as many as 12 locations per treatment, including the interiors (centers) of various wood members, by means of thermocouples. The thermocouple wires were numbered and passed through a small hole drilled in the wall. They were gathered together at one point, where they were arranged in a switching device by means of which temperatures at up to 12 locations could be monitored in rapid sequence merely by moving a pointer to numbered points on a dial connected to the thermocouple.

Many temperature curves were determined for various locations in the house. For example, in a test in which the interior of a 2x4-in ceiling joist reached a temperature of 48°C (120°F) in 30 minutes, it took 85 minutes to reach the same temperature in a similar joist embedded in R19 insulation. In this test, the room temperature was not allowed to rise above 81°C (180°F).

In another test, with room temperature no higher than 70°C (160°F), the interior of a 2x4-in ceiling joist again reached 48°C (120°F) in 30 minutes. In the interior of a 6x12-inch roof beam, however, it required 4 hours to reach a temperature of 46°C (115°F). Heating was then discontinued because it was known from previous tests that temperature in the interior of a very large beam continues to rise for a considerable period after heat is turned off.

In this beam, the interior temperature reached 48°C (120°F) in about 280 minutes and 52°C (127°F) in 320 minutes. A 1/4-inch tunnel had been drilled down to the center of the 6x12-inch roof beam from the roof. Drywood termite nymphs and flour beetles were placed in the bottom of the tunnel and the latter was then packed with fiberglass insulation. These insects were killed by the treatment; a half hour at 48°C (120°F) would have sufficed.

Compared to wood-infesting insects, which are somewhat protected in their galleries from high temperatures, free-living insects are killed very rapidly. Twenty German cockroach nymphs and adults, 20 adult flour beetles, and numerous cat flea, *Ctenocephalides felis*, larvae, pupae, pre-adults, and adults were confined in appropriate plastic containers and placed on a bench in the house after a temperature of 48°C (120°F) was reached and maintained

Table 1. Time Required For 100% Mortality of Four Species of Insects at Four Temperatures

Temperature (C°)	(F°)	Period for 100% mortality (minutes) German cockroach (adult males)	Flour beetle (adults)	Drywood termite (nymphs)	Argentine ant (adults)
46	115	58	123	265	8
49	120	27	16	33	4
51	125	16	9	10	2.5
54	130	7	4	6	1

at that level. The immature fleas were placed at the bottom of the fibers in the naps of small sections of carpet. Within 15 minutes the cockroaches and flour beetles and all stages of the cat flea were dead.

Twenty adult German cockroach adults and 20 nymphs were placed in a wall void with drywall cover. In this test, room temperature was not allowed to rise above 65°C (150°F). The cockroaches were periodically observed by removing a section of "2x4" at the top of the void. As temperature increased, the insects moved down to the bottom, the coolest part of the void. It took another hour for temperatures at the bottom to reach 48°C (120°F). In another half hour the temperatures had reached 51°C (125°F) and the cockroaches were all dead.

FIELD TESTS

By the time we were ready to begin field testing we had possession of a smaller and lighter heater than the one shown in Figure 2. The blower and burner were contained in one cabinet, which weighed only 90 pounds, and was easily carried by two men.

In the Los Angeles area we never had infestations brought to our attention that required the treatment of more than one room. We treated five drywood termite infestations and one carpenter ant infestation.

In the second story of a two-story condominium we were asked to treat two bedroom-livingroom units, with large ceiling beams infested with drywood termites, and one bathroom where alates had apparently entered through a ceiling vent. All three rooms were accessible from balconies, to each of which the heater was carried. Propane gas was conducted to the heater through a hose from a propane tank on the ground outside the building. Access to the bathroom was obtained by means of a duct, 18 inches in diameter, that was slipped over one end of the cabinet of the heater (Figure 3) and extended for 20 feet through the bedroom-livingroom and on to the bathroom.

When measured, the ceiling beams were 3x8 inches. In each room a hole was drilled to the center of a ceiling beam and a sensor inserted, after which the hole was packed with insulation. A temperature of 48°C (120°F) was reached in the beam in 53 minutes in the first room to be treated, while the room temperature nearby was 80°C (177°F). An hour later, the temperature in the beam was 55°C (132°F), and the room temperature was 84°C (184°F). In the next room to be treated, the gas pressure was reduced in the heater, and temperature in the beam reached 48°C (120°F) in 110 minutes. However, in 3 hours it had reached 61°C (143°F).

FIGURE 3. *An insulated flexible 18-inch duct is slipped over one end of a stainless steel heating unit, placed on a balcony, to conduct heated air for a distance of 30 feet through a bedroom and into a bathroom infested with western drywood termites.*

In one home it was the 4x6-inch railing of the second story balcony that was infested. A plastic tarp was placed over the balcony and was loosely held in place by means of duct tape. The heater was left on the ground and heat was conducted up to the balcony and beneath the tarp by means of the flexible duct. Temperature in the space under the tarp rose from 23°C (74°F) to 59°C (140°F) in 6 minutes. Temperature in the interior (center) of the beam reached 48°C (120°F) in 76 minutes and heat was turned off in 88 minutes when the beam temperature reached 51°C (125.3°F). It required another 72 minutes for the temperature in the beam to drop back to 48°C (120°F).

In one property, hot air was conducted through a duct from the doorway of the basement of a hillside home to reach an infested area of the basement. The heated area could not be isolated from other parts of the large basement, and foundation vents were left open. Nevertheless, our sensors within infested 2x4-inch studs, registered 49°C (121°F) in 82 minutes in one of them, and 48°C (120°F) in 123 minutes in the two others. In 164 minutes, the heat was turned off with the temperatures in the studs at 52, 51.7, and 50.6°C (127, 126, and 124°F).

One treatment was directed against carpenter ants, *Camponotus clarithorax*. These ants had been infesting a kitchen-breakfastroom-utility room area for about ten years, but their nest had never been found. The heater was placed outside the utility room door, which had a window that could be lowered to provide access for the duct. The duct was then extended down to the floor and a strong current of hot air was discharged along the floor level, thereby avoiding the stratification of heat that had been noted in previous experiments.

Temperatures averaged 69°C (157°F) at floor level and 68°C (155°F) at the ceiling during the entire period of treatment, but averaged 80°C (177°F) and 79°C (175°F), respectively, during the last hour. A sensor was placed in the center of a 2x4-inch stud under the sink cabinet, which had been left open for this test. To reach the sensor, heat had to penetrate 3/8-inch of plywood and then to the center of the stud. Temperature at this site was 48°C (120°F) in 3 hours and 56°C (134°F) in 4 hours. Before the heat treatment, a few worker ants could be seen on any warm night. Every year there was at least one flight of winged reproductives, increasing in numbers with the years. Neither workers nor alates have been seen since the heat treatment.

In all the heat treatments for drywood termites, the writers aimed for a great "overkill," based on the monitored temperatures at sites presumed to be the most difficult to reach with heat. All visible fecal pellets were removed at the time of treatment. No new pellets have since been

found by the occupants or by us in our occasional surveys of the treated properties.

We have noticed no damage to the usual house furnishings and contents except for candles, which melt at 54°C (130°F), "magnetic butterflies" that are commonly attached by magnets to refrigerator doors, and some thin-walled plastic containers, which became somewhat distorted at the higher temperatures required when treating for wood-infesting insects. Also, when heat is applied to only one side of a door, as in a closed room, the door will slightly warp, with the concave surface on the side heated. The door returns to its normal shape when it becomes cool again.

TREATMENT OF "TENTED" HOUSE

In Miami we had the opportunity to treat a two-bedroom house which had, including the attic, an estimated volume of 15,000 cubic feet. The pest species was the powderpost termite, *Cryptotermes brevis*, which infests any part of the wood structure of a house. It also infests furniture to a much greater extent than other drywood termite species in the U.S.

Nearly every piece of furniture in the house had piles of insect fecal pellets on the floor beneath it. The house was covered with a tarp in the same manner as for fumigation. Our machine discharged heat through the front door. The skirt of the tent was draped over the cabinet of the heater, which is at normal temperature during use because of its insulation from the burner (Figure 4). The attic was not insulated, and the access hole to the attic from the hallway was left open.

For monitoring temperatures, we drilled into the various wood members. In addition, a device constructed of synthetic materials with the heat permeability characteristics of wood was placed in the attic where wood members of the house structure were monitored. In the exact centers of the wood members and simulators were sensors with wire leading outside to our thermocouple. Air temperatures in the attic and livingspace were also monitored.

Lethal temperatures (51°C; 125°F or higher) were reached within two hours in all areas where the sensors had been placed. Dead termites were dug out of the top and upper part of one of the legs of an infested table. However, the termites in the bottom of one of the legs of a stool taken from a closet were still alive. At least in that closet, heat stratification had prevented enough heat to kill wood-infesting insects from reaching the floor level. This posed a problem that was solved in subsequent experiments.

FIGURE 4. *Heater (H) blowing hot air under a tarp and into a tented house to create temperatures lethal to powderpost termites.*

[Editors' Note: Charles Forbes is Associate Professor of Earth Sciences, California State Univ., Dominguez Hills. Walter Ebeling is Professor Emeritus, Entomology, Univ. of California at Los Angeles. They plan to market the heating units described in this article together with a training program for PCOs in use of this technology. Units should be available later this year. For further information, contact Forbes at 7343 Via Lorado, Rancho Palos Verdes, CA 90274; 213/541-3479; or Ebeling at 10659 Rochester Ave., Los Angeles, CA 90024; 213/474-2326.]

REFERENCES:

Bursell, E. 1964. Environmental aspects: temperature. In The Physiology of Insects. M. Rockstein, Ed. Vol. I, pp. 283-321.

Forbes, C.F. and W. Ebeling. 1986. Update: liquid nitrogen controls drywood termites. *The IPM Practitoner* 8(8):1-4

Gunn, D.L. and F.B. Notley. 1936. The temperature and humidity relation of the cockroach. IV. Thermal deathpoint. *J. Exptl. Biol.* 13:28-34.

Mellanby, K. 1932. The influence of atmospheric humidity on the thermal deathpoint of a number of insects. *J. Exptl. Biol.* 9:222-231.

IPM Jobs, Services & Products Network

BIRC receives many requests for information on IPM-related jobs, services, and products. These requests come from people seeking employment, and from firms, universities, public agencies, and consumers who want to hire persons with IPM training. We also hear from businesses, manufacturers, & investors looking for environmentally-sound pest control products.

We do our best to help people make the right connections. One way we can improve the visibility of this informal service is by encouraging greater use of our classified ad section for those seeking or providing IPM employment or services, or seeking investors for new products. The ad rates are modest and help to support the services we provide our members. Most importantly, the audience reading the ads includes thousands of the most progressive institutions and individuals in pest management.

Ads must be placed five weeks prior to the issue of the *IPMP* in which they are to appear (copy for the September issue must be received by July 27). For further details, see the back page.

Heat Penetration of Structural Timbers

By Walter Ebeling

Ed. Note: Heat penetration of structural timbers depends on their size and the kind of wood being treated. Information in this paper might help a PCO better estimate the time necessary to treat a given structure.

To kill wood-infesting insects with heat, it is necessary for the heat to penetrate wood—up to 2 or 3 inches (5 to 7.6 cm) of it in the larger wood members in some wood-frame construction. One generally thinks of wood as a notably poor conductor of heat, and for ordinary purposes this is true. But we found that all sizes of structural wood members encountered to date in houses and condominiums could be successfully treated with heat within practicable limits of temperature and time. Different kinds of wood have different heat penetration times, and the author investigated this aspect of heat treatment with a number of laboratory experiments.

Heat Penetration into Wood

In a thermostatically controlled temperature cabinet, the author made tests to determine the time required to reach temperatures of 120, 125, and 130°F (48.9, 51.7, 54.4°C) in the center of a block of well-seasoned Douglas fir wood that was 3.25 x 1.5 inches (8.3 x 3.8 cm) in cross section and 4 inches (10.2 cm) long. After each test, the block was cooled to ambient temperature before it was used for the next test. Table 1 shows that the greatest reduction in the time required to reach the desired temperature in the center of the block was obtained by increasing the temperature in the cabinet from 140°F to 150°F (60 to 65.6°C). The difference in the effect of these two temperatures increased exponentially as the temperature in the center of the wood block was increased from 120°F (48.9°C) to 125°F (51.7°C) and particularly from 125°F (51.7°C) to 130°F (54.4°C) (see Ebeling and Forbes 1989). This exponential relationship is graphically shown in Figure 1. *[Ed. Note: About 150°F (65.6°C) the heat insulating properties of wood begin to break down, and it becomes more of a heat conductor. Thus, air temperatures of 150°F or more are required to efficiently heat wood to the 120°F required to kill termites.]*

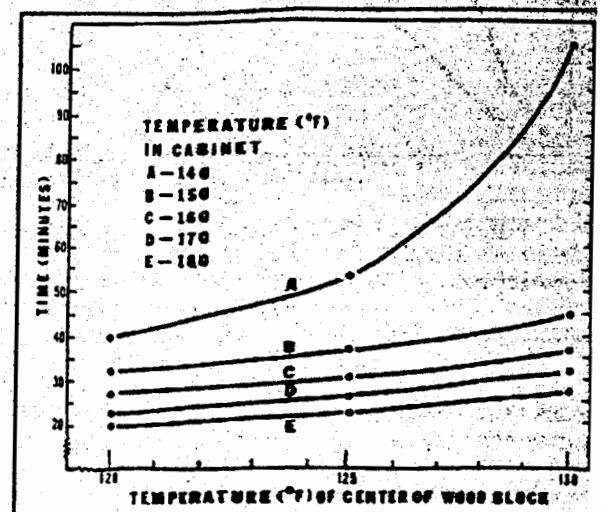


Figure 1. Time required for the center of a block of wood to reach 120°F, 125°F, and 130°F, in separate trials, when the block was held at each of 5 temperatures, ranging from 140°F to 180°F.

Effects of Size on Heating Rate

Figure 2 shows how size affects the heating rate at the center of a wood block. Two blocks of Douglas fir differing in cross section by 50% were exposed at a constant air temperature of 150°F (65.6°C). The arrows show the point in time when the blocks were removed from the cabinet. The center of the smaller block A reached 120°F (48.9°C) in minutes while block B took 74 minutes. *[Ed. Note: With two pieces of wood the same density, heating time is roughly proportional to volume.]* a heated block is removed from the cabinet when its center reaches the desired temperature and is then placed bare in an ambient temperature similar to the one at which heating began, it will lose heat at the same rate as it gained heat, as is shown by the symmetry of the two curves

Table 1. Time Required to Reach Temperatures of 120°F, 125°F, and 130°F in the Center of a Wood Block Heated in a Temperature Cabinet*.

Temperature in Cabinet (°F)	Time (minutes) to Reach Temperatures of: 120°F	Time (minutes) to Reach Temperatures of: 125°F	Time (minutes) to Reach Temperatures of: 130°F
140	40	53	106
150	32	37	45
160	27	31	37
170	23	27	32
180	20	23	27

*The wood block was a section of Douglas-fir stud 3 1/4 x 1 1/2 inches in cross section and 4 inches long.

Larger Wood Beams Cool Slowly

Figure 2 shows that the center of a wood block in-

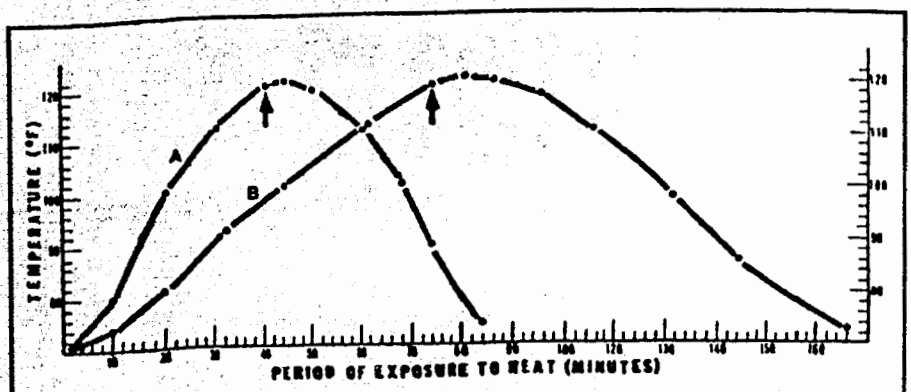


Figure 2. Time-temperature relation in the centers of wood blocks 2 x 2 x 5 inches (A) and 3 x 3 x 5 inches (B), when the blocks were kept at a constant temperature of 150°F and then removed to the ambient temperature when the block centers reached 120°F.

creases in temperature for a few minutes after the block is removed from the heat. The greater the thickness of the block, the longer the center remains above its temperature at the time the heat was discontinued. If no effort is made to speed up the cooling of a room after the heat is turned off, this action prolongs the period the interior of the wood beam remains at above-lethal temperature. For example, in one heat treatment when in 6 hours the center of an 8.5 x 9-inch (21.6 x 22.9 cm) beam reached 120°F (48.9°C) the heat was turned off, but the temperature at the center of the beam continued to rise until it reached 133.3°F (56.3°C), then slowly declined. It took 6 hours from the time the heat was turned off for the temperature in the center of the beam to get back down to 120°F (48.9°C). (See Forbes and Ebeling 1987.)

Wood Density and Heating Rate

Another experiment was conducted with 3 blocks of wood, each 2 x 1.75 inches (5.1 x 4.5 cm) in cross section and 8 inches (20.3 cm) long. The blocks were cut from old, dry, scrap pieces of lumber of 3 species that vary greatly in density in the ratio oak>Douglas fir>sapwood of redwood. (The last named is comparatively light when it is very dry). The object was to determine the difference in the way heat penetrates the 3 wood species.

Each wood block was prepared as follows: A tunnel 3/8 inch (0.95 cm) in diameter was drilled down through the center for a distance of 3 inches (7.6 cm). A copper wire leading from a thermocouple, with the terminal end of the wire wrapped with fiberglass insulation up to within a half inch (1.3 cm) from the end, was inserted in the tunnel so that the sensor at the end of the wire was in a half-inch-long cavity, with the remainder of the tunnel well insulated. Also, the end of the block through which the wire was inserted was covered with insulation held in place with masking tape.

The three blocks were placed in the temperature cabinet at a constant temperature of 160°F (71.1°C). Both ends of each block rested on block of wood so as to avoid conta with the hot metal of the supporti shelf. The period required for the terior of each block to reach 120°F (48.9°F) is shown in Table 2.

Conclusions

We had speculated that the greater the density of the wood the more rapidly heat would penetrate since the denser wood contains les air, a good insulator. But as the data in Table 2 show, the rate of heat penetration was inversely pro portional to wood density. Of the three wood types tested, low-densi redwood heated fastest, high-densi oak heated slowest and the heatin rate of Douglas fir was intermediat

The wood blocks were cooled down to room temperature (75°F; 23.9°C) and were again placed in t cabinet at a constant 160°F (71.1°(They were both removed when thei interiors reached 130°F (54.4°C) an were then placed on a table with both ends resting on a block of woo so as to provide contact of all four sides of each block to room temper ture. The results are shown in the last column in Table 2. As might b expected, oak, the wood species tha was the slowest in gaining heat, wa also the slowest in losing it.

REFERENCES

Ebeling, W. and C.F. Forbes. 1989. Heat treatment for powderpost beetles. *The IPM Practitioner* 11(9):1-4.

Forbes, C.F. and W. Ebeling. 1987. Updat Use of heat for elimination of structural pests. *The IPM Practitioner* 9(6):1-5.

■

Table 2. Periods for Heat Gain at a Constant Temperature of 160°F and Heat Loss at Room Temperature (75°F) in the Centers of Blocks of 3 Wood Species.*

Wood Species	Weight of Block (Grams)	Relative Weight (Redwood = 1)	Period of Heat Gain 75 to 120°F (Minutes)	Period of Heat Loss 130 to 120°F (Minutes)
Redwood	135	1.0	19	8
Douglas fir	201	1.5	25	10
Oak	376	2.8	34	13

*Each block of wood was 2 x 1.75 inches in cross section and 8 inches long.

Thermal Mortality of Hawaiian Subterranean and Drywood Termites (Isoptera: Rhinotermitidae, Kalotermitidae)

R. Joseph Woodrow and J. Kenneth Grace
Department of Entomology, College of Tropical Agriculture and Human Resources
University of Hawaii at Manoa

Introduction

The purpose of this study was to determine the thermal thresholds for termite species occurring in Hawaii. The critical thermal thresholds of insects are of particular interest in Hawaii because of the economic damage caused by termites, influence of tropical temperatures on termite distribution in the islands, and potential application of modified temperatures in thermal pest eradication or TPE. The TPE method as outlined by Ebeling (1994) involves tarping a structure as in gas fumigation and pumping heat into it to achieve and maintain an internal ambient temperature of between 145° to 150°F (63°-66°C). These ambient temperatures are usually maintained for a period necessary for the internal wood temperatures to exceed 120°F (49°C) for a minimum 30 minute duration.

The thermal relationships of a number of insect taxa have been reported, including cockroaches, blister beetles, imported fire ants, earwigs and termites. Most of these results have been in the form of critical thermal maxima (CTMax) and minima (CTMin). Critical thermal maxima range from about 109° to 124°F (43°-51°C) for most insect species. Because of discrepancies in the studies utilizing the CTMax/Min methodology, we adopted a more conservative "dose-mortality" approach in which we measured termite mortality at specific temperature-time intervals. We generated three dimensional matrices of temperature, time and mortality for two Hawaiian termite species, *Coptotermes formosanus* Shiraki (Rhinotermitidae) and *Incisitermes immigrans* (Light) (Kalotermitidae).

Methods

Coptotermes formosanus

Formosan subterranean termites were collected in wooden traps on the Manoa campus of the University of Hawaii in Honolulu. Time and temperature were varied over the ranges of 10 minutes to 90 minutes and 40°C to 49°C, respectively. The experimental units consisted of covered 100 x 20 mm glass petri plates which contained 50 workers (pseudergates) each. Three replicate units were chosen at random from a pool of all possible units to receive a particular time-temperature combination; all treatments at a given temperature were run concurrently. Petri plates were placed in an incubator (Accuracy: ±0.5°C from 40°C to 50°C) at ca. 5% relative humidity at time zero and quickly removed at their respective treatment times over ten minute intervals extending up to ninety minutes. The number of dead, moribund and live individuals were then counted and a single piece of filter paper was placed in each petri dish along with 1 ml of distilled water. The plates were then covered and placed in an incubator set to 28°C (±0.5°C) for a period of 24 hours at which point the number of dead, moribund and live individuals were again assessed. The values reported here represent 24 hour mortalities.

Incisitermes immigrans

This species was examined in the same manner as *C. formosanus* with some minor modifications. Test subjects were late instar nymphs from several individual colonies taken from dead standing wood collected near the University of Hawaii at Manoa campus. Individual colonies extracted from wood samples were placed in individual plastic containers along with tongue depressors as a food source and a number of pieces of filter paper soaked with distilled water. The covered containers were placed in an incubator set to 28°C and the colonies allowed to acclimate for a period of no less than 24 hours prior to testing. Because of the relative difficulty in obtaining large numbers of this species, treatments consisted of three replicates of twenty nymphs each placed in smaller (60 X 15 mm Kimax) glass petri plates. Treatments were conducted as previously described for *C. formosanus*, with mortality assessed 24 hours after removal from each particular time-temperature regime.

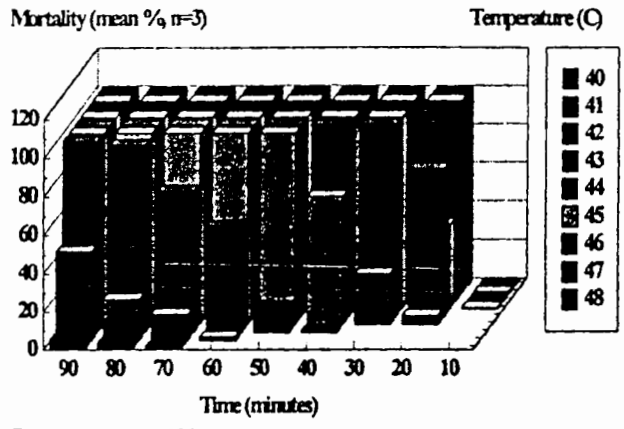
Results and Discussion

Figures 1 and 2 present the mean (n=3) mortalities for each termite species under each of the times and temperatures. These charts display a wide temporal spectrum of the effects of temperature on termite mortality. At the low end of the temperature scale, an upward trend in the mortality of *C. formosanus* can be seen at 40°C from 70 minutes upward; while with *I. immigrans*, this same trend is apparent at a significantly higher temperature (43°C) from 60 minutes. The lowest extreme of total (100%) mortality is reported for *C. formosanus* at temperatures as low as 42°C at 80 minutes and for *I. immigrans* at 45°C and 70 minutes.

It has been demonstrated with a number of insect species that CTMax as well as other physiological parameters are correlated with habitat; xerically adapted insect species seem to have higher CTMax values. The data generated on the two Hawaiian termite species is thus consistent with the biology of these species; ie., *C. formosanus* is adapted for a subterranean habitat while *I. immigrans* typically occupies hot xeric above-ground sites.

Over equal time intervals, the thermal thresholds reported here for *C. formosanus* are consistently lower than the CTMax values reported previously. Sponsler and Appel (1991) reported the CTMax for *C. formosanus* workers to be 46.3°C and the upper lethal

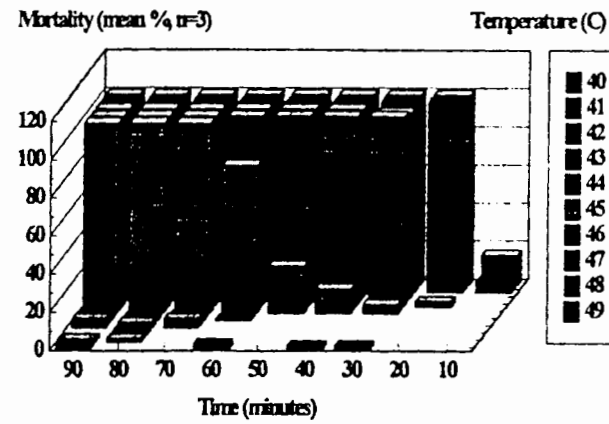
Figure 1. *Coptotermes formosanus* thermal mortality.



limit (ULL) to be 48.0°C. In that study, elapsed times ranged from 20 to 30 minutes [time elapsed = (CTMax-initial temperature) X (1°C/min)]. For 20 to 30 minute exposures at constant temperatures, in our study, 100 % mortality was produced in the range of 44° to 46°C for *C. formosanus*. The slight discrepancy between CTMax data and our results could be attributed to the cumulative effects of lower temperatures in the CTMax test scenario being less than that of a constant temperature or very rapid initial increase in our test. Thus, CTMax values would be slightly inflated over true lethal temperature thresholds.

No previous studies have reported CTMax for *I. immigrans*. However, the CTmaxima for *Incisitermes fruticavus* Rust and *Incisitermes minor* (Hagen) were reported to be in the range of 51° to 53°C. At equal elapsed times in our study, 100% mortality was

Figure 2. *Incisitermes immigrans* thermal mortality.



achieved with *I. immigrans* at 48° C and 46° C for 20 and 30 minute exposures respectively.

Despite the differences between the thermal maxima reported here and CTmaxima reported from previous studies, our threshold temperatures fall well within the bounds of the temperature exposure recommended for commercial termite control [120°F (49°C) for 30 minutes] (Ebeling 1994). At this temperature we achieved complete mortality of both *C. formosanus* and *I. immigrans* in 20 minutes.Tests are continuing with other termite species.

Selected References

Ebeling, W. 1994. The thermal pest eradication system for structural pest control. The IPM Practitioner. 16(2): 1-7.

Sponsler, R. C. & A. G. Appel. 1991. Temperature tolerances of the Formosan and Eastern subterranean termites (Isoptera: Rhinotermitidae). Journal of Thermal Biology 16: 41-44.

Field Studies on the Use of High Temperatures to Control *Cryptotermes brevis* (Isoptera: Kalotermitidae)

by

R. J. Woodrow & J. K. Grace[1]

ABSTRACT

Nine separate commercial high temperature treatments were observed throughout the State of Hawaii. Both ambient temperatures and structural wood core temperatures were monitored in the areas most prone to slow rates of temperature increase, i.e., the largest, lowest structural lumber and timbers next to potential heat-sinks. Data were analyzed to determine the range of temperature increase rates under various conditions as well as to test the impact of those conditions on heating rates.

The mean maximum wood core and ambient temperatures were 55.1°C and 68.1°C, respectively. The longest time that it took to achieve the target wood core temperature of 49°C was 5h. The mean rate of temperature increase was 0.28°C/min, the minimum was 0.04°C/min and the maximum was 1.41°C/min. Minor and repairable property damage was observed during two high temperature treatments when ambient treatment temperatures exceeded 70°C. The rates of temperature increase observed in field applications were generally considerably lower than those used in laboratory studies of the effects of rate on the thermal tolerance of *C. brevis*. Degree of surface exposure to heated air had a significant effect on the rate of temperature increase in lumber.

INTRODUCTION

Cryptotermes brevis (Walker) is an economically important species throughout the southernmost region of the United States as well as throughout the subtropics (Gay 1969). High temperatures have recently been used to control drywood termites (Ebeling 1997). Thermal treatment provides a non-chemical alternative to conventional control methods of drill-and-treat insecticide injection and structural fumigation.

Evaluations of the use of high temperature to control drywood termites have revealed some difficulties. Lewis and Haverty (1996), utilizing a structural mock-up, evaluated the use of excessive temperatures to control the drywood termite *Incisitermes minor* (Hagan) and

[1]Department of Entomology, University of Hawaii at Manoa, 3050 Maile Way, Room 310, Honolulu, HI 96822

observed a lack of efficacy in wood in the substructure next to a heat sink (concrete foundation). This lack of efficacy may be attributable to an inability to achieve lethal wood temperatures or to some other phenomenon such as termite acclimation. The research performed in support of the high temperature control method (Forbes and Ebeling 1987) utilized a thermal tolerance bioassay in which test insects (*I. minor*) were placed at preset temperatures and the time until death was determined at each temperature. Other researchers (e.g., Woodrow and Grace 1995) have used similar methods in laboratory studies. More recent studies, however, have found differences between results obtained using constant temperature methods and those utilizing controlled rates of thermal increase and it has been hypothesized that slow rates of temperature increase may allow time for termite acclimation (Woodrow and Grace 1998).

Scheffrahn et al. (1997) investigated the effects of several different rates of temperature increase on the thermal tolerance of *C. brevis* and did not observe any overall effects of thermal rate on thermotolerance. However, the lowest rate of increase studied by these researchers was 0.5°C/min. Ebeling (1994) reported that 7.6 X 7.6 X 12.7cm Douglas-fir blocks required 74min to reach an internal temperature of 48.9°C when subjected to a constant temperature of 65.6°C. This change of temperature converts to an overall rate of increase of 0.34°C/min. Since Ebeling's tests were carried out under laboratory conditions and many structural timbers exceed a width of 7.6 cm and a length of 12.7cm, actual rates of temperature increase in the field are likely to be less than those previously studied.

In the present report, nine separate commercial high temperature treatments were observed throughout the State of Hawaii. Both ambient temperatures and structural wood core temperatures were monitored in the areas most prone to slow rates of temperature increase, i.e., the largest, lowest structural lumber and timbers next to potential heat-sinks. Resulting data were analyzed to determine the range of temperature increase rates under various conditions as well as to test the impact of those conditions on heating rates.

MATERIALS AND METHODS

Commercial high temperature treatments were conducted by Certified Pest Control and Fumigation, Lahaina (Maui) and Hilo (Hawaii), under license from TPE Associates Isothermic/Biothermotec Inc., Orange, CA. The minimum target regime was a wood core temperature of 49°C for 30 minutes (Forbes and Ebeling 1987). During the first four treatments, temperatures were monitored using 18 gauge type-t ther-

mocouples attached to an Omega HH-21 single input type-t thermocouple thermometer (Omega Engineering, Inc., Stamford, CT) equipped with a six channel thermocouple switch. Both core and ambient temperatures were monitored throughout the area of treatment, particularly in areas subject to slow rates of increase, such as baseboards, large beams, sill plates, etc. Core temperature probes were installed by drilling (0.476cm [3/16"] drill-bit) to the center of the selected wooden member, placing the thermocouple in the hole and sealing the hole with duct tape. Six channels were recorded manually at 30 minute intervals.

For the remaining five high temperature control treatments, a model E-23000-30 eight channel self-contained thermistor data logger (Cole Parmer Instrument Company, Vernon Hills, IL) was used to collect core and ambient temperature data. Eight general purpose YSI series 400 thermistor probes (Cole Parmer Instrument Company, Vernon Hills, IL) were placed similarly to the thermocouples described above. Careful records were kept as to the location of monitored core and ambient temperatures as well as the dimensions of lumber used for core readings.

Linear regression (SAS Institute 1985) was applied to determine the rates of increase from ambient to 49°C with all the core temperature data that were collected. A general linear model (SAS Institute 1985) was used to test the significance of ambient treatment temperature, height off the floor, degree of exposure, and width of lumber on the rate of thermal increase in type III *F*-tests (SAS Institute 1985).

RESULTS

Nine high temperature control treatments were observed in the State of Hawaii, four on the island of Oahu, four on the island of Hawaii and one on the island of Maui.

Waikiki Shore Apartments

This first treatment observation was performed at the Waikiki Shore Apartments, Kalia Rd, Honolulu, Oahu on 5 September 1995. The owner of the condominium apartment had noted termite damage along the book shelves next to the kitchen (Fig. 1). The entire apartment was treated with high temperatures by placing propane gas blowers at the front and back lanai doorways. Thermal blankets were placed in the doorways to prevent the heated air from escaping the structure. To facilitate air circulation, three fans were placed in the apartment: one in the kitchen doorway, one in the hallway to the bathroom and the other in the living/bedroom area (Fig. 1). To monitor wood core temperatures, thermocouples were placed at floor level in 3.8 X 8.6cm

studs in the living room/ bedroom closet, in the kitchen cabinets, and in the bathroom door jam. Ambient temperatures were monitored in the same general vicinity as the core probes at a height of ca. 2m above the floor (Fig. 1). The treatment commenced at 0915 hours and was concluded at 1520 hours.

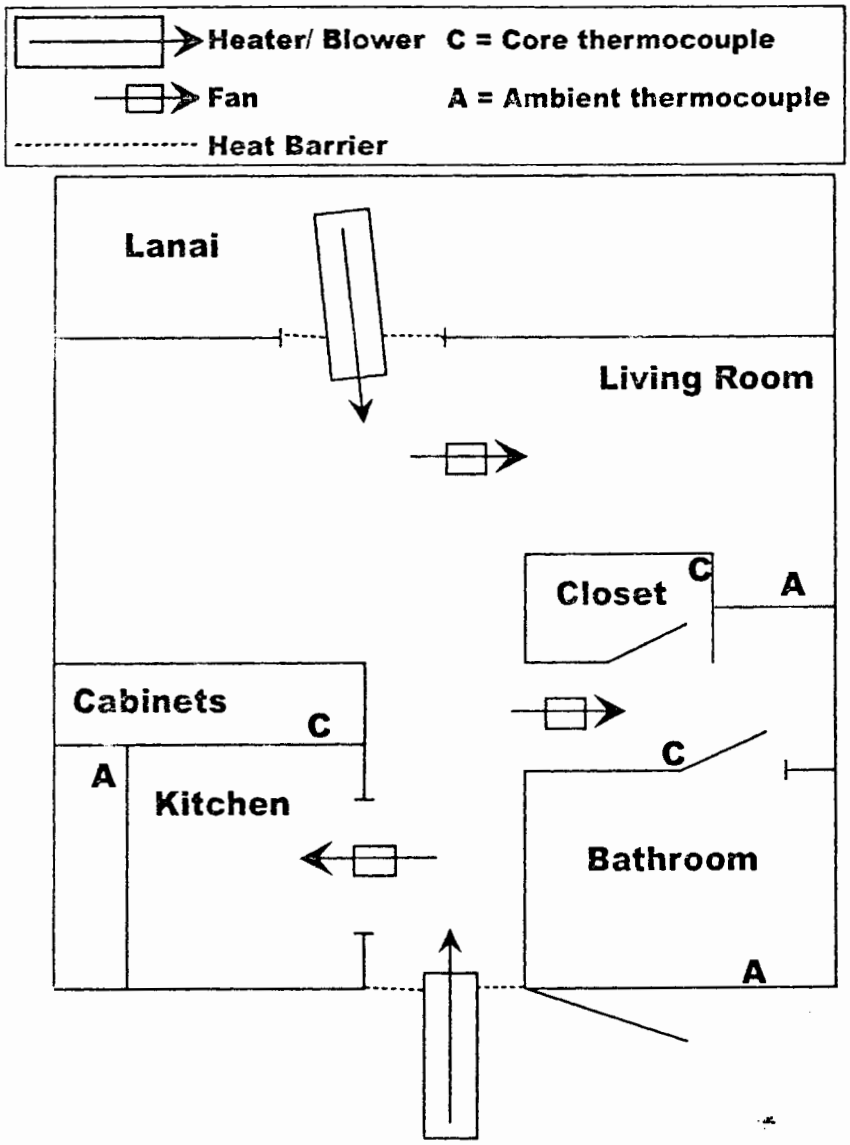


Fig. 1. Overhead drawing of the high temperature treatment at Waikiki Shore Apartments, Honolulu, Oahu, 5 September 1995.

Table 1. Summary statistics for the high temperature treatment at Waikiki Shore Apartments, Honolulu, Oahu, 5 September 1995.

Location	Height (m)[a]	C/A[b]	Wood dimension (cm)	Rate (°C/min)	Max temp[c] (°C)	Time to 49[d] (min)
Bath	0	C	3.8 X 8.6	0.065	54.3	270
Bath	2	A	—	—	71.8	—
Closet	0	C	3.8 X 8.6	0.039	54.6	180
Closet	2	A	—	—	59.4	—
Kitchen	0	C	1.9 X 3.8	0.041	52.9	240
Kitchen	2	A	—	—	62.0	—

[a]=Height from floor to probe.
[b]=Core (C) or ambient (A) probe.
[c]=Maximum temperature.
[d]=Time required to reach a core temperature of 49°C.
—= No data collected.

Rates of wood temperature increase ranged from 0.039°C/min in the closet to 0.065°C/min in the bathroom (Table 1). It took 4.5h (270 min) for the temperature to reach 49°C in the bathroom core and ca. 3h in the closet core. The slow rates of temperature increase were most likely due to the low ambient temperatures in these areas which ranged from 59.4°C in the closet to 71.8°C in the bathroom.

Hawaii Kai

The second high temperature control treatment was in a single family dwelling on Poipu Drive in Hawaii Kai, Oahu on 10 May 1995. Drywood termite damage was found in the front and rear attic sections as well as in the front office (Fig. 2). The treatment was performed in two sections, front and rear of the house. Two propane blowers were used in the front, one to heat the office and the other directed up into the attic through a duct (Fig. 3). The office doorways and attic vents were sealed with fumigation tarps (Figs. 2 and 4). In the front section, tarps were hung from the eves and secured to the ground with sand snakes (Fig. 4). In the attic sections, temperatures were monitored with core probes in 3.8 X 18.4cm ceiling joists and ambient probes placed next to the core locations (Fig. 2). In the office, core temperature was monitored within a 8.6 X 26cm beam located on top of a concrete masonry unit (CMU) wall at ceiling height (ca. 2.5m) and ambient temperature was monitored with a thermocouple secured to a bookcase at ca. 1.5m high. In the attic sections, fans were used to facilitate air circulation (Fig. 2). Heating commenced in the front section at 1000 hours and terminated at 1500 and 1600 hours for the attic and office areas, respectively. The rear attic was treated similarly to the front attic, with a propane heater directed

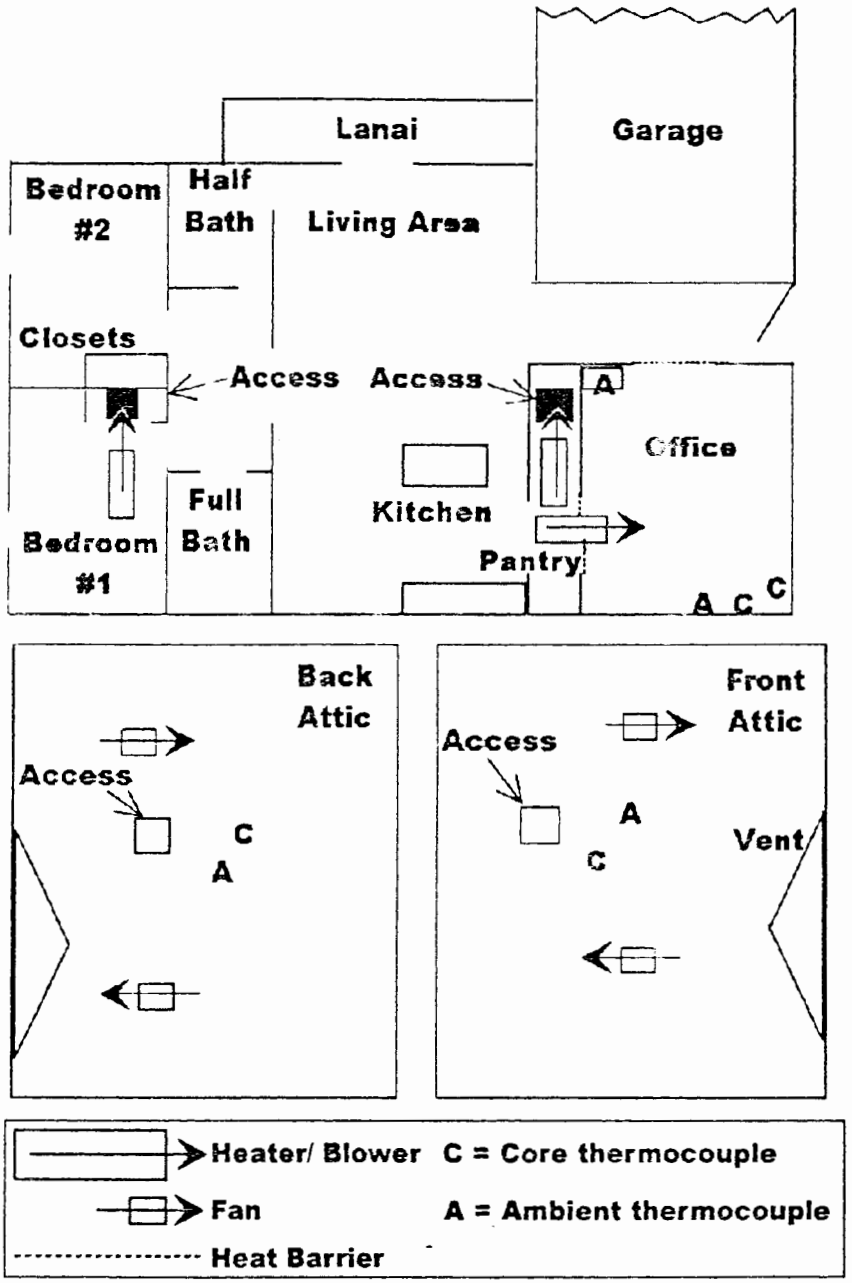


Fig. 2. Overhead drawing of the high temperature treatment at Hawaii Kai, Oahu, 10 May 1995.

Table 2. Summary statistics for the high temperature treatment at Hawaii Kai, Oahu, 10 May 1995.

Location	Height (m)[a]	C/A[b]	Wood dimension (cm)	Rate (°C/min)	Max temp[c] (°C)	Time to 49[d] (min)
Office	2.5	C	13.3 X 26.0	0.09	54.4	300
Office	1.5	A	—	—	71	—
Front Attic	0	C	3.8 X 18.4	0.13	57.6	120
Front Attic	1	A	—	—	72.9	—
Back Attic	0	C	3.8 X 8.6	0.23	58.3	90
Back Attic	1	A	—	—	65.4	—
Eve	2.5	C	3.8 X 8.6	0.23	56.3	90

[a]=Height from floor to probe.
[b]=Core (C) or ambient (A) probe.
[c]=Maximum temperature.
[d]=Time required to reach a core temperature of 49°C.
—= No data collected.

into the crawl space. Heating commenced in the back section at 1115 hours and was terminated at 1600 hours.

Ambient air temperatures were considerably higher than those observed at the previous site, with high ambient temperatures ranging from 65.4°C in the rear attic to 72.9°C in the front attic (Table 2). In the front office, the heat-sink effect of the CMU wall is obvious from the slow rates of increase (0.09°C/min) and the five hours required to reach 49°C in the 8.6 X 23.5cm beam given an adequate ambient high temperature of 71°C.

Marine Fisheries Lab

This high temperature control treatment was conducted on 11 May 1995 at the National Oceanographic and Atmospheric Administration Marine Fisheries Research Lab (Kewalo Basin), Honolulu, Oahu. The structure was a ca. 50-year-old warehouse that contained four offices and two restrooms framed in Douglas Fir 3.8 X 8.6cm studs and 3.8 X 13.3cm joists covered with unfinished 1.25cm plywood (Fig. 5). Most of the ceiling joists and plywood were heavily infested with *C. brevis*. The six rooms were treated in two sections. The front section contained three offices and the rear section contained the remaining office and the restrooms (Fig. 5). The ceiling areas of the front section were infested along with the joists, so fumigation tarps were used to cover the entire section as a unit. Three propane heaters were used to treat the front section, one partially directed into room # 1 and down the hall under the tarp and the remaining two directed into rooms #2 and #3. The

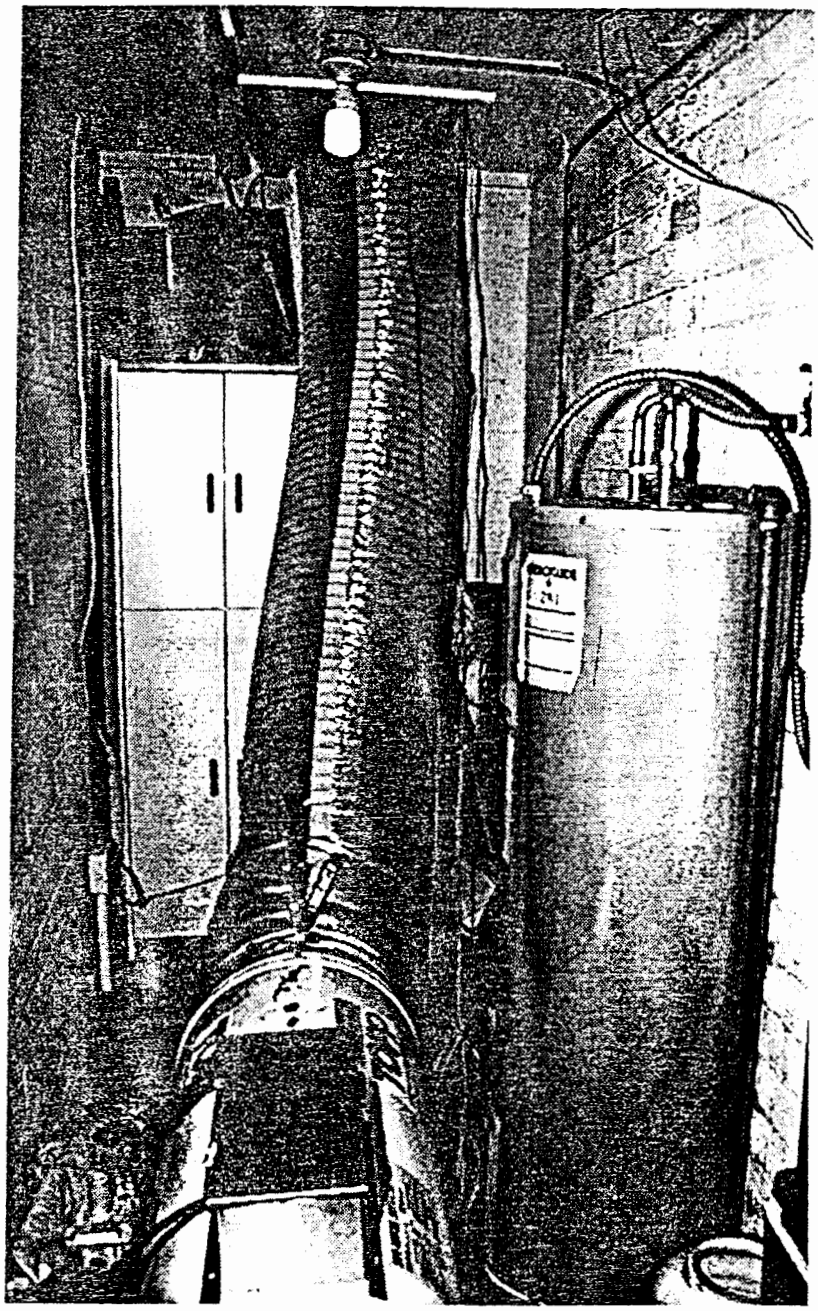


Fig. 3. Duct work used to direct heated treatment air up into the ceiling crawl space during the high temperature treatment at Hawaii Kai, Oahu, 10 May 1995.

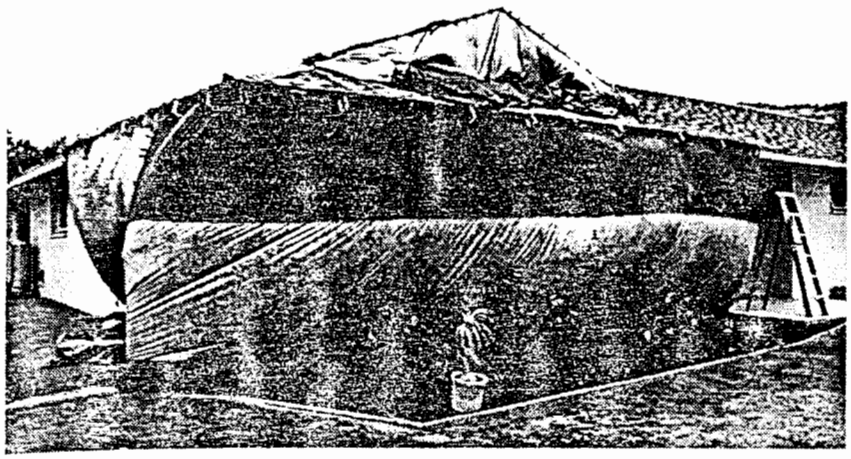


Fig. 4. Side view of the high temperature treatment done at Hawaii Kai, Oahu, 10 May 1995.

remaining rooms in section two were treated individually. Ambient air temperature was monitored at the center door jam and at ceiling height in rooms # 3 and #4 (Fig. 5). Two thermocouples were placed into 3.8 X 13.3cm ceiling joists, one in room #3 and one in room #4. Core temperatures were monitored in baseboards of rooms #1, #2, #4 and the ladies restroom. Heating commenced at 1000 hours and was terminated at 1530 hours.

Table 3. Summary statistics for the high temperature treatment at the Marine Fisheries Lab, Honolulu, Oahu, 11 May 1995.

Location	Height (m)[a]	C/A[b]	Wood dimension (cm)	Rate (°C/min)	Max temp[c] (°C)	Time to 49[d] (min)
Room #3	2.5	C	3.8 X 13.3	0.12	43.8	135
Room #3	2.5	A	—	—	51.8	—
Center door	2	A	—	—	59.6	—
Room #4	2.5	C	3.8 X 13.3	0.08	48.7	120
Room #4	2.5	A	—	—	61.7	—
Ladies	0	C	1.9 X 8.6	0.07	50.2	120
Room #4	0	C	1.9 X 8.6	0.08	48.3	120
Room #1	0	C	1.9 X 8.6	0.10	51.7	90
Room #2	0	C	1.9 X 8.6	0.04	39.2	—

[a]=Height from floor to probe.
[b]=Core (C) or ambient (A) probe.
[c]=Maximum temperature.
[d]=Time required to reach a core temperature of 49°C.
—= No data collected.

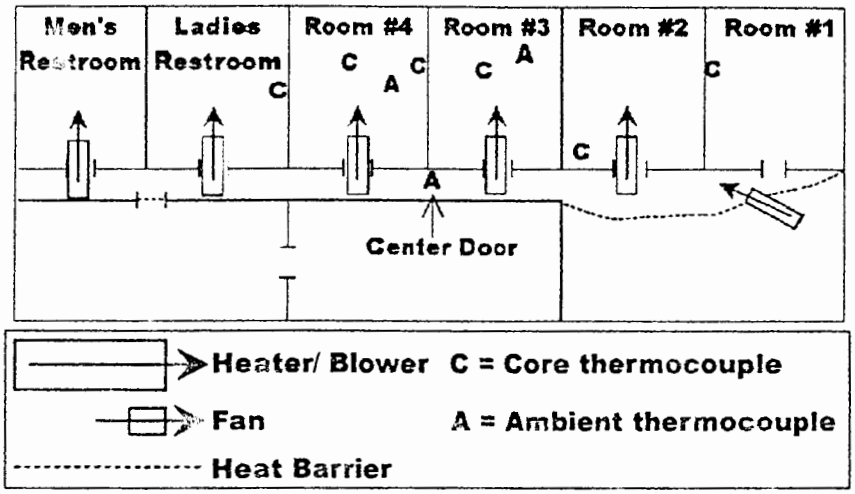


Fig. 5. Overhead drawing of the high temperature treatment at the Marine Fisheries Lab in Honolulu, Oahu, 11 May 1995.

Maximum ambient treatment air temperatures were relatively low during this treatment, ranging from 51.8 to 61.7°C (Table 3). Rates of wood thermal increase ranged from 0.04°C/min in a 1.9 X 18.4cm baseboard to 0.13°C/min in a 3.8 X 13.3cm ceiling joists.

Table 4. Summary statistics for the high temperature treatment at Island Princess Candies, Honolulu, Oahu, 13 May 1995.

Location	Height (m)[a]	C/A[b]	Wood dimension (cm)	Rate (°C/min)	Max temp[c] (°C)	Time to 49[d] (min)
201	0	C	1.9 X 8.6	0.35	51.9	60
201	2	A	—	—	72.1	—
201A	0	C	3.8 X 8.6	0.17	52.9	90
201A	2	A	—	—	68.2	—
207	0	C	1.9 X 8.6	0.05	51.3	30
207	2	A	—	—	71.6	—
205	0	C	1.9 X 8.6	0.20	54.8	30
209	0	C	3.8 X 8.6	0.12	51.7	30
203	0	C	1.9 X 8.6	0.13	52.1	90
203	2	A	—	—	66.5	—

[a]=Height from floor to probe.
[b]=Core (C) or ambient (A) probe.
[c]=Maximum temperature.
[d]=Time required to reach a core temperature of 49°C.
_ = No data collected.

Island Princess Candies

This treatment took place on 13 May 1995 at the Island Princess Candies warehouse and offices, Honolulu, Oahu. The area of treatment was a second story office complex within the industrial warehouse. Termite damage was evident in rooms 201, 201A, 203, 205, 207, 208 and 209 in door jams and moldings (Fig. 6). Only those rooms with evidence of infestation were treated. During this treatment, blowers were directed into each room individually until the suggested endpoints had been reached, then moved to the next nearest room. During the treatments, doorways were covered with thermal blankets to prevent heat loss. A single ambient and a single core thermocouple were used to monitor treatment temperatures in each room. Treatment commenced at 1015 hours in rooms 201, 201A and 205 and were concluded in rooms 203, 207 and 209 at ca. 1500 hours (Fig. 6). No data were available for room 208.

Both the highest and lowest rates of temperature increase occurred in 1.9 X 8.6cm baseboards. The lowest observed rates were 0.05°C/min in room 207, the largest room, and 0.35°C/min in room 201, a relatively small room (Table 4).

Kona Palisades Estates

This treatment was the first in a series of treatments observed on the island of Hawaii, 24 July 1995 at Kona Palisades Estates, Kailua-Kona. The treatment area was a tool shed built against the garage of a single-story house (Fig. 7). Evidence of drywood termite damage was primarily in 1.9cm (3/4") plywood shelving in the shed. A single blower was directed into one side of the shed and the area around the door was sealed with the use of fumigation tarps. A single ambient probe was placed in the opposite end of the shed at ca. 3m high and four core

Table 5. Summary statistics for the high temperature treatment at Kona Palisades Estates, Kailua-Kona, Hawaii, 24 July 1995.

Location	Height (m)[a]	C/A[b]	Wood dimension (cm)	Rate (°C/min)	Max temp[c] (°C)	Time to 49[d] (min)
Far side	1	C	1.9 (plywood)	0.70	61.2	29.3
Far side	1	C	3.8 X 8.6	0.75	63.6	30.9
Far side	3	C	3.8 X 8.6	—	72.3	14.9
Near side	1	C	8.6 X 8.6	0.41	59.0	54.4
Far side	3	A	—	—	75.9	—

[a]=Height from floor to probe.
[b]=Core (C) or ambient (A) probe.
[c]=Maximum temperature.
[d]=Time required to reach a core temperature of 49°C.
— = No data collected.

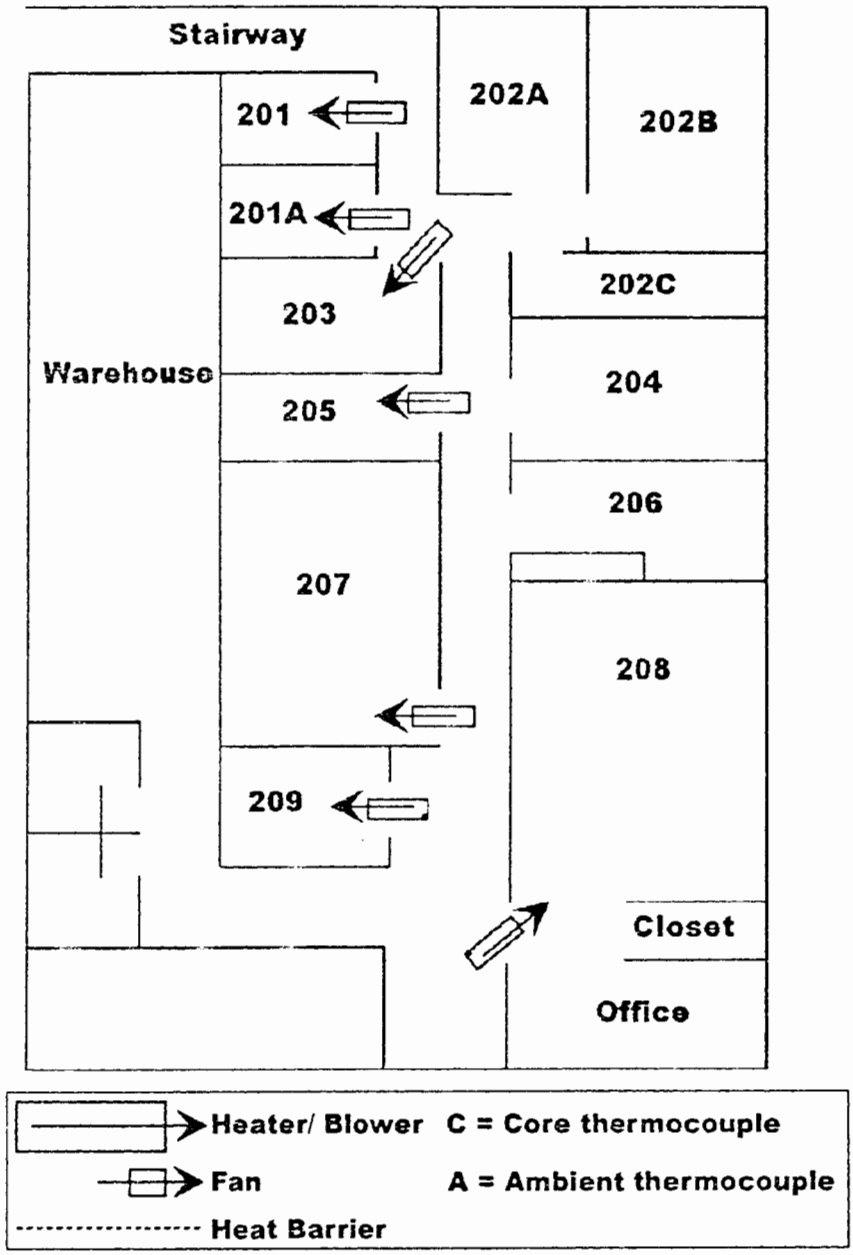


Fig. 6. Overhead drawing of the high temperature treatment at Island Princess Candies, Honolulu, Oahu, 13 May 1995.

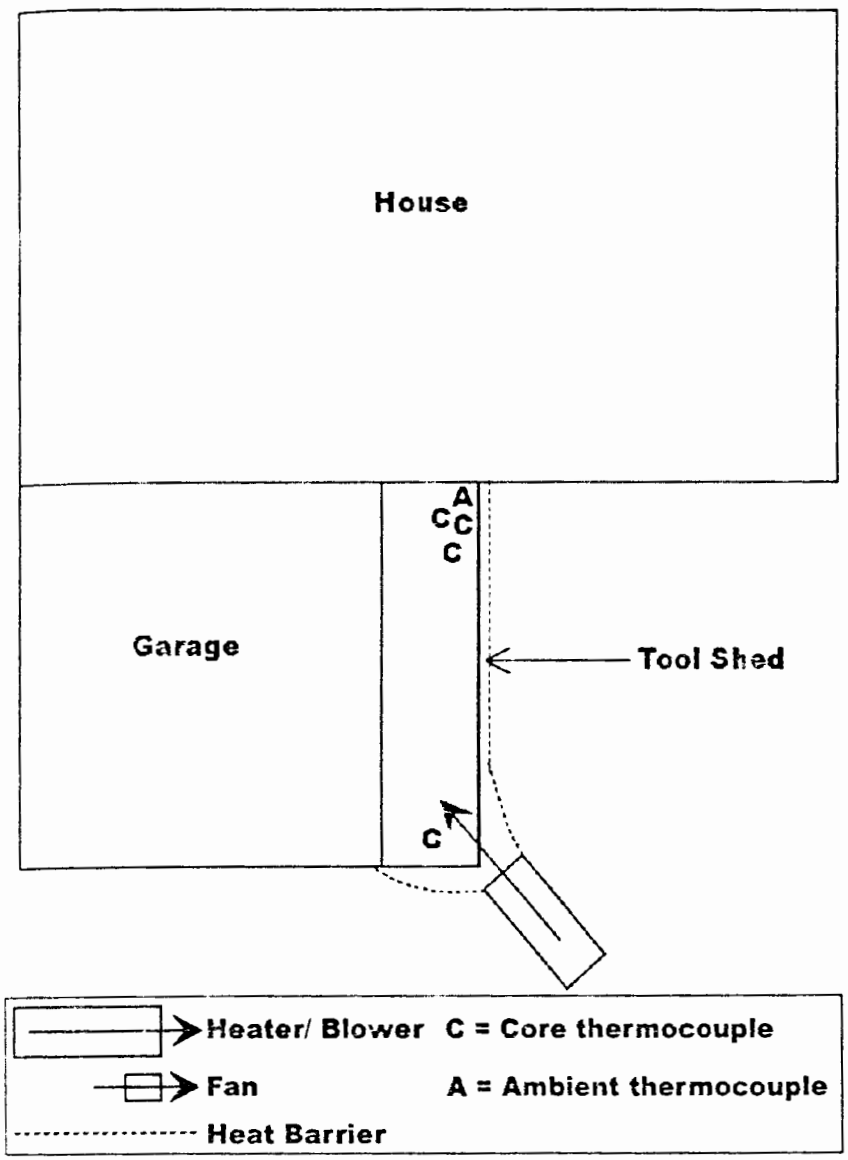


Fig. 7. Overhead drawing of the high temperature treatment at Kona Palisades Estates, Kailua-Kona, Hawaii, 24 July 1995.

locations were monitored with thermistors: one in a 8.6 X 8.6cm beam at 1m high in the treatment doorway, two in vertical 3.8 X 8.6cm lumber opposite the treatment side (one at 1m and one at 3m high) and the

Table 6. Summary statistics for the high temperature treatment at Plantation Estates, Kailua-Kona, Hawaii, 25 July 1995.

Location	Height (m)[a]	C/A[b]	Wood dimension (cm)	Rate (°C/min)	Max temp[c] (°C)	Time to 49[d] (min)
Middle support	0	C	13.3 X13.3	0.13	51.8	151.4
Side support	0	C	13.3 X13.3	0.09	66.2	222.2
Middle support	2.5	C	13.3 X13.3	0.33	44.8	55.7
Main beam	3	C	8.6 X 23.5	0.33	63.6	53
Ceiling	3	A	—	—	85.1	—
Bath	1	A	—	—	66.2	—
Ceiling joist	2.5	C	8.6 X 18.4	0.13	51.8	147.57

[a]=Height from floor to probe.
[b]=Core (C) or ambient (A) probe.
[c]=Maximum temperature.
[d]=Time required to reach a core temperature of 49°C.
— = No data collected.

remaining core-probe in the 1.9cm plywood shelving at 1m high. Heating commenced at 1012 hours and was stopped at 1140 hours .

This treatment, being relatively small, yielded rapid rates of thermal increase and required only a short time to reach 49°C (Table 5). The lowest rate of increase was 0.41°C/min in a 8.6 X 8.6cm beam and the highest was 0.70°C/min in the 1.9cm plywood shelving.

Plantation Estates

This treatment took place in a two-story home in the Plantation Estates of Kailua-Kona, Hawaii on 25 July 1995. Two blowers were used to treat the second floor, one placed vertically on the first floor directed

Table 7. Summary statistics for the high temperature treatment at Hilo Terrace Apartments, Hilo, Hawaii, 27 July 1995.

Location	Height (m)[a]	C/A[b]	Wood dimension (cm)	Rate (°C/min)	Max temp[c] (°C)	Time to 49[d] (min)
Facia	2.5	C	1.9 X 8.6	1.03	66.2	35.5
Brace	0.5	C	3.8 X 18.4	0.70	63.6	49.8
Floor	0	A	—	—	69.0	—
Beam	2.5	C	8.6 X 8.6	0.18	53.4	118.7

[a]=Height from floor to probe.
[b]=Core (C) or ambient (A) probe.
[c]=Maximum temperature.
[d]=Time required to reach a core temperature of 49°C.
— = No data collected.

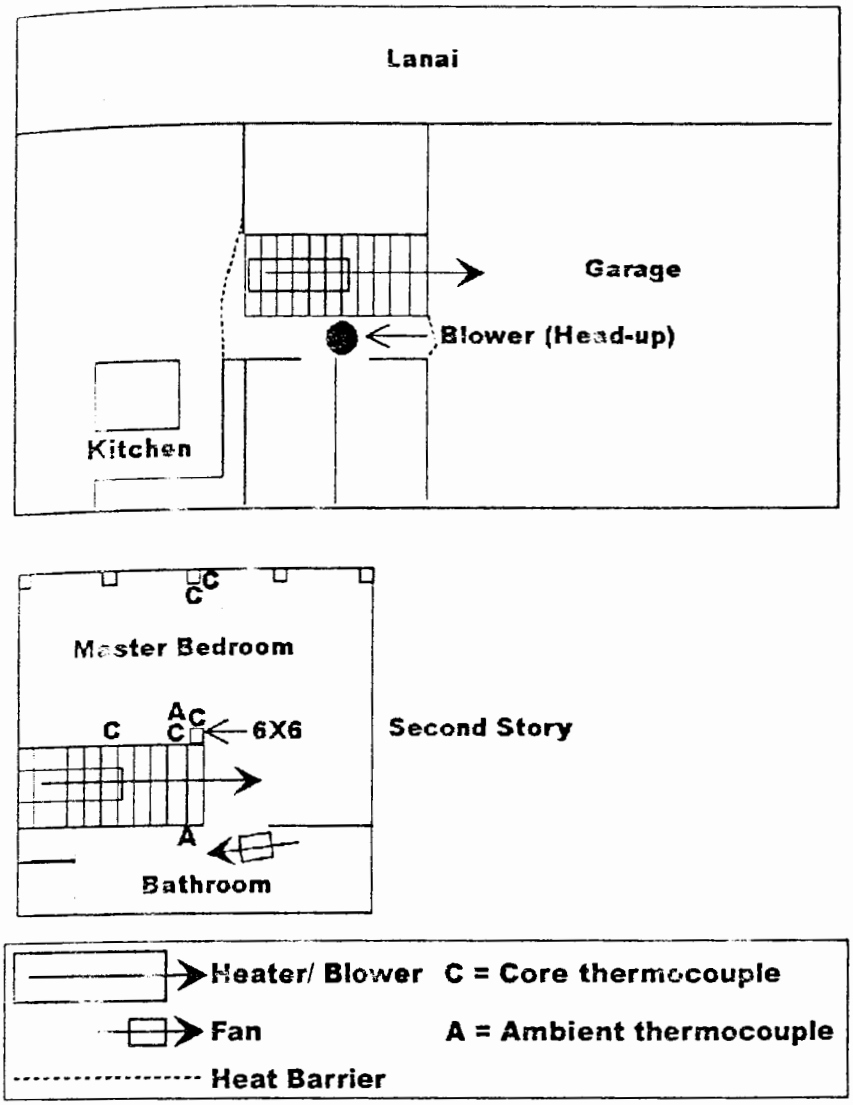


Fig. 8. Overhead drawing of the high temperature treatment at Plantation Estates, Kailua-Kona, Hawaii. 25 July 1995.

up into the loft and the other directed up the stairway to the second floor (Fig. 8). Plastic sheeting was used to seal the second floor and the stairway section from heat loss. A single fan was used to facilitate circulation on the second floor. Ambient temperature was monitored with the use of thermistor probes, one at 1m in the second story bathroom and the other in the peak of the second story. Five core

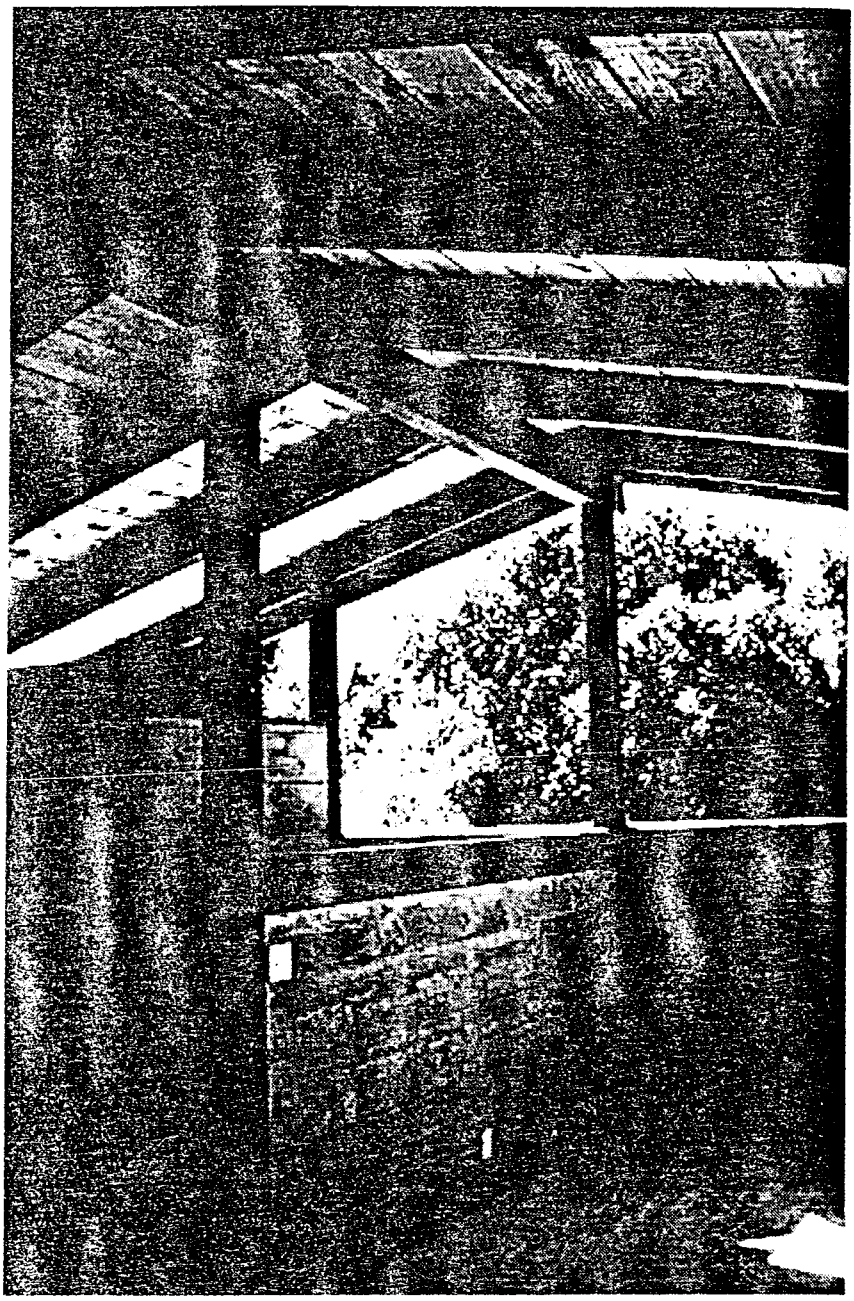


Fig. 9. Inside view of the high temperature treatment at Plantation Estates, Kailua-Kona, Hawaii, 25 July 1995.

Table 8. Summary statistics for the high temperature treatment at Punahele Estates, Kailua-Kona, Hawaii, 28 July 1995.

Location	Height (m)[a]	C/A[b]	Wood dimension (cm)	Rate (°C/min)	Max temp[c] (°C)	Time to 49[d] (min)
Cabinet	0.5	C	1.9 (plywood)	1.44	61.2	33.4
Cabinet floor	0.25	A	—	—	75.9	—

[a]=Height from floor to probe.
[b]=Core (C) or ambient (A) probe.
[c]=Maximum temperature.
[d]=Time required to reach a core temperature of 49°C.
— = No data collected.

locations were monitored: two in a 13.3 X 13.3cm beam in the side wall of the second story (one at floor level and one ca. 2.5m), two in the center 13.3 X13.3cm beam (one at floor level and the other at the junction with the main beam) and the remaining one in the 8.6 X 23.5cm main beam (Figs. 8 and 9). Heating was started at 1005 hours and was terminated at 1330 hours.

In this treatment the fans did not adequately facilitate air movement and the air stratified, with hotter air at the ceiling. The highest temperature at 1m was 66.2°C, while in the peak of the ceiling the temperature reached as high as 85.1°C (Table 6). The ambient temperatures induced relatively fast rates of thermal increase (0.33°C/min) in the large 8.6 X 23.5cm and 13.3 X 13.3cm beams at ceiling level, which reached the target temperature of 49°C in 53 and 55.7min, respectively. The floor level core monitoring locations in the same beams, on the other hand, had rates of thermal increase of 0.13 and 0.09°C/min and required at least an additional 100min to reach 49°C. During this treatment some checking (minor splitting) was observed in the 13.3 X 13.3cm beams which could have been the result of the high ambient temperatures. The slow rate of temperature increase in the 8.6 X 18.4cm ceiling joist (0.13°C/min) as compared to the two upper monitoring locations was most likely the result of heat loss to the outside air being that the joist was monitored close to the outside wall.

Hilo Terrace Apartments

This high temperature treatment took place in a two-bedroom apartment in the Hilo Terrace Apartments, Hilo, Hawaii on 27 July 1995. Fumigation tarps were used to cover the outside exposure of the lanai and a single blower was directed into the lanai from the living room (Fig. 10). Thermistors were placed at floor level to monitor ambient temperatures and were placed in a 8.6 X 8.6cm beam boxed by 2.5cm

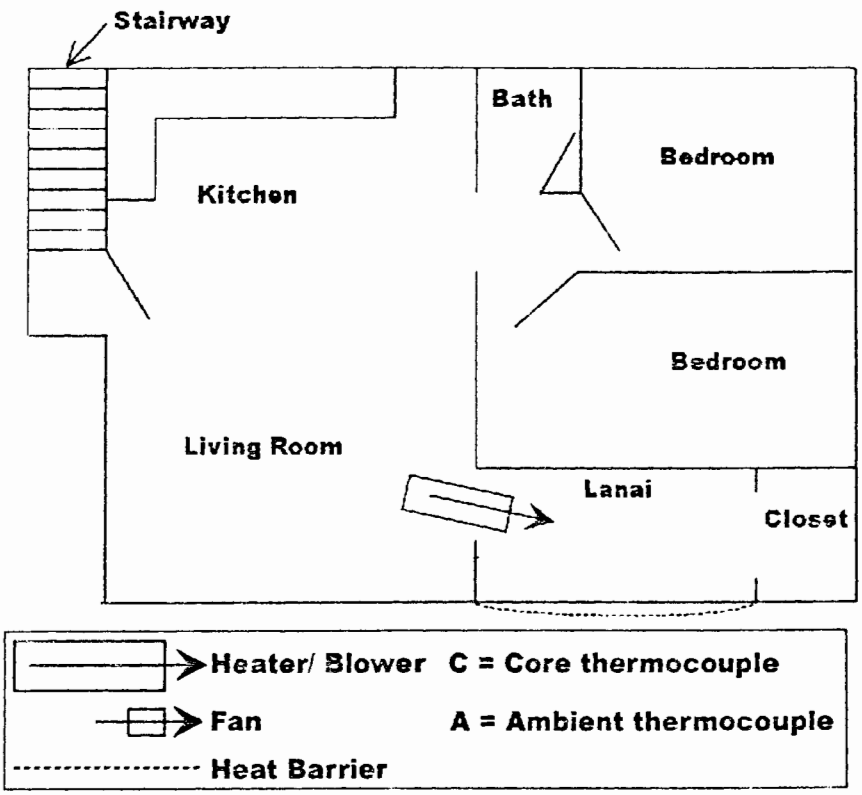


Fig. 10. Overhead drawing of the high temperature treatment at Hilo Terrace Apartments, Hilo, Hawaii, 27 July 1995.

lumber, in a 1.9 X 18.4cm facia, and in a 3.8 X 18.4cm railing to monitor wood core temperatures. The treatment commenced at 1030 hours and concluded at 1300 hours. Rates of temperature increase ranged from 0.18°C/min in a 8.6 X 8.6cm beam to 1.03°C/min in the 1.9 X 8.6cm facia that surrounded the beam (Table 7).

Punahele Estates

The last high temperature treatment observed on the island of Hawaii was on a cabinet constructed entirely out of 1.9cm (3/4in) plywood and located on the lanai of a two-bedroom condominium in the Punahele Estates, Kailua-Kona on 28 July 1995. The area of the lanai containing the cabinet was isolated with the use of fumigation tarps and a single blower was placed on the lanai and directed into the isolated area (Fig. 11). Ambient temperature was monitored at ca. 10cm from the bottom of the cabinet and a single core probe was located in the bottom of the

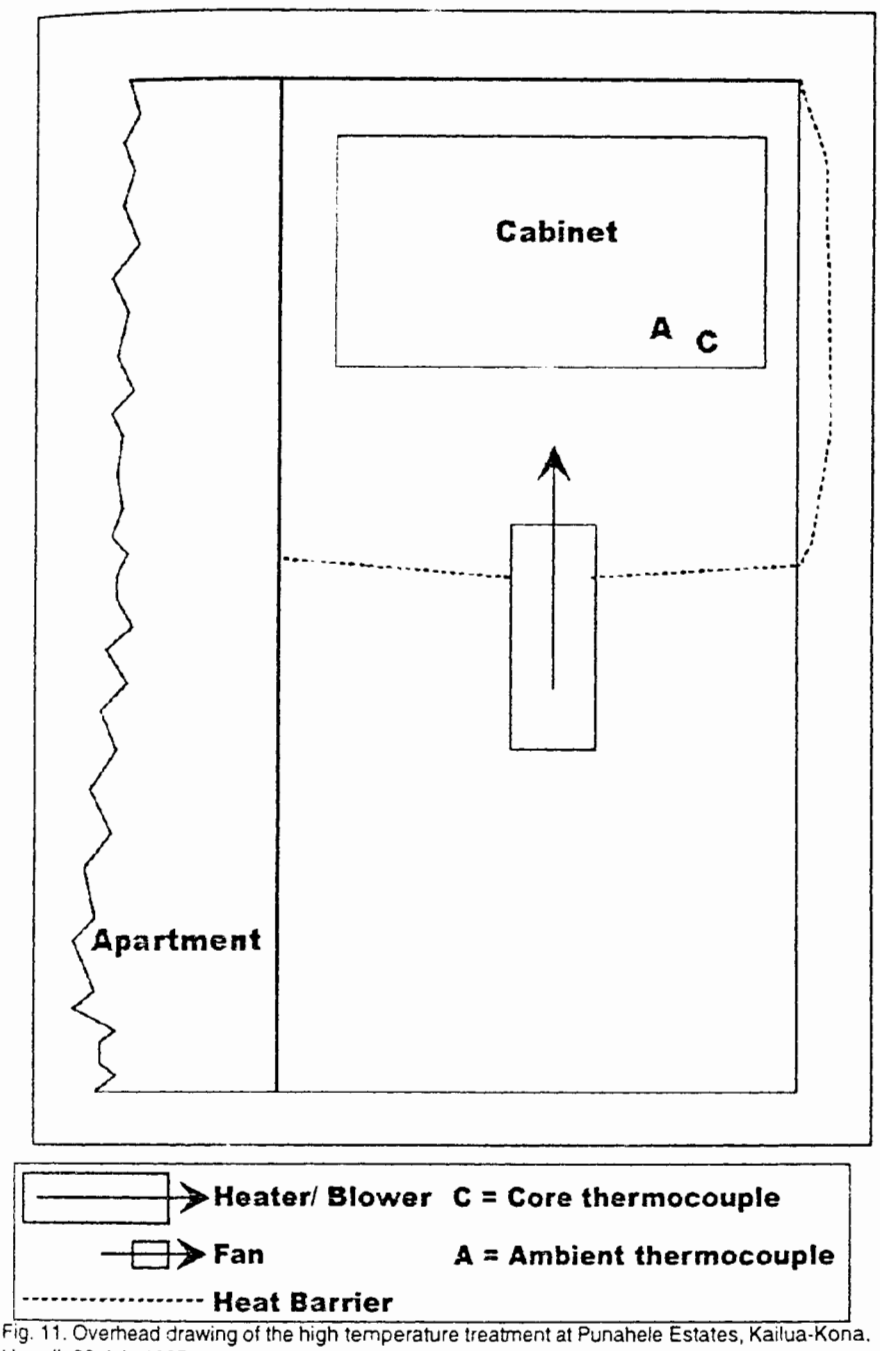


Fig. 11. Overhead drawing of the high temperature treatment at Punahele Estates, Kailua-Kona, Hawaii, 28 July 1995.

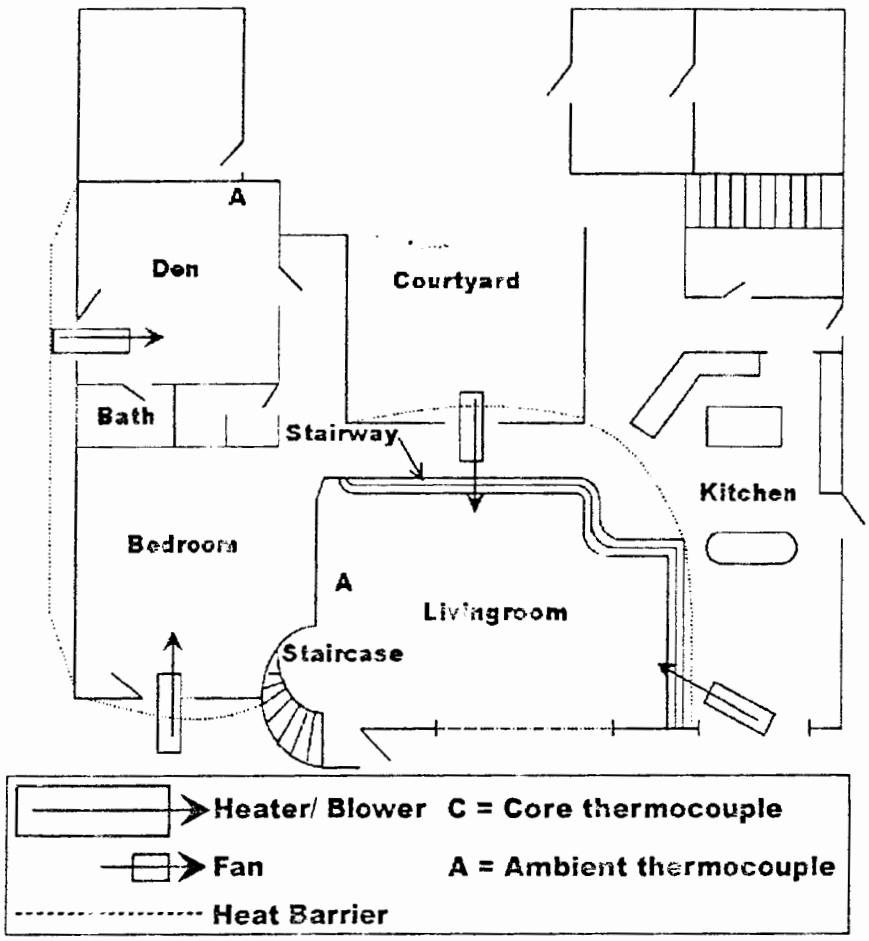


Fig. 12. Overhead drawing of the high temperature treatment at Lahaina, Maui, 11 May 1996.

cabinet in the 1.9cm plywood. The treatment started at 1010 hours and finished at 1040 hours. This treatment produced the fastest rate of temperature increase of 1.41°C/min in 1.9cm plywood and took the least amount of time, 33.4min (Table 8).

Maui

The only treatment observed on Maui was in a two-level home in Lahaina, Maui on 11 May 1996. There were a number of *C. brevis* infestations throughout the structure, most notably in the hardwood flooring. The entire structure was to be treated over a three-day period, and the researcher was granted access during the first day. The area of

Table 9. Summary statistics for temperature data collected during 8 separate high temperature termite treatments in the state of Hawaii.

Variable	N	Mean	SEM[a]	Min	Max
Rate (°C/min)	29	0.28	0.06	0.04	1.44
Max. core temp. (°C)	32	55.12	1.25	39.20	72.30
Time to 49°C (min)	29	98.00	13.70	15.00	300.00
Max. ambient temp. (°C)	18	68.12	1.80	51.80	85.10

[a] Standard error of the mean.

treatment was isolated with the use of fumigation tarps as well as plastic sheeting (Fig. 12). Ambient probes were placed 2m high in the living room and the den. The treatment started at 0935 hours and concluded at 1440 hours

No wood core temperature data were collected at this site because of the potential damage that would have been caused by drilling into the elaborate inner detailing. Ambient temperatures reached as high as 72.1°C in the living room. During the treatment it was observed that paint was bubbling on one wall, however it was found that the damage was minor and readily repairable.

DISCUSSION

Maximum ambient air temperatures within treated structures ranged from 51.8°C to 85.1°C with a mean of 68.1°C (Table 9). The mean maximum wood core temperature was 55.12°C. The longest time taken to achieve the target wood core temperature of 49°C was 5h.

Minor and repairable property damage was observed during two high temperature treatments. For example, during the treatment on Maui, paint began bubbling on the wall when the ambient temperature reached approximately 72°C. The highest ambient temperature of 85.1°C observed during a treatment on the island of Hawaii (Table 6) resulted in some visible checking in 13.3 X 26.0cm and 13.3 X 23.5cm Douglas-fir beams.

The rates of temperature increase observed in field applications were lower than those used in laboratory studies of the effects of rate on thermal tolerance. As previously mentioned, the lowest rate studied by Scheffrahn et al. (1997) with *C. brevis* was 0.5°C/min. However, during some high temperature treatments in Hawaii, the mean rate of temperature increase was 0.276°C/min, with some rates as low as 0.04°C/min (Table 9). Further studies are needed to assess the impact of rates of temperature increase as low as those measured during commercial treatments.

During two of the high temperature control sessions, it was observed that target treatment temperatures were not achieved at some of the probe locations selected by the researcher, as opposed to the technicians (Tables 3 and 6). This does not indicate that these treatments were ineffective as the goal of the commercial technicians was to monitor temperatures in areas thought to contain drywood termites, whereas the intention of the researcher was to seek out worst case areas in the vicinity of the treatment. Thus, our research objective was to measure thermal dynamics, not treatment efficacy. Having said this, the temperature differences observed between the research and commercial monitoring sites during the field studies indicates that probe placement may be crucial, especially given that large thermal differentials are possible within an individual treatment area. Given the fact that conventional drywood termite detection using physical evidence is far from definitive (Scheffrahn et al. 1993), we suggest that thermal monitoring should be located in worst case areas regardless of the outward evidence of infestation.

Recommended temperatures were achieved in the largest structural members during high temperature control sessions; some of them proximate to potential heat sinks. During the Hawaii Kai session, temperatures were monitored in a 8.6 X 26cm beam on top of a CMU wall (Fig. 2), and during the Plantation Estate session, temperatures were monitored in a 8.6 X 18.4cm ceiling joist that had outside exposure (Fig. 8). In both cases, the rates of temperature increase were quite low (0.09°C/min and 0.13°C/min, respectively); nonetheless, the target of 49°C was met, although requiring as long as 5h (300 min) for the Hawaii Kai treatment (Table 2).

In statistical tests, the only significant factor was degree of lumber exposure ($p<0.005$), which had an effect on the rate of temperature increase. The mean rate of increase for single-sided exposures was 0.19°C/min, while when heated from both sides the mean was twice as high at 0.38°C/min.

These observations demonstrate that the original suggested treatment temperature of 49°C (Ebeling 1994) is readily achievable in worse-case areas within a reasonable amount of time. However, the current practice of placing core temperature probes in specific areas of suspected infestation may be risky considering that large thermal gradients are possible, even within a given treatment area, and current drywood termite detection methods are not perfect. Additionally, minor and repairable property damage is possible if excessive ambient temperatures are utilized during high temperature control sessions. Thus, the efficacy of this non-chemical termite control method can be assured by

placing thermocouples in worse case areas and maintaining adequate ambient treatment temperatures to achieve the recommended thermal endpoints while not exceeding safe limits.

ACKNOWLEDGMENTS

We thank Certified Pest Control and Fumigation, especially Michael Krupnick and Brian Abak, for their assistance and cooperation during the commercial treatments. We are also grateful to Julian R. Yates III, Arnold H. Hara and Carrie H. M. Tome for their comments on the manuscript. This research was supported by USDA-ARS Specific Cooperative Agreement 58-6615-4-037. This is Journal Series No. 4316 of the Hawaii Institute of Tropical Agriculture and Human Resources.

REFERENCES CITED

Gay, F. J. 1969. Species introduced by man, pp. 459-494. *In* K. Krishna & F. M. Weesner, (eds.) The Biology of Termites, vol. 1. Academic Press, London.

Ebeling, W. 1997. Thermal pest eradication. Pest Control Magazine 65: 58-59.

Ebeling, W. 1994. Heat penetration of structural lumbers. IPM Practitioner 11:1-4.

Forbes, C. F., and W. Ebeling. 1987. Update: the use of heat for the eradication of structural pests. The IPM Practitioner 9: 1-6.

Lewis, V. R., and M. I. Haverty. 1996. Evaluation of six techniques for control of the western drywood termite (Isoptera: Kalotermitidae) in structures. Journal of Economic Entomology 89: 922 - 934.

SAS Institute. 1985. SAS User's Guide: Statistics. SAS Institute, Cary, NC.

Scheffrahn, R. A., G. A. Wheeler, N-Y SU. 1997. Heat tolerance of structure-infesting drywood termites (Isoptera: Kalotermitidae) of Florida. Sociobiology 29: 237-245.

Scheffrahn R. H., W. P. Robbins, P. Busey, N-Y. Su, and R. K. Mueller. 1993. Evaluation of a novel, hand-held, acoustics emission detector to monitor termites (Isoptera: Kalotermitidae, Rhinotermitidae) in wood. Journal of Economic Entomology 86: 1720-1729.

Woodrow R. J., and J. K. Grace. 1998. Thermal tolerances of four termite species (Isoptera: Rhinotermitidae, Kalotermitidae). Sociobiology 32(1): 17-25.

Woodrow R. J., and J. K. Grace. 1995. Thermal mortality of Hawaiian subterranean and drywood termites (Isoptera: Rhinotermitidae, Kalotermitidae), pp. 170-171. *In*: Proceedings, Hawaii Agriculture: positioning for growth. 5-6 April 1995, Honolulu, HI. College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa, Honolulu, HI.

Heat Tolerance of Structure-Infesting Drywood Termites (Isoptera: Kalotermitidae) of Florida

by

Rudolf H. Scheffrahn[1], Gregory S. Wheeler[1], & Nan-Yao Su[1]

ABSTRACT

Heat tolerance studies were conducted against *Cryptotermes brevis* (Walker) and *Incisitermes snyderi* (Light) pseudergates to determine temperature and heating time requirements at target sites for controlling structural infestations. Complete mortality of *C. brevis* was obtained following exposure times of 4 and 10min at 50 and 48°C, respectively, while *I. snyderi* required a minimum 15min exposure at 50°C. Relative humidities (RH, ca. 10, 50, and 90%) did not significantly influence the heat tolerance of *C. brevis*. Mortality was similar in termites exposed to these RH levels within exposure times (25, 35, and 45min) when termites were heated to 45°C indicating that the amount of water vapor in the air had no effect on heat tolerance of this species. The rate at which the temperature was increased significantly affected *C. brevis* mortality only at 50°C with a 1min hold time. Pseudergates treated with the slowest temperature increase (0.5°C/min) had the highest mortality compared with the more rapid increases (1.0 and 3.0°C/min). Gradual acclimation of *C. brevis* pseudergates at 35°C for 10d had no significant effect on heat tolerance. The recommended commercial exposure of 54.4°C internal wood temperature for 60min will achieve control of economically important drywood termites in Florida and could be substantially reduced if temperatures of all target sites can be monitored.

INTRODUCTION

The application of heat as a kiln method to eradicate drywood termite infestations in stored lumber was first recommended by Horner & Bowe (1934). Related studies by Randall & Doody (1934), found that the western drywood termite, *Incisitermes minor* (Hagen), was killed at 51.5 - 52°C (exposure time unspecified). The commercial use of heat to control structural infestations of drywood termites, however, was not seriously pursued until Forbes & Ebeling (1987) presented data which showed that high-capacity forced-air heaters could raise the temperature of wood within a large airspace to levels that they found lethal to

[1]Ft. Lauderdale Research and Education Center, University of Florida - Institute of Food & Agricultural Sciences, 3205 College Ave., Ft. Lauderdale, Florida 33314-7700

I. minor. A recent evaluation of a commercial heat application method against *I. minor* in California produced 97.5% overall mortality in simulated whole-structure field trials based on non-target internal wood temperatures of 50°C for ≥1hr (Lewis & Haverty, 1996).

Although the limited research conducted by Forbes & Ebeling (1987) was adequate to support commercial temperature and time regimes for *I. minor*, little or no data exist on the lethality of excessive heat against other structure-infesting drywood termite species. *Cryptotermes brevis* and *I. snyderi* are the two major drywood termite pests in Florida (Scheffrahn *et al.* 1988) with the former also having worldwide distribution (Gay 1967). Because heat treatments are currently commercially offered in Florida, we were curious about the heat tolerance of these two species and how current commercial recommendations relate to their heat tolerance.

In this laboratory study, we identified lethal heat exposures (i.e. constant temperature hold times) of *C. brevis* and *I. snyderi* pseudergates and assessed the effects of humidity, rate of temperature increase, and heat acclimation on the heat tolerance of *C. brevis*.

MATERIALS AND METHODS

Termites.

C. brevis were collected from two south Florida structures, one in Key West, Monroe County, and the second in Miami, Dade County. *I. snyderi* were collected from Brazilian-pepper (*Schinus terebinthifolius* Raddi) in Deerfield Beach, Broward County, FL. Colonies were extracted from their home wood by sawing wood members in to ca. 200cm lengths and then splitting the wood with a hammer and wedge. Exposed termites were gently dislodged from their galleries by tapping the wood over a pan containing slivers of wood. After several days, healthy termites clinging to slivers were isolated from debris, injured, and dead nestmates, and transferred to plastic containers provisioned with 3mm-thick *Picea* spp. wood slats. Moisture was supplied infrequently with water-saturated dental wick (2cm-long). Termites were held at 25±1°C and tested between 5d and 2mo of collection.

Lethal heat exposures.

Groups of 20 pseudergates (>third instar) were placed inside polystyrene foam cups (355ml) which were then covered with organdy cloth. The low heat capacity and low heat conductance of the foam ensured that the termite substrate would not act as a heat sink during heating or a heat source during cooling. The termites were heated in a gas chromatograph oven (HP 5890 series II) equipped with a program-

mable temperature control. Heat exposures began at 25°C and the temperature was increased at 1°C/min unless otherwise described until the target temperature was achieved. Temperatures inside the cups were monitored with an electronic thermometer (Fisher Scientific; traceable dual channel) calibrated to ±0.5°C. After heat treatment, the cups were removed from the oven and instantly brought to room conditions. The termites were transferred to petri dishes fitted with two filter paper pads (4.7cm diam., Gelman Sciences, Ann Arbor, MI) and their latent mortality was observed for at least 1wk. Termites which could not right themselves several days after exposure were considered moribund and scored as dead. All treatments were replicated 4 times. Unless otherwise specified, control termites were from the same population and were held at ambient temperature during heat treatments.

Internal cup air for *C. brevis* replicates from Key West was raised to maximum temperatures of 46, 48, or 50°C. At 46°C, termites were held for 10, 15, 30, 45, or 60min; at 48°C for 1, 3, 5, 10, 15, or 20min, and at 50°C for 0, 2, 4, 8, or 10min. To compare results at exposures yielding maximum mortality and the shortest hold time from treatments above, *C. brevis* pseudergates from Miami were held at 46, 48, and 50°C for 45, 10, and 4min, respectively. Pseudergates of *I. snyderi* were heated to and held at 46°C for 60min; 48°C for 15, 20, or 30min; 50°C for 5, 10, 15, or 20min; or 52°C for 5 or 10min.

Humidity effects on heat tolerance.

C. brevis pseudergates from Key West were exposed to heat under low, intermediate, and high initial relative humidities (RHs) to determine if RH influenced maximum heat tolerance. Termites were placed in small open plastic vials (Thornton Plastic Co., Salt Lake City, UT; 20 ml). These were placed in larger (180 ml) sealed plastic vials which contained either Drierite (low RH), moist sand and paper towels (high RH), or only ambient air (intermediate RH). Lids of the sealed vials were perforated to relieve pressure during heating. The temperature and humidity inside each sealed vial were monitored during heating with a digital thermo-hygrometer (Omega Engineering, Inc., Stamford, CT) and electronic thermometer (see above) inserted through the lid of each container.

Rate of temperature increase.

Three temperature rate increases (0.5, 1.0, and 3.0°C/min) beginning at 25°C were selected to determine the effect of heating rate on heat tolerance to *C. brevis* (Key West) pseudergates. At each rate, termites were held at a maximum of 48°C for 5 or 10min, and at 50°C

for 1min.

Acclimation of termites at higher temperatures

Pseudergates of *C. brevis* (Key West), held in their maintenance containers, were placed in a 25°C incubator. Incubator temperature was increased at 1°C/d to 35°C and termites were kept at 35°C for an additional 10d. Control termites from the same population were maintained at 25°C over the same period. Both groups were simultaneously heated to 45°C and held for 45min.

Statistical analysis

The effect of humidity on termite heat tolerance was analyzed within each constant temperature hold time with an analysis of variance (ANOVA; PROC GLM; SAS Institute, Inc. 1988). All percent data were arcsin transformed before analysis. The effect of the rate of temperature increase was analyzed within each hold time with an ANOVA (PROC GLM) and means were compared with a Ryan's Q multiple range test ($P = 0.05$). The effect of acclimation on heat tolerance was determined with an ANOVA (PROC GLM).

RESULTS AND DISCUSSION

In general, estimation of mortality immediately following heat exposures was a poor indicator of actual mortality as 1d after treatment many termites reverted from supine to upright postures. By 1wk, however, short-term mortality or recovery were fully expressed. Possible chronic effects of heat exposure were not assessed in this study, but defaunation of gut symbionts has previously been noted to occur in drywood termites at "sublethal" temperatures (Megenasa 1964, Williams 1976)

Lethal heat exposures

Mortalities resulting from all drywood termite final temperature and hold time combinations are given in Table 1. Complete mortality of both *C. brevis* pseudergate populations was obtained following exposure times of 4 and 10min at 50 and 48°C, respectively. At 46°C, the Key West population yielded 95% mortality at both 45 and 60min exposure times, while all *C. brevis* from Miami were dead after the 45min exposure. No mortality occurred among the control termites except the 46°C/30min and the 50°C/0min treatments where 5% died in each.

In ecological studies with West African *C. brevis*, Williams (1976) exposed pseudergates to temperatures between 39 and 44°C for 1, 2, or 3hrs. He attained complete mortality (5 of 5 termites) at 43 and 44°C after 3hrs and 1hr, respectively. At 46°C, our longest exposure time of

Table 1. Percent mortalities of *C. brevis* and *I. snyderi* pseudergates at 1wk after exposure to air heated 1°C/min from 25°C to final temperature and hold time.

Species/ Source	Final Hold Temperature (°C)	Hold Time (min)	Mean Percent Mortality (± SEM)
C. brevis, Key West, FL			
	46	10	0.0 ± 0.0
	46	15	16.3 ± 6.6
	46	30	83.8 ± 6.3
	46	45	95.0 ± 5.0
	46	60	95.0 ± 2.0
	48	1	3.8 ± 2.4
	48	3	6.3 ± 3.2
	48	5	33.8 ± 18.5
	48	10,15,20	100.0 ± 0.0
	50	0	3.8 ± 2.4
	50	2	95.0 ± 5.0
	50	4,6,8	100.0 ± 0.0
C. brevis, Miami, FL			
	46	45	100.0 ± 0.0
	48	10	100.0 ± 0.0
	50	4	100.0 ± 0.0
I. snyderi, Deerfield Beach, FL			
	46	60	85.0 ± 6.5
	48	15	41.3 ± 20.9
	48	20	72.5 ± 18.3
	48	30	81.3 ± 18.8
	50	5	26.3 ± 13.9
	50	10	68.8 ± 18.1
	50	15,20	100.0 ± 0.0
	52	5,10	100.0 ± 0.0

60min yielded 95% mortality suggesting that the Florida populations of *C. brevis* were more heat tolerant than those from Africa by ca. 2°C.

Pseudergates of *I. snyderi* were slightly more tolerant of heat than *C. brevis* (Table 1). Complete mortality of *I. snyderi* was achieved at a minimum 15min exposure at 50°C. Results with *I. snyderi* compared favorably with those of Forbes & Ebeling (1987) who reported 100% mortality of *I. minor* pseudergates in 33, 10, and 6 min at 49, 51, and 54°C, respectively. Their methods were not specified, but they implied that termites were placed in a preheated temperature cabinet resulting in instantaneous exposure to stated temperatures. This technique would require longer hold times as treatments with more rapid temperature increases result in lower mortality (see heating rate results below). Results with drywood termites also fall in the range of heat tolerance of subterranean termite species native to seasonally hot

climates which show little survival when exposed to peak expos... between 43.5 and 54°C (Collins *et al.* 1973, Mitchell *et al.* 1993).

Humidity effects on heat tolerance

As expected, humidity decreased in each vial as the temperature ... increased. Relative humidity decreased from 90±0 to 81.7±1.2, 51.7... to 29.3±4.4, and 12.0±1.0 to 0±0%, respectively, for the high, inter... diate, and low RH vials. Termite mortality within each hold time (25, ... or 45min) did not differ significantly (25min: F=2.44, df=2,9, P>0.1; ... min: F=0.07, df=2,9, P>0.1; 45min: F=0.85, df=2,9, P>0.1) among ... humidities tested (Table 2) indicating that the amount of water va... in the air had no effect on heat tolerance of *C. brevis*. No mortal... occurred among the control termites.

In assessing the heat tolerance of the arid-land Nearctic drywoo... termite, *Marginitermes hubbardi* (Banks), Megenasa (1964) consider... RH as a tolerance factor. Results showed that oven-heated *M. hubbar...* pseudergates were all killed at similar time/temperature combinations (2-7min at 51-47°C, respectively) at two humidity regimes (<10 and 50%). At lower temperatures (42-46°C) heat tolerance of *M. hubbar...* was greater at the higher RH. Collins *et al.* (1969) and Mitchell *et al.* (1993) also found little or no significant difference in survival ... subterranean termites exposed to heat at high or low RHs.

Rate of temperature increase

At 48°C final temperature and 5 and 10min hold times, mortality wa... similar at the different rates of increasing temperature (5min: F = 2.4... df = 2,9, P>0.1; 10min: F=0.11, df = 2,9, P>0.1) (Table 3). However, ... 50°C final temperature and 1 min hold time, heating rates significantly affected termite survival (F = 62.81, df = 2,9, P < 0.0001). Percen...

Table 2. Percent mortality of *C. brevis* pseudergates at 1 wk after exposure to air heated to 45... and held for different periods at either high, intermediate, or low relative humidity. In... temperature was 25°C. No significant effect of humidity was found (P > 0.1) for each hold ti...

Hold time (min)	Humidity	Mean Percent Mortality (± SEM)
25	High	6.7 ± 4.4
	Intermediate	1.3 ± 1.3
	Low	0.0 ± 0.0
35	High	12.5 ± 6.0
	Intermediate	10.0 ± 5.4
	Low	10.0 ± 5.4
45	High	88.8 ± 6.6
	Intermediate	75.0±15.7
	Low	97.5 ± 2.5

Table 3. Percent mortality of *C. brevis* pseudergates at 1 wk after exposure to air heated at different rates of temperature increase from 25°C to the final temperature and hold times.

Final Hold Temperature (°C)	Hold Time (min)	Mean Percent Mortality (± SEM) at Rate Increase (°C/min): 0.5	1.0	3.0
48	10	98.8 ±1.3a	95.0 ±5.0a	97.5 ±2.5a
48	5	26.3 ±7.2a	8.8 ±2.4a	12.5 ±8.3a
50	1	97.5 ±1.4a	25.0±12.4b	1.3 ±1.3c

Percent mortality in rows for same temperature and hold time followed by different letters are significantly different according to a Ryan's Q multiple comparison test ($P = 0.05$).

mortality was greatest at 0.5, intermediate at 1.0, and lowest at 3.0 °C/min. As temperatures increase more slowly, more time is spent approaching the target temperatures. These temperatures (e.g. 48-49°C) are generally not lethal for short duration hold times, but when the temperature increases slowly, more time is spent at these temperatures resulting in increased mortality. Therefore, our results indicate that the rate of temperature increase is important only when the target temperature is above 48°C.

Acclimation of termites at higher temperatures

Gradual acclimation of *C. brevis* pseudergates at 35°C for 10d had no substantial effect on termite heat tolerance. Percent mortality of the acclimated termites (15±8.9%) was not significantly different (F=3.33, df= 1,6, P>0.1) from the control group (47.5±15.6%) held at a constant 25°C before heating.

CONCLUSIONS

Our results verify that the recommended commercial rates of 54.4°C internal wood temperature for 60min (Isothermics/TPE Associates, Orange, CA) will achieve control of economically important drywood termites in Florida. In fact, we found that 48°C for 10min and 50°C for 15min produced complete mortality of *C. brevis* and *I. snyderi* pseudergates, respectively. The 54.4°C/60min standard was established to include the "worst case" situations where internal wood temperature of suspected inaccessible infestations of *I. minor* cannot be monitored and other nearby wood members are measured instead. For drywood termite infestations in Florida in situations where such concerns are unwarranted (i.e, no deep, hidden infestations), especially those involving *C. brevis*, lower temperature/shorter exposure treatments would reduce energy and time costs as well as minimize the possibility of damage to heat labile structural furnishings. Moreover, these

recommendations are appropriate for a wide range of relative humidities as we and others (Collins *et al.* 1973, Megenasa 1964, Mitchell et 1993) found that this factor had no effect on termite heat tolerance fr evaporative cooling or other means.

Because wood is a heterogeneous matrix and its insulative prop ties vary (Ebeling 1994) it is essential that thermocouples be seal inside the center of thickest, most thermally protected wood membe suspected to be infested and that the entire member be heated. Th recommendation is validated by findings of Cabrera & Rust (1996) wh showed that *I. minor* followed temperature gradients away fro unpreferred, potentially lethal (>45°C) temperatures suggesting th the termites move into the cooler refugia of deeper galleries or le heated portions of their gallery system during heat treatments.

ACKNOWLEDGMENTS

We thank F.W. Howard and T. Weissling for reviewing this manuscript. This is article R-05336 of the Florida Agricultural Experiment Station Journal Series.

REFERENCES

Cabrera, B.J. & M.K. Rust. 1996. Behavioral responses to light and thermal gradients by the western drywood termite (Isoptera: Kalotermitidae). Environ. Entomol. 25: 436-445.

Collins, M.S., M.I. Haverty, J.P La Fage, & W.L. Nutting. 1973. High-temperature tolerance in two species of subterranean termites from the Sonoran Desert in Arizona. Environ. Entomol. 2: 1122-1123.

Ebeling, W. 1994. Heat penetration of structural timbers. IPM Practitioner 16: 9-10.

Forbes, C.F. & W. Ebeling. 1987. Update: use of heat for the elimination of structural pests. IPM Practitioner 11: 1-4.

Gay, F.J. 1967. A world review of introduced species of termites. CSIRO Bull. 286, Melbourne, 88 pp.

Horner, A.C., & E.E. Bowe. 1934. Lumber storage piles. I. Recommendations for preventing and repairing damage. Pp. 735-739 *in* Kofoid, C.A. (ed.) Termites and termite control. University of California Press, Berkeley, Calif. 795 pp.

Lewis, V.R. & M.I. Haverty. 1996. Evaluation of six techniques for control of the western drywood termites (Isoptera: Kalotermitidae) in structures. J. Econ. Entomol. 89: 922-934.

Megenasa, T. 1964. The effect of relative humidity on the upper thermal death point of the dry-wood termite, *Marginitermes hubbardi* (Banks) (Isoptera: Kalotermitidae). M.S. Thesis, Dept. of Entomology, University of Arizona, Tucson.

Mitchell, J.D, P.H. Hewitt, and T.C. de K. Van Der Linde. 1993. Critical thermal limits and temperature tolerance in the harvester termite *Hodotermes mossambicus* (Hagen). J. Insect Physiol. 39: 523-528.

Randall, M. & T.C. Doody. 1934. Wood preservatives and protective treatment. Pg 385-416 *in* Kofoid, C.A. (ed.).Termites and termite control. University of California Press, Berkeley, Calif. 795 pp.

SAS Institute, Inc. 1988. STAT user's guide, release 6.04. SAS Institute, Cary, NC.

Scheffrahn, R.H., J. R. Mangold, & N.-Y. Su. 1988. A survey of structure-infesting termites of peninsular Florida. Florida Entomol. 71: 615-630.

Williams, R.M.C. 1976. Factors limiting the distribution of building-damaging dry-wood termites (Isoptera: *Cryptotermes* spp.) in Africa. Mater. Organismen 3:393-406.

Thermal Tolerances of Four Termite Species (Isoptera: Rhinotermitidae, Kalotermitidae)

by

R.J. Woodrow & J.K. Grace[1]

ABSTRACT

Upper thermal tolerances were determined for four species of termite pseudergates and nymphs using both a preset temperature method and a bioassay in which the temperature was increased at a known rate. Termites were acclimated at 28°C for a minimum of 24h prior to being placed into an oven preset to temperatures of 40°C to 49°C, or placed into an oven at room temperature (ca. 25°C) which was then raised at 1.0°C/min . In preset bioassays, the lowest temperature that caused 100% mortality in all replicates was 42°C for *Coptotermes formosanus* Shiraki and 45°C for *Incisitermes immigrans* (Light). In temperature rate bioassays, upper lethal limits (ULL) were 47.9°C, 51.0°C, 51.3°C and 51.3°C for *C. formosanus*, *I. immigrans*, *Neotermes connexus* Snyder, and *Cryptotermes brevis* (Walker), respectively. These elevated ULL values could be due to a time-lag between the body temperature and the chamber temperature, or result from increased thermotolerance; both of which are possibilities with gradually increasing temperatures. Actual lethal thresholds are likely to be lower than observed lethal tolerances generated by the ULL method.

INTRODUCTION

Thermal tolerances of termites are of more than academic interest because of the potential application of modified temperatures for termite control. The primary target of high temperature control in Hawaii is the West Indian drywood termite, *Cryptotermes brevis* (Walker) (Isoptera: Kalotermitidae). The high temperature control method as described by Ebeling (1994) involves isolating the area of termite infestation within a structure and introducing heated air to achieve and maintain an ambient temperature between 63°C and 70°C. These ambient temperatures are maintained for a period necessary for the internal wood temperatures to exceed a suggested thermal end-point for a minimum amount of time. To establish high temperature control procedures, Forbes and Ebeling (1987) studied the temperature tolerance of *Incisitermes minor* (Hagan) and several other insects. These

[1]Department of Entomology, University of Hawaii at Manoa, 350 Maile Way, Room 310, Honolulu, HI 96822

authors utilized a thermal tolerance bioassay in which test insects were placed at preset temperatures and the time until death was determined at each temperature. Recent studies, however, have reported thermal tolerances in the form of critical thermal maxima (CTMAX) or upper lethal limits (ULL).

Determination of critical thermal maxima involves subjecting insects to rates of temperature increase as opposed to constant temperatures. Rates of temperature increase are more appropriate for testing the bioclimatology of insects because they simulate actual microclimatic conditions experienced by insects; temperatures never change instantaneously in nature. Test insects are observed throughout the process, removed when torpor is noted and observed for recovery for a predetermined period of time. The highest knockdown temperature which later results in recovery is termed a CTMAX and the lowest knockdown temperature without recovery is the ULL. Critical thermal maxima and ULL have been reported for a number of insects, including cockroaches (Appel 1991; Appel and Sponsler 1989), blister beetles (Cohen and Pinto 1977), and earwigs (Karboutli and Mack 1993) as well as termites (Sponsler and Appel 1991; Mitchell *et al.* 1993; Rust *et al.* 1979). CTMAX range from about 43°C to 51°C for most insect species with ULL being only slightly (ca. 1°C) higher.

In light of the differences between these two methods, the purpose of our study was to compare the temperature rate method and the constant temperature method of Forbes and Ebeling (1987) to determine if a definitive thermal death point could be produced and used to refine high temperature control recommendations. Preset temperature tolerances where determined for *Incisitermes immigrans* (Light) and *Coptotermes formosanus* Shiraki and upper lethal limits were determined for these same species in addition to *Neotermes connexus* Snyder and *C. brevis*.

MATERIALS AND METHODS

Preset temperature method

For the preset method, we chose to work with two termite species, *C. formosanus* and *I. immigrans* which were readily collected and easily cultured in the lab. *Coptotermes formosanus* was collected in wooden traps on the Manoa campus of the University of Hawaii (Tamashiro *et al.* 1973). Time and temperature were varied over the ranges of 10 min. to 90 min. and 40°C to 49°C, respectively. The experimental units consisted of covered 100 x 20mm glass petri plates containing 50 pseudergates each. Three replicate units were chosen at random to receive each time-temperature combination. Petri plates were placed

into a Fisher model 655F Isotemp oven (±0.5°C) (Fisher Scientific, Pittsburgh, PA) at time zero and quickly removed at their respective treatment times (this methodology precluded the control of relative humidity). The number of dead, moribund and live individuals were then counted and held in separate petri dishes containing a single piece of filter paper and 1ml of distilled water. The plates were covered and placed in a Precision model 815 incubator (Precision Scientific Inc., Chicago, IL) set to 28°C (±0.5°C) for a period of 24h, then the number of dead, moribund and live individuals were again assessed. The values reported here represent 24h mortality.

Incisitermes immigrans test subjects were at least third instar nymphs (determined by size) selected from several different colonies collected from dead standing Kiawe (*Prosopis pallida* [Lam.]) near the University of Hawaii at Manoa campus. Each colony extracted from wood samples was placed into an individual 21 X 34.3 X 8.9cm plastic container (Consolidated Plastics Company, Inc., Twinsburg, Ohio) along with hardwood tongue depressors as a food source. The covered containers were placed at 28°C (±0.5 C) and allowed to acclimate for a period of no less than 24h prior to testing. Because of the difficulty in obtaining large numbers of this species, treatments consisted of three replicates of twenty nymphs each placed in smaller (60 X 15 mm Kimax) glass petri plates. Treatments were conducted as previously described for *C. formosanus*, with mortality assessed 24h after removal from each time-temperature regime.

Temperature rate method

Coptotermes formosanus, *I. immigrans*, *N. connexus*, and *C. brevis* pseudergates were tested using the temperature rate bioassay. *Coptotermes formosanus* and *I. immigrans* were collected as previously discussed. *Neotermes connexus* was collected from infested Koa Haole (*Leucocaena leucocephala* [Humb. & Bonpl. ex Wild]) and *C. brevis* from infested plywood taken from a warehouse on the Honolulu seaboard. Extracted termites were placed into plastic boxes along with tongue depressors and paper towels and held at 28°C (±0.5 C) for no less than 48h prior to treatment. Ten pseudergates were arbitrarily selected from cultures and placed into a 15cm diameter glass petri dish lined with a Whatman no. 2 filter paper. The dishes were placed on inverted 50ml beakers inside of a 500ml Qorpak jar which contained 200ml of distilled water to maintain saturated conditions during the test. Temperatures within the petri dishes were monitored with a 20 gauge type-T thermocouple attached to the petri plate with tape and threaded through a 2mm diameter hole in the lid of the Qorpak jar and connected to a Cole Parmer model 8110-25 thermocouple thermometer (Cole Parmer In-

strument Company, Vernon Hills, IL). The jar containing the termites was then placed into a Hewlett Packard model 5700A gas chromatograph. The gas chromatograph oven was programmed to increase the temperature of the oven at 1°C/min; actual rate of increase within the test chamber was determined to be ca. 0.70°C/min. Termites were removed from the oven at 0.5°C increments starting at 45°C up to the point of no recovery. Once removed from the oven, 0.2ml of distilled water was added and the plates were covered and incubated at 28°C. Mortality was assessed 24 h post-treatment.

In order to determine the difference between the test chamber and the body temperature of test insects, a 33 gauge hypodermic temperature probe (Omega Engineering Inc., Stamford, CT) was inserted through the anus into the haemolymph of a third instar *C. brevis* nymph. The probe with termite and a second identical bare probe were affixed with 1.4cm masking tape to the edge of a small glass petri plate containing a 5.5cm Whatman #2 filter paper. The petri plate was placed on top of an inverted 50ml beaker inside of a 500ml Qorpak jar containing 100ml distilled water. Singly, the jars were firmly capped and placed onto the center shelf of a Salvis Thermocenter Top Oven. The oven was programmed to equilibrate at 30°C for 15 min. prior to increasing the temperature at 0.5°C/min to 70°C. Test chamber and body temperature were manually monitored with by way of a Cole Parmer model 8110-25 type-T thermocouple thermometer (Cole Parmer Instrument Company, Chicago, IL) (accuracy: ± 0.25°C). Once the test chamber reached 52°C, the jars were removed. The test was replicated 8 times and the data analyzed in a one-sample T-test (SAS Institute 1985) to test the null hypothesis that the difference between body and chamber temperatures equaled zero ($\mu=0$ or $\mu>0$).

RESULTS AND DISCUSSION

Tables 1 and 2 present the mean (n=3) mortality for *I. immigrans* and *C. formosanus* exposed to each preset time/temperature combination. At the low end of the temperature scale, an upward trend in the mortality of *C. formosanus* can be seen at 40°C from 70 min. onward; while with *I. immigrans*, this same trend is apparent at 44°C from 60 minutes onward. Results obtained with *I. immigrans* (Table 2) were converted to a form comparable to those for *I. minor* reported by Forbes and Ebeling (1987) (Table 3). The lowest temperature exposure producing total (100%) mortality for *C. formosanus* was 42°C at 90 min. and 45°C at 70 min. for *I. immigrans*. In our tests, the minimum exposure times required for 100% mortality of *I. immigrans* at 46°C and 49°C were 30 min. and 20 min., respectively. Minimum exposure times reported

Table 1. Mean percent mortality of *Coptotermes formosanus* pseudergates at various combinations of temperature and time.

Time (min)	Temperature (°C) 40	41	42	43	44	45	46	47
90	5 (0.67)	47 (5.5)	100	—	—	—	—	—
80	3 (1.3)	22 (4.7)	98 (1.2)	—	—	—	—	—
70	1 (0.67)	14 (8.3)	74 (3.2)	100	—	—	—	—
60	0	33 (1.2)	56 (16)	100	—	—	—	—
50	0	0	14 (4.2)	100	100	—	—	—
40	—	0	3 (1.3)	67 (17.7)	100	100	—	—
30	—	—	0	27 (13.5)	100	100	100	100
20	—	—	0	5 (1.3)	77 (14.7)	44 (26.6)	100	100
10	—	—	—	0	0	0	1 (0.67)	1 (0.67)

Values in parentheses represent standard errors of the means (n=3) greater than 0.
— = No data collected

Table 2 . Mean percent mortality of *Incisitermes immigrans* nymphs at various combinations of temperature and time.

Time (min)	Temperature (°C) 42	43	44	45	46	47	48	49
90	2 (1.7)	5	36 (8.3)	—	—	—	—	—
80	2 (1.7)	3 (1.7)	20 (5.0)	100	—	—	—	—
70	0	5	30 (9.0)	100	—	—	—	—
60	0	0	12 (1.7)	80 (12.6)	—	—	—	—
50	—	0	0	26 (13.4)	100	—	—	—
40	—	—	0	14 (6.3)	100	100	—	—
30	—	—	—	5 (2.9)	100	100	100	100
20	—	—	—	0	3 (1.7)	90 (10)	100	100
10	—	—	—	0	0	2 (1.7)	7 (4.4)	17 (6.7)

Values in parentheses represent standard errors of the means (n=3) greater than 0.
—= No data collected.

for *I. minor* (Forbes and Ebeling 1987) were considerably higher: 256 min. and 30 min., respectively, suggesting that *I. minor* is more heat tolerant than *I. immigrans* (Table 3).

Upper lethal limits developed with the temperature rate method are presented in Table 4 for the four termites species tested. The ULL for *C. formosanus* pseudergates (47.9°C) was close to that of 48.0°C reported by Sponsler and Appel (1991) while the ULL of *C. brevis* was somewhat similar to that generated by Scheffrahn *et al.* (1997) for this species. The other two termite species have not been previously studied. However, the ULLs for congeners *Incisitermes fruticavus* Rust and *I. minor* were

Table 3. Exposure times (minutes) producing 100% (n=3) mortality at various constant temperatures.

Temperature(°C)	Species *Incisitermes immigrans*	*Coptotermes formosanus*
42	90+	90
43	90+	50
44	90+	30
45	70	30
46	30	20
47	30	20
48	20	—
49	20	—

—= No data collected.

reported to be in the range of 51°C to 53°C (Rust *et al.* 1979), comparable to the value we generated for *I. immigrans* (51.3°C). The similarity of *I. immigrans* to *I. minor* in the ULL method is interesting considering the results of the preset bioassays which revealed a distinct difference in lethal exposure times at 46°C between *I. minor* (256 min.) (Forbes and Ebeling 1987) and *I. immigrans* (30 min.).

The ULL values generated for the drywood termites in our study, *I. immigrans*, *N. connexus* and *C. brevis*, are similar to CTMAX values reported for xeric adapted beetles in the family Meloidae (Cohen and Pinto 1977), while the ULL for the rhinotermitid *C. formosanus* is similar to values reported for mesic-adapted cockroaches (Appel 1991), earwigs (Karboutli and Mack 1993) and other subterranean termites (Mitchell *et al.* 1993; Sponsler and Appel 1990). These observations are consistent with the biology of these taxa; drywood termites, as their name suggests live in relatively warm and dry habitats, whereas *C. formosanus* exists in a cool moist subterranean habitat.

The differences between the two bioassay methods were striking. ULL values generated in the thermal rate bioassay (Table 4) were 47.9°C and 51.3°C for *C. formosanus* and *I. immigrans*, respectively, while results of the preset method (Tables 1 and 2) indicated that temperatures as low as 42°C and 45°C were lethal to these two species. These differences, however, are consistent with previous work. Using the temperature rate procedure, Rust *et al.* (1979) produced knockdown with recovery at 52°C for *I. minor*, while in the constant temperature experiments with this species significant mortality was produced at temperatures as low as 46°C (Forbes and Ebeling 1987). The question posed by these results is whether the two methods produced different values due to a physical artifact of the tests or an actual change in

Table 4. Mean (n=3) upper lethal limits of 4 species of termites collected in Hawaii.

Species	ULL (°C)	Standard error
Coptotermes formosanus	47.9	0.49
Neotermes connexus	51.0	0.14
Incisitermes immigrans	51.3	0.14
Cryptotermes brevis	51.3	0.37

thermotolerance of the insect. The later possibility would caste some doubt on existing high temperature control recommendations.

Biologically, a possible explanation for the different values could be an increase in thermotolerance in the ULL procedure. This is likely since the insects are subjected to a gradually increasing temperature and presumably have some time to make physiological adjustments as the temperature increases. The preset method, on the other hand, does not allow for any acclimatory adjustment because the change of temperature is instantaneous. However, recent work by Scheffrahn *et al.* (1997) with *C. brevis* did not find any effect of rate of temperature increase on thermotolerance down to 0.5°C/min. However, nothing is known about acclimation at rates of temperature increase below 0.5°C/min and such low rates are not uncommon in commercial practice (Woodrow and Grace 1998).

Since humidity was not controlled during the preset temperature study, the effects of desiccation on mortality during extended exposures warrants discussion. Rust *et al.* (1979) demonstrated that low humidity had a detrimental effect on the survival of both *I. minor* and *I. fruticavus* in long-term thermal exposure tests. This effect, however, was only evident with exposure times of 4h or greater, while the longest exposure in the current study was 90 minutes. Thus, it is unlikely that the degree of difference between the two thermotolerance methods is entirely attributable to desiccation.

Given the lack of evidence for desiccation effects, the most likely possibility is a body temperature time-lag produced by a widening gradient between internal body temperature and rapidly increasing ambient temperature in the test chamber. The study of body temperature of *C. brevis* nymphs produced a significant mean gradient of 0.41°C ($T=5.05$; 7 d.f.; $p=0.0008$) between the body and the test chamber air at a rate of increase of 0.5°C/min (1-sample T-test of $m=0$ or $m>0$; SAS Institute 1985). The variation between the body temperature and the test chamber was not consistent, with a standard deviation of 0.23°C and a range from 0.004 to 0.7°C. This degree of time lag at 0.5°C/min provides sufficient evidence to conclude that body temperature time-lag

is a factor which should be considered when conducting thermal assays using rates of temperature increase.

The thermal rate concept with respect to establishing CTMAX and ULL values in insects originated from research with poikilothermic vertebrates such as fish and salamanders. In rate bioassay work conducted by Hutchinson (1961) a rate of temperature increase of 1°C/min was chosen to determine thermal tolerances of salamanders because this rate was slow enough to minimize any time-lag effect between body and aqueous test-chamber temperatures. The 1°C/min rate of temperature increase has since become the conventional rate for thermal studies on terrestrial insects, but may not be entirely appropriate given that the thermal conductivity of water is much greater than that of air. Despite the initial assumption that the conventional 1°C/min rate of temperature increase would not lead to a body temperature time-lag, our observations provide compelling evidence that this occurs. As well as observed body-temperature time-lags, lethal effects were seen for *I. immigrans* at constant preset temperatures as low as 45°C, while at a rate of 0.7°C/min, a temperature of 6.3°C higher was required. Thus, it is likely that the true lethal body temperatures are somewhat lower than the thermal thresholds measured by the rate method. In addition, slower rates of thermal increase may be more appropriate for testing the thermal tolerance of terrestrial organisms and may have to be further adjusted according to thermal characteristics (i.e., mass, volume, conductivity, etc.) of the test animal.

In commercial high temperature termite control practice, the original recommendation of 49°C for a 30min exposure (Ebeling 1994) was selected to maximize the effect on termites while minimizing any possible damage to heat sensitive materials such as plastics and paints (Forbes and Ebeling 1987). However, this recommendation has recently been raised to 54.4°C for a minimum 60 minute duration (Ebeling 1997). Based on our results, the true lethal body temperature of *C. brevis* is somewhat lower than the ULL of 51.3°C and the current recommendation should be more than adequate for the control of this drywood termite. These data also suggest that a lower treatment temperature held for a longer exposure period could be equally effective with less probability of thermal damage to heat-sensitive materials in the structure.

ACKNOWLEDGMENTS

We thank C.H. M. Tome and the student helpers of the Termite Project for their technical assistance. We are also grateful to Julian R. Yates III and Arnold H. Hara for their comments on the manuscript. This

research was supported by USDA-ARS Specific Cooperative Agreement 58-6615-4-037. This is Journal Series No. 4315 of the Hawaii Institute of Tropical Agriculture and Human Resources.

REFERENCES

Appel, A. G. 1991. Water relations and thermal sensitivity of several cockroach species (Dictyoptera: Blattidae and Blaberidae). Comparative Biochemistry and Physiology 100A: 355-356.

Appel, A. G. , and R. C. Sponsler. 1989. Water and temperature relations of the primitive xylophagus cockroach *Cryptocercus punctulatus* Scudder (Dictyoptera: Cryptocercidae). Proceedings of the Entomological Society of Washington 91: 153-156.

Cohen, A. C., and J. D. Pinto. 1977. An evaluation of the xeric adaptiveness of several species of blister beetles (Meloidae). Annals of the Entomological Society of America 70: 741-749.

Ebeling, W. 1997. Thermal pest eradication. Pest Control Magazine 65: 58-59.

Ebeling, W. 1994 The thermal eradication system for structural pest control. The IPM Practioner 11:1-7.

Forbes, C. F., and W. Ebeling. 1987. Update: the use of heat for the eradication of structural pests. The IPM Practitioner 9: 1-6.

Hutchinson, V. H. 1961. Critical thermal maxima in salamanders. Physiological Zoology 34: 92-125.

Karboutli M. S. and T. P. Mack. 1993. Tolerance of the striped earwig (Dermaptera: Labiduridae) to hot and dry conditions. Environmental Entomology 22: 663-668.

Mitchell, J. D., P. H. Hewitt, and T. Cd. K Van der Linde. 1993. Critical thermal limits and temperature tolerance in the harvester termite *Hodotermes mossambicus* (Hagen). Journal of Insect Physiology 39: 523-528.

Rust, M. E., D. A. Reierson , and R. H. Scheffrahn. 1979. Comparative habits, host utilization and xeric adaptations of the southwestern drywood termites, *Incisitermes fruticavus* Rust and *Incisitermes minor* (Hagen) (Isoptera: Kalotermitidae). Sociobiology 4: 239-255.

SAS Institute. 1985. SAS User's Guide: Statistics. SAS Institute, Cary, NC.

Scheffrahn, R. A., G. A. Wheeler, N-Y SU. 1997. Heat tolerance of structure-infesting drywood termites (Isoptera: Kalotermitidae) of Florida. Sociobiology 29: 237-245.

Sponsler R. C. and A. G. Appel. 1991. Temperature tolerances of the Formosan and eastern subterranean termites (Isoptera: Rhinotermitidae). Journal of Thermal Biology 16: 41-44.

Woodrow R. J. and J. K. Grace. 1998. Field studies on the use of high temperatures to control *Cryptotermes brevis* (Isoptera: Kalotermitidae). Sociobiology 32(1): 27-49.

Responses of Red Flour Beetle Life Stages to Heat

Anil Menon and Bhadriraju Subramanyam
Department of Grain Science and Industry,
Kansas State University, Manhattan, KS 66506
E-mail: amenon@wheat.ksu.edu; bhs@wheat.ksu.edu

Heat sterilization is a methyl bromide alternative

Heat sterilization or heat treatment has been used to disinfest flour mills since the early 1900s (Dean 1911). There is renewed interest in using heat because of the impending phase out of methyl bromide. During heat treatment, temperatures within a food-processing facility or flour mill are raised to 50ºC or higher, and are held at these high temperatures for 24-36 hours (Imholte and Imholte-Tauscher 1999). Very little is known about the effects of high temperatures on life stages of the red flour beetle, *Tribolium castaneum* (Herbst), during an actual heat treatment. Therefore, the impact of high temperatures on *T. castaneum* life stages was evaluated during heat treatment of a pilot flour mill, and in a laboratory growth chamber at 50ºC.

Tests in the pilot flour mill

During March 17-21, 2000, the pilot flour mill in the Department of Grain Science and Industry, Kansas State University, was subjected to steam heat treatment. The temperature profiles are shown in Figure 1. Twenty eggs (1-d-old), younger larvae (2nd instars), older larvae (5th instars), pupae (2-d-old), or adults (2 wk-old) of *T. castaneum* were held in plastic boxes with 0.5-g of whole-wheat flour. These boxes were placed in the 2nd floor of the flour mill. Temperatures near the boxes were measured using HOBO data loggers (Onset Computer Corp., Pocasset, MA). Boxes were removed at different times during heat treatment. Adults were observed for mortality 24 h after they were removed from the mill. In the case of eggs, larvae, and pupae, mortality counts were based on those that failed to emerge into adults after incubation at 28ºC and 65% RH. Control boxes were maintained at 28ºC and 65% RH.

A fraction of adults emerging from pupae exposed to heat had separated wings, and these numbers were enumerated. Larvae emerging from eggs that survived heat treatment were weighed after two weeks of emergence, to determine reduction in weight relative to weight of control larvae.

Laboratory tests

Eggs, larvae, pupae, and adults of *T. castaneum* (same ages as above) were exposed to 50ºC for varying lengths of time inside a growth chamber to estimate time-mortality relationships.

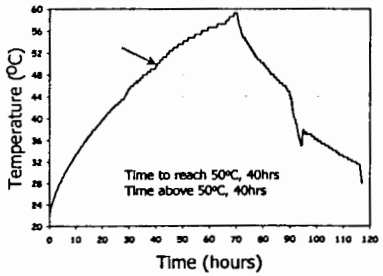


Figure 1. Temperature profile observed near test boxes in the flour mill. Arrow indicates the threshold temperature of 50ºC.

Table 1. Mortality of *T. castaneum* life stages during steam heat treatment of the pilot flour mill (March 17-21, 2000).

Hours[a]	Temp. (ºC)	Mortality (% Mean ± SE) [b,c]				
		Eggs	Younger Larvae	Older Larvae	Pupae	Adults
33.0	46.4	55.0 ± 5.0 a	3.3 ± 3.3 a	3.3 ± 1.7 a	5.0 ± 0 a	0.0 ± 0.0 a
34.0	46.9	78.0 ± 1.7 b	20.0 ± 10.4 a	11.7 ± 11.7 a	10.0 ± 2.9 ab	0.0 ± 0.0 a
35.0	47.4	85.0 ± 2.9 b	63.3 ± 1.7 b	8.3 ± 4.4 a	21.7 ± 11.7 b	45.0 ± 7.6 b
35.5	48.0	96.7 ± 1.7 c	78.3 ± 10.1 b	18.3 ± 7.3 a	43.3 ± 4.4 c	91.7 ± 1.7 c
36.0	48.0	96.7 ± 1.7 c	90.0 ± 5.1 b	63.3 ± 10.1 b	50.0 ± 5.8 c	100.0 ± 0.0 d

[a]Hours after heat was turned on.
[b]For each stage, means within a column followed by the same letter are not significantly different ($P > 0.05$; by linear contrasts).
[c]Control mortality was 0%.

Table 2. Percentage reduction in weight of *T. castaneum* larvae emerging from eggs that survived steam heat treatment.

Hours[a]	Temp (ºC)	Number of larvae[b]	Mean wt ± SE (mg)[c]	% Reduction (mean)
Control	28.0	15 (3)	2.77 ± 0.02 a	
33.0	46.4	15 (3)	2.07 ± 0.16 ab	25.27
34.0	46.9	13 (3)	1.57 ± 0.51 bc	43.32
35.0	47.4	9 (3)	1.22 ± 0.16 cde	55.96
35.5	48.0	2 (2)	0.65 ± 0.05 de	76.53
36.0	48.0	2 (2)	0.70 ± 0.0 e	74.53

[a]Hours after heat was turned on.
[b]Numbers within parenthesis are replications.
[c]Means followed by the same letters are not significantly different ($P > 0.05$; by linear contrasts).

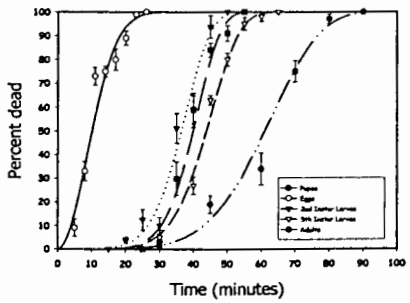


Figure 2. Observed data and fitted lines describing mortality of life stages of *T. castaneum* at 50ºC. Each datum is based on $n=5$ replications. At each n, 20 insects were used.

Table 3. Percentage of *T. castaneum* adults with separated wings that emerged from pupae exposed to steam heat treatment

Hours[a]	Temp. (ºC)	Adults with separated wings (% Mean ± SE)[b]
Control	28.0	0.0 ± 0.0 a
33.0	46.4	20.0 ± 5.0 b
34.0	46.9	43.3 ± 8.3 cd
35.0	47.4	41.7 ± 12.0 bc
35.5	48.0	61.7 ± 4.4 cd
36.0	48.0	63.3 ± 3.3 d

[a]Hours after heat was turned on.
[b]Means within a column followed by the same letter are not significantly different ($P > 0.05$; by LSMEANS).

Data analysis

Data were subjected to analysis of variance using the PROC GLM procedure of SAS. Raw percentage data were transformed to angular values before analysis. Means were separated using linear contrasts or LSMEANS. The mortality data of the different life stages at 50ºC were analyzed using a complementary log-log model.

Significant findings

Adverse effects of heat on *T. castaneum* life stages increased with increasing exposure time. All exposed adults, and only 50% of pupae, were killed when the mill temperature reached 48ºC (Table 1). Larvae emerging from eggs exposed to heat were smaller and lighter in weight than those in the control (Table 2). Many adults emerging from heat-treated pupae had separated wings (Table 3). At 50ºC, the degree of heat tolerance among stages was as follows: pupae > older larvae > adults > younger larvae > eggs (Figure 2).

Conclusions

Heat is a viable alternative to methyl bromide for disinfesting flour mills, as indicated by the flour mill and laboratory tests. Our results showed that at 50ºC, an exposure for 1.5-2 h is sufficient to kill all life stages of *T. castaneum*. However, additional data are needed on responses of other stored-product insects to heat, and on the economics of heat treatment, to make this method more acceptable to the food industry.

References

Dean, D. A. 1911. Heat as a means of controlling mill insects. J. Econ. Entomol. 4: 142-158.

Imholte, T., and Imholte-Tauscher, T. 1999. Engineering for Food Safety and Sanitation. Technical Institute of Food Safety. Woodinville, Washington.

Menon, A., Subramanyam, Bh., Dowdy, A., and Roesli, R. 2000. Heat treatment: a viable alternative to methyl bromide for managing insects. World Grain (March): 68-69.

Acknowledgment

This research was supported by funds from Temp-Air, One Rupp Plaza, 3700 West Preserve Boulevard, Burnsville, MN 55337.

Does Relative Humidity During Heat Treatment Influence Survival of *Tribolium castaneum* Herbst ?

Rennie Roesli and Bhadriraju Subramanyam

Department of Grain Science and Industry, Kansas State University. 205 Shellenberger Hall, Manhattan, Kansas U.S.A. KS 66506
E-mail: rroesli@wheat.ksu.edu; bhs@wheat.ksu.edu

Introduction

Heating a food processing facility to ≥50°C for 24-36 h is an old insect control method (Fields 1992, Imholte and Imholte-Tauscher 1999). It is gaining popularity because of the impending phaseout of methyl bromide–an ozone depleting chemical currently used for fumigating food-processing facilities (Menon et al. 2000). There is no information on the influence of relative humidity during heat treatment on insect survival. Therefore, experiments were conducted in a pilot flour mill to determine the effects of relative humidity on survival of the red flour beetle, *Tribolium castaneum* Herbst, a common insect pest associated with flour mills worldwide.

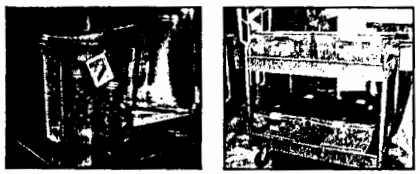
Methods

The pilot flour mill located in the Department of Grain Science and Industry, Kansas State University, was subjected to steam heat treatment during November 23–26, 1999, and during March 17–20, 2000. All tests were conducted on the 2nd floor of the flour mill.

November heat treatment: To obtain a range of humidities, 50:50, 65:35, and 73:27% glycerol:water solutions (v/v) were made. These solutions (0.2-L) were added into separate 3.3-L plastic cereal storage containers with lids (Figure 1a). Two glass culture jars with wire-mesh lids, each containing 20, 2-wk-old adults of *T. castaneum,* were placed inside each container. To obtain a wider range of humidity levels, the lids of half of the containers were left open during heat treatment. Temperature and relative humidity inside containers were recorded using HOBO data loggers (Onset Computer Corp., Pocasset, Massachusetts). Insects were sampled 24, 48 and 72 h after the heaters were switched on to assess survival.

March heat treatment: Following procedures similar to those outlined above, humidity gradients were created in 41-L plastic boxes. The total volume of glycerol:water solution in each box was about 2-L (Figure 1b). One box was devoid of any solution. A cohort of insects, kept in a laboratory growth chamber (28±1°C), served as the control treatment. Insects were observed for survival 24 and 47 h after the heaters were turned on.

During heat treatment, the temperature was stable (50-52°C) for an hour. Survival of adults of *T. castaneum* at these temperatures, over a range of humidity levels, was observed for 20, 30 and 50 min. These data were subjected to a 2-way analysis of variance using the PROC GLM procedure. Means were separated using LSD at α = 0.05.



(a) (b)

Figure 1. Plastic container used during November heat treatment (a). Plastic boxes used during March heat treatment (b).

Table 1. Exposure time, temperature and relative humidity profiles, and *Tribolium castaneum* survival during November heat treatment.

Exposure time (h)	Glycerol (%)	Enclosure	Temp. range (°C)	Hours to reach 50°C	Hours above 50°C	Humidity range (%)	Survival[b] (%)
24	50	Closed	26.3 - 42.5	0.0	0.0	22.1 - 23.7[a]	100.0
	65	Closed	23.2 - 36.8	0.0	0.0	60.2 - 70.5	100.0
	65	Open	25.6 - 42.0	0.0	0.0	29.9 - 42.5	100.0
	73	Closed	24.8 - 40.1	0.0	0.0	50.4 - 52.7	100.0
	73	Open	26.7 - 43.0	0.0	0.0	23.3 - 31.3	100.0
48	50	Closed	26.3 - 53.5	36.3	9.8	21.2 - 23.7[a]	0.0
	65	Closed	26.0 - 54.1	34.0	12.0	55.7 - 59.5	0.0
	65	Open	25.2 - 52.4	40.3	5.8	33.6 - 56.8	0.0
	73	Closed	23.6 - 49.6	0.0	0.0	52.3 - 55.2	0.0
	73	Open	25.2 - 53.0	36.5	8.8	22.8 - 42.3	0.0
72	50	Closed	26.3 - 57.9	36.3	31.5	20.9 - 23.7[a]	0.0
	65	Closed	24.0 - 56.6	39.0	27.3	61.0 - 71.1	0.0
	65	Open	26.7 - 59.2	32.3	34.3	19.0 - 40.9	0.0
	73	Open	23.2 - 54.7	43.8	22.3	19.7 - 44.0	0.0
	73	Open	26.3 - 58.6	33.3	33.3	20.9 - 23.3	0.0

[a]Reading failure of the HOBO data logger.
[b]Each mean is based on n = 2 replications. At each n, 20 adults were used.

Table 2. Exposure time, temperature and relative humidity profiles, and *Tribolium castaneum* survival during March heat treatment.

Exposure time (h)	Glycerol solution (%)	Temp. range (°C)	Hours to reach 50°C	Hours above 50°C	Humidity range (%)	Survival[c] (%)
24	50	22.1 - 42.0	0.0	0.0	68.0 - 76.4	100.0
	65	22.1 - 42.0	0.0	0.0	55.4 - 60.5	100.0
	73	22.1 - 41.5	0.0	0.0	49.6 - 52.5	100.0
	NS[a]	22.1 - 41.5	0.0	0.0	24.0 - 39.1	100.0
	GC[b]	27.5 - 28.3	0.0	0.0	27.0 - 37.4	98.3
47	50	22.1 - 51.8	43.0	4.0	55.6 - 76.4	0.0
	65	22.1 - 51.8	43.0	4.0	46.7 - 60.5	0.0
	73	22.1 - 50.7	44.5	2.5	33.8 - 52.5	0.0
	NS[a]	22.1 - 51.2	44.0	3.0	20.4 - 39.1	0.0
	GC[b]	27.5 - 28.7	0.0	0.0	27.0 - 39.5	100.0

[a]The plastic box was devoid of any solution.
[b]Insects kept as a control in a growth chamber in the laboratory.
[c]Each mean is based on n = 3 replications. At each n, 20 adults were used.

Table 3. The influence of relative humidity and exposure time at lethal temperature (50.1-52.4°C) on survival of *Tribolium castaneum* adults.

% Humidity	% Glycerol	Exposure time (min)		
		20	30[a]	50
53.6-63.1	50	100.0	71.0 b	0.0
46.1-49.3	65	100.0	6.2 c	0.0
31.6-48.1	73	100.0	2.7 c	0.0
20.4-20.5	NS[a]	100.0	5.0 c	0.0
32.4-38.1	GC[b]	100.0	100.0 a	100.0

[a]Means followed by different letters are significantly different (P < 0.05; by Fisher's Protected LSD).
[a] No glycerol:water solution.
[b] Growth chamber in the laboratory.

Results

The target temperature of 50°C in the 2nd floor of the flour mill was reached within 45 h during November heat treatment, and within 42 h during March heat treatment. During both heat treatments, temperatures ≥50°C were maintained for about 20 h. Temperatures ≥50°C for 3 h are sufficient to kill adults of several stored-product insects (Roesli et al., 2000).

A broad range of humidity gradients was created with glycerol solutions (Tables 1-3). Opening the plastic containers reduced the humidity levels (Table 1). During both heat treatments, all *T. castaneum* adults survived the steam-heat treatment when exposed for 24 h, irrespective of the humidity level (Tables 1 and 2). Within this 24 h period, the target temperature of 50°C was not attained. In general, none of the *T. castaneum* adults survived ≥2.5- h exposure to 50°C at all humidity levels (Tables 1 and 2).

At 50.1-52.4°C, the survival of *T. castaneum* adults varied with the time of exposure (F = 328.64; df = 2, 30; P < 0.001), and the level of humidity (F = 86.01; df = 4, 30; P < 0.001). Also, the exposure time x humidity level interaction was significant (F = 29.04; df = 8, 30; P < 0.001). Survival of adults was not affected by a 20-min exposure (Table 3). Decreasing the level of humidity from 54-63% to less than 50% significantly decreased the survival of adults exposed for 30-min from 71% to less than 10%. None of the adults, at all humidity levels, survived a 50-min exposure. All adults kept in the growth chamber survived during this test period (Table 3).

Conclusion

The level of humidity during a heat treatment is not an important factor affecting survival of *T. castaneum* adults, if the target temperature of 50°C is maintained for ≥2.5 h.

References

Fields, P. G. 1992. The control of stored-product insects and mites with extreme temperatures. J. Stored Prod. Res. 28: 89–118.

Imholte,T. J. and Imholte-Tauscher, T. 1999. Engineering for Food Safety and Sanitation. Technical Institute of Food Safety. Woodinville, Washington.

Menon, A., Subramanyam, Bh., Dowdy, A., and Roesli, R. 2000. Heat treatment: a viable alternative to methyl bromide for managing insects. World Grain, March, 68–69.

Roesli, R., Subramanyam, Bh., Fairchild, F., and Behnke, K. 2000. Trap catches of stored-product insects before and after heat treatment of a pilot feed mill. J. Stored Prod. Res. (Submitted)

Acknowledgment: This work was funded by the Temp-Air, One Rupp Plaza, 3700 West Preserve Boulevard, Burnsville, Minnesota 55337.

Heat and Conventional Insecticides

Frank H. Arthur
USDA-ARS-GMPRC
Manhattan KS 66502

Spot, Crack & Crevice Treatments

- Organophosphate and pyrethroid insecticides are used as spot or crack & crevice treatments
- Specific language on the label defining a spot (often 2 ft^2 or less)
- Specific directions for crack & crevice applications

General Surface Treatments

- Spray volume and area are specified
- 1 gal of formulated spray per 1,000 ft^2
- Different label language and application directions
- Limited number compared to crack & crevice

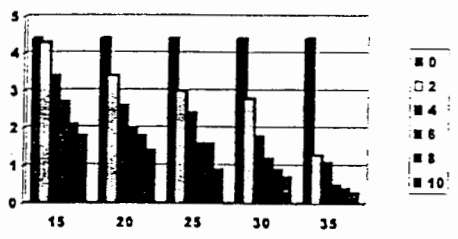
Insecticides

- Malathion: OP, not being reregistered
- Cyfluthrin EC & WP (Tempo): pyrethroid
- Hydroprene (Gentrol): insect growth regulator

Residual degradation or inactivation

- OPs degrade as temperature increases
- Summer degradation is a serious problem with grain protectants
- Residues drop below levels that will control insects
- Example: degradation at controlled temperatures

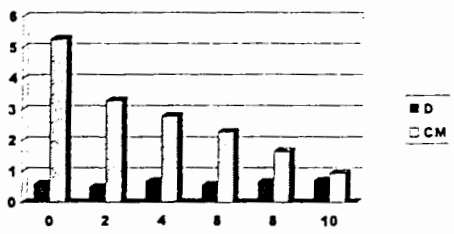
Degradation of chlorpyrifos-methyl on wheat (values in ppm)



Pyrethroids

- More heat-stable compared to OPs
- Degrade primarily by UV light
- Example: wheat treated with chlorpyrifos-methyl and deltamethrin
- Wheat stored in a metal shed from Oct-July in south GA
- Mean monthly temp was 14-31 °C during the study

Degradation of chlorpyrifos-methyl (CM) and deltamethrin (D) on wheat stored for 10 months (values in ppm)



Heat treatments and insecticides

- Insecticide would probably degrade rapidly at 45-55 °C
- Pyrethroids a more practical choice

Cyfluthrin WP

- Gives better residual control on porous surfaces than cyfluthrin EC
- Common treatment in food warehouses and other indoor structures
- Will extreme temperatures associated with heat treatments affect residual efficacy?

Heat combined with conventional insecticides to control stored-product insects in flour mills

Frank H. Arthur
USDA-ARS-GMPRC
Manhattan KS 66502

Residual insecticides are used as spot, crack and crevice, and general surface treatments inside flour mills, food storage facilities, and other indoor structures where processed food is stored. Organophosphate and pyrethroid insecticides are commonly used as crack and crevice or spot treatments, and there will be specific language on the insecticide label defining the area of a spot (often 2 ft^2 or less). There will be specific directions for crack & crevice applications, such as how to direct the spray band into the crack.

In contrast, general surface treatments can be applied to large areas. The spray volume and area are specified, as in 1 gal of formulated spray per 1,000 ft^2, and there will be different label language and application directions compared to crack and crevice sprays. There are few general surface treatments, compared to the available registrations for crack and crevice or spot treatments. Malathion is an organophosphate that is not being reregistered for most post-harvest uses, including indoor applications. The pyrethroid cyfluthrin (Tempo) is available as an emulsifiable concentrate (EC) and a wettable powder (WP), and is perhaps the most common general surface treatment used in pest control operations. The insect growth regulator hydroprene (Gentrol) is labeled as a general surface treatment and as an aerosol.

Residual degradation or inactivation of organophosphates will increase in response to increasing temperatures. Summer degradation is a serious problem with chlorpyrifos-methyl, an organophosphate registered as a protectant of stored wheat. Residues can rapidly drop to levels that will not control an insect infestation. This is illustrated by a study where wheat was treated at the target rate of 6 ppm, stored at 15 to 35 °C for 10 months, and sampled at bimonthly intervals (Arthur et al. 1992). Actual measured deposition was 4.4 ppm. As temperatures increased from 15 to 35 °C, residue degradation increased in response to the increasing temperatures (Table 1).

Table 1. Degradation of chlorpyrifos-methyl in ppm (mean ± SEM) on wheat stored at 15, 20, 25, 30, and 35 °C, 12.5% moisture content. Actual measured deposition was 4.39 ± 0.47 ppm.

Month	Temperature (°C)				
	15	20	25	30	35
2	4.3 ± 0.86	3.4 ± 0.49	3.0 ± 0.50	2.8 ± 0.63	1.3 ± 0.10
4	3.4 ± 0.66	2.6 ± 0.39	2.4 ± 0.56	1.8 ± 0.38	1.1 ± 0.11
6	2.7 ± 0.78	2.0 ± 0.31	1.6 ± 0.30	1.2 ± 0.22	0.5 ± 0.06
8	2.1 ± 0.53	1.8 ± 0.30	1.6 ± 0.26	0.9 ± 0.23	0.4 ± 0.09
10	1.8 ± 0.35	1.4 ± 0.19	0.9 ± 0.21	0.7 ± 0.14	0.3 ± 0.07

In contrast to organophosphates, pyrethroids are more heat stable, and degrade primarily by UV light. In this next example, wheat treated with targeted rates of 1 ppm deltamethrin and 6 ppm chlorpyrifos-methyl, and stored in a metal shed from Oct-July in south Georgia (Arthur 1994b). Actual measured deposition was 0.60 ppm deltamethrin and 5.27 ppn chlorpyrifos-methyl, and the average monthly temperature during the study ranged from 14-31 °C. Residues of deltemethrin remained constant, while residues of chlorpyrifos-methyl followed the expected pattern of degradation for organophosphates (Table 2).

Table 2. Degradation of deltamethrin and chlorpyrifos-methyl and on wheat stored for 10 months in south Georgia, USA (values in ppm).

Month	Deltamethrin	Chlorpyrifos-methyl
0	0.60 ± 0.04	5.27 ± 0.08
2	0.50 ± 0.04	3.29 ± 0.22
4	0.69 ± 0.02	2.79 ± 0.17
6	0.56 ± 0.04	2.27 ± 0.08
8	0.63 ± 0.02	1.65 ± 0.07
10	0.70 ± 0.02	0.94 ± 0.05

The toxicity of organophosphates often increases when temperatures increase, in contrast to pyrethroid toxicity, with is inversely related to temperature. The relative degradation patterns of organophosphates compared to pyrethroids indicates that organophosphate insecticides may not be suitable for use in conjunction with heat treatments (Johnson 1990, Arthur 1999). Residue degradation would occur rapidly at temperatures of 45-55 °C, which are often achieved during heat treatments. Cyfluthrin may be a more practical choice, and it can be used both as a general surface spray and a crack and crevice or spot treatment. Cyfluthrin WP gives better residual control on porous surfaces than cyfluthrin EC (Arthur 1994b). Laboratory studies indicates that cyfluthrin WP will not degrade at the extreme temperatures associated with heat treatments.

References Cited

Arthur, F. H. 1994a. Residual efficacy of cyfluthrin emulsifiable concentrate and wettable powder formulations applied to sealed and unsealed concrete. J. Stored Prod. Res. 30: 79-86.

Arthur, F. H. 1994b. Efficacy of unsynergised deltamethrin and deltamethrin + chlorpyrifos-methyl combinations as protectants of stored wheat and stored corn. J. Stored Prod. Res. 30: 87-94.

Arthur, F. H. 1999.Effect of Temperature on Residual Toxicity of Cyfluthrin Wettable Powder. J. Econ. Entomol. 92: 695-699.

Arthur, F. H., J. E. Throne, and R. A. Simonaitis. 1992. Degradation and biological efficacy of chlorpyrifos-methyl on wheat stored at five temperatures and three moisture contents. J. Econ. Entomol. 85: 1994-2002.

Johnson, D. L. 1990. Influence of temperature on toxicity of two pyrethroids to grasshoppers (Orthoptera: Acrididae). J. Econ Entomol. 83: 366-373

Survival of red flour beetles on heated versus unheated concrete treated with cyfluthrin WP: Field demonstration trial

Frank H. Arthur
USDA-ARS-GMPRC
Manhattan KS 66502

Cyfluthrin WP is a pyrethroid insecticide applied as a residual treatment on flooring surfaces. There are 2 label rates, 9.5 and 19 g/1000 ft^2, or 0.1 and 0.2 g/m^2. In laboratory studies, concrete treated with 0.2 g/m^2 cyfluthrin WP was heated continually for 4-16 hours at 45 and 55 °C. There was no difference in survival of red flour beetles (RFB, *Tribolium castaneum*) exposed on heated versus unheated concrete. The objectives of this field trial were to conduct a field trial as part of a heat treatment at the KSU flour mill, determine survival of RFB exposed on concrete heated for different time intervals in the mill, and to compare results with unheated concrete.

Exposure arenas were constructed by pouring ready-mix concrete slurry into each of 70 Petri dishes (100 by 15 mm). After drying, concrete disks removed from the dish, and cyfluthrin WP applied at 10% of the maximum label rate, or 20 mg/m^2 on 60 arenas. Five replicates of 30 treated arenas and 5 untreated controls put in the mill and in an office at 1:30 PM 25 June. The arenas were removed from each location 6 to 42 hours after heating commenced. On Monday 28 June, the concrete disks were brought to the Grain Marketing Production and Research Center, and set on a laboratory counter. Ten adult mixed-sex red flour beetles were exposed inside a plexiglass cylinder set on each dish. At selected post-treatment intervals of 0.5, 1.0, 2.0, 3.0, 5.0, 8.0, 18, 24, 48, 72, and 120 hours, the percentage of beetles that were mobile, knocked down, and dead on each concrete disk was assessed. Mobile beetles were considered to have "survived" exposure, since they couldn't escape the residues.

Survival on untreated controls at various post-exposure intervals was 98 to 100%. The time at which dishes were removed from either the mill or the office was not significant with respect to survival, therefore data were combined for time. Survival of red flour beetles decreased as exposure interval increased from 0.5 to 120 hours, and except for the 0.5 hour readings, survival was greater on dishes held in the office versus dishes heated in the mill. There was no degradation or loss of activity because of heating, in fact, heating may have increased the efficacy of cyfluthrin WP. Results with this test at 10% of the maximum label were comparable to lab tests with full rate. This test will be repeated in the feed mill, following the same procedures. Data will be compared with results from the flour mill.

Survival of red flour beetles on heated versus unheated concrete treated with cyfluthrin WP

Frank H. Arthur
USDA-ARS-GMPRC
Manhattan KS 66502

Introduction

- Cyfluthrin WP is a pyrethroid insecticide applied as a residual treatment on flooring surfaces
- There are 2 label rates, 9.5 and 19g/1000 ft^2, or 0.1 and 0.2 g/m^2
- In a previous test, concrete treated with 0.2 g/m^2 cyfluthrin WP was heated continually for 4-16 hours at 45 and 55° C
- No difference in survival of red flour beetles (RFB) exposed on heated versus unheated concrete

Objectives

- Confirm lab results in a field trial as part of a heat treatment at the KSU flour mill
- Determine survival of RFB exposed on concrete heated for different time intervals in the flour mill
- Compare results with unheated concrete

Methods

- Exposure arenas were constructed by pouring ready-mix concrete slurry into each of 70 Petri dishes (100 x 15 mm)
- After drying, concrete disks were removed from the dishes, cyfluthrin WP applied at 20 mg/m^2 on 60 arenas
- Five replicates of 30 treated dishes and 5 untreated controls put in the mill and in an office at 1:30 PM 6/25
- Dishes were removed from each location 6 to 42 hours after heating commenced

Methods cont.

- On Monday 6/28, 10 adult mixed-sex flour beetles were exposed inside a plexiglass cylinder set on each dish
- Percent of RFB mobile, knocked down, and dead on each disk assessed at 0.5 to 120 hours post-exposure
- Mobile beetles were considered to have "survived" exposure, since they couldn't escape the residues

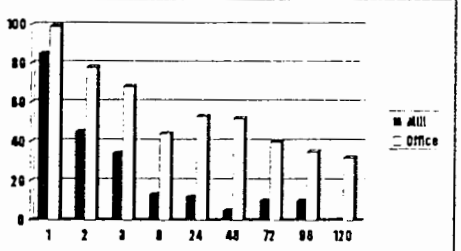
Results

- Survival on untreated controls at various post-exposure intervals was 98 to 100%
- Time at which dishes were removed from either the mill or office was not significant with respect to survival
- Data combined for time

Results cont.

- Survival of RFB decreased as exposure interval increased from 0.5 to 120 hours
- Survival was greater on dishes held in office versus dishes heated in the mill

Percent Survival of RFB 0.5 to 120 hours post-exposure



Conclusions

- No degradation or loss of activity because of heating
- Heat appeared to increase activity of cyfluthrin WP
- Results with this test at 10% of maximum label rate comparable to lab tests with full rate

Feed Mill

- Test will be repeated in the feed mill following the same procedures
- Results compared with data from flour mill

PERGAMON

Journal of Stored Products Research 35 (1999) 175–182

Journal of STORED PRODUCTS RESEARCH

Mortality of red flour beetle, *Tribolium castaneum* (Coleoptera: Tenebrionidae) exposed to high temperature and diatomaceous earth combinations*

Alan K. Dowdy *

USDA, ARS, Grain Marketing and Production Research Center, 1515 College Avenue, Manhattan, KS 66502, USA

Accepted 23 October 1998

Abstract

Four diatomaceous earth formulations and one calcium carbonate formulation were evaluated in combination with high temperature as a control method for the adult stage of the red flour beetle, *Tribolium castaneum* (Herbst). At 34°C, exposure to the insecticidal dusts for 15 or 30 min did not increase mortality relative to beetles not exposed to the dusts. However, at 50°C, exposure increased mortality by 8–100%. Exposure to the Protect-It® formulation caused greater beetle mortality than exposure to any of the other materials. The calcium carbonate formulation exhibited no insecticidal activity. Withholding food from the beetles after exposure to heat plus diatomaceous earth increased mortality 2–4 times beyond the level for beetles that were not denied food. A combination treatment of heat with an effective diatomaceous earth formulation may be useful for managing this pest in cereal-grain processing facilities. Published by Elsevier Science Ltd.

Keywords: Diatomaceous earth; Calcium carbonate; Heat treatment; Stored products; *Tribolium castaneum*; Red flour beetle

1. Introduction

As an alternative to fumigating cereal-grain processing facilities with methyl bromide, many companies are revisiting the use of heat treatment to control stored-product insects. A typical heat treatment of a processing facility consists of heating the building to a target temperature

This article reports the results of research only. Mention of a proprietory product does not constitute an endorsement or recommendation by the USDA at the exclusion of other products.

* Tel.: +1 785-776-2719; Fax: +1 785-537-5584; e-mail: dowdy@usgmrl.ksu.edu

0022-474X/99/$ - see front matter Published by Elsevier Science Ltd.
PII: S0022-474X(98)00043-5

for 20–30 h. This allows time for building materials to expand and adjust to the change (Imholt, 1984). Buildings constructed of steel and concrete are better able to tolerate temperatures in excess of 45°C and relative humidity values below 20% than older facilities constructed primarily of wood. The air temperature at "eye level" is maintained at 50–55°C for 20–30 h. Although stored-product insects will die in < 1 h at these temperatures (Fields, 1992), the longer time is necessary for the heat to penetrate into equipment and wall cavities that may harbor insects.

Unfortunately, some plastic materials in modern processing equipment may warp and sensitive electronic equipment may be damaged if exposed to temperatures above 50°C for extended periods of time. Additionally, wooden equipment and floors may dry out and crack resulting in damage and lost production time. Fields et al. (1997) demonstrated that the use of heat sterilization in combination with diatomaceous earth was more effective in controlling confused flour beetles (*Tribolium confusum* Jacquelin du Val) than the use of heat sterilization alone. Diatomaceous earth has been used with varying effectiveness as a protectant on raw commodities (Golob, 1997; McLaughlin, 1994; Quarles and Winn, 1996; Subramanyan et al., 1994). Several diatomaceous earth formulations are also labeled for use as structural treatments and may be effective when used in combination with high temperatures. The efficacy, however, depends on the source of diatomaceous earth used in the formulation; thus, some commercially available products are more efficacious than others (McLaughlin, 1994). Although comparisons of diatomaceous earth efficacy have been conducted under ambient conditions, no work has been published to examine different formulations at high temperature. The objective of this study was to evaluate the effectiveness of brief exposures to diatomaceous earth formulations in combinations with high temperature as a control for stored-product insects. In addition, a calcium carbonate formulation was evaluated.

2. Materials and methods

Cultures of red flour beetles (*T. castaneum*) were maintained at 34°C and 65 ± 5% r.h. Beetles were reared at this temperature so they would be conditioned to a temperature that is common in many food processing facilities. All tests were conducted using unsexed adult beetles 1–2 wks old. The diatomaceous earth compounds examined were Concern® (85% DE, 10% other elemental oxides, 5% moisture) (Necessary Organics, Inc., New Castle, VA), Insecto® (90% DE, 10% inert) (Natural Insecto Product, Inc., Orange, CA), Natural Guard® (90% DE, 10% inert) (VPG Co-op Gardening Group, Inc., Bonham, TX), and Protect-It® (90% DE, 10% silica gel) (Hedley Technologies, Vancouver, BC). A calcium carbonate compound, Pennac-P® (98.1% $CaCO_3$, 0.9% $MgCO_3$, 0.8% HCl, 0.2% inert) (Plocher Produktions GmbH, Meersburg, Germany), was also examined to determine if it had any insecticidal activity when used alone or in combination with heat.

The insecticidal potential of the dusts was assessed using the methods described by Korunic (1997). Characteristics used to determine the insecticidal potential were pH (Corning Model 240), tapped density (g/l), bulk density reduction (kg/hl), and adherence of dust on wheat kernels (%). The grain used in the last two tests was hard red winter wheat with a test weight of 77.4 kg/hl and 12.1% m.c., wet weight.

Test arenas consisted of glass Petri dishes (60×15 mm). The dusts were applied to the dishes at a rate of 5 g/m^2 (9.05 mg per dish) and evenly distributed using a variable speed touch mixer (Model 232, Fisher Scientific, Pittsburgh, PA). Beetles were exposed to the materials for 15 or 30 min. The short exposure times were selected based on preliminary laboratory results (data not shown). One Petri dish within each of the four replicates was left untreated to serve as a control. The temperatures tested were 34 and 50°C. Relative humidity during the tests was 60% (±5%). Heating was accomplished by placing the Petri dishes on a covered hot block and preheating prior to introducing the beetles. HOBO® Temp temperature loggers (Onset Computer Corporation, Pocasset, MA) were used to record the temperature on the surface of the Petri dish. The beetles were exposed to the heat for 15 or 30 min, while one dish of beetles in each replicate was left unheated to serve as a control. The resulting treatment combinations were heat alone, insecticidal dust alone, heat plus insecticidal dust, and a control with no heat or dust. After the beetles were exposed to insecticidal dust or heat, they were transferred to shell vials (8-dram) and maintained at 34°C and 65 ± 5% r.h. To determine the impact of withholding food after treatment, half of the beetles were given about 0.5 g whole-wheat flour, while the remaining beetles received nothing. Mortalities were determined 1 and 7 d post treatment.

The experimental design was a split–plot configuration with time and temperature at the main plot level and insecticidal dust treatment at the subplot level. The impact of food after treatment was not included in the main analysis because in an applied situation, such as a grain processing facility, the likelihood is small that no food would be available. The resulting treatment combinations were heat only, insecticidal dust only, heat plus insecticidal dust, and untreated control. Within each of the four replications, 20 beetles were exposed to each of the four treatment combinations. Data were analyzed using the GLM procedure (SAS, 1995) to test for significant differences among treatment levels and means were separated using least significant difference tests (Steel and Torrie, 1980).

3. Results and discussion

An assessment of the insecticidal potential of the dusts indicated that Pennac-P®, which is composed of calcium carbonate, was not effective for controlling *T. castaneum*: the values for the four parameters were not characteristic of efficacious material (Table 1). The Protect-It® formulation appeared to have the best insecticidal potential because all four parameters were within the desired ranges. Concern® and Insecto® formulations appeared to be the next most effective materials with three of the four parameters scoring within the desired ranges. Natural Guard® appeared to have the least insecticidal potential of the diatomaceous earth formulations tested with only one of the four parameters scoring at an acceptable level (Table 1). Thus, these tests predicted that the insecticidal potential of these dusts, from most effective to least effective, is Protect-It®, Concern® and Insecto®, Natural Guard® and Pennac-P®.

The resulting mortality for beetles not fed after exposure to heat and/or insecticidal dust represents what may be expected under perfect sanitation conditions that are unattainable in most food processing facilities. Therefore, the data for beetles fed and not fed after exposure

Table 1
Characteristics of insecticidal dusts (mean ± SD) that are important for assessing their insecticidal potential

	Desirable value	Pennac-P®	Natural Guard®	Concern®	Insecto®	Protect-It®
pH	< 8.5	9.79 ± 0.01	9.06 ± 0.02	8.31 ± 0.03*	6.37 ± 0.01*	5.36 ± 0.02*
Tapped density (g/l)	< 300	1298.70 ± 0.00	259.10 ± 3.58*	255.33 ± 1.88*	186.17 ± 0.86*	185.35 ± 3.82*
Test weight (kg/hl)	< 74.9[a]	76.40 ± 0.20	75.10 ± 1.30	75.40 ± 0.60	75.50 ± 0.60	73.40 ± 0.80*
Adherence to kernels (%)	> 70%	35.33 ± 0.03	67.00 ± 0.10	76.67 ± 0.01*	75.50 ± 0.05*	78.67 ± 0.02*

* Indicates values that are characteristic of efficaceous insecticidal dusts (Korunic, 1997). [a]Based on a net change in test weight > 2.5 g/l.

were analyzed separately to better evaluate the impact of heat and insecticidal dust on mortality. Withholding food from the beetles after exposure to heat and/or insecticidal dust significantly increased mortality. The 1 d mortality of beetles fed after exposure averaged 16.8 ± 2.7% compared to an average of 34.7 ± 3.7% for beetles that were not fed ($F = 32.37$; d.f. = 1, 3; $P = 0.02$). After 7 d, the mortality for beetles fed and not fed after exposure averaged 21.4 ± 3.0% and 88.9 ± 2.2%, respectively ($F = 506.13$; d.f. = 1, 3; $P = 0.01$). Similar results were reported for the mortality rate of *T. confusum* and *Oryzaephilus mercator* Fauvel exposed to silica aerogel insecticidal dust at room temperature when deprived of food (Vrba et al., 1981; Loschiavo, 1988; White and Loschiavo, 1989). Food provides water as well as

Table 2
Analysis of variance for 1 and 7 d mortalities of *T. castaneum* exposed to insecticidal dusts and 50 C for 15 or 30 min which were fed or starved after treatment

	1 d mortality			7 d mortality		
Source	d.f.	*F*	*P*	d.f.	*F*	*P*
			With food post-treatment			
Temperature	1, 3	791.16	0.0001	1, 3	313.95	0.0004
Time	1, 3	88.76	0.0025	1, 3	131.33	0.0014
Temperature * time	1, 3	66.68	0.0037	1, 3	61.30	0.0043
Dust	5, 60	15.93	0.0001	5, 60	9.99	0.0001
Temperature * dust	5, 60	13.56	0.0001	5, 60	7.42	0.0001
Time * dust	5, 60	2.22	0.0638	5, 60	0.68	0.6425
Temperature * time * dust	5, 60	2.25	0.0610	5, 60	0.78	0.5688
			Without food post-treatment			
Temperature	1, 3	71.22	0.0035	1, 3	2.17	0.2369
Time	1, 3	95.46	0.0023	1, 3	0.40	0.57
Temperature * time	1, 3	220.95	0.0007	1, 3	1.38	0.3245
Dust	5, 60	117.37	0.0001	5, 60	31.74	0.0001
Temperature * dust	5, 60	6.55	0.0001	5, 60	0.54	0.7421
Time * dust	5, 60	3.04	0.0165	5, 60	0.03	0.9995
Temperature * time * dust	5, 60	0.85	0.5230	5, 60	0.69	0.6334

Table 3
The % mortality (mean ± SD)[a] after 1 and 7 days of exposure of *T. castaneum* adults to insecticidal dusts and 50 C for 15 or 30 min and fed after treatment

Exposure temperature (°C)	Exposure time (min)	Control	Pennac-P®	Natural Guard®	Concern®	Insecto®	Protect-It®
				1 d mortality			
34	15	0.0 ± 0.0	0.0 ± 0.0	1.3 ± 1.3	2.5 ± 1.4	1.3 ± 1.3	2.5 ± 1.4
	30	0.0 ± 0.0	2.5 ± 2.5	0.0 ± 0.0	1.3 ± 1.3	1.3 ± 1.3	2.5 ± 2.5
50	15	0.0 ± 0.0c	7.5 ± 6.0b	12.5 ± 2.5b	8.8 ± 3.8b	8.8 ± 3.8b	36.3 ± 7.2a
	30	36.3 ± 4.7bc	38.8 ± 10.9c	35.0 ± 14.0c	51.3 ± 5.5b	53.8 ± 5.2b	100.0 ± 0.0a
				7 d mortality			
34	15	1.3 ± 1.3	0.0 ± 0.0	2.5 ± 1.4	2.5 ± 1.4	1.3 ± 1.3	3.8 ± 2.4
	30	0.0 ± 0.0	5.0 ± 2.9	3.8 ± 2.4	6.3 ± 3.8	3.8 ± 3.8	6.3 ± 4.7
50	15	3.8 ± 2.4c	8.8 ± 5.5bc	16.3 ± 5.2b	13.8 ± 5.9b	8.8 ± 3.8bc	41.3 ± 9.9a
	30	56.3 ± 4.3l c	50.0 ± 12.9c	51.3 ± 14.1c	63.8 ± 5.9b	62.5 ± 5.2b	100.0 ± 0.0a

[a] Within a row, means followed by the same letter are not significantly different ($P > 0.05$). Rows with no letters following means indicate no significant difference among treatments.

Least significant difference (LSD) test for means separation.

	24 h mortality	7 d mortality
LSD for temperature =	3.5	6.6
LSD for time =	6.8	7.1
LSD for insecticidal dust =	6.7	7.5

nutrition, both moisture directly in the food and, to a lesser degree, metabolic water (Hadley, 1994).

3.1. Beetles with food after treatment

For all dust treatments, exposing the beetles to 50°C for 15 or 30 min resulted in significantly higher mortality than for beetles that were maintained at 34°C (Table 2 and 3). Mortalities at 1 and 7 d post-treatment for beetles heated to 50°C for 15 min but not exposed to a dust were not significantly different from beetles exposed to 34°C ($P > 0.05$) but exposure to 50°C for 30 min resulted in higher mortality for all dust treatments, including the control, than exposure for 15 min (Tables 2 and 3). At both 1 and 7 d, however, the mortality of beetles exposed for 30 min to insecticidal dust only was not different from beetles exposed for 15 min.

The interaction of temperature with insecticidal dust was significant (Table 2). There were significant differences in beetle mortality among the insecticidal dust compounds when combined with heating at 50°C but not when maintained at 34°C. One day after treatment, beetles exposed for 15 min had significantly higher mortality in all heat plus dust treatments than those exposed to heat alone (Tables 2 and 3). The mortalities, however, of beetles exposed for 30 min to heat plus Natural Guard® or Pennac-P® were not significantly different from

Table 4
The % mortality (mean ± SD)[a] after 1 and 7 days of exposure of *T. castaneum* adults to insecticidal dusts and 50 C for 15 or 30 min and not fed after treatment

Exposure temperature (C)	Exposure time (min)	Control	Pennac-P®	Natural Guard®	Concern®	Insecto®	Protect-It®
				1 d mortality			
34	15	1.3 ± 1.3cd	0.0 ± 0.0d	12.5 ± 5.2b	16.3 ± 2.4b	8.8 ± 3.8bc	93.8 ± 4.7a
	30	0.0 ± 0.0e	1.3 ± 1.3de	18.8 ± 8.0c	30.0 ± 12.9b	8.8 ± 5.5d	91.3 ± 5.9a
50	15	1.3 ± 1.3e	1.3 ± 1.3e	45.0 ± 8.4b	17.5 ± 3.2d	27.5 ± 7.8c	95.0 ± 5.0a
	30	28.8 ± 6.3d	26.3 ± 10.9d	76.3 ± 11.4b	70.0 ± 7.9bc	62.5 ± 11.1c	100.0 ± 0.0a
				7 d mortality			
34	15	55.0 ± 11.0b	73.8 ± 12.8b	100.0 ± 0.0a	98.8 ± 1.3a	97.5 ± 2.5a	100.0 ± 0.0a
	30	42.5 ± 12.7c	77.5 ± 11.6b	100.0 ± 0.0a	100.0 ± 0.0a	100.0 ± 0.0a	100.0 ± 0.0a
50	15	51.3 ± 16.0c	85.0 ± 7.9b	100.0 ± 0.0a	100.0 ± 0.0a	100.0 ± 0.0a	100.0 ± 0.0a
	30	65.0 ± 15.6c	87.5 ± 7.2b	100.0 ± 0.0a	100.0 ± 0.0a	.00.0 ± 0.0a	100.0 ± 0.0a

[a] Within a row, means followed by the same letter are not significantly different ($P > 0.05$).

Least significant difference (LSD) test for means separation.

	24 h mortality	7 d mortality
LSD for temperature =	8.4	7.9
LSD for time =	5.3	4.7
LSD for insecticidal dust =	8.4	9.5

beetles exposed to heat alone. Exposure to the Protect-It® formulation caused significantly higher mortality than the other dusts for both 15 and 30 min exposures.

When mortality was measured 7 d after treatment, heat plus Protect-It® was significantly more effective than all of the other heat plus insecticidal dust combinations at both 15 and 30 min exposures (Tables 2 and 3). At the 15 min exposure, heat in combination with Concern®, Natural Guard® or Protect-It® produced significantly higher mortality than treatments of heat only. At the 30 min exposure, however, only heat plus Protect-It® caused significantly greater mortality than the treatment of heat alone. Mortality caused by exposure to Concern® and Insecto® was significantly greater than that for beetles exposed to Natural Guard® and Pennac-P®.

3.2. Beetles without food after treatment

The results obtained for the impact of temperature were not as clear for the beetles that were denied food after treatment as for those that were fed. At 1 d after treatment, beetles exposed to 50°C for 15 min and treated with Insecto® or Natural Guard® had significantly greater mortality than those maintained at 34°C (Tables 2 and 4). Exposure to 50°C for 30 min resulted in significantly greater mortality than prolonged maintenance at 34°C for all dust treatments except Protect-It®. The latter result, however, was due to the high level of mortality for all treatment combinations that contained Protect-It®. There was no significant difference in mortality due to temperature 7 d after exposure (Table 2). Mortality was >97.5% for all treatments containing diatomaceous earth formulations (Table 4).

As with temperature, the results obtained for time effects were not as clear for beetles that were not fed compared with those that were fed after treatment. Mortalities at 34 C exposure after 1 d were significantly higher for beetles exposed for 30 min with Concern® or Natural Guard® than beetles exposed for 15 min (Tables 2 and 4). At 50°C exposure, mortality after 1 d was significantly higher for beetles exposed for 30 min than beetles exposed for 15 min except for those exposed to Protect-It®, again due to high mortality in all treatments with this product. Beetle mortality after 7 d was not significantly different due to the length of time the insects were exposed to the treatment combinations (Tables 2 and 4).

The 1 d mortality was significantly higher for beetles exposed to Protect-It® than for the beetles in the other treatments (Tables 2 and 4). Concern®, Insecto® and Natural Guard® generally caused higher mortality than when beetles were not exposed to dusts. There was no significant difference, however, in mortality between beetles exposed to Pennac-P® and beetles not exposed to any dusts. After 7 d, the mortality of beetles exposed to the diatomaceous earth products was significantly greater than the mortality of those exposed to Pennac-P® or the beetles not exposed to dusts (Tables 2 and 4).

The data presented here agree with those reviewed by Fields (1992): high temperatures for short periods of time are effective for killing stored-product insects. Additionally, diatomaceous earth is an effective control agent against these species (Subramanyan et al., 1994). When combined, the resulting insect mortality for heat plus diatomaceous earth is greater than that for heat or diatomaceous earth alone. It appears that as the diatomaceous earth absorbs cuticular lipids from the insect's cuticle, water regulation is compromised which results in an increased rate of desiccation due to the heating. Fields et al. (1997) suggested that the temperature necessary for insect control in a processing facility may be reduced when diatomaceous earth is used in combination with heat sterilization. Additionally, the time necessary for effective control may also be reduced. However, this apparent effect requires additional study.

The rapid assessment method of Korunic (1997) was developed to assess the insecticidal potential of diatomaceous earth formulations at 25°C. The results of the present work indicate that the rapid assessment method is also a good predictor of the efficacy of diatomaceous earth at higher temperatures. The rapid assessment method predicted that Protect-It® would be the most efficacious, Pennac-P® least efficacious and the other three compounds would be intermediate.

With treatment of heat plus diatomaceous earth, the Protect-It® formulation was more effective than any of the other diatomaceous earth formulations. It resulted in consistently high mortality more quickly than the other products tested. Conversely, Pennac-P®, a calcium carbonate compound, appears to have no insecticidal activity against *T. castaneum* under these conditions and would be of no value in a pest management program for stored-product insects.

Acknowledgements

I thank M. Zuercher (USDA, Manhattan) and J. Ayala (Kansas State University) for assistance in the laboratory and F. Arthur (USDA, Manhattan), P. Fields (Agriculture & Agri-Food Canada, Winnipeg), Bh. Subramanyan (University of Minnesota) and P. Weston (Kentucky State University) for critical reviews of this manuscript. Insecto® was supplied by Natural Insecto® Product; Inc. Protect-It® was supplied by Hedley Technologies, Inc.

References

Fields, P.A., 1992. The control of stored-product insects and mites with extreme temperatures. Journal of Stored Products Research 28, 89–118.

Fields, P., Dowdy, A., Marcotte, M., 1997. Structural pest control: the use of an enhanced diatomaceous earth product combined with heat treatment for the control of insect pests in food processing facilities. Canada–United States Working Group on Methyl Bromide Alternatives. http://res.agr.ca/winn/Heat-DE.htm.

Golob, P., 1997. Current status and future perspectives for inert dusts for control of stored product insects. Journal of Stored Products Research 33, 69–79.

Hadley, N.F., 1994. Water Relations in Terrestrial Arthropods. Academic Press, San Diego.

Imholt, T., 1984. Engineering for food safety and sanitation: a guide to the sanitary design of food plants and food plant equipment. Technical Institute of Food Safety, Crystal, MN.

Korunic, Z., 1997. Rapid assessment of the insecticidal value of diatomaceous earths without conducting bioassays. Journal of Stored Products Research 33, 219–229.

Loschiavo, S.R., 1988. Availability of food as a factor in effectiveness of a silica aerogel against the merchant grain beetle (Coleoptera: Cucujidae). Journal of Economic Entomology 81, 1237–1240.

McLaughlin, A., 1994. Laboratory trials on desiccant dust insecticides. In: E. Highley, E.J. Wright, H.J. Banks, B.R. Champ (Ed.). Proceedings of the 6th International Working Conference on Stored-Product Protection. Canberra, Australia, pp. 638–645.

Quarles, W., Winn, P.S., 1996. Diatomaceous earth and stored product pests. IPM Practitioner 18, 1–10.

SAS Institute, 1995. SAS user's guide: statistics. SAS Institute, Cary, NC.

Steel, R.G.D., Torrie, J.H., 1980. Principles and Procedures of Statistics. McGraw-Hill, New York.

Subramanyan, Bh, Swanson, C.L., Madamanchi, N., Norwood, S., 1994. Effectiveness of Insecto®, a new diatomaceous earth formulation, in suppressing several stored-grain insect species. In: E. Highley, E.J. Wright, H.J. Banks, B.R. Champ (Ed.). Proceedings of the 6th International Working Conference on Stored-Product Protection. Canberra, Australia, pp. 650–659.

Vrba, C.H., Arai, H.P., Nosal, M., 1981. The effect of silica aerogel on the mortality of *Tribolium confusum* (Duval) as a function of exposure time and food deprivation. Canadian Journal of Zoology 61, 1481–1486.

White, N.D.G., Loschiavo, S.R., 1989. Factors affecting survival of the merchant grain beetle (Coleoptera: Cucujidae) and the confused flour beetle (Coleoptera: Tenebrionidae) exposed to silica aerogel. Journal of Economic Entomology 82, 960–969.

Use of Insect Traps in Mills

Michael A. Mullen
USDA ARS GMPRC
Manhattan, KS 66502

Pheromone traps can provide useful information to the mill operator. The most obvious is the presence or absence of insects at low levels. However, it can also be used to pinpoint the location of infestations by examining trap catch numbers from trap in nearby locations. Although not an exact science, to is possible to determine relative numbers of insect using a technique called spatial mapping. In this method spatial statistics are applied to trap catch numbers to produce contour maps similar to land contour maps. These maps can than be used to determine the location and relative numbers of insects in various locations throughout the facility. Using this method hidden pest populations can be identified and eliminated by treating only specific areas. This method has been used successfully in feed mills, processing plants, warehouses, and retail outlets.

Pheromone trapping is essential tool to develop an effective integrated pest management system (IPM). Traps provide an early warning monitoring system for pests. They work 24 hours a day, reduce labor costs associated with facility inspections, and provide scientifically sound information that can be used to make pest management decisions. A recent survey taken jointly by the USDA and the American Institute of Baking (AIB) in Manhattan has shown that most users found that traps are reasonable in cost and do provide useful information.

Until recently the most reliable method to estimate population of pest from pheromone trap was to compare trap catches from one sampling period to the next. Increased numbers generally means and increasing problem. With the development and application of spatial mapping information obtained from trap catch is more useful than ever.

Placement of traps in a facility must be tailored to fit each location, however, there are some basic guidelines that should always be followed. Ideally traps should be placed in a grid pattern, however, this is not always possible. Place traps near suspected problem areas and keep them away from heavy traffic areas. Employees should be informed of the importance of the traps and an effort should be made to ensure that they are not accidently destroyed, lost, or tampered with. Traps, especially in mills, can be quickly fouled with dust and become ineffective. Dust-resistant traps are being developed, but they can not eliminate the problem completely. To be dust-resistant traps must be covered and have a sufficient opening size that will not to impede insect entry or the flow of the pheromone plume. Unfortunately, it is difficult to meet all criteria to ensure a dust free trap. To reduce the problem traps with a sticky trapping surface must be replaced more frequently in dusty environments. Traps with an oil filled pit as the trapping surface can be cleaned with a rag and the oil replaced.

Traps should be checked on a regular schedule and lures should be replaced as recommended by the manufacture. Carefully collected trapping data will be a useful tool to make efficient and effective pest control decisions.

Use of Insect Traps in Mills

Michael A.Mullen
USDA, ARS, GMPRC
MANHATTAN, KS

WHAT INFORMATION DO WE GET FROM TRAPPING

- Presence or absence of insects
- Location of insects
- Species of insects
- Relative numbers

ADVANTAGES OF TRAPPING

- Work 24 hrs per day without complaining
- Relatively inexpensive
- Reduces labor costs
- Provides scientifically sound information

DISADVANTAGES OF TRAPPING

- Not always sure what the numbers trapped mean
- Traps can be lost
- Traps must be maintained
- Dust can be a problem

TRAP PLACEMENT

- Ideal method is to use a grid pattern but this is not always possible
- Place traps near suspected problem areas
- Keep away from high traffic areas

TRAP PLACEMENT (CONT.)

- Clearly label traps
- Traps in dusty areas should be serviced and cleaned frequently
- Inform and educate employees abouT traps and why they are important

DUST RESISTANT TRAPS

- Dust reduces the effectiveness of traps
- Sticky surfaces become coated and ineffective
- Oil baits can become clogged
- Escape proof trap become lose their ability to retain insects

DUST RESISTANT TRAPS (CONT.)

- Less exposed surface area means less dust problem
- Flite trak has developed a dust resistant cover that will be available soon as well as a low profile trap for moths

Spatial mapping of trapping data to interpret insect density and location

HIGH TEMPERATURE THERMAL DISINFESTATION

Rashid Qaisrani, Research Engineer, Stored Grain Research Laboratory, CSIRO, Canberra - AUSTRALIA

HEAT TREATMENT WORKSHOP – KANSAS STATE UNIVERSITY, MANHATTAN KS USA
4-6 AUGUST 1999

HIGH TEMPERATURE THERMAL DISINFESTATION

Rashid Qaisrani, Research Engineer, Stored Grain Research Laboratory,
CSIRO, Canberra - AUSTRALIA

Heat disinfestation is a controlled elevation of temperatures, evenly distributed across the storage for a predetermined exposure period at a selected temperature that is lethal to all stages of insect development. Heat treatment exposure temperatures varying from about 51-57°C for 12-24 hours are commonly used with good result. Most of the stored grain products insect can be killed instantly when grain temperature are raised to 60-63°C, It requires immediate cooling to avoid serious damage to stored grain products.

At present, storers and managers have few options to control insect pests in grain and storage structures. Heat treatment appears potentially very attractive as a further option, being both rapid and pesticide-free, Further research aims to provide new options using heat, that will be suitable for both large and small scale in-line as well as small scale (upto 60t) in-situ disinfestation, Heat has always been thought of as too expensive, but as the storage costs and options change and technological advances are being made, this is changing.

Advantages

- Reliable
- Comparatively safer
- Cost Effective
- Completely suppress the growth of pest population
- Grain quality is preserved to a larger extent

Disadvantages

- Higher initial costs
- Possible adverse impact on some machinery and equipment

Heat damage to grain depends upon

- Type of cereal grains heat treated
- Inlet air temperature
- Grain moisture contents at the time of heat treatment
- Time for which grains are subjected to higher temperature

Heat treatment techniques commonly used

A. Fluidised bed heat disinfestation system

Grains are fluidised with hot air. The throughput of the fluidised bed heat treatment system depends upon the air inlet temperature, bed height, width and length, grain moisture contents, and path length grain need to travel. A small scale fluidised bed heat treatment system for grain was developed by CSIRO, The unit was capable of heat treating grain upto 10 t/h. Another pilot plant was designed and built by CSIRO for VIC-Grain in 1980s and it was capable of heat treating grain upto 200t/h. The plant worked well and the only problem encountered during its operation was dust control in its air re-circulation system. Few of the filters and air inlet ports in the bed were blocked partially. It required frequent cleaning for effective operation. Some of the small scale fluidised beds are still in operation in Australia though most of these are used as driers rather than heat disinfestor. A fluidised paddy drier is very recently developed in Thailand. The design is based on Australian concept. Most of these fluidised bed driers can very easily be used as heat disinfestor with some minor modifications.

C. Spouted bed heat disinfestation system

Spouted bed is a modified (alternative) version of fluidised bed which allows air to enter through a nozzle (orifice) above which grains are fluidised. It then circulates grain, first falling into the surrounding area of low air velocity then re-entering the air stream. It develops lower pressures than fluidised beds and can be used for fluidising bigger grain size such as corn which otherwise is difficult to fluidise.

The temperature time relationships obtained from fluidised beds can be used as a guide for a pilot scale trials on spouted bed heat disinfestor The system comprises of a hopper bed (capacity depends upon the disinfestation rate) usually with a 60° conical bottom, Claflin (1986) reported that the mortality of immature *Rhizopertha dominica* was achieved in 2.5-13.5 minutes with an inlet air temperature between 180-80°C corresponding to grain final temperatures of 66-60°C. It was estimated that a spouted bed of 1 m diameter can disinfest grain at a rate of 3-4t/h and 2 m diameter bed can disinfest grain upto 10-15t/h. Higher throughputs can be achieved by increasing the number of cells. A seven cells spouted bed can disinfest grain at a rate of 50-200t/h depending upon the size of the hopper and air inlet temperature. Claflin (1986) observed in an experiment that insect mortality in spouted bed system is partially because of mechanical damage and partially because of heat. However spouting with ambient air took unacceptably longer time (hour)s to achieve reasonable mortality.

C. In-situ (in-bin) heat disinfestation system

A method based on established heat and mass transfer theory is presented for designing and predicting the performance of an on-farm heat disinfestation system. The method is new and is under investigation at Stored Grain Research Laboratory–CSIRO, Australia. We are investigating a system capable of heat treating 50t silos without moving grains out. This includes rapid heating to a predetermined temperature (possibly 57°C and maintaining it at that level for 4-6 hours) followed by passive cooling. The silo will be heated up to half of its depth by blowing hot air (70°C) in. Ambient air will then be blown in at a flow rate that will not disperse the temperature front created during heat treatment of grains. The top half of the silo will be heated up by moving the temperature front through it.

For given ambient and inlet air states, initial grain states and the quantity of grain, one can determine the airflow rate and heat input required to achieve a predetermined grain temperature in a specified time. Once airflow rate is determined, the corresponding air pressure drop encountered can be calculated for a particular type and size of the bin. It makes it easier to estimate the time required to heat up the grains to a predetermined temperature and then cool them back to a desired temperature.

Heat treatment strategy

Mortality of the stored product insects depends upon the temperature to which they are subjected and the time for which they are exposed to higher temperature. Therefore, it is important to choose a heat treatment strategy that will achieve control of pests without damaging grains. For fluidised and spouted beds heat disinfestation systems, higher inlet air temperatures and higher grain temperature (60-65°C for few seconds or for a couple of minutes) are selected as they are subjected to hot air currents for a very short period of time. Where as for in-bin (in-situ) heat disinfestation system, grain are subjected to hot air for longer time. It is therefore, important to heat up the grain to lower temperatures (55-57°C) and maintain at this temperature for longer time (hours).

Heat dosage for safer disinfestation of grains

It is important that the grains are not damaged in the process of killing insects. We need to determine the degree of damage at a range of temperature and grain moisture contents. Kreyger (1972) found that the germination of grains was unlikely to decrease by more than 15% if temperatures did not exceed 62.7, 61.7, 58.3 and 52.7°C for grains at equilibrium relative humidity of 60, 70, 80 and 90% respectively. Lindberg and Sorenson (1959) obtained similar results on germination and baking quality of wheat (Table 1). Table 2 shows time required to kill various insect at different grain temperatures.

Table 1: Temperature (°C) at which seed and baking quality of wheat are not likely to decline

	Moisture Content (%)						
Category	15	17	19	21	23	25	27
Seed	62.7	60	57.7	55	52.7	48.9	48.9
Baking	67.2	63.3	60	57.2	55	55	49.4

Source: Lindberg and Sorenson (1959)

Table 2: Time required (min) to kill Stored Product Beetles in an oven

		Temp °C		
Species		50	60	70
Stiphilus granarius (all stages)		55	2	--
S.oryzae:	Adults	70	3.5	1.8
	Larvae	120	16	7
Oryzaephilus surinamenis: Adults		3.1	0.6	0.4

Ghaly and Taylor (1982) stated that wheat at 12% moisture contents could be heated to 70°C for periods longer than those required to kill the insects without damaging its germination and quality. Complete kill of *Rhyzopertha dominica* was achieved at temperatures 65-70°C at an air flow rate of 2.1-2,4 kg/s-m^2 in 2.5 – 4.5 minutes without damaging grain in any form in a fluidised bed experiment. Using an inlet air temperature of 165°C and maximum grain temperature of 65°C, Thorpe and Evans (1983) predicted that at 50t/h grain can be dried from 14% to 12% moisture contents in fluidised bed without affecting grains adversely.

65°C grain temperature (2 minutes required to kill all the pests)
Ref: Dermott and Evans (1978)

54°C grain temperature (12-24 hours to kill all the pests)
Ref: Heaps and Black (1994)

51-57°C grain temperature (24-30 hours to kill all the pests)
Ref: Clarke (1998)

65°C grain temperature (2 minutes to kill all the pest when inlet air temperature is 80°C and few seconds when inlet air temperature is 100°C)
Ref: information obtained personally from Stephen Backett

Williams, M. W. and C. S. Williams. 1964. Collection and toxicity studies of ant venom. Proc. Soc. Exp. Biol. and Med. 116: 161-3.
Williams, M. W. and C. S. Williams. 1965. Toxicity of ant venom. Further studies of the venom from *Pogonomyrmex barbatus*. Proc. Soc. Exp. Biol. and Med. 119: 344-6.

J. Georgia Entomol. Soc. 8(4) October, 1973 pp. 249-64.

ELEVATED TEMPERATURES TO CONTROL INSECT INFESTATIONS IN WHEAT

Robert L. Kirkpatrick and Elvin W. Tilton[1,2]
Stored-Product Insects Research and Development Laboratory
Agricultural Research Service, USDA
Savannah, Georgia 31403

ABSTRACT

Samples of wheat containing rice weevils, *Sitophilus oryzae* (L.), and lesser grain borers, *Rhyzopertha dominica* (F.), of known age were exposed to temperatures of 39±1 C or 43.3±1 C with relative humidities ranging from 75 to 50% during a 4-day adult ovipositional period, and a continuous exposure to 39±1 C and 60% relative humidity during immature stages of development. Ninety-nine percent or more control was obtained at 39±1 C with a relative humidity of 60% for the rice weevil and at 43.3±1 C with a relative humidity of 50% for the lesser grain borer.

Key Words: Elevated temperature, rice weevils, lesser grain borers, stored-grain insects.

Temperature and humidity are two important physical factors that affect the growth and development of insects. During the early part of this century Dean *et al.* (1937) developed a method for using hot air recirculated from steam radiators to heat flour mills to temperatures ranging from 49-51 C for 10 to 12 hr to control insects. This method was found to be effective and inexpensive, and the heat had no deleterious effect on the baking qualities of the flour.

Recently, studies have been made of the potential use of microwaves (Baker *et al.* 1956, Boulanger *et al.* 1971, Kirkpatrick and Roberts 1971) and infrared (Frost *et al.* 1944, Tilton and Schroeder 1963, Kirkpatrick and Tilton 1972) heating of infested commodities for insect control. Both microwave heating (Tilton *et al.* 1972) and infrared heating (Cogburn *et al.* 1971) have been suggested as adjuncts to gamma radiation to increase the effectiveness and lower the dose of gamma radiation required for insect control.

In these suggested techniques, commodity temperatures ranging from ca. 49 to 65 C are required. If bulk commodities are heated to this level and placed in storage, commodity temperatures of 40 C or above are

[1]The assistance of Aklee Cagle, Agricultural Research Technician, is gratefully acknowledged.

[2]Mention of a commercial or proprietary product in this paper does not constitute an endorsement of this product by the U.S. Department of Agriculture.

likely to be maintained for several days, unless provisions are made to cool the commodity purposely. Certainly, it should be possible to maintain temperatures in excess of 40 C with supplemental heating through aeration systems.

Okasha *et al.* (1970) showed that exposures of *Rhodnius* adults to sublethal high temperatures not only inhibited reproduction during the exposure period but also exerted harmful effects on their activity when they were returned to normal temperature conditions. However, Cogburn (1967) found that a short exposure to a sublethal dosage of infrared radiation (at 44 C or more) did not inhibit reproduction of surviving rice weevils, *Sitophilus oryzae* (L.); lesser grain borers, *Rhyzopertha dominica* (F.); or Angoumois grain moths, *Sitotroga cerealella* (Olivier).

Humidity may also be a limiting factor in insect survival during exposure to elevated temperatures. Exposure to high temperatures for short periods of time (ca. 1 hr) may be less severe under dry conditions than if the air is moist. However, after exposure periods of 24 hr or more the effect is reversed and desiccation may be a major factor in insect mortality (Edney 1957). If heat retained from infrared or microwave treatments could be used to supplement the initial effects of that treatment, then the use of lower treatment temperatures might be possible. The study reported here was conducted to determine the effects of 4-day exposure during the adult oviposition to 39±1 C or 43.3±1 C at various relative humidities and also to determine the effects of continuous exposure to 39±1 C and 60% relative humidity on the egg, larvae, or pre-emerged adult mortality and reproduction of the rice weevil and lesser grain borer.

METHODS AND MATERIALS

Rice weevils and lesser grain borers used in the tests were from laboratory strains reared for many generations on wheat under standard conditions of ca. 27±1 C and 60±3% relative humidity. In each test 32 samples of 200 g of wheat were infested. Sixteen infested samples were treated and 16 samples served as checks in each test. A temperature of 39±1 or 43.3±1 C was used in all treatments. At all times, except during the treatment period, both treated and untreated samples were maintained at a temperature of 27±1 C and 60±3% relative humidity. Moisture analyses were made at random among samples of wheat before and immediately after the various treatments with an automatic Steinlite moisture meter. The average moisture content before treatment was 14.5±0.5% and after treatment the moisture was ca. 12.2±0.5%.

The first test was designed to determine the effects of temperature and relative humidity on adult mortality and reproductive potential. Fifty unsexed adult rice weevils or lesser grain borers were placed in each sample.

Samples containing rice weevil adults were treated for 4 days in a Precision Scientific Model 805 incubator maintained at 39±1 C at 75, 65, or 60% relative humidity. Adult rice weevils were removed from the wheat, checked for mortality, and discarded. Samples of wheat were returned to standard conditions of 27±1 C and 60±3% relative humidity for F_1 emergence observations.

The same procedure was used for the lesser grain borers, except that the adults were treated at 39±1 C and 60% relative humidity or 43.3±1 C and 50% relative humidity.

Table 1. Percentage of reduction of adult rice weevils and lesser grain borers exposed to elevated temperatures during a 4-day oviposition period and the numbers and percentages of reduction in their F_1 progeny.[1]

Species	Temperature (±1 C)	Relative humidity (±3%)	P_1 adult mortality (%)	F_1 progeny from P_1 adults	
				Emergence (No.)	Reduction (%)
Rice weevil	39	75	1.8	35	99.5
	39	65	12.1	4	>99.9
	39	60	100	1	>99.9
Lesser grain	39	60	8	3,855	26.3
borer	43.3	50	99.7	1	>99.9

[1]Untreated insects maintained at 27±1 C and 60±3% relative humidity. The treated insects also remained at these conditions except during the 4-day treatment.

A second test was designed to determine the effects of 39±1 C and 60% relative humidity on various stages of insect development. One hundred unsexed adult rice weevils or lesser grain borers, ca. 1.5 wk old, were placed in each sample for a 4-day oviposition period. These samples of wheat were infested 1-5, 15-19, or 25-29 days before treatment to give egg, larval, or pupal and pre-emerged adult stages of development. The infested wheat to be treated was placed in 39±1 C and 60% relative humidity conditions on the 5, 19, and 29 day after oviposition and remained in the treatment chambers until the test was completed.

RESULTS AND DISCUSSION

The percentage of mortality for the treated adult rice weevils and lesser grain borers and for their progeny is shown in Table 1. Rice weevil mortality increased as the relative humidity decreased. There was little or no difference in the mortality of the treated and untreated rice weevil adults when the treated insects wre exposed to a temperature of 39±1 C and 75% relative humidity. However, when the relative humidity was lowered to 60%, 100% control of rice weevil adults was obtained. In contrast, only 8% mortality was obtained with the lesser grain borer adults treated at 39±1 C and 60% relative humidity. However, when the temperature was raised to 43.3±1 C and the relative humidity lowered to 50%, mortality increased to 99.7%.

Numbers of progeny of treated adult rice weevils, exposed 4 days to temperature of 39±1 C and at 75, 65, and 60% relative humidities, were reduced 99% or more. However, the number of lesser grain borer progeny was reduced only 26.3% at 39±1 C and 60% relative humidity. A temperature of 43.3±1 C with a 50% relative humidity reduced number of progeny more than 99.9%.

The emergence and percentage of reduction during the second test

Table 2. Number emerged and percentage of reduction in emergence of rice weevils and lesser grain borers exposed in different developmental stages to 39±1 C and 60% relative humidity until test was completed.[1]

Species	Emergence		
	Untreated (No.)	Treated (No.)	Reduction (%)
Rice weevil			
Egg	8,618	0	100
Larva	8,957	0	100
Pupa and pre-emerged adult	13,226	151	98.9
Lesser grain borer			
Egg	7,416	708	90.5
Larva	11,632	108	99.1
Pupa and pre-emerged adult	15,809	5,538	65.0

[1]Untreated insects maintained at 27±1 C and 60±3% relative humidity. The treated insects remained at these conditions except during exposure to 39±1 C and 60% relative humidity.

for 3 developmental stages of the rice weevil and the lesser grain borer within kernels of wheat are shown in Table 2. The amount of infestation varied, but it was sufficient in all age groups to yield reliable results. The temperature of 39±1 C and 60% relative humidity gave 100% control of the rice weevils in both the egg and larval stages of development (20 days or less). Only 1% of the rice weevils that were treated during their pupal and pre-emerged adult stages (25-29 days) of development emerged. Lesser grain borer eggs and larvae were less susceptible to these conditions than were rice weevils—reduction of eggs was 90.5% and of larvae, 99.1%. Thirty-five percent of the pupal and pre-emerged adult stages (25-29 days of development) of the lesser grain borers survived these conditions.

These data suggest that heat retention from an infrared, microwave, or other heat treatment to grain may be an effective supplemental insect control method.

LITERATURE CITED

Baker, V. H., D. E. Wiant and O. Taboada. 1956. Some effects of microwaves on certain insects which infest wheat and flour. J. Econ. Entomol. 49(1): 33-7.

Boulanger, R. J., W. M. Boerner and M. A. K. Hamid. 1971. Microwave and dielectric heating systems. Milling 153(2): 18-28.

Cogburn, R. R. 1967. Infrared radiation effects on reproduction by three species of stored-product insects. J. Econ. Entomol. 60(2): 548-50.

Cogburn, R. R., J. H. Brower and E. W. Tilton. 1971. Combinations of gamma and infrared radiation for control of the Angoumois grain moth in wheat. J. Econ. Entomol. 64(4): 923-5.

Dean, G. A., R. T. Cotton, and G. B. Wagner. 1937. Mill insects and their control. USDA Cir. No. 390, rev. ed., 40 pp.

Edney, E. B. 1957. The Water Relations of Terrestrial Arthropods. Cambridge University Press, London. 93 p.

Frost, S. W., L. E. Dillis and J. E. Nicholas. 1944. The effects of infrared radiation on certain insects. J. Econ. Entomol. 37(2): 287-90.

Kirkpatrick, R. L. and J. R. Roberts. 1971. Insect control in wheat, by use of microwave energy. J. Econ. Entomol. 64(4): 950-1.

Kirkpatrick, R. L. and E. W. Tilton. 1972. Infrared radiation to control adult stored-product Coleoptera. J. Ga. Entomol. Soc. 7(1): 73-5.

Okasha, A. Y. K., A. M. M. Hassanein and A. Z. Farahat. 1970. Effects of sub-lethal high temperature on an insect. *Rhodnius prolixus* (Stal.). J. Exp. Biol. 53: 25-36.

Tilton, E. W. and H. W. Schroeder. 1963. Some effects of infrared irradiation on the mortality of immature insects in kernels of rough rice. J. Econ. Entomol. 56(6): 727-30.

Tilton, E. W., J. H. Brower, G. A. Brown and R. L. Kirkpatrick. 1972. Combination of gamma and microwave radiation for control of the Angoumois grain moth in wheat. J. Econ. Entomol. 65(2): 531-3.

J. Georgia Entomol. Soc. 8(4) October, 1973 pp. 264-8.

WING FOLDING IN *PINOTUS CAROLINUS* (COLEOPTERA: SCARABAEIDAE: SCARABAEINAE)

Henry R. Hermann and Cecil L. Smith
Department of Entomology
University of Georgia
Athens, Georgia 30602

ABSTRACT

The metathoracic wings of Coleoptera are considerably larger than their protective coverings, the elytra. In order to be accommodated beneath the elytra, the wings generally must be folded both longitudinally and transversely. Since many buprestid species possess broad wings that are not longer than the elytra, there is no transverse fold.

Key Words: Transverse folding, longitudinal folding, convex and concave folding.

With the exception of Forbes' rather comprehensive treatment of wing folding in the Coleoptera (1926a, 1926b), very little attention has been directed towards the exact procedure involved in this process (Britton 1970, Chapman 1969, Jeannel 1949, Snodgrass 1935). In his paper, Forbes ascertained, in various degrees of completeness, the folding patterns as they exist in the wings of many of the coleopteran families.

His treatment of superfamily Scarabaeoidea (Lamellicornia), which includes the Scarabaeidae, Passalidae and Lucanidae, was relatively limited since he considered this a very homogeneous group in both folding and venation, the principal difference being the relative size of the apical region of the wing. The folding scheme of only two species of this group, *Lachnosterna fusca* and *Osmoderma* sp. (both Scarabaeidae), were presented.

Since individual variations in wing flexing, which occur between the many and diverse species in this group, have been largely ignored, a representative *Pinotus carolinus* (Linn.) (Scarabaeidae: Scarabaeinae), was selected to elucidate its specific folding pattern.

MATERIALS AND METHODS

Specimens of *P. carolinus* preserved in 95% ethanol were used in this study. Wing venation and folding patterns were determined by first removing the left elytron of individual specimens and then the underlying wing was severed at its points of attachment at the wing base. The outer part of the wing has then partially and gradually unfolded, plotting the remaining folds as they became visible, always with reference to the veins so far as they could be seen, and noting in every case whether the folds were convex or concave as seen in the unfolded wing, and whether the areas were right side up or reversed in folding.

RESULTS AND DISCUSSION

The hind wing of *P. carolinus* and other coleopteran species is extended into the flight position by the contraction of the direct flight muscles, rotating the wing forward on its base. This movement results in a simultaneous spreading of the wing, opening the longitudinal folds (Fig. 1). This, in turn, automatically opens the transverse folds (TFld, Fig. 1, A) due to the inherent stiffness of the wing membrane. As a result, the costal edge, which is acutely folded at the hinge (TFld) when at rest, straightens as the wing is rotated forward. This forward motion also causes the cubital (CuFld) and jugal folds (JFld) to open and the entire wing flattens as the membrane tightens.

Flexing of the wing is initiated by a relaxation of the flight muscles. This results in a general relaxation of the wing membrane causing the jugal fold (JuFld) to flip back into place under the wing surface, and automatically leads to folding along the longitudinal lines of stiffness produced by adjacent veins (CuFld and MFld, Fig. 1, A). Only in the Archostemmata and Myxophaga does this plan of flexion vary significantly. In these groups the apices of the wings are rolled into a double spiral instead of being folded.

Once longitudinal folding is accomplished the wing is in a position to be folded transversely, the transverse folding mechanism being centered on the costal hinge (TFld, Fig. 1, A). The exact lines of transverse folding are predetermined by terminations of and weak hinge-points in the veins. The final stage of closure is assisted by movements of the abdomen, legs

Control of the Lesser Grain Borer, *Rhyzopertha dominica* (F.), and the Rice Weevil, *Sitophilus oryzae* (L.), in Wheat with a Heated Fluidized Bed[1]

H. H. VARDELL AND E. W. TILTON
Stored-Product Insects Research and Development Laboratory, Agricultural Research, Scientific and Educational Administration, USDA, Savannah, Georgia 31403

ABSTRACT: Grain temperatures of 67° and 60°C in a heated fluidized bed completely controlled all stages of the lesser grain borer, *Rhyzopertha dominica* (F.), and rice weevil, *Sitophilus oryzae* (L.), respectively, in wheat. No holding time at treatment temperatures was necessary when the grain was brought up to these temperatures.

There is currently a great need for a rapid means of disinfesting grain in the marketing channels. Most of the disinfesting procedures now in use, i.e., fumigation or insecticide treatments, require holding times of several days before shipment, leave undesirable residues on the grain, or both. There is a renewed interest in the elimination of these problems through the use of high temperature for insect control in grain. Much recent work has been done with microwave, dielectric, and infrared heating as a means of disinfesting grain (Boulanger et al., 1971; Nelson, 1973; Kirkpatrick and Tilton, 1972; Kirkpatrick et al., 1972; Kirkpatrick, 1975; Watters, 1976). In general, all of these workers evaluated the effectiveness of rapid heating of grain as a means of disinfestation.

Dermott and Evans (1978) evaluated the use of a fluidized bed for the disinfestation of wheat with air temperatures of 60°, 70°, and 80°C. Because of the efficiency of heat transfer and short grain retention time, this method of grain disinfestation seemed promising indeed.

The tests described here were designed to determine the grain temperatures required with a heated fluidized bed to completely control all stages of the lesser grain borer, *Rhyzopertha dominica* (F.), and the rice weevil, *Sitophilus oryzae* (L.), infesting wheat.

---

[1] This paper presents the results of research only. Mention of a commercial or proprietary product in this paper does not constitute an endorsement by this product by the USDA.

Received for publication 25 August 1980.

Material and Methods

This test was conducted with a batch treatment fluidized bed assembled at this laboratory. The bed used a centrifugal fan with a vertical outlet, which was adapted to fit a 56-cm length of 15.24-cm diameter sheet metal tubing. Within the adaptor was mounted a 15.24-cm diameter, 1500 w Calrod® surface heating unit, which served as the heat source. The sheet metal tube had a stainless-steel screen (4 × 4 mesh per cm) mounted 5 cm from the bottom and served as the treatment chamber.

Temperatures were monitored during testing by means of thermistors inserted through the walls of the adaptor and the treatment chamber. These were positioned: 1) in the center of the fan intake opening, 2) in the plenum of the adaptor 10 cm above the heater element, 3) in the center of the grain mass, and 4) in the head space 10 cm above the grain surface. Preliminary testing showed that the maximum weight of wheat that could be fluidized in the bed was 700 g. Air flow through the bed was 11.6 liter per sec. Air temperature in the plenum was maintained at 80°C.

The insects used were obtained from the rearing facility of this laboratory, where they have been in culture for many years. Each of the two species were handled separately. Jars containing ca. 500 g of soft red winter wheat were infested with ca. 250 adults and held in a constant temperature cabinet maintained at 27° ± 1°C and 60% RH until the first progeny began to emerge. Thus, all stages of the insects were present in the infested cultures. For treatment, the insect cultures were sieved to remove the dust. One culture was thoroughly mixed with 5.5 kg of soft red winter wheat of ca. 12.25% moisture content. This mixture was then divided into 700-g samples. These samples were then used as one replicate. The grain for each replicate was handled separately. Each of the 700-g samples of infested wheat was treated in the fluidized bed until the wheat reached the designated treatment temperature as indicated by the thermistor in the wheat. The treatment chamber was then immediately removed from the blower unit and the wheat dumped from the chamber. No attempt was made to cool the grain. Each treatment sample (700 g) was subdivided into 5 subsamples for ease of handling and counting. Each subsample was placed in a 0.27-liter Mason jar and covered with filter paper and screen wire lids, which were held in place with a metal ring. The jars containing the subsamples were then placed in a constant temperature cabinet maintained at 27° ± 1°C and 80% RH for maturation of the immatures. Post-exposure survival counts were made after 1 week. Each subsample was sieved at weekly intervals and adult insects counted for 6 weeks. The emerged adults were then discarded, the wheat returned to the jar, and the jars returned to the constant temperature room until the next counting.

The time needed for the grain to reach the treatment temperature was

Table 1. Mean[1] percentage lesser grain borer emergence relative to controls from wheat treated in a heated fluidized bed at the indicated temperatures.

Treatment temperature (°C)	No. of weeks postexposure					
	1	2	3	4	5	6
55	[2]57.8 a	46.9 a	42.0 a	42.9 a	31.6 a	38.0 a
57	52.0 ab	35.1 ab	32.2 ab	34.6 ab	23.1 a	39.5 a
59	29.3 bc	21.1 bc	17.3 b	13.4 bc	10.9 b	20.2 ab
61	15.1 cd	13.2 c	10.4 b	3.7 c	8.0 bc	10.3 b
63	10.3 d	7.7 cd	6.0 bc	5.2 cd	5.8 bc	9.0 bc
65	0.6 d	0.5 d	0.7 c	0.4 d	0.6 c	1.3 c
67	0 d	0 d	0 c	0 d	0 d	0 d

[1] All means are based on 5 replicates except those from treatment at 65°C, which are based on 10 replicates.

[2] Means in a column followed by a different letter are significantly ($P < 0.05$) different according to Duncan's multiple range test.

dependent upon the temperature increase from ambient to the treatment temperature. These times varied from 1.75 to 4.75 minutes to reach 50° and 67°C, respectively, at an ambient temperature of 26°C at the time of treatment. The controls were treated with air at ambient temperature for ca. 2 minutes. Each treatment was replicated 5 times, except the 65°C treatment for the lesser grain borer and 58°C treatment for the rice weevil, which were replicated 10 times.

The numbers of emerging adults were transformed to percentage of the number of adults emerging from the control for that replicate to eliminate any variation due to a difference in infestation rate of the wheat among replicates. The mean percentage emergence from each treatment and week post exposure was analyzed by use of Duncan's multiple range test at the 0.05 level of significance.

Results

LESSER GRAIN BORER: In general, the numbers of emerging F_1 adult lesser grain borers decreased with each increase in treatment temperature (Table 1). Results of 55° and 57°C treatments did not differ significantly from each other or from the controls. However, even after exposure at these low temperatures, the overall numbers of emerging adults for the 6 weeks' post exposure were 43.2 and 36.1 percent of the controls at 55° and 57°C, respectively. Each successive week post emergence yielded fewer emerging adults, except in the sixth week, in which the numbers of emerging adults during this last week of the test are the sum of the F_1 and F_2 progeny emerging during that week. In general, control of the lesser grain borer exceeded 99% after treatment at 65°C. Complete control was attained when the grain was heated to 67°C.

Table 2. Mean[1] percentage rice weevil emergence relative to controls from wheat trea in a heated fluidized bed at the indicated temperatures.

Treatment temperature (°C)	No. of weeks postexposure					
	1	2	3	4	5	6
50	[2]61.7 a	39.3 a	34.7 a	22.6 a	25.8 a	35.0 a
52	32.2 b	22.4 b	20.5 b	14.7 b	10.9 b	19.6 b
54	17.0 c	15.0 c	12.4 c	6.7 c	4.5 c	14.2 c
56	10.6 d	7.6 d	4.4 d	1.2 d	2.0 d	3.7 d
58	0.6 e	0.5 e	0.0 e	0.0 e	0.0 e	0.1 d
60	0.0 f	0.0 f	0.0 e	0.0 e	0.0 e	0.0 e

[1] All means are based on 5 replicates except those from treatment at 58°C which are ba on 10 replicates.

[2] Means in a column followed by a different letter are significantly ($P < 0.05$) differ according to Duncan's multiple range test.

RICE WEEVIL: With each 2°C increase in treatment temperature from through 58°C, the numbers of emerging F_1 adult rice weevils was signi cantly reduced during each of the post-exposure sampling periods (Table The numbers of emerging adult rice weevils were slightly reduced duri the 5th and 6th weeks post-exposure sampling periods. These increas appeared to be a result of the beginning of the emergence of the F_2 adu and thus were the sum of the end of the F_1 emergence plus the first of t F_2 emergence adult rice weevils. During the 5th week sampling period, adults emerged from the 58° or 60°C treatments. During the 6th week po exposure sampling period, 99.9% control was attained with the 58°C tre ment, and complete control was attained with the 60°C treatment.

Overall, exposure of wheat infested with the rice weevil at 58°C produc a 99%+ reduction in the numbers of emerging adults. Control was comple after treatment at 60°C. Grain moisture was 12.25% before treatment a 12.0 and 10.8% for the 50 and 67°C treatments, respectively, after treatme

Discussion

The results reported here generally agree with those reported by Dermo and Evans (1978). The main differences between their test and that report here are the exposure times and the cooling after treatment. The treatme time necessary to disinfect grain by this method is dependent upon t temperature change of the grain from ambient to 67°C. Therefore, final gra temperature must be used as the treatment end point and not treatment tim as inferred by Dermott and Evans (1978). Dermott and Evans (1978) al cooled the grain after treatment by means of an additional fluidized bed ar evaporative cooling. This type of cooling restores some of the grain moistu lost during treatment. However, the cost of providing the airflow for fi

ev. ..nergence relative to controls from wheat treate
ed temperatures.

No. of weeks postexposure			
3	4	5	6
34.7 a	22.6 a	25.8 a	35.0 a
20.5 b	14.7 b	10.9 b	19.6 b
12.4 c	6.7 c	4.5 c	14.2 c
4.4 d	1.2 d	2.0 d	3.7 d
0.0 e	0.0 e	0.0 e	0.1 d
0.0 e	0.0 e	0.0 e	0.0 e

xcept those from treatment at 58°C which are base

lifferent letter are significantly ($P < 0.05$) differe
t.

ncrease in treatment temperature from 50
nerging F_1 adult rice weevils was signifi
post-exposure sampling periods (Table 2)
ice weevils were slightly reduced during
sure sampling periods. These increase
inning of the emergence of the F_2 adult
of the F_1 emergence plus the first of the
During the 5th week sampling period, no
atments. During the 6th week post
l was attained with the 58°C trea
tained with the 60°C treatment.
ed with the rice weevil at 58°C produce
emerging adults. Control was complet
sture was 12.25% before treatment an
eatments, respectively, after treatmen

cussion

y agree with those reported by Dermo
ces between their test and that reporte
cooling after treatment. The treatmen
y this method is dependent upon the
ambient to 67°C. Therefore, final grain
ment end point and not treatment time
1978). Dermott and Evans (1978) also
eans of an additional fluidized bed and
ng restores some of the grain moisture
cost of providing the airflow for flui

dization is a major cost of the treatment. This added cost, as well as the additional delay of the grain flow, would be detrimental factors in the use of fluidized beds. Cooling of the grain in a fluidized bed after treatment may not be necessary. If the grain from the heated fluidized bed is transported in a pneumatic system, there may be enough cooling for the safe storage of the grain. This hypothesis should be verified with large-scale testing.

The heated fluidized bed was determined to be an effective means of controlling the lesser grain borer and the rice weevil in wheat. Largescale studies should be conducted to determine the most efficient means of providing this rapid treatment for grain before recommendations can be made for its use by the grain industry.

Literature Cited

Boulanger, R. J., W. M. Boerner, and M. A. K. Hamid. 1971. Microwave and dielectric heating systems. Milling 153(2):18–21, 24–28.

Dermott, T., and D. E. Evans. 1978. An evaluation of fluidized-bed heating as a means of disinfesting wheat. J. Stored Prod. Res. 14:1–12.

Kirkpatrick, R. L. 1975. Infrared radiation for control of lesser grain borers and rice weevils in bulk wheat (Coleoptera: Bostrichidae and Curculionidae). J. Kans. Entomol. Soc. 48:101–104.

Kirkpatrick, R. L., J. H. Brower, and E. W. Tilton. 1972. A comparison of microwave and infrared radiation to control rice weevils in wheat (Coleoptera: Curculionidae). J. Kans. Entomol. Soc. 45:434–438.

Kirkpatrick, R. L., and E. W. Tilton. 1972. Infra-red radiation to control adult stored product coleoptera. J. Ga. Entomol. Soc. 7:73–75.

Nelson, S. O. 1973. Insect-control studies with microwave and other radio-frequency energy. Bull. Entomol. Soc. Am. 19:157–163.

Watters, F. L. 1976. Microwave radiation for control of *Tribolium confusum* in wheat and flour. J. Stored Prod. Res. 12:19–25.

PERGAMON

Journal of Stored Products Research 36 (2000) 309–318

Journal of STORED PRODUCTS RESEARCH

www.elsevier.com/locate/jspr

Control of insects and mites in grain using a high temperature/short time (HTST) technique

H. Mourier[a,*], K.P. Poulsen[b]

[a]*Danish Pest Infestation Laboratory, Skovbrynet 14, DK 2800, Lyngby, Denmark*
[b]*Department of Biotechnology, Building 221, Technical University of Denmark, DK 2800, Lyngby, Denmark*

Accepted 7 November 1999

Abstract

Wheat infested with grain mites (Acari) and *Sitophilus granarius*, and maize infested with *Prostephanus truncatus*, were exposed to hot air in a CIMBRIA HTST Microline toaster®. Inlet temperatures of the hot air were in the range of 150–750°C decreasing to outlet temperatures in the range of 100–300°C during the exposure period. A rotating drum, connected to a natural-gas burner was fed with grain which was in constant movement along the drum and thereby mixed thoroughly during the process. The capacity of the toaster was 1000 kg per hour.

Complete control of grain mites and adult *S. granarius* in wheat was obtained with an inlet temperature of 300–350°C and an average residence time in the drum of 6 s. More than 99% mortality was obtained for all stages of *S. granarius* with an inlet temperature of 300–350°C and an average exposure period of 40 s. For control of *P. truncatus* in maize, an inlet temperature of 700°C resulted in a complete disinfestation when the exposure time was 19 s.

The reduction in grain moisture content was 0.5–1% at treatments giving 100% control. Germination tests indicate that it is possible to choose a combination of inlet temperatures and exposure periods which effectively kills mites and insects in small grains, without harming the functional properties of the grain.

Economy of the method was considered to be competitive with fumigation using phosphine. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: HTST treatment; Grain insects; Grain mites

* Corresponding author. Tel.: +45-45-87-80-55; fax: +45-45-93-11-55.
E-mail address: ssl@ssl.dk (H. Mourier).

0022-474X/00/$ - see front matter © 2000 Elsevier Science Ltd. All rights reserved.
PII: S0022-474X(99)00054-5

1. Introduction

For many years chemical control measures have dominated the methods for pest control in grain, but recently more interest has been directed towards non-chemical methods.

Such methods are needed because all major species of stored product insects have developed varying degrees of resistance to the limited number of insecticides which are internationally accepted for use on grain (Champ and Dyte, 1976; Taylor 1989). At the same time, new chemicals that are safe enough for use on foodstuffs are only slowly becoming available, because of the high cost of developing and registering them. Increasingly sophisticated markets are expecting that cereals and other foodstuffs are "residue free", and in organic food production the use of insecticides is ruled out.

A technique that has been used successfully for many years against stored-product pests is the use of elevated temperatures. The thermal limits of insects and mites usually fall between 0 and 45°C, and temperatures within these limits determine the rates of population growth. More extreme temperatures have an acute influence. At the upper limit, the high temperatures destabilize phospholipid membranes and affect intracellular proteins adversely (Bligh et al., 1976). Heat disinfestation requires only that all particles of a given batch of infested grain are heated to an appropriate lethal temperature/time combination, and this is basically a simple process. It can be adapted to both "low tech" (Kitch et al., 1992) and "high tech" circumstances.

Research on high temperature control has focused on using hot air in a fluid bed, spouted bed or pneumatic conveyer equipment, and on the use of high frequency waves, microwaves and infrared radiation to heat the grain or flour before rapidly cooling the commodity (Buscarlet, 1990).

Information on susceptibility to high temperatures is scattered and comparisons are difficult because many factors influence the results. The temperatures fluctuate and are difficult to measure, while the rates of heating and cooling depend on the method used, the product being treated, its moisture content (m.c.) size distribution and several other factors.

Different mite and insect species and stages have different susceptibilities to heat treatment, but most species will not survive more than 12 h at 45°C, 5 min at 50°C and 30 s at 60°C (Fields, 1992). Mortality is obviously related to the temperature to which the insects are exposed and the exposure period, but recent research indicates that the rate at which the grain is heated is also of importance, an increased rate of heating apparently giving higher mortality (Evans, 1986).

The sensitivity of the commodity to high temperatures varies with, among other factors, m.c., and is measured in terms of decreased germination and deleterious chemical and biochemical changes (Pomeranz, 1992). Many different ways of determining the influence of heat on protein quality, nutritional value, vitamin content, functional properties like baking ability, etc. have been reported (Theander and Westerlund, 1988; Friedman et al., 1987; Holm et al., 1988).

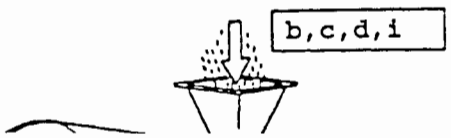
Earlier research has shown that short heating periods permit grain to be heated to much higher temperatures than would be acceptable in conventional grain drying (Sutherland et al., 1986).

This study was conducted as part of a major research project on heat treatment of grain, the effect on mould and mycotoxins having already been reported (Wilkins et al., 1992), to determine the effect on insect and mite mortality of various time/temperature exposures in an experimental HTST toaster.

2. Materials and methods

2.1. Equipment

The experiments were performed in a HTST Microline toaster, ("Cimbria Unigrain Ltd", Denmark). The heating of the grain is achieved by contact with air heated directly from a natural-gas burner in combination with infra-red radiation. The grain is moved through a



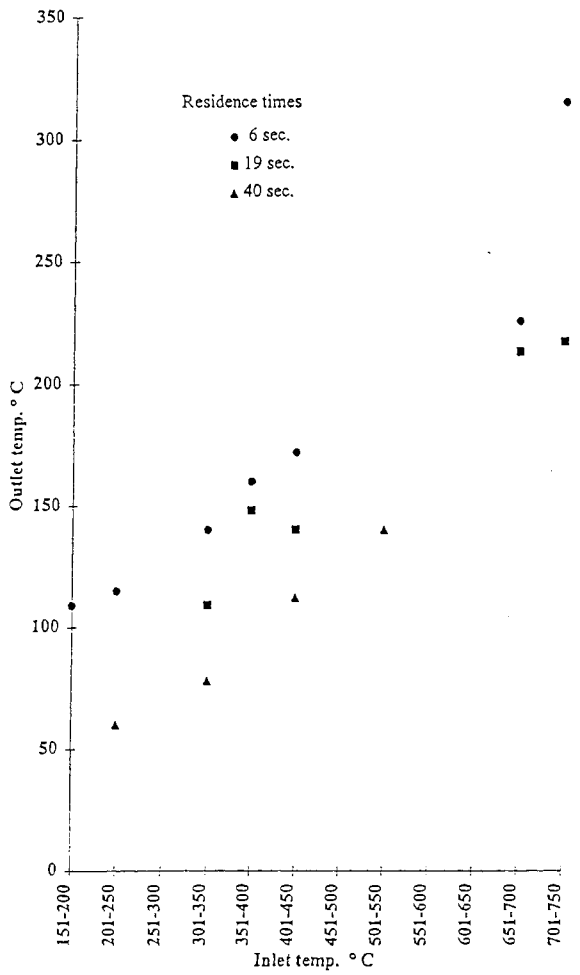


Fig. 2. Relation between inlet and outlet temperatures, measured in the drum at different residence times. Feed load and revolutions per minute were kept constant.

rotating drum by a combination of inclination of the drum, and air velocity. The drum is furnished with blades that mix the grain thoroughly during the process (Fig. 1).

Intensity of treatment depends on several factors: Air temperature at inlet of grain, air flow, temperature and m.c. of material at inlet, amount loaded into the drum and residence time for the material.

The air temperature in the drum was measured with thermosensors, located at the inlet and outlet of the drum. During the process the temperature of the grain increases and the air temperature decreases. Inlet and outlet temperatures at different residence times are shown in Fig. 2. To calculate the energy efficiency, average temperatures of the grain at the outlet were measured by filling a thermos flask furnished with a thermometer which was read after

equilibrium was reached. Directly after the heat treatment, the kernels were cooled by air and reached ambient temperatures in about 2 min.

Attempts were made to measure surface temperature of the grains at the outlet with a Minolta infrared thermometer calibrated before use by heating grain to well defined relevant temperatures.

Air velocity in the drum was measured by a revolving vane anemometer. The rate of flow during the tests was 400–600 kg per hour.

Average residence times of 6, 19 and 40 s were chosen for the actual tests, corresponding to 15, 6 and 3 degrees inclination of the drum respectively.

The distribution of the residence times of the kernels leaving the drum at the three average times aimed at (6, 19 and 40 s) was measured by adding samples of 150 coloured grains to the grain flowing through the drum. At different time intervals samples were collected at the outlet, and the number of coloured grains was counted.

2.2. Insects

The granary weevils (*Sitophilus granarius* (L.)) used in the tests were from a laboratory strain reared for several generations at the Danish Pest Infestation Laboratory (DPIL) on wheat at approximately 25 ± 2°C and 65 ± 5% r.h. The infested grain was produced by placing 600 granary weevils, approximately two weeks old, in plastic containers with 500 g clean wheat. After a six-day oviposition period the adult beetles were sieved from the grain. The infested grain was then incubated for varying periods at 25°C and 65 ± 5% r.h. In this way, batches of six age groups were produced, representing the egg stage (0–6 days), young larvae (12–18 days), old larvae (26–30 days), pupae and pre-emerged adults (30–36 days) and adults.

The infested grain batches of each age group were thoroughly mixed and divided into samples of 1.2 kg each. Each of these were mixed with 8.8 kg of uninfested wheat, to give test samples of 10 kg.

The larger grain borer, *Prostephanus truncatus* (Horn), also came from a strain that had been reared for several generations on maize at 25 ± 2°C and 65 ± % r.h.

The test samples were produced by mixing 2 kg infested maize grains, containing a mixture of stages, with 8 kg of clean maize.

The grain mites for the tests came from samples taken from a grain store, naturally infested with several species belonging to the genera *Lepidoglyphus, Acarus* and *Tyrophagus*. The infested grain was mixed with clean wheat to give 10 kg test samples.

At all times, except during the transport from DPIL to Cimbria Unigrain Ltd and back, and during the treatment period, both treated and untreated samples were kept at 25 ± 2°C and 65 ± 5% r.h.

2.3. Disinfestation procedure and assessment of mortality

The procedures for *S. granarius, P. truncatus* and the mites were similar.

From each 10 kg test sample, one subsample of 500 g was taken for observation of the control emergence from an untreated sample.

On the basis of preliminary tests inlet temperature ranges from 150–200°C to 700–750°C

Table 1
Percentage reduction in survival (as measured by emergence) of different stages of *Sitophilus granarius* in wheat exposed to different temperature/time combinations[a]

	Average exposure time								
	6 s			19 s			40 s		
Inlet temperature (°C)	Surviving (n/kg)	Reduction (%)	Stage	Surviving (n/kg)	Reduction (%)	Stage	Surviving (n/kg)	Reduction (%)	Stage
150–200				438	25.7	o.l.	682	45.4	o.l.
				879	39.2	y.l.			
				322	57.7	o.l.			
200–250				664	14.1	y.l.	370	59.3	o.l.
							394	71.8	o.l.
250–300							80	88.9	o.l.
							12	98.8	o.l.
							44	99.7	o.l.
							0	100	o.l.
300–350	0	100	ad.	197	72.5	o.l.	0.6	99.9	o.l.
				244	75.8	y.l	0	100	o.l.
350–400	0	100	e.	3.3	99.2	e.	0	100	o.l.
							0	100	o.l.
400–450	48	93.5	p.	12	98.3	p.	0	100	o.l.
	16	97.5	o.l.	0	100	y.l.			
	0	100	y.l.	0	100	o.l.			
				0	100	ad.			
450–500							0	100	o.l.
500–550	3.7	99.6	o.l.	50	99.2	o.l.			
				2	99.7	y.l			
550–600	0.6	99.9	o.l.						
600–650	0	100	y.l.	0.4	99.9	o.l.			
	0	100	o.l.	0	100	e.			
				0	100	y.l.			
650–700									
700–750	1.5	99.8	o.l.	0	100	y.l.			
	0	100	e.	0	100	o.l.			
	0	100	y.l.	0	100	p.			
	0	100	p.						
Control emergence 550–1375/kg									

[a] e.: eggs; y.l.: young larvae; o.l.: old larvae; p.:pupae; ad.: adults. Each set of data represents the treatment of one 9.5 kg sample. Corresponding outlet temperatures see Fig. 2.

were chosen for the tests. Combinations of inlet temperatures and residence times for the different species are shown in Table 1.

When the desired flow rate and air-inlet temperature were adjusted in the toaster, using clean grain, an infested sample of 9.5 kg was sent through the system. As the treated grain left the drum, it was directed into the air cooler and reached room temperature in about 2 min.

One sample of 2 kg was then taken for the assessment of mortality, and a 200 g sample for measurement of m.c. The emerged adult beetles *S. granarius* and *P. truncatus* were sieved from the grain and counted 50 days after the last egg-laying day to make sure that all survivors had emerged. The grain mites were sieved from the samples 5 days after the treatment, and surviving mites counted. The number emerged from each sample, treated and controls, was corrected to a standard sample size of 1 kg, and the effect of the treatment was calculated as the percent reduction in emergence in relation to the control.

2.4. Grain quality

The m.c. of both heat-treated and untreated grain was determined by weighing 2 g ground grain samples before and after drying in an oven at 130°C for 2 h.

3. Results

Inlet temperatures of 300–350°C used for exposure periods as short as 6 s resulted in 100% mortality of adult *S. granarius* (Table 1). For average residence times of 6 s an inlet temperature of 500–550°C was needed to obtain more than 99% kill of the juvenile stages living inside the wheat kernels.

At 19 s residence time an inlet temperature range of 400–450°C was necessary to obtain 99% mortality of all stages. A 40 s exposure period — a realistic residence time in a full scale toaster — and inlet temperatures of 300–350°C were sufficient to obtain more than 99% disinfestation of small grains, wheat in this case.

The observations on wheat infested by grain mites were performed at 6 s residence time only, and resulted in almost complete mortality at inlet temperatures of 200–250°C (Table 2).

Table 2
Percentage reduction in survival (as measured by emergence) of grain mites in wheat exposed to different temperatures for 6 s[a]

Inlet temperature (°C)	Surviving (n/kg)	Reduction (%)
150–200	–	–
200–250	354	95.6
400–450	0	100
Control emergence	8070	

[a] Each set of data represents the treatment of one 9.5 kg sample. Corresponding outlet temperatures see Fig. 2.

High inlet temperatures of 700–750°C for a residence time of 19 s were needed for complete control of *P. truncatus* (Table 3).

The distribution of the residence times of the kernels in the drum show standard deviations between 0.5 and 4.9 for the average residence times aimed at in the present tests: 6, 19 and 40 s, corresponding to inclinations of the drum of 15, 6 and 3 degrees respectively (Table 4). The air velocity in the drum during the tests was measured as between 2 and 3 m/s. The reduction in grain m.c., at the temperature/time combinations observed, was relatively small. Using grain at 12.5% m.c., the water loss was 0.5–1%.

4. Discussion

As the grain kernels rotate and collide during their passage through the drum, theoretical considerations concerning heat transfer to the kernels are complicated. Furthermore, the surface temperature of the kernels is influenced by radiation from the inner wall of the drum and from the burner. Attempts to measure surface temperature of grains by infrared cameras were not accurate because of the influence from the hot surroundings.

Calculation of the Biot number hr/k (h being heat transfer coefficient, r the radius of the sphere, and k the thermal conductivity) assuming that kernels are spheres and only heated from the surrounding hot air, demonstrates that the air velocity should be more than 15 m/s in order to obtain a higher surface than centre temperature (Müller, 1995). As actual air velocities were measured at about 2 m/s, this was too low to create temperature gradients inside the kernels.

It is evident that considerable variability exists as regards the residence time in the drum. This is partly explained by the fact that for particles of similar shapes, the residence time in the drum of the small particles will be shorter than that of the larger (Stokes law, analogies). As

Table 3
Percentage reduction in survival (as measured by emergence) of *Prostephanus truncatus* in maize exposed to different temperature/time combinations[a]

	Average exposure time			
	6 s		19 s	
Inlet temperature (°C)	Surviving (n/kg)	Reduction (%)	Surviving (n/kg)	Reduction (%)
150–200	357	None	295	None
200–250	175	35.3	111	44.4
400–450	163	None	56	70.9
600–650	0.8	99.5	8	89.9
700–750	0.9	99.3	0	100
Control emergence 79–231/kg				

[a] Each set of data represents the treatment of one 9.5 kg sample.

the smaller particles need a shorter processing time, in this way all particles are given a relatively uniform treatment and the risk of over/under treatment is partly neutralized.

However, the variability in exposure period may explain that a few individuals survive even at high temperatures e.g. 99.8% mortality at 700–750°C and 6 s residence time.

Germination tests carried out in connection with the studies on the effect of the HTST treatment on *Tilletia caries* (De Candolle) Tulasne (Hansen, 1993) showed only a marginal decline in germination properties at inlet temperatures of 400°C and residence periods of 19 s.

The investment for a toaster with a capacity of 25 tonnes per hour is about GBP 100,000. Based on an annual throughput of 40,000 tonnes fixed costs can be calculated as 0.5 GBP per tonne. The energy consumption necessary to obtain complete disinfestation of insects from wheat is calculated to be 20 Mcal per ton. This principal cost element can be calculated as 0.4 GBP per tonne. This is competitive with insecticide treatment but both energy prices and taxation on insecticides vary greatly from place to place so that it is hard to draw definite economic conclusions.

5. Conclusion

The data suggest that complete disinfestation of grain infested by grain mites and insects living outside the kernels can be performed using a HTST process without harming the quality of the grain.

Control of insect stages living inside kernels by this technique may result in some decrease of germination properties but the grain will still be useful for food and feed. Heat treatment can therefore be used as an alternative to fumigation and insecticide treatment.

Table 4
Distribution of residence times of wheat grains in the drum[a]

	Residence time (s)		
Number of grains	Mean	Dispersion	Standard deviation
151	5.5	4.2–6.7	0.6
154	5.7	3.5–7.0	0.6
159	6.2	2.2–7.3	0.8
152	6.7	5.4–8.0	0.5
144	17.9	14.9–24.1	2.0
150	18.5	13.2–24.4	2.8
136	19.5	16.2–28.7	2.3
141	20.5	16.3–24.3	1.9
133	45.4	36.5–54.4	4.9

[a] The results relate to three settings, 15, 6 and 3 degrees inclination of the drum.

Acknowledgements

This work was funded by the Danish Directorate for Development. We thank Ole Toftdahl Olesen from Cimbria Unigrain Ltd for assistance.

References

Bligh, J., Cloudsley-Thomson, J.E., MacDonald, A.G., 1976. Environmental physiology of animals. Blackwell Scientific Publications, Oxford.

Buscarlet, L.A., 1990. Methodes physiques de protection des denrées alimentaires stockées. In: Fleurat-Lessard, F., Ducom, P. (Ed.). Proceedings 5th International Working Conference on Stored Product Protection, Bordeaux, France, vol. 2, pp. 1089–1102.

Champ, B.R., Dyte, C.E. 1976. Report of the FAO global survey of pesticide susceptibility of stored grain pests, FAO Plant Production and Protection Series no 5. (Food and Agricultural Organisation of the United Nations, Rome).

Evans, D.E. 1986. Some biological and physical constraints to the use of heat and cold for disinfesting and preserving stored products. In: Donahaye, E., Navarro, S. (Eds.), Proceedings 4th International Working Conference on Stored Product Protection, Tel Aviv, Israel, pp. 149–164.

Fields, P.G., 1992. The control of stored-product insects and mites with extreme temperatures. Journal of Stored Products Research 28, 89–118.

Friedman, M., Gumbmann, M.R., Ziderman II 1987. Nutritional value and safety in mice of proteins and their admixtures with carbohydrates and vitamin C after heating. In: Antinutritional Effects of Heated Proteins. American Institute of Nutrition.

Hansen, S.H. 1993. HTST-behandling af korn, Bekæmpelse af hvedens stinkbrand *Tilletia caries*. Report, Department of Biotechnology, Technical University of Denmark, 161 pp.

Holm, J., Björck, I., Eliasson, A., 1988. Effects of thermal processing of wheat on starch: I. Physico-chemical and functional properties. Journal of Cereal Science 8, 249–260.

Kitch, L.W., Ntoukam, G., Shade, R.E., Wolfson, J.L., Murdock, L.L., 1992. A solar heater for disinfesting stored cowpeas on subsistence farms. Journal of Stored Products Research 28 (4), 261–267.

Müller, C. 1995. Continuous HTST treatment of grain. M.Sc. University of Reading and Technical University of Denmark.

Pomeranz, Y. 1992. Biochemical,functional and nutritive changes during storage. In: Sauer, D.B. (Ed.), Storage of cereal grains and their products. American Association of Cereal Chemists, St.Paul, pp. 55–118.

Sutherland, J.W., Evans, D.E., Fane, A.G., Thorpe, G.R. 1986. Disenfestation of grain with heated air. In: Donahaye, E., Navarro, S. (Eds.), Proceedings 4th International Working Conference on Stored-Product Protection, Tel Aviv, Israel, pp. 261–274.

Taylor, R.W.D., 1989. Phosphine — a major fumigant at risk. International Pest Control 31, 10–14.

Theander, O., Westerlund, E., 1988. The effects of aqueous ethanol-soluble carbohydrates and protein in heat-processed whole grain wheat and white flour. Journal of Cereal Science 7, 145–152.

Wilkins, C.K., Torngren, C., Filtenborg, O., Poulsen, K.P. 1992. Destruction of mold spores, mycotoxins and insects in grain by HTST (High Temperature Short Time) treatment. In: Singh, R.P., Wirakartakusumah, M.A. (Eds.), Advances in Food Engineering. CRS Press, Boca Raton, USA, pp. 263–272.

S.P.E.R.E.S.
STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE
Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

IDENTIFYING FEATURES

Red flour beetle adults are small and reddish-brown in color. Adults are 2.3-4.4 mm long and 0.97-1.26 mm wide with 11-segmented, club-shaped antennae (Figure 1). In the red flour beetle, the 3 terminal antennal segments are significantly larger than the other antennal segments. However, in a related species—the confused flour beetle, *Tribolium confusum* (Jacquelin duVal)—the antennal segments increase gradually in size from the base to the tip (Figure 2). Furthermore, in the red flour beetle adults, the compound eyes extend ventrally, and distance between eyes on the ventral side is equal to the transverse ventral diameter of the eye (see Figure 2). The front and middle pairs of legs have 5 tarsal segments, while the hind pair has 4 tarsal segments. The femur of the front pair of legs in males has a hairy puncture on the ventral surface (Figure 3). This aspect is absent in females. The hairy puncture, also referred to as the sex or setiferous patch, is believed to be the site of pheromone production (see section on 'Chemical Ecology' for details).

Figure 1. Scanning electron micrograph of the head of an adult red flour beetle.

Figure 2. Scanning electron micrograph showing the ventral view of the head of adult red flour beetle (top) and confused flour beetle (bottom).

Unlike the confused flour beetle, the red flour beetle can fly. Red flour beetle eggs are oblong and white. They are 0.6-0.7mm long and 0.3-0.4 mm wide. The eggs are tacky, and therefore, eggs laid in flour are covered by finer flour particles.

The larvae are yellowish white. The tenebrionid larvae have a characteristic shape with 3 pairs of legs. These larvae closely resemble wireworms or larvae of the click beetles. Therefore, tenebrionid larvae are sometimes called false wireworms. The cuticle

of red flourbeetle larva is hard (sclerotized) and has a banded appearance with 2 pointed projections (Urogomphi) at the tip of the 9th abdominal segment (Figure 4). The 1st through 4th abdominal segments of larva have 2 hairs (setae) above and 2 below an imaginary line drawn from the spiracle (Figure 5). The femur of the first pair of legs on the ventral side has 3 setae (Figure 6).

The 1st instar is 1.1 mm long, and the head capsule is 0.2 mm wide. Typically there are 6-7 instars. The instars can be distinguished either by head capsule width measurements or by weight. Larvae that go through 6 instars tend to develop faster and have a lower body weight than those that go through 7 instars. The individuals that go through 7 instars are better able to withstand adverse environmental conditions. Adults emerging from such individuals are less productive but are more resistant to environmental adversity. On the other hand, adults emerging for larvae that go through 6 instars are more productive and are considered "colonizers". The pupa is white (naked), 3.3-3.4 mm long, 1.1 mm wide, and weighs about 2.5 mg. External genitalic structures on pupae can be used to separate males and females (Figure 7).

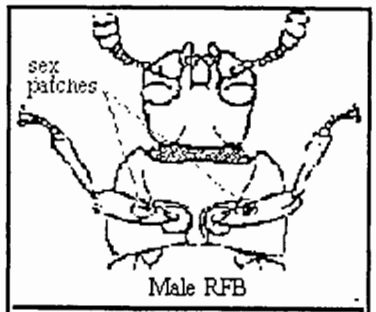


Figure 3. Hairy puncture on the femur of the front pair of legs is present only in red flour beetle males (top). This puncture, also known as the sex or setiferous patch (SP) (bottom), has fluted setae and secondary reservoirs (SR). The aggregation pheromone is secreted from this site.

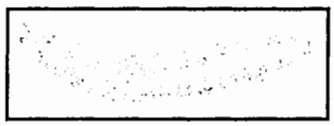


Figure 4. Larva of the red flour beetle with pointed projections (Urogomphi) at the tip of the abdomen.

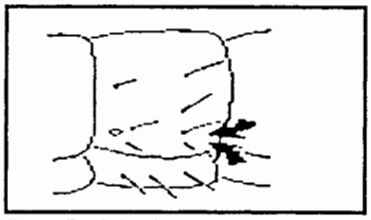


Figure 5. Abdominal segments 1- 4 of larva, each with 2 hairs above and 2 below an imaginary line drawn posterity from spiracle (round opening in picture).

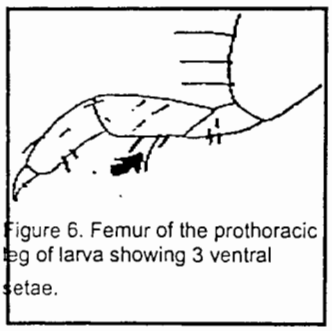


Figure 6. Femur of the prothoracic leg of larva showing 3 ventral setae.

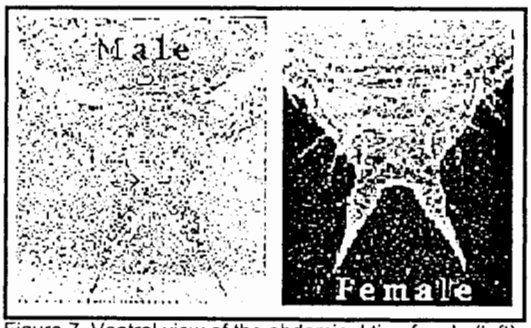


Figure 7. Ventral view of the abdominal tip of male (left) and female (right) pupa of the red flour beetle. The 2 long processes at the tip are the Urogomphi. Above the Urogomphi, the genital papillae (finger-like structures) are easily apparent in females. These structures are greatly reduced in males.

Identifying Features | Life History | Chemical Ecology | Trapping and Monitoring
Pesticide Resistance | Signs of Insect Presence and Damage | Web Sites

S.P.E.R.E.S.
STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE
Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

LIFE HISTORY

In nature, red flour beetles have been reported from bee nests in Hawaii and acorns in South Africa. However, the beetles were able to successfully infest acorns only with a longitudinally split testa or seed coat. Red flour beetles have been reported from bark habitats in Britain, United States, West Indies, and India. The bark habitat provides protection from predators as well as food sources of both plant and animal origin. Natural habitats exist for many stored product insects. However, large populations are always associated with manufactured, harvested, and/or stored food and feed products. The red flour beetle is an economic pest because of its association with stored cereal grains, oilseeds, nuts, dried fruits, spices, and pulses (legumes). Both larvae and adults feed on seed embryo, grain dust, and broken kernels. Beetles also survive and reproduce on molds, notably *Alternaria, Mucor, Cladosporium, Nigrospora, Absidia, Curvularia* and *Scopulariopsis.* In stored grain, the beetles are often found in damp or moldy grain. When there are too many insects present relative to the available food (i.e., under crowded conditions), adults and larvae tend to be cannibalistic and feed on eggs and pupae of their own species.

On sound or undamaged grain kernels, these insects develop less effectively than on damaged or broken kernels. Damage to kernels by machines during harvesting and handling, or by insects such as the weevils and borers during storage, creates an ideal environment for red flour beetle infestation and establishment. Therefore, red flour beetles are considered secondary pests, because of their reduced ability to successfully feed and thrive on sound kernels. These insects prefer floury materials and are important economic pests in flour mills, grocery stores, and homes.

The production of adults on various food products is variable, and the addition of yeast significantly enhances progeny production (Table 1). Therefore, yeast is added to whole-wheat flour when culturing these insects in the laboratory.

Table 1. Effect of yeast on red flour beetle progeny production in four food substrates at 29°C and 70% relative humidity. Five pairs of adults were placed on 4g of food, and were transferred every 3 days to 4g of fresh food. There were six such transfers.

Food Substrate	Mean No. Adults, w/o Yeast	Mean No. Adults, w/ Yeast
Corn	543.5	914.0
Polished rice	9.5	720.0
Whole wheat flour	409.5	1,030.0
Soy	183.5	218.0

Red flour beetle adults have a long life span. Under laboratory conditions (18-29°C), the average life span of males and females is 130 and 198 days, respectively. Some red flour beetle adults have been reported to live for several years. Mating occurs 17-26 hours after emergence. Adults are capable of reproduction throughout their life. Eggs are laid by females 10-15 days after emergence. At 25°C and 70% relative humidity, a mated female lays 3-5 eggs/day for the first few days followed by 2-3 eggs/day for the rest of her life. A female, on average, lays a total of 360 eggs (range, 195-569 eggs). Typically, egg laying decreases in females over 100 days old.

Temperature affects both adult longevity and the number of eggs laid (Table 2). At cooler temperatures (20°C and 14-16% moisture food), adult survival is essentially unaffected, but few or no eggs are laid by the females. At warmer temperatures (27°C and 32°C), adult survival decreases with age. At these temperatures, females lay a majority of eggs within the first 8 weeks. Relative humidity affects the number of eggs laid. Fewer eggs are laid at 30% relative humidity than at 70% relative humidity. Egg hatchability is generally high, about 84% (range, 76-93%). At the end of adult life, only 20% of the eggs laid by females hatch successfully.

Table 2. Effect of temperature and relative humidity on the number of eggs laid by female red flour beetles.

Temperature, °C (°F)	Relative Humidity	Mean No. Eggs/Female*
25.0 (77.0)	30%	84.4
30.0 (86.0)	30%	186.9
35.0 (95.0)	30%	413.1
22.5 (72.5)	70%	119.2
25.0 (77.0)	70%	146.1
27.5 (81.5)	70%	352.0
30.0 (86.0)	70%	253.0
32.5 (90.5)	70%	539.2
35.0 (95.0)	70%	466.4
37.5 (99.5)	70%	355.0

* Mean number of eggs laid in 7 weeks

Development from the egg to adult stage takes 66 days at 22.5°C and 22 days at 37.5°C. The developmental time is shortest at 35°C (Table 3). Table 4 gives the percentage of time spent in egg, larval, and pupal stages (immature stages) when reared on diets of less than 12% or more than 12% moisture. On less than 12% moisture diets, a greater percentage of time is spent in the larval stage compared with insects reared on diets of more than 12% moisture. At a given diet moisture level, the percentage of time spent in egg, larval, and pupal stages is consistent across a broad range of temperatures. Thus, the duration of each immature stage can be calculated by multiplying the percentage of time spent in egg, larval, or pupal stage with the egg-to-adult developmental time. For example, at 30°C and on more than 12% moisture diets, the egg, larval, and pupal developmental

times are 0.15 x 24.3 = 3.6 days, 0.66 x 24.3 = 16.0 days, and 0.19 x 24.3 = 4.6 days, respectively.

Table 3. Mean egg-to-adult developmental time of red flour beetles at various temperatures*.

Temperature, °C (°F)	Mean Duration (Days)
22.5 (72.5)	66.4
25.0 (77.0)	41.9
27.5 (81.5)	28.2
30.0 (86.0)	24.3
32.5 (90.5)	19.7
35.0 (95.0)	18.8
37.5 (99.5)	21.7

*Data based on insects reared on wheat flour + 5% yeast diet.

Table 4. Mean percentage of time spent in egg, larval, and pupal stages on more than 12% and less than 12% moisture diets*.

Stage	Diets With More Than 12% Moisture	Diets With Less Than 12% Moisture
Egg	15	11
Larva	66	74
Pupa	19	15

* Data based on insects reared on wheat, wheat flour, millet and cracked corn.

Identifying Features | Life History | Chemical Ecology | Trapping and Monitoring
Pesticide Resistance | Signs of Insect Presence and Damage | Web Sites

BACK TO INSECTS & IPM

S.P.E.R.E.S.
STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE
Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

CHEMICAL ECOLOGY

Glands on the thorax and abdomen of red flour beetle adults produce compounds that have a characteristic odor. These compounds, first identified in 1943, primarily consist of 2-methyl-1,4 benzoquinone and 2-ethyl-1,4 benzoquinone. Adults produce these compounds when they are disturbed. Therefore, benzoquinones may play a role in insect defense. The benzoquinones have been reported as anti-bacterial, anti-fungal, and spermicidal. Methyl quinone is used in contraceptive preparations. The synthetic benzoquinones have a rat sub-cutaneous LD50 (lethal dose that kills 50% of test animals) of 25-50 mg/kg of body weight. The LD50 of natural benzoquinones (those isolated from Tribolium spp.) is 46 mg/kg against a cba/J strain of mice. Sub-acute poisoning in humans is known to produce jaundice, anemia, hemoglobinuria (hemoglobin in urine), and thrombocytopenia (abnormal decrease in platelet numbers). Synthetic benzoquinones have been implicated as carcinogens. However, there is no evidence to suggest that humans exposed to these compounds through infested food will develop cancer.

In addition to producing benzoquinones, the male red flour beetles produce a pheromone, 4,8-dimethyl decanal, from the setiferous patch (Figure 3) located on the ventral side of the prothoracic femora (femur of the 1st pair of legs). This pheromone attracts both sexes, and therefore, serves as an aggregation pheromone. Generally, males produce the pheromone after contacting and ingesting food. Therefore, attraction of adults to the pheromone is greatly increased in the presence of food volatiles. In the laboratory, more males than females responded to the pheromone. Responses of mated and unmated adults were similar, suggesting that attraction to the pheromones was independent of mating status. However, response to the pheromone changes with insect age. Under laboratory conditions, about 63% of 19-day old adults responded to the pheromone compared with only 40% of 1-3 day old adults. This increased response to pheromone by older adults coincides with adult maturity and female egg laying discussed above. Typically adults respond to the pheromone throughout the day, but under laboratory conditions, more adults responded to the pheromone between 12:00 noon and 2:00 PM. However, insects breeding outdoors or under different temperature and light conditions may respond at different times.

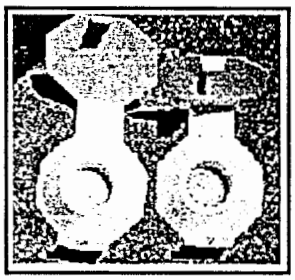
Identifying Features | Life History | Chemical Ecology | Trapping and Monitoring
Pesticide Resistance | Signs of Insect Presence and Damage | Web Sites

BACK TO INSECTS & IPM

S.P.E.R.E.S.
STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE
Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

TRAPPING AND MONITORING

The aggregation pheromone is commercially available as part of a Flit-Trak trap kit. Each kit contains 5 pheromone lures, a bottle with a food lure (oil), 5 filter paper disks, 5 shallow plastic holders, and 5 cardboard enclosures with holes for the lures (adjacent figure). Our research, and that of others, has shown that more beetles are attracted to food lure plus pheromone compared with food lure or pheromone alone. Insects attracted to the food and pheromone lures fall into the shallow receptacle containing the oil. Adults suffocate and die as the oil spreads on the insect's body, clogging the spiracles (exterior openings of the insect respiratory system). The efficiency of Flit-Trak traps in capturing red flour beetles has been characterized under laboratory conditions. In general, the traps capture only 20-30% of the released red flour beetles (about 50-100 beetles were released in these experiments). Presently there are other commercially available traps for red flour beetle (example, Pantry Patrol).



The food-baited traps should not be used in bulk-stored grain, as the food odors from the grain will mask the effectiveness of these traps. The traps are best suited for placement in homes, warehouses, flour mills, feed mills, pet stores, and grocery stores, to detect and monitor red or confused flour beetles. The traps can also be used before and after a control treatment (with pesticides or alternatives) to judge the degree and duration of insect control.

What is the "zone of influence" of a red flour beetle pheromone or food-baited trap? For red flour beetles, the maximum distance from which insects respond to the pheromone or food lure has not been experimentally determined. This information is valuable for determining the minimum distance between traps, and consequently the optimum number of traps to be used in a given area. Anecdotal reports from users indicate that the Flit-Trak traps with the pheromone plus food bait are effective only short distances. However, it is unclear what that short distance might be. If traps are indeed effective only short distances, it is clearly an advantage. For example, insects captured in traps would indicate an infestation near trap vicinity. If visual inspection does not reveal an infestation, then it would be logical to assume that red flour beetles arrived at the trap site from a distance, as the beetles are strong fliers. Therefore, interpreting red flour beetle trap catches is difficult. Furthermore, the absence of insects in traps does not indicate that the area being trapped is insect-free. Sometimes, insects may be present at low levels but are not attracted to the trap. Therefore, using more traps is always better than using fewer traps when monitoring red flour beetles. More work is needed to determine the biological (adult age, sex, actual density, flight patterns) and environmental (wind speed and direction, temperature) factors affecting capture of red flour beetles in traps.

In the absence of objective information on "zone of influence of a trap" and the environmental and biological factors that affect trap catches, it would be difficult to develop a cost-effective monitoring program. Although there is limited information on the "zone of influence" of the traps, one can still use these traps to detect and monitor red flour beetles. The traps may be placed on the floor or under pallets, and off the floor in any convenient location (pallet racks, beams, etc.). Traps should be placed near suspected sources of infestation or foods susceptible to infestation. A grid pattern for trap placement is usually recommended. However, it is not necessary to place traps in a grid pattern as long as trap locations are marked. This allows one to map trap locations, and analyze trap catch data using mapping programs (for example, *Surfer* for MS Windows). Mapping the distribution of insect numbers, along with the distributions of temperature, relative humidity, and food availability within a facility helps in understanding reasons for such distributions, and in precisely targeting pest management measures.

Identifying Features | Life History | Chemical Ecology | Trapping and Monitoring
Pesticide Resistance | Signs of Insect Presence and Damage | Web Sites

BACK TO
INSECTS & IPM

S.P.E.R.E.S.
STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE
Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

PESTICIDE RESISTANCE

The red flour beetles, by far, are the most commonly tested species with pesticides to document or determine resistance. Resistance in red flour beetles to pesticides, based on laboratory evaluations, is severe and widespread. There are numerous studies documenting resistance in red flour beetles to different classes of insecticides. Widespread resistance to lindane, a chlorinated hydrocarbon, in red flour beetles collected from 85 countries around the world during 1972-73 was reported in 1977. Despite the use of synergized pyrethrins for several decades, these beetles have not developed high levels of resistance to them. For example, only 2 of the 16 strains collected from peanut warehouses in southeastern United States showed a low level of resistance to synergized pyrethrins. The level of resistance to organophosphates among red flour beetle populations or strains is variable. Resistance to malathion is severe in red flour beetles collected from different parts of the world. The magnitude of malathion resistance steadily increased between 1970 and 1995, a result of increased use of malathion to protect stored food products, especially raw commodities. Some strains of red flour beetles are resistant to other organophosphates such as dichlorvos, etrimfos, fenitrothion, methacrifos, pirimiphos-methyl, and chlorpyrifos-methyl. Resistance to pyrethroids has been documented in red flour beetles infesting grain in Australia. For example, two strains of red flour beetles from Australia are resistant to the following pyrethroids: bioresmethrin, cyfluthrin, cyhalothrin, cypermethrin, deltamethrin, fenvalerate, flucythrinate, fluvalinate, permethrin, and d-phenothrin. These two strains are also resistant to carbaryl, chlorpyrifos-methyl, fenitrothion, malathion, methacrifos, and pirimiphos-methyl. Resistance in red flour beetles to methyl bromide is not severe. However, resistance to phosphine in red flour beetles collected from grain stores and flour mills is steadily increasing. Nevertheless, field failures due to resistance development have been documented only with malathion and some pyrethroids. It is important to note that most resistance assessments are done under laboratory conditions. Laboratory assessments, which do not take insect behavior into consideration, fail to document the actual level of resistance in insects. For example, the ability of insects to escape pesticide treatment by crowding, immobility, narcosis, and seeking refuge in cracks and crevices, significantly affects insect susceptibility to pesticides. More work is needed to document and manage red flour beetle resistance to pesticides in "real-life" settings.

There is renewed interest in exploring alternatives to control stored product insects, because of the 1996 Food Quality Protection Act which threatens to cancel organophosphates currently used for stored product protection, resistance development in insects, and increased use of IPM practices by the grain and food industry. IPM methods currently being explored for red flour beetle control in food processing facilities include the use of diatomaceous earth, heat, or a combination of diatomaceous earth and heat.

Identifying Features | Life History | Chemical Ecology | Trapping and Monitoring

S.P.E.R.E.S.
STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE
Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

SIGNS OF INSECT PRESENCE AND DAMAGE

Adult activity on the food surface is the most obvious indicator of an infestation. This usually occurs in laboratory culture jars, and may not occur under field conditions until populations reach high levels. Larval and adult tunnels are common in infested flour, as well as on dusty surfaces in food processing facilities and grain elevators. Tunnels or tracks on dusty surfaces, especially in a flourmill, may indicate red or confused flour beetle infestation. Foods infested with red flour beetles for several months contain all life stages of the insect, cast skins, and fecal pellets. The food material may also be discolored or tainted with a disagreeable odor. The odor is due to benzoquinones secreted by the adults. Food quality is decreased as infestation leads to an increase in free fatty acid and uric acid contents. Bread made from flour infested with red flour beetles for a month is of poor quality, having reduced loaf volume, color changes, and off flavor and odor. The benzoquinones bind to proteins. Therefore, food materials infested with red flour beetles will impart the odor even after all the insects have been killed or removed from such food. Cooking does not completely remove the odors from infested food. Therefore, it is important to prevent food contamination by red flour beetles. If food is infested with the beetles, it is advisable to discard the food rather than consume it.

Identifying Features | Life History | Chemical Ecology | Trapping and Monitoring
Pesticide Resistance | Signs of Insect Presence and Damage | Web Sites

BACK TO
INSECTS & IPM

S.P.E.R.E.S.

STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE

Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

WEB SITES

Note: All the links in this page point to external sites. Clicking on any of them will take you out of the S.P.E.R.E.S Proposal site. You may want to use your browser's 'Back' button to come back here.

There are several web sites that deal with basic biology and control of red flour beetles. Some sites contain specific information on molecular biology, genetics, and population dynamics of red flour beetles.

For information on rearing and handling red flour beetles, we highly recommend the following web site: http://bru.usgmrl.ksu.edu/beeman/tribolium.html
This page also has excellent insect pictures and information on red flour beetle mutants, genetics, and genes associated with insecticide resistance.

Basic information on controlling red flour beetles in homes is given at the following site: http://pmo.umext.maine.edu/factsht/flourbtl.htm

Excellent line slides with notes on the insect are available at http://www.okstate.edu/OSU_Ag/agedcm4h/pearl/e912/ch13/ch13f15.htm

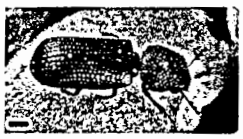
Identifying Features | Life History | Chemical Ecology | Trapping and Monitoring
Pesticide Resistance | Signs of Insect Presence and Damage | Web Sites

BACK TO INSECTS & IPM

RECOGNITION OF ADULTS
OF STORED-PRODUCT INSECTS

Rennie Roesli
Department of Grain Science and Industry
Kansas State University
for
Flour Milling Short Course June 5-16, 2000
International Grains Program, KSU

Lesser grain borer
Rhyzopertha dominica (F.)



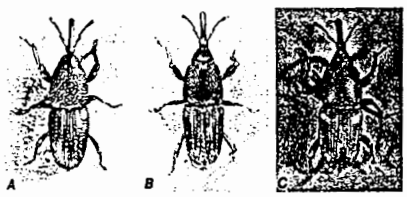
- Body is cylindrical; 2 – 3 mm long
- Head invisible (concealed) from above; pronotum has rows of teeth.
- Antennae with large, loose 3-segmented club.
- Wings have rows of punctures.

Weevils (*Sitophilus* spp.)

- ✓Body 2.3 – 4.5 mm long.
- ✓Front of head with snout.
- ✓Antennae elbowed and clubbed.

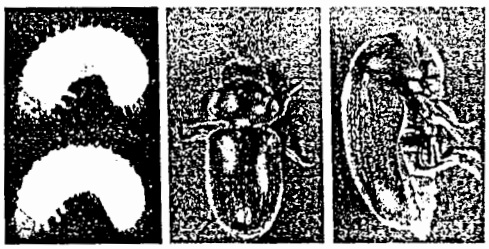
Rice, maize and granary weevils

- Rice and maize weevils: 4 oval marking on the forewings; small circular punctures on the pronotum
- Granary weevil: no markings on the forewings; punctures are widely separated, large and oblong



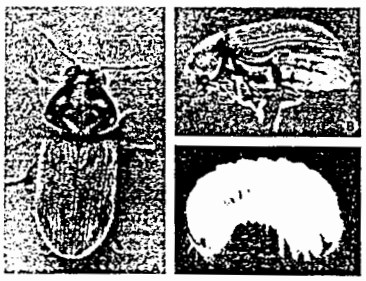
Cigarette beetle, *Lasioderma serricorne* (Fabricius)

- Body oval, 2 – 2.5 mm long, light brown in color.
- Wings are smooth.
- Antennae are ½ the length of the body; 11 segments; 4th – 10th are serrate (saw like).



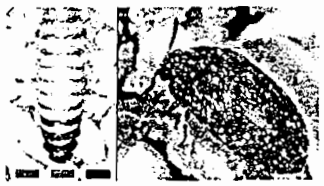
Drugstore beetle, *Stegobium paniceum* (L.)

- Similar to Cigarette beetle, except.
- Antennae: last 3 segments form loose club.
- Wings have longitudinal stirae (rows of punctures); and rough.



Khapra/warehouse beetles (*Trogoderma* spp.)

- ✓ Body 2 – 3 mm, reddish-brown (thorax darker), oval, top surface covered with fine hairs.
- ✓ A median ocellus between compound eyes.
- ✓ Antennae 11 segmented, 3 – 5 segments forming clubs.



Red/confused flour beetles (*Tribolium* spp.)

- ❖ Body 2.3 – 4.4 mm long; red brown
- ❖ Forewings with longitudinal lines.
- ❖ Eyes divided by head margins.
- ❖ Last segments of antennae are clubbed.

- ➢ Confused flour beetle
- ➢ Red flour beetle

Small-eyed flour beetle, *Palorus* spp.

- ➢ Body 2.7 – 3.0 mm long; red brown; similar to red flour beetle.
- ➢ Each compound yes is undivided (round)
- ➢ Antennae are not clubbed.

Flat and rusty grain beetles (*Cryptolestes* spp.)

- ✓ Body 1.5-2 mm long; oblong, flattened light brown.
- ✓ Head and prothorax account for ½ the body length.
- ✓ Antennae are filiform and long (≥ the body length).

Merchant and sawtoothed grain beetles (*Oryzaephilus* spp.)

- ➢ Body 2.5 – 3.5 mm long; slender and dark-brown.
- ➢ Antennae are short and clubbed.
- ➢ Prothorax has 6 tooth-like projections along each side.

Angoumois grain moth, *Sitotroga cerealella* (Olivier)

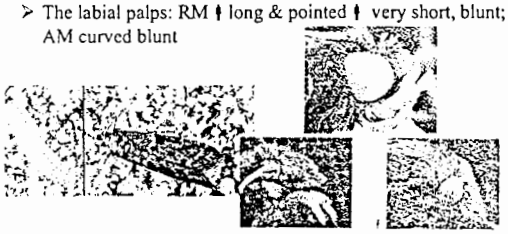
- ✓ Body is 5 - 7 mm long; yellowish brown.
- ✓ Fore-wings have small black spots; the hind-wings have a long fringe of hairs (> ½ wings width).
- ✓ Labial palps are long, slender and sharply pointed

Indianmeal moth, *Plodia interpunctella* (Hubner)

- Body is 7 – 10 mm long.
- The fore-wings are bicolor: basal 2/5 is cream the rests dark-reddish brown.
- Labial palps point directly forwards.

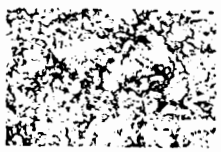
Rice moth, *Corcyra cephalonica* (Stainton) and Almond moth, *Ephestia cautella* (Walker)

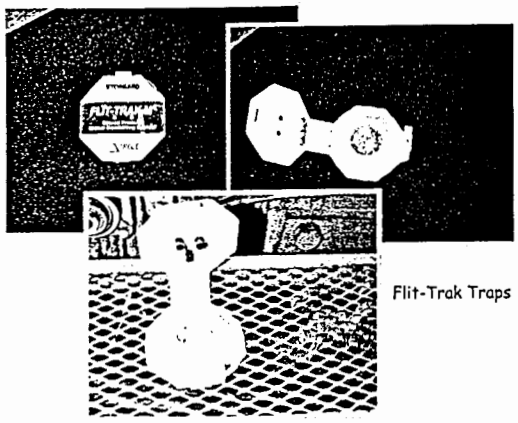
- Body is 7 – 10 mm long.
- Forewings are grayish brown with vague darker brown lines along the wing veins.
- The labial palps: RM ↑ long & pointed ↑ very short, blunt; AM curved blunt



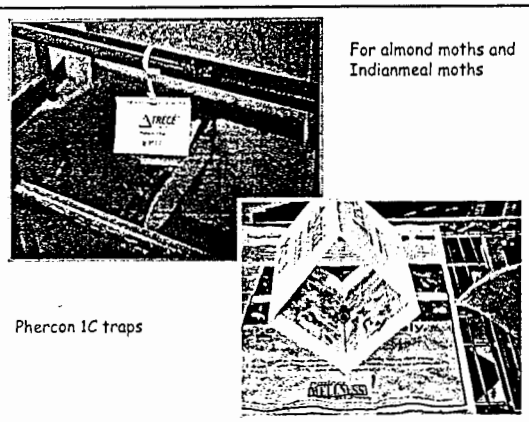
Booklice/psocid, *Liposcelis* spp

- Body about 1 mm long; transparent/pale; flattened.
- Hind legs with broadened thigh (Lipos=fat + skelis=leg/thigh).
- Hair like and long antennae.
- Wingless.





Flit-Trak Traps



For almond moths and Indianmeal moths

Phercon 1C traps

Table 1. Scientific and common names and feeding preference of stored-product insects

Scientific name	Common name	Feeding preference		
		Internal	External	Fungus
Order: COLEOPTERA	Beetle / Weevil			
Family: Anobiidae				
Lasioderma serricorne	Cigarette beetle		x	
Stegobium paniceum	Drugstore beetle		x	
Family: Anthribidae				
Araecerus fasciculatus	Coffee bean weevil	x		
Family: Bostrichidae				
Dinoderus spp.	Bamboo powderpost beetle	x		
Prostephanus truncatus	Larger grain borer	x		
Rhyzopertha domonica	Lesser grain borer	x		
Family: Bruchidae				
Acanthoscelides obtectus	American seed beetle	x		
Callosobruchus analis	Chinese beetle	x		
Callosobruchus chinensis	Adzuki bean weevil	x		
Callosobruchus maculatus	Chinese beetle	x		
Callosobruchus phaseoli	Cowpea weevil	x		
Caryedon serratus	Groundnut seed-beetle	x		
Family: Cerylonidae				
Murmidius ovalis	Murmidius beetle		x	x
Family: Curculionidae				
Sitophilus granarius	Granary weevil	x		
Sitophilus oryzae	Rice weevil	x		
Sitophilus zeamais	Maize weevil	x		
Family: Dermestidae				
Attagenus megatoma	Black carpet beetle		x	
Trogoderma glabrum	Larger cabinet beetle		x	
Trogoderma granarium	Khapra beetle		x	
Trogoderma inclusum	Larger cabinet beetle		x	

Scientific name	Common name	Feeding preference		
		Internal	External	Fungus
Family: Dermestidae continued				
Trogoderma variable	Warehouse beetle		x	
Family: Laemophloeidae				
Cryptolestes ferrugineus	Rusty grain beetle		x	
Cryptolestes pusillus	Flat grain beetle		x	
Family: Lophocateridae				
Lophocateres pusillus	Siamese grain beetle		x	
Family: Mycetophagidae				
Typhaea stercorea	Hairy fungus beetle			x
Family: Nitidulidae				
Carpophilus dimidiatus	Corn sap beetle		x	
Carpophilus hemipterus	Dried fruit beetle		x	
Family: Ptinidae				
Gibium psylloides				
Mezium americanum	American spider beetle		x	
Ptinus clavipes	Brown spider beetle		x	
Ptinus fur	Whitemarked spider beetle		x	
Ptinus viliger	Hairy spider beetle		x	
Family: Silvanidae				
Ahasverus advena	Foreign grain beetle		x	x
Cathartus quadricollis	Squarednecked grain beetle		x	
Oryzaephilus mercator	Merchant grain beetle		x	
Oryzaephilus surinamensis	Sawtoohed grain beetle		x	
Family: Tenebrionidae				
Alphitobius diaperinus	Lesser mealworm		x	
Alphitobius laevigatus	Black fungus beetle		x	
Cynaeus angustus	Larger black flour beetle		x	
Gnatocerus cornutus	Broadhorned flour beetle		x	
Gnatocerus maxillosus	Slenderhorned flour beetle		x	
Lathetricus oryzae	Longheaded flour beetle		x	
Palorus ratzeburgii	Smalleyed flour beetle		x	
Palorus subdepressus	Depressed flour beetle		x	

Scientific name	Common name	Feeding preference		
		Internal	External	Fungus
Family: Tenebrionidae continued				
Tenebrio molitor	Yellow mealworm		x	
Tenebrio obscurus	Dark mealworm		x	
Tribolium audax	American black flour beetle		x	
Tribolium castaneum	Red flour beetle		x	
Tribolium confusum	Confused flour beetle		x	
Tribolium destructor	Dark flour beetle		x	
Family: Trogositidae				
Tenebroides mauritanicus	Cadelle beetle		x	
Order: LEPIDOPTERA	Moth			
Family: Pyralidae				
Corcyra cephalonica	Rice moth		x	
Ephestia cautella	Almond moth		x	
Ephestia elutella	Tobacco moth		x	
Ephestia kuehniella	Mediterranean flour moth		x	
Plodia interpunctella	Indianmeal moth		x	
Family: Gelechiidae				
Sitotroga cerealella	Angoumois grain moth	x		
Order: PSOCOPTERA				
Family: Liposcelididae				
Liposcelis bostrichophila	Booklice or psocid		x	x
Liposcelis entomophila	Booklice or psocid		x	x
Liposcelis paeta	Booklice or psocid		x	x

Rennie Roesli
June, 2000
Department of Grain Science and Industry
Kansas State University

Table 2. Biological aspects, and temperature and r.h. requirement for the growth of some stored-product insect pests

Common name	Approximate life span (days)	Average or range of eggs laid / female	Temperature (^{0}C) Minimum	Optimum	Minimum % r.h.
Adzuki bean weevil	up to 12	up to 70	19	28 - 32	30
Almond moth	7 - 9	up to 300	17	30 - 35	20
American black flour beetle	–	–	–	27	–
American seed beetle	–	–	17	27 - 31	30
American spider beetle			20	31 - 34	30
Angoumois grain moth	2 - 14	40 - 400	16	26 - 30	20
Bamboo powderpost beetle	–	–	–	–	–
Black carpet beetle	15 - 60	100	–	–	–
Black fungus beetle	–	–		30 - 35	70
Booklice or psocid	40 - 207	30 - 204	15	30 - 35	50
Broadhorned flour beetle	–	–	16	25 - 30	40
Cadelle beetle	360 - 720	1,000	–	30	–
Chinese beetle	–	–	22	30 - 33	1
Cigarette beetle	14 - 42	20 - 110	22	32 - 35	30
Coffee bean weevil	85 - 135	up to 50	22	28 - 32	–
Confused flour beetle	365 - 540	up to 450	21	30 - 33	1
Corn sap beetle	90 - 365	1,000	17.5	28	10
Cowpea weevil	up to 12	up to 115	22	30 - 35	10
Dark flour beetle	–	–	5	25	–
Dark mealworm	–	–	14	25 - 27	20
Depressed flour beetle	–	–	17.5	30 - 32.5	50
Dried fruit beetle	90 - 365	1,000	19	31 - 34	50
Drugstore beetle	13 - 65	20 - 100	17	25 - 28	60
Flat grain beetle	365	100 - 400	22	28 - 33	60
Foreign grain beetle	–	–	–	30	65

Common name	Approximate life span (days)	Average or range of eggs laid / female	Temperature (^{0}C) Minimum	Optimum	Minimum % r.h.
Granary weevil	210 - 240	50 - 250	11	26 - 30	50
Groundnut seed-beetle	_	_	22	28 - 30	30
Hairy fungus beetle	_	_	_	30	_
Indianmeal moth	100 - 400	4 - 13	16	28 - 32	30
Khapra beetle	4 - 16	35	24	33 - 37	1
Larger grain borer			18	30 - 34	40
Lesser grain borer	up to 180	300 - 500	23	32 - 35	30
Lesser mealworm	_	_	_	30 - 35	70
Longheaded flour beetle	_	_	25	33 - 37	30
Maize weevil	120 - 150	up to 150	17	25 - 30	50
Mediterranean flour moth	9 - 14	120 - 680	15	24 - 27	1
Merchant grain beetle	150 - 260	125	20	31 - 34	10
Murmidius beetle	_	_	17.5	30	60
Red flour beetle	365 - 380	350 - 450	22	32 - 35	1
Rice moth	2 - 26	40 - 400	18	30 - 35	20
Rice weevil	90 - 185	300 - 400	17	27 - 31	50
Rusty grain beetle	_	up to 200	23	32 - 35	10
Sawtoohed grain beetle	20 - 80	50 - 375	21	31 - 34	10
Siamese grain beetle	_	_	17.5	30	10
Slenderhorned flour beetle	_	_	18	29 - 30	6
Smalleyed flour beetle	_	_	17.5	30 - 32.5	20
Squarednecked grain beetle	_	_	_	25 - 30	_
Tobacco moth	7 - 9	up to 300	10	30	30
Yellow mealworm	_	_	14	25 - 27	20

Rennie Roesli
June, 2000
Department of Grain Science and Industry
Kansas State University

S.P.E.R.E.S.

STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE

Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

RESEARCH AT K-STATE

Heat Treatment Workshop

Heat and IPM

Heat and Insect Numbers

Feed Mill IPM

Grocery/Pet Store IPM

Stored Grain IPM

Ultrasound and Moth Reproduction

LINKS TO RESEARCH AT OTHER UNIVERSITIES

Purdue University

Research results on stored product insects and their management at K-State and other academic and government institutes in the United States will be featured here.

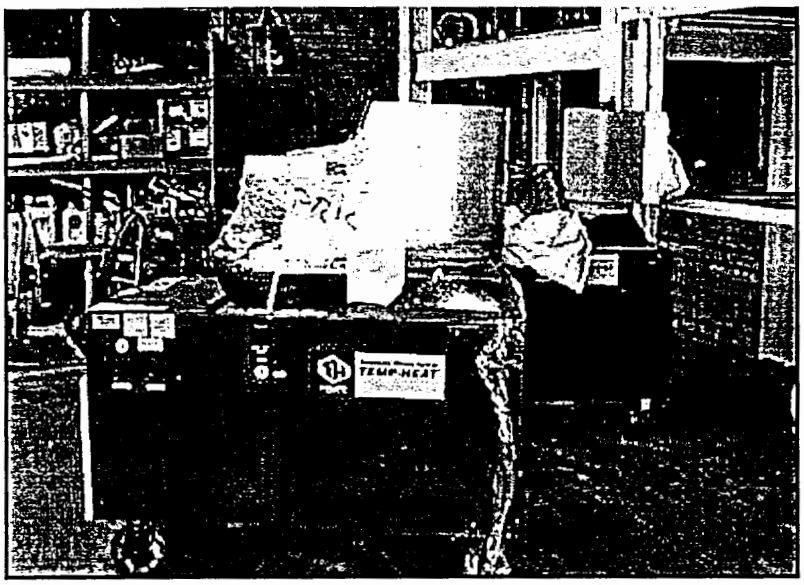
Heat and IPM

Project Title: Use of high temperatures for managing insects in flour and feed mills.

Investigators: Anil Menon, Bh. Subramanyam, and Alan Dowdy

Objectives: To determine the temperatures attained during heat treatment of mills outside and inside equipment; influence of heat on all life stages of caged insects; determine impact of relative humidity on insect mortality; develop predictive models to estimate heat required to kill insects in the laboratory and evaluate models in the field.

Methods: Field studies will be conducted during actual heat treatment of Kansas State University pilot flour and feed mills or actual mills in the US, and laboratory studies will be conducted using a programmable oven. HOBO units will be used to monitor temperature and relative humidity during a heat treatment outside and inside pieces of equipment. A range of humidities and their impact in killing insects during a heat treatment will be studied by placing insects inside plastic cereal holders. Glycerol solutions of different specific gravities will be used to alter humidity. Insect species that will be exposed include: the red flour beetle, cigarette beetle, and Indianmeal moth. Life stages of insects will be exposed to various time periods during an actual (field) or simulated (laboratory) heat treatment to determine acute and delayed mortality, and reproductive potential of insects exposed to high temperatures. Experiments will be run at constant temperatures above 40°C to establish a lower temperature threshold for accumulating temperatures and to develop a degree-hour model to predict insect mortality. Field validation of the model will be conducted during an actual heat treatment and HOBO and insect bioassay data will be used for model validation.



Rupp Heaters used in Heat Treatment of Feed Mills

Impacts: Presently, very few scientific papers have characterized temperature distributions within a mill being heat treated, and only a few papers have studied the acute and delayed effects of heat on insects.Our research will provide a more quantitative and practical basis for evaluating effectiveness of heat treatments in killing insects, and may suggest a minimum temperature and time than the currently recommended exposure of 24 hours at or above 50°C.

BACK TO
NEWS & REVIEWS

S.P.E.R.E.S.

STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE

Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

RESEARCH AT K-STATE

Heat Treatment Workshop

Heat and IPM

Heat and Insect Numbers

Feed Mill IPM

Grocery/Pet Store IPM

Stored Grain IPM

Ultrasound and Moth Reproduction

LINKS TO RESEARCH AT OTHER UNIVERSITIES

Purdue University

Research results on stored product insects and their management at K-State and other academic and government institutes in the United States will be featured here.

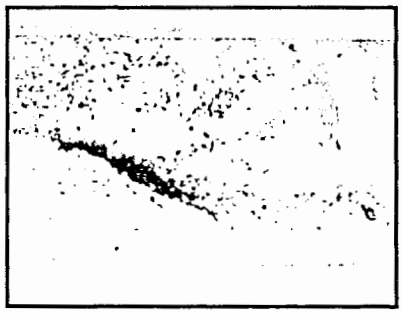
Heat and Insect Numbers

Project Title: Insect populations before and after heat treatment of mills.

Investigators: Bh. Subramanyam and Rennie Roesli

Objective: To determine the degree and duration of suppression of various insect species in mills following a heat treatment.

Methods: Commercial traps will be used to sample moths and beetles in mills before and after heat treatments. Insects will be monitored throughout the year in Kansas State University pilot flour and feed mills using traps on a biweekly basis. Contour analysis of trap catches will be used to determine areas of reinfestation.



Dead Insects Following Heat Treatment

Impacts: Information is lacking on insect population dynamics before and after heat treatments. Our research will document at what rate insect reinfestation can occur following a control measure.

BACK TO NEWS & REVIEWS

S.P.E.R.E.S.

STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE

Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

RESEARCH AT K-STATE

Heat Treatment Workshop

Heat and IPM

Heat and Insect Numbers

Feed Mill IPM

Grocery/Pet Store IPM

Stored Grain IPM

Ultrasound and Moth Reproduction

LINKS TO RESEARCH AT OTHER UNIVERSITIES

Purdue University

Research results on stored product insects and their management at
K-State and other academic and government institutes in the United States will be featured here.

Feed Mill IPM

Project Title: Development of an IPM program for feed mills

Investigators: Mauricio Valencia, Bh. Subramanyam, and D. W. Hagstrum

Objective: To develop a simple and practical IPM program for feed mills.

Methods: Survey 5 feed mill managers within Kansas City or neighboring states to determine their pest management practices; sample raw ingredients received and stored at the facility; set up a trapping program for beetles and moths; conduct a visual inspection every other month; sample mill streams; characterize insect distribution and abundance and pin point sources of infestation; and develop simple and practical ways for managing insect pests.

Impacts: Presently, there are little or no published reports documenting insect problems in feed mills. Our information will document species typically present in feed mills. In addition, it will show the most likely sources of these insects. Management efforts to suppress pests, therefore, can be precisely targeted in these areas, rather than the entire mill.

BACK TO NEWS & REVIEWS

S.P.E.R.E.S.

STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE

Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

RESEARCH AT K-STATE

Heat Treatment Workshop

Heat and IPM

Heat and Insect Numbers

Feed Mill IPM

Grocery/Pet Store IPM

Stored Grain IPM

Ultrasound and Moth Reproduction

LINKS TO RESEARCH AT OTHER UNIVERSITIES

Purdue University

Research results on stored product insects and their management at
K-State and other academic and government institutes in the United States will be featured here.

Grocery/Pet Store IPM

Project Title: Development and evaluation of pest management programs in retail and pet stores.

Investigator: Bh. Subramanyam and a M.S. student.

Objectives: To determine insect species associated with retail and pet stores and their distribution within stores; develop quick methods for counting insects and determining their distribution; and develop simple methods for insect management. The spread of infestation of insects within a store will be determined in a simulated store environment.

Methods: Traps and store manager surveys will be used to determine pest problems within stores. Electronic tools and software programs will be developed to get an electronic map of the store and insect distribution within a store. Practical IPM practices will be implemented after first year trapping to determine impact of implemented practices on insect numbers.

Impacts: Promote awareness and develop simple solutions for managing insect pests in retail and pet stores.

BACK TO NEWS & REVIEWS

S.P.E.R.E.S.

STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE

Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

RESEARCH AT K-STATE

Heat Treatment Workshop

Heat and IPM

Heat and Insect Numbers

Feed Mill IPM

Grocery/Pet Store IPM

Stored Grain IPM

Ultrasound and Moth Reproduction

LINKS TO RESEARCH AT OTHER UNIVERSITIES

Purdue University

Research results on stored product insects and their management at
K-State and other academic and government institutes in the United States will be featured here.

Stored Grain IPM

Project Title: Effectiveness of Spinosad on stored product insects.

Investigators: Bh. Subramanyam, Carl Reed, and Frank Arthur

Objectives: To characterize the fate and efficacy of Spinosad, a reduced-risk bacterial pesticide applied to hard, red winter wheat stored in bins.

Methods: Wheat stored in 1,000 bushel bins will be treated with Spinosad at 0, 1 and 3 ppm (mg of Spinosad/kg of wheat). Treated and untreated wheat will be sampled over time and residues of Spinosad measured in germ, bran, and endosperm fractions. Grain will be sampled for insects in the field. Samples brought to the laboratory will be assayed with insects. Residue breakdown and efficacy against insects at three temperatures and moisture contents will be determined in the laboratory. Several classes of wheat will be treated with Spinosad to determine influence of wheat class on insect susceptibility to Spinosad.

Impacts: Laboratory study conducted in 1998 indicated that Spinosad was very effective against lesser grain borers, rice weevils, Indianmeal moth, red flour beetles and sawtoothed grain beetles. This product appears to be a suitable replacement to the organophosphates malathion, actellic, and reldan, which are at risk of being cancelled under the 1996 Food Quality Protection Act. If found to be effective under field conditions, Spinosad could be a suitable product worthy of consideration for an Environmental Protection Agency (EPA) registration.

S.P.E.R.E.S.

STORED PRODUCT ENTOMOLOGY RESEARCH & EDUCATION SITE

Department of Grain Science & Industry
Kansas State University, Manhattan, KS 66506-2201

RESEARCH AT K-STATE

Heat Treatment Workshop

Heat and IPM

Heat and Insect Numbers

Feed Mill IPM

Grocery/Pet Store IPM

Stored Grain IPM

Ultrasound and Moth Reproduction

LINKS TO RESEARCH AT OTHER UNIVERSITIES

Purdue University

Research results on stored product insects and their management at
K-State and other academic and government institutes in the United States will be featured here.

Ultrasound and Moth Reproduction

Project Title: Effects of ultrasound pulses on stored product moth reproductive success.

Investigators: Bh. Subramanyam, Fangeng Huang and Jim Campbell

Objectives: To examine the influence of variable frequencies, sound pressure levels and pulse durations on the reproductive behavior of Indianmeal moth, *Plodia interpunctella* (Hubner).

Methods: The impact of different frequencies, sound pressure levels and pulse durations will be generated in the laboratory. Adult males and females of Indianmeal moths will be exposed to the sounds and their responses will be recorded. Experiments will be conducted in flight tunnels and in cages or rooms to determine the impact of ultrasound on pheromone-mediated flight of males, pheromone release behavior of females, and on the mating success.

Impacts: There is preliminary evidence to show that ultrasound technology will work on stored product moths. A commercial model will be developed to manage Indianmeal moths in bins and in commercial food/feed handling facilities. Our goal is to develop a unit to which the moths do not get habituated.

BACK TO NEWS & REVIEWS

Author	Year	Title	Journal
Dean, G.A	1913	Furthur data on heat as a means of controlling mill insects	J.Econ.Entomol 6(1):40-53
Dean, G.A	1913	Heat as a means of controlling mill insects	Mill and stored grain insects, Kansas Agric. College Agrl Expt. Station Bull no 189 pp145-176
Dean, G.A	1921	Some preventive and remedial rethods for the control of mill and stored grain insects	Assoc. of Operative Millers Bull :May 1921 pp 39-45
Goodwin, W.H	1922	Heat for control of cereal insects	Ohio Agric.Expt. Station Bull no 354 18pp
Grossman, E.F.	1931	Heat treatment for controlling the insect pests of stored corn.	University of Florida Agricultural Experiment Station, Bull No 239. 24 p.Gainesville, Fla.
Mellanby, K	1932`	The influence of atmospheric humidity in the thermal death point of a number of insects	J.Exptl. Biology 9:222-231
Oosthuzien, M.J	1935	The effect of high temperature on the confused flour beetle	Univ. of Minnesota Agric. Expt. Station Bull no. 107 45pp
Pepper, J.H and A.L. Strand	1935	Superheating as a control for cereal-mill insects	Montana Agric. Expt station Bull no 297 26pp
Pepper, J.H and A.L.Strand	1935	The importance of surface temperatures in heat sterilization	J.Econ.Entomol 28:242-244
Gunn, D.L and F.B.Notley	1936	The temperature and humidity relation of the cockroach. IV Thermal deathpoint	J.Exptl. Biology 13:28-34
Dean, G.A	1936	Flour-mill insects and their control	USDA cir no 390 34pp
Kenaga, E.E and F.W.Fletcher	1943	Effect of high temperature on several household and storage grain pests	J.Econ. Entomol 35:(6):944
Bare, C.O, J.N.Tenhet and W.D.Reed	1947	Effect of the thermal-vacuum process on insects in stored tobacco	J.Econ.Entomol 39(5):612-613
Godkin.W.J. and W.H.Catheart	1949	Effectiveness of heat in controlling insects infesting the surface of bakery products	Food Technology 3:254-257

Author	Year	Title	Journal
Anonymous	1955	Home Remedies for the Control of Insects in Dry Beans and Cowpeas	USDA Agrl Marketing Service, Marketing ResearchDivision
Cotton, R.T	1958	Insect control in flour mills	USDA Agric Marketing Service, Marketing Research Division Agric.Handbook no 133
Ho, F.K	1965	Heat treatment of Tribolium confusum imagoes	Research Notes from Tribolium information Bullettin TIB8:78-79
Kirkpatrick, R.L and E.W.Tilton	1972	Infrared radiation to control adult stored-product coleoptera	J.Georgia Entomol.Soc.7(1):73-75
Kirkpatrick, R.L and E.W.Tilton	1973	Elevated temperatures to control insect infestations in wheat	J.Georgia Entomol.Soc. 8(4): 264-268
Yoshida, T	1974	Effect of sun-drying on the mortality of immature rice weevils, Sitophilus zeamais Motsch. (Coleoptera, Curculionidae).	Scientific Reports of the Faculty of Agriculture, Okayama University. 1974, No.43, 11-17, 2 fig., 14 ref.
Cox, P.D	1974	The influence of temperature and humidity on the life cycles of Ephesita figulella Gregson and Ephestia calidella (Guenee)(Lepidoptera:Phycitidae)	J.stored Prod.Res 10:43-55
Kirkpatrick, R.L	1975	The use of infrared and microwave radiation for control of stored-product insects.	Proc. of the First International Working Conference on Stored-Product Entomology, Savannah, Georgia, USA, October 7-11, 1974.
Gonen, M	1977	Survival and reproduction of heat-acclimated Sitophilus granarius (Coleoptera:Curculionidae) at a moderately high temperature	Ent.exp.& appl 21(1977):249-253
Gonen, M	1977	Susceptibility of Sitophilus granarius and S.oryzae (Coleoptera: Curculionidae) to high temperature after exposure to supra-optimal temperature	Ent.exp.& appl 21(1977):243-248
Lunn, P.T.M	1977	High temperature inhibition of development of eupyrene sperm and of reproduction in Plodia interpunctella and Ephestia cautella	J.Georgia Entomol.Soc. 12(3):199-203
Vardell, H.H and C.E.Shelby	1978	Heat sensitivity of mutant strains of Tribolium confusum Jacquelin Duval	J.Georgia Entomol.Soc 13(3)261-265
Dermott, T and D.E. Evans.	1978	An evaluation of fluidized-bed heating as a means of disinfesting wheat.	J.Stored Prod.Res. 1978, 14: 1, 1-12, 4 fig., 30 ref.
Evans, D.E and T.Dermott	1979	The potential of a fluidized-bed heating system for the disinfestation of grain.	Australian contributions to the symposium on the protection of grain against insect damage during storage, Moscow, 1978. 1979, 32-38, 5 fig., 9 ref.

Author	Year	Title	Journal
Vardell, H.H and E.W.Tilton	1981	Control of the lesser grain borer, Rhyzopertha dominica (F.), and the rice weevil, Sitophilus oryzae (L.), in wheat with a heated fluidized bed.	J.Kansas Entomol. 1981, 54: 3, 481-485, 7 ref.
Vardell, H.H and E.W.Tilton	1981	Control of the lesser grain borer, Rhyzopertha dominica (F.), and the rice weevil, Sitophilus oryzae (L.), in rough rice with a heated fluidized bed.	J.Georgia Entomol. 1981, 16: 4, 521-524, 6 ref.
Evans, D.E, and T.Dermott	1981	Dosage-mortality relationships for Rhyzopertha dominica (F.) (Coleoptera: Bostrychidae) exposed to heat in a fluidized bed.	J.Stored Prod.Res. 1981, 17: 2, 53-64, 1 fig., 13 ref.
Arbogast, R.T	1981	Mortality and reproduction of Ephestia cautella and Plodia interpunctella exposed as pupae to high temperatures	Environ.Entomol. 10(708-711
Evans, D.E	1981	The influence of some biological and physical factors on the heat tolerance relationships for Rhyzopertha dominica(F.) and Sitophilus oryzae(L.)(Coleoptera:Bostrychidae and Curculionidae)	J.stored Prod.Res 17:65-72
Vardell, H.H and E.W.Tilton	1981	Heat sensitivity of the lesser grain borer, Rhyzopertha dominica(F)	J.Georgia Entomol.Soc. 16(1):116-121
Vardell, H.H and E.W.Tilton	1981	Heat sensitivity of the Indian meal moth, Plodia interpunctella (Hubner), immatures.	J.Georgia Entomol. 1981, 16: 1, 7-11, 7 ref.
Liu, R.Z., Xiong, Y.Q., Wang, C.	1982	Studies on heat treatment of wheat grains in China [Traditional method to control insects].	Chemistry and world food supplies : the new frontiers, Chemrawn II , invited papers presented at the International Conference on Chemistry and World Food Supplies, Manila,
Suss, L, Moroni, E	1982	Survival of the eggs of several Lepidoptera Phycitidae at different temperatures used in the production and conservation of foodstuffs.	3o simposio sulla difesa antiparassitaria nelle industrie alimentari e la protezione degli alimenti. 1982, publ. 1984, 267-278, 5 fig., 15 ref.
Tilton, E.W, H.H. Vardell and R.D.Jones	1983	Infrared heating with vacuum for control of the lesser grain borer, (Rhyzopertha dominica F.) and rice weevil (Sitophilus oryzae (L.)) infesting wheat.	J.Georgia Entomol. 1983, 18: 1, 61-64, 9 ref.
Seville, JR, Bateman, PLG (ed.)	1983	The pest problem and its prevention in the confectionery industry.	Proceedings of the Sixth British Pest Control Conference. Robinson College, Cambridge, September 7th-10th 1983. 1983?, 7 pp.
Oxley, T.A, S.Barry and R.J. Elorduy de Conconi	1983	Laser light as a new potential method for pest control in preserved foods.	Biodeterioration 5. Papers presented at the 5th International Biodeterioration Symposium Aberdeen, September 1981. 1983, recd. 1985, 592-608, 17 fig., 16 ref.
Al- Azawi, A.F, H.S.El- Haidari , H.M.Al-Saud and F.M.Aziz	1983	Effect of reduced atmospheric pressure with different temperatures on Ephestia cautella Walker (Lepidoptera, Pyralidae), a pest of stored dates in Iraq.	Date Palm J. 1983, 2: 2, 223-233, 13 ref.
Al-Azawi.A.F, H.S.El-Haidari, F.M.Aziz and A.K. Murad	1983	Effect of high temperatures on fig moth Ephestia cautella Walker (Lepidoptera: Pyralidae) in Iraq.	Date Palm J. 1983, 2: 1, 79-85, 8 ref.

Author	Year	Title	Journal
Davidson, S	1983	Heat as an insecticide	Rural Research, CSIRO Spring 1983 p 13-15
Evans, D.E	1983	The influence of relative humidity and thermal acclimation on the survival of adult grain beetles in cooled grain	J.stored Product Res.19(4):173-180
Obretenchev, D	1983	The effect of low and high lethal temperatures on individual stages of the saw-toothed grain beetle Oryzaephilus surinamensis (L.) (Coleoptera, Cucujidae).	Rasteniev-dni-Nauki. 1983, 20: 5, 45-50, 12 ref.
Imholte, T.J	1984	Heat Sterilization	Engineering for food safety and sanitation. T.J.Imholte and T. Imholte-Tauscher Technical Institute of food safety, Woodinville, WA p303-309
Sheppard, K.O.	1984	Heat sterilization (superheating) as a control for stored-grain pests in a food plant.	Insect management for food storage and processing. F. J. Baur (ed). American Association of Cereal Chemists, St. Paul, Minn. 194-200.
Elsey, K. D and J. Brower	1984	Sterilization of the pickleworm (Diaphania nitidalis) (Lepidoptera: Pyralidae) by ionizing radiation or heat.	J.Econ.Entomol 77(5): 1236-1239
Thorpe, G.R, Evans, D.E, Sutherland, J.W	1984	The development of a continuous-flow fluidized-bed high-temperature grain disinfestation process.	Controlled atmosphere and fumigation in grain storages. Proceedings of International Symposium, 11-22 April 1983, Perth, Australia. 1984, 617-622, 1 fig. BL, 5 ref.
Claflin, J.K., Evans, D.E., Fane, A.G., Hill, R.J.	1984	Thermal disinfestation of wheat in a spouted bed.	Proceedings of the Third International Working Conference on Stored-Product Entomology : Oct 23-28, 1983, Kansas State Univ., Manhattan, Kansas
Al-Alawy, S.A, M.M.Al-Zeibadi and M.T. Mahdi	1985	Effect of high temperatures on red flour beetles, Tribolium castaneum (Herbst) (Coleoptera: Tenebrionidae), an important pest of flour in Iraq.	Journal-of-Agriculture-and-Water-Resources-Research. 1985, 4: 2, 47-57, 12 ref.
Banker, E	1985	Fighting bugs without fumigants.	Farmline U.S.D.A.Econ-Res-Serv. Washington, D.C. : The Service. May 1985. v. 6 (5) p. 4-6. ill.
Lessard, F. F	1985	Thermal treatments for disinfestation of cereals and cereal products: possibility of practical usage and sphere of application.	Bulletin,-Organisation-Europeenne-et-Mediterraneenne-pour-la-Protection-des-Plantes. 1985, 15: 1, 109-118, 4 fig., 20 ref.
Tilton, E.W and J.H. Brower	1985	Supplemental treatments for increasing the mortality of insects during irradiation of grain.	Food-Technol. Chicago, Ill. : Institute of Food Technologists. Dec 1985. v. 39 (12) p. 75-79. charts.
Shirvani, M and H. Berger	1985	Possibilities of controlling the bean weevil (Acanthoscelides obtectus Say.) in storage.	Pflanzenschutz. 1985, No. 1, 7, 3 ref.
Al- Azawi, A.F, H.S. El- Haidari, F.M.Aziz and H.M. Al- Saud	1985	Effect of reduced atmospheric pressure with different temperature on Oryzaephilus surinamensis (L.) (Coleoptera, Cucujidae). A pest of stored dates in Iraq.	Date Palm J. 1985, 4: 1, 77-90, 20 ref.

Author	Year	Title	Journal
Cooney, K.M	1985	If you can't stand the heat	Food Sanitation 1(24):37-39
Smirnov, A.M.	1985	Combined method of thermal treatment.	Pchelovodstvo. Moskva : Agropromizdat. May 1985. (5) p. 14-16.
Lapp, H.M, F.J.Madrid and L.B. Smith	1986	A continuous thermal treatment to eradicate insects from stored wheat.	Paper,-American-Society-of-Agricultural-Engineers. 1986, No. 86-3008, 13pp., 2 fig., 5 ref.
Thaung, M, Collins, P.J	1986	Joint effects of temperature and insecticides on mortality and fecundity of Sitophilus oryzae (Coleoptera: Curculionidae) in wheat and maize.	J.Econ.Entomol. 1986, 79: 4, 909-914, 5 fig., 18 ref.
CLaflin, J.K, D.E.Evans, A.G Fane and R. J .Hill	1986	The thermal disinfestation of wheat in a spouted bed.	J.Stored Prod.Res22(3): 153-161
Sutherland, J., G.R. Thorpe and P.W. Fricke	1986	Grain disinfestation by heating in a pneumatic conveyor.	Conference on agricultural engineering, Adelaide, Australia, 24-28 August, 1986. Preprints of papers. 1986, 419-425, National Conference Publication No. 86-9, 14 ref.
Ahmed, M. S. H., A.A. Hameed and A. Kadhum	1986	Disinfestation of commercially packed dates by a combination treatment.	Acta Alimentaria 15(3): 221-226
Wilkin, D.R., Nelson, G.	1987	Control of insects in confectionery walnuts using microwaves.	Monograph-Br-Crop-Prot-Counc. Thornton Heath : The Council. 1987. (37) p. 247-254.
Evans, D.E	1987	The influence of rate of heating on the mortality of Rhyzopertha dominica (F.) (Coleoptera: Bostrychidae).	J.Stored Prod.Res. 1987, 23: 1, 73-77, 2 fig., 15 ref.
Torpe, G. R	1987	The thermodynamic performance of a continuous-flow fluidized bed grain disinfector and drier.	J. of Agricultural Engineering Res. 37(1): 27-42
Kato, K, Yamashita, R	1987	Stored-grain insect control by dielectric heating.	Journal-of-the-Japanese-Society-of-Agricultural-Machinery. 1987, 49: 5, 443-450, 4 ref.
Evans, D.E	1987	Some biological and physical constraints to the use of heat and cold for disinfesting and preserving stored products.	Proceedings of the Fourth International Working Conference on Stored-Product Protection, Tel Aviv, Israel, 21-26 September 1986. 1987, 149-164, 78 ref.
Mohan, S, G.Balasubramanian, M. Gopalan and S. Jayaraj	1987	Solar heat treatment - a novel method to check rice weevil and red flour beetle infestation in sorghum during storage.	Madras-Agricultural-Journal. 1987, 74: 4-5, 235-236, 1 ref.
Rosenberg, U., Bogl, W.	1987	Microwave pasteurization, sterilization, blanching, and pest control in the food industry.	Food-Technol. Chicago, Ill. : Institute of Food Technologists. June 1987. v. 41 (6) p. 92-99. charts.

Author	Year	Title	Journal
Lessard, F.F.	1987	Control of storage insects by physical means and modified environmental conditions. Feasability and applications.	Monograph-Br-Crop-Prot-Counc. Thornton Heath : The Council. 1987. (37) p. 209-218. ill.
Davis, R., J.Boczek,D. Pankiewicz-Nowicka and M. Kruk	1987	Effects of suboptimal temperature in Tribolium confusum and T. castaneum.	Proceedings of the Fourth International Working Conference on Stored Product Protection, Tel Aviv, Israel, 21-26 September 1986. 1987, 547-554, 8 ref.
Forbes, C.F and W.Ebeling	1987	Update: Use of heat for elimination of structural pests	IPM Practitioner 9(8):1-15
Toms, S.V	1988	The effect of high temperatures on the organism of Adesmia gebleri (Coleoptera, Tenebrionidae).	Zoologicheskii Zhurnal 67(8): 1171-1179
Davis, R and J. Boczek	1988	Thermal acclimation in the grain mite Acarus siro (Acari: Acaridae).	Experimental & Applied Acarology 5(1-2): 175-180
Heaps, J.W	1988	Turn on the heat to control insects	Dairy and Food Sanitation 8(8):416-418
Gaffney, J.J and J.W.Armstrong,	1989	High-temperature forced-air research facility for heating fruits for insect quarantine treatments.	J.Econ.Entomol. 1989, 83: 5, 1959-1964, 16 ref.
Sharp, J. L	1989	Hot-water immersion appliance for quarantine research.	J.Econ.Entomol 82(1): 189-192
Locatelli, D.P and S. Traversa	1989	Microwaves in the control of rice infestants.	Italian J. of Food Science 1(2): 53-62
Sutherland, J, W, P.W. Fricke and R.J. Hill	1989	The entomological and thermodynamic performance of a pneumatic conveyor wheat disinfestor using heated air.	J. of Agricultural Engineering Res. 44(2): 113-124
Gaffney, JJ, Hallman, GJ, Sharp, JL	1989	Vapor heat research unit for insect quarantine treatments.	J.Econ.Entomol. 1989, 83: 5, 1965-1971, 26 ref.
Ebeling, W., C.F.Forbes and S.C.Ebeling	1989	Heat treatment for powder post beetles	IPM Practitioner 11(9):1-4
Gaffney, J. J, G. J.Hallman and J.L.Sharp	1990	Vapor heat research unit for insect quarantine treatments.	J.Econ.Entomol 83(5): 1965-1971
Thayer, D.W.	1990	Food irradiation: benefits and concerns.	J-Food-Qual. Trumbull, Conn. : Food & Nutrition Press. June 1990. v. 13 (3) p. 147-169.

Author	Year	Title	Journal
Sokhansanj, S., Wood, H.C., Venkatesan, V.S.	1990	Simulation of thermal disinfestation of hay in rotary drum dryers.	Trans-A-S-A-E. St. Joseph, Mich. : American Society of Agricultural Engineers. Sept/Oct 1990. v. 33 (5) p. 1647-1651. ill.
Mills.R and J.Pedersen(ed)	1990	Heat sterlization checklist	Flour Mill Sanitation Manual, Appendix D: 157-159
Chen, C. P, R.E. Lee (Jr) and D.L. Denlinger	1991	Cold shock and heat shock: A comparison of the protection generated by brief pretreatment at less severe temperatures.	Physiol. Entomol. 16(1): 19-26
Sharp, JL, Gaffney, JJ, Moss, JI, Gould, WP	1991	Hot-air treatment device for quarantine research.	J.Econ.Entomol. 1991, 84: 2, 520-527, 8 ref.
Fields, P.G	1992	The control of stored-product insects and mites with extreme temperatures	J.stored Prod. Res 28(2): 89-118
Soderstrom, E.L., Brandl, D.G., Mackey, B.	1992	High temperature combined with carbon dioxide enriched or reduced oxygen atmospheres for control of Tribolium castaneum (Herbst) (Coleoptera: Tenebrionidae).	J-Stored-Prod-Res. Exeter : Pergamon Press. Oct 1992. v. 28 (4) p. 235-238.
Saxena, B.P., P.R.Sharma, R.K.Thappa and K.Tikku	1992	Temperature induced sterilization for control of three stored product beetles	J.Stored Prod.Res. 28(1):67-70
Saxena, B.P, Sharma, P.R, Thappa, R.K, Tikku, K	1992	Temperature induced sterilization for control of three stored grain beetles.	J.Stored Prod.Res. 1992, 28: 1, 67-70, 15 ref.
Hansen, J.D.	1992	Heating curve models of quarantine treatments against insect pests.	J.Econ.Entomol. Lanham, Md. : Entomological Society of America. Oct 1992. v. 85 (5) p. 1846-1854.
Brokerhof, A.W, J.H.Banks and R. Morton	1992	A model for time-temperature-mortality relationships for eggs of the webbing clothes moth, Tineola bisselliella (Lepidoptera: Tineidae), exposed to cold.	J.Stored Prod.Res. 1992, 28 (4) 269-277.
Jang, E.B., Chan, H.T.	1993	Thermal death kinetics: importance in development of heat-based quarantine treatments.	Fruit flies biology and management / Martin Aluja, Pablo Liedo, editors. New York : Springer-Verlag, c1993.. p. 345-351.
Zewar, M.M	1993	The use of high temperatures for disinfesting wheat from Sitophilus granarius L., and cowpea Callosobruchus maculatus (F.).	Egyptian J. AgriculturalResearch. 1993, 71: 3, 671-678, 4 ref.
Madsen, B.	1994	Heat treatment as an alternative to Methyl Bromide fumiagation in mills	Alternatives to methly bromide, TemaNord 1995(574):51-55
Ebeling, W	1994	The thermal pest eradication system for structural pest control	The IPM Practitioner 16(20:1-7

Author	Year	Title	Journal
Birch, L.C	1994	The effect of temperature and dryness on the survival of the eggs of Calandra oryzae L.(small strain) and Rhyzopertha dominica Fab. (Coleoptera)	Australilan J. Experimental Biology and Medical Science 22:265-269
Hallman, G.J., Armstrong, J.W.	1994	Heated air treatments.	Quarantine treatments for pests of food plants /. Boulder : Westview Press , New Delhi : Oxford & IBH Pub., 1994.. p. 149-163.
Heaps, J.W. and T.Black	1994	Using portable rented electric heaters to generate heat and control stored product insects	Bull. Assoc. of Operative Millers July:6408-6411
Heaps, J.W	1994	Temperature control for insect elimination	Bull. Assoc. of Operative Millers Dec 1994: 6467-6470
Nair, P.R., T.S.U.Nair, M.Cyriac and J. K.George	1994	Thermal treatment for the prevention of insect infestation in dried fish: Use of a tunnel drier/solar tent drier.	Fishery-Technology. 1994, 31 (2) 133-141.
Longstaff, B.C	1994	The management of stored product pests by non-chemical means: an Australian perspective.	J.Stored Prod.Res. 1994, 30: 3, 179-185, 42 ref.
Taheri, MS	1994	The effect of temperature as a controlling factor of Tribolium confusum Duv. (Col. Tenebrionidae).	Applied-Entomology-and-Phytopathology. 1994, 61: 1&2, 20-21 Ar 52-60, 4 ref.
Hallman, G.J., Sharp, J.L.	1994	Radio frequency heat treatments.	Quarantine treatments for pests of food plants /. Boulder : Westview Press , New Delhi : Oxford & IBH Pub., 1994.. p. 165-170.
Mueller, DK	1994	Phosphine, heat and carbon dioxide deliver death punch to insects.	Pest Control. 1994, 62: 3, 42, 44, 46, 48.
Ebeling, W.	1994	Heat and silica aerogel are synergistic.	Tech-note-For-Eng-Res-Inst-Can. Pointe Claire, Quebec : Forest Engineering Research Institute of Canada. Feb 1994. v. 16 (2) p. 11-12.
Sharp, J.L (ed.), Hallman, GJ	1994	Quarantine treatments for pests of food plants.	1994, ix + 290 pp., Westview Studies in Insect Biology, many ref.
Dosland, O	1995	The Chester heat treatment experiment 6/94	Assoc. of Operative Millers Sep Bulletin pp 6615-
Whiting, D.C., G.M.O'Connor, J. van den Heuvel and J.H. Maindonald	1995	Comparative mortalities of six tortricid (Lepidoptera) species to two high-temperature controlled atmospheres and air.	J.Econ.Entomol. 88 (5): 1365-1370.
Locatelli, D, P, Biglia, M, C	1995	Development of Ephestia kuehniella (Zeller) and Plodia Interpunctella (Hubner) (Pyralidae: Phycitinae) in baking ingredients and products.	Italian-Journal-of-Food-Science. 1995, 7 (4) 333-340.

Author	Year	Title	Journal
Jones, V.M., B.C.Waddell, and J.H.Maindonald	1995	Comparative mortality responses of three tortricid (Lepidoptera) species to hot water.	J.Econ.Entomol. 88 (5) : 1356-1360.
Pradzynska, A	1995	The role of higher temperatures in control of granary weevil (Sitophilus granarius L.).	Prace-Naukowe-Instytutu-Ochrony-Roslin. 1995, 36: 1-2, 119-127, 6 ref.
Tuncbilek, A.S	1995	The effect of temperature upon the radiation susceptibility of grain weevil, Sitophilus granarius (L.) (Coleoptera, Curculionidae).	Turkiye Entomoloji Dergisi. 1995, 19: 1, 27-35, 10 ref.
Dowdy,A.K, McGaughey, W.H.	1995	Heat susceptibility of flour beetles as influenced by age and sex.	1995 annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions / International Research Conference on Methyl Bromide Alternatives and
Locatelli, D.P and Biglia,M.C	1995	Development of Tribolium confusum Duval (Coleoptera: Tenebrionidae) in baking ingredients and products.	Tecnica Molitoria. 1995, 46: 9, 937-943, 30 ref.
Nordic Council of Ministers	1995	Alternatives to Methly Bromide	TermaNord 1995:574, 1-67
Hansen, L.S., Jensen, K.M., vagn.	1996	Upper lethal temperature limits of the common furniture beetle Anobium punctatum (Coleoptera: Anobiidae).	Int-biodeterior-biodegrad. Oxford, U.K. : Elsevier Science Limited. 1996. v. 37 (3/4) p. 228-232.
Heaps, J.W	1996	Review of the methyl bromide situation rationale for heat treatment	Bull. Assoc. of Operative Millers April: 6703
Dosland, O	1996	Practical research to determine effective heat parameters for the control of stored product insects	Assoc. of Operative Millers. April Bulletin pp 6703-6706
Mire, M	1996	Heat Sterilization	Assoc. of Operative Millers. April Bulletin pp 6707-6710
Norstein, S.	1996	Heat treatment in the Scandinavian milling industry - heat treatment as an alternative to methyl bromide.	Norwegian Pollution Control Authority, Environmental Technology 96: 02E 73pp
Heaps, J.W	1996	Heat for stored product insects.	IPM Practitioner. 1996, 18: 5-6, 18-19, 3 ref.
Chinwada, P, Giga, D.P	1996	Sunning as a technique for disinfesting stored beans.	Postharvest-Biology-and-Technology. 1996, 9: 3, 335-342, 11 ref.
Donahaye, E.J., S.Navarro, M.Rindner and A. Azriella	1996	The combined influence of temperature and modified atmospheres on Tribolium castaneum (Herbst)(Coleoptera: Tenebrionidae)	J.Stored Prod. Res. 32(3): 225-232

Author	Year	Title	Journal
Anonymous	1997	Temperature control: an alternative to traditional insecticides and fumigants in food handling facilities	Fumigation, National Pest Control Association, NPCA pest management library update: 3p.
Ali, Mahmoud, Fadl , Abdel, Reheem, Elham, F, M, Abdel, Rahman, H, A	1997	Effect of temperature extremes on the survival and biology of the carpet beetle Attagenus fasciatus (Thunberg) (Coleoptera: Dermestidae).	J.Stored Prod.Res. 1997, 33 (2) 147-156.
Sharma, P.R., Thappa, R.K., Tikku, K., Chand, D., Saxena, B.P.	1997	Control of stored-product moths and beetles by suboptimum temperatures.	Trop-sci. London : Whurr Publishers Ltd. 1997. v. 37 (1) p. 28-34.
Bala, B.K	1997	Drying and storage of cereal grains.	1997, ix + 302 pp., 57 ref.
Salin, C , Vernon, P, Vannier, G	1998	The supercooling and high temperature stupor points of the adult lesser mealworm Alphitobius diaperinus (Coleoptera: Tenebrionidae).	J.Stored Prod.Res. Oct., 1998, 34 (4) 385-394.
Levinson, H , Levinson, A	1998	Control of stored food pests in the ancient Orient and classical antiquity.	Journal-of-Applied-Entomology. June, 1998, 122 (4) 137-144.
Dowdy, A.K	1998	Heat treatment as an alternative to methyl bromide fumigation in cereal processing plants	Proc. Of the 7th International Working Conference n Stored Product Protection; Beijing, China
Lewthwaite, S. E, P.R.Dentener, S.M. Alexander,K.V. Bennett, D.J. Rogers,vJ.H. Maindonald	1998	High temperature and cold storage treatments to control Indian meal moth, Plodia interpunctella (Hubner).	J.Stored Prod.Res. April-July, 1998, 34 (2-3) 141-150.
Beckett, S. J , R. Morton and J.A. Darby	1998	The mortality Rhyzopertha dominica (F.) (Coleoptera: Bostrychidae) and Sitophilus oryzae (L.) (Coleoptera: Curculionidae) at moderate temperatures.	J.Stored Prod.Res. Oct., 1998, 34 (4) 363-376.
Holcomb, M	1998	Extreme temperatures can control insects	The Sanitarian pp3
Evans, D.E and T.Dermott	1998	The potential of fluidized-bed techniques in insect control	Proceedings of the second internations working conference on stored product entomology, Abadan, Nigeria
Bursick, B	1999	Heat Sterilization	Grain Journal p 194-195
Dowdy, A.K and P.G. Fields	1999	The right mix. Diatomaceous earth plus heat can destroy insect pests.	Resource,-Engineering-and-Technology-for-a-Sustainable-World. 1999, 6: 4, 7-8.
Mankin, R.W , Shuman, D , Weaver, D. K	1999	Thermal treatments to increase acoustic detectability of Sitophilus oryzae (Coleoptera: Curculionidae) in stored grain.	J.Econ.Entomol. April, 1999, 92 (2): 453-462.

Author	Year	Title	Journal
Dowdy, A.K	1999	Insect control in flour mills using heat sterilization	The Sanitarian p 6-7
Sargent, J., M. Sheperdigian, and J. Weir	1999	Heat treatment: capabilities and limitations	International research conference on methly bromide alternatives and emission reductions, Nov 1, 1999
Gooch, H.	1999	The Contenders: Beyond Methyl Bromide	Pest Control Jan 1999: 46 - 48
Salin, C, Vernon, P , Vannier, G	1999	Effects of temperature and humidity on transpiration in adults of the lesser mealworm, Alphitobius diaperinus (Coleoptera: Tenebrionidae).	J.Insect Physiol.. Oct., 1999, 45 (10): 907-914.
Menon, A., Bh.Subramanyam, A.K. Dowdynd R. Roesli.	2000	Heat sterilizationt: A safe and viable alternative to Methyl Bromide	Grain Journal
Na, J.H and M.I Ryoo	2000	The influence of temperature on the development of Plodia interpunctella (Lepidoptera: Pyralidae) on dried vegetable commodities	J.stored Prod.Res 36:125-129
Mourier.H and K.P.Paulsen	2000	Control of insects and mites in grain using a high temperature/short time (HTST) technique	J.stored Prod.Res 36:319-318