THE EFFECTS OF HEAT ON TEN SPECIES OF COMMON HOUSEHOLD INSECT PESTS

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PREFACE

Recent developments in insect control have indicated that undesirable residues may result from the use of current insecticides. This is the reason that this thesis problem was selected. The effects of high temperature on the survival and activity of ten species of common household insect pests were studied in a series of experiments conducted under controlled laboratory conditions.

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INTRODUCTION

There are many different species of insect pests which are commonly found in the home. The most widely used method of controlling these pests is by the application of insecticide. Many times, this method of control is costly, inefficient, and dangerous.

The objectives of the investigation reported in this thesis were to provide more information on the effectiveness of high temperatures on the control of some of the more common household insect pests.

Observations were made in a series of tests where the insects were confined in test cages in a constant temperature cabinet. In another series of tests conducted in a room which simulated as nearly as possible the normal environment of the test insects in the home, observations were made on the effects of high temperatures when the test insects were free to move about and escape the effects of the heat. Studies also were made of the effects of high temperature on some of the more common household finishes.

Data were collected also on the effects of constant temperature and relative humidity in the range of 10% to 90% on all stages of P. americana. Physiological mechanisms causing death were considered.

REVIEW OF THE LITERATURE

Insect Control by Heat

Dean (1911) used heat as a means of controlling insect pests in mills. In experiments with the larvae, pupae, and adults of Silvanus surinamensis (L.), Ephestia kuehniella (Zell.), Tenebrionides mauritanicus (L.), and the adults of Calandra oryza (L.), he demonstrated that heat would kill these insects. A temperature of 47 C proved to be fatal to the adults of E. kuehniella while a temperature of 48 C was required to kill the larvae and pupae. A temperature of 48 C was fatal to the adults of C. oryza and a temperature of 48.5 C proved to be lethal to all stages of S. surinamensis. A temperature of 49 C was necessary to kill the majority of all stages of the T. mauritanicus.

Dean (1913) determined that in mills where insects were able to breed in places that were inaccessible to gas or the vapor of any fumigating material, heat could be used for control, as it would pass through all of the obstructions and would penetrate into the innermost recesses. He also found that many mill insects were not readily killed by hydrocyanic acid gas, but that no mill insects could withstand, for any length of time, a temperature of 48.2 C to 50 C. He demonstrated in these tests that heat was the most practical, convenient, efficient, and inexpensive method of controlling mill insects.

The practical value of high temperatures, 48 C to 50 C, for the destruction of pests affecting cereal products was reported by Goodwin

(1914). He concluded that the effect of these temperatures was decreased when the heated atmosphere contained a moisture content greater than 40% to 50%. In practical work where the moisture content of the heated atmosphere remains constant or is greatly increased as the temperature rises, there must be a proportional increase in the amount of heat necessary to maintain or to raise the temperature to the fatal or killing point.

Bacot (1914) determined the influence of temperature on the survival of eggs and larvae of Cimex lectularius (L.). In his tests, 20 unfed C. lectularius kept at a temperature of 45 C did not survive after 15 hours exposure. In another series of tests, unfed bugs kept at 45 C were all dead after 1 3/4 hours of exposure.

Schribaux (1916) found that weevils infesting seeds were destroyed in two minutes by a temperature of 50 C, while Bruchus spp. could not survive at 60 C. Results of these experiments indicate that cereals, except for maize, can withstand a temperature of 100 C for one hour without detrimental effect on germination.

Howard (1917) demonstrated that the effects of temperature on Blattella germanica (L.) vary considerably below 49 C but that exposures to temperatures of 50 C and above for 20 minutes result in a 100% kill.

Goodwin (1922) reported that heat was an effective method of controlling mill insects. Insects were controlled in mills that were equipped with a heating plant which maintained a temperature of 54.5 C to 60 C for four days or more. Practically all life stages of such insects were destroyed. Data included in his report were obtained from tests in which insects were successfully controlled in more than 30 mills in Ohio and Pennsylvania.

Heat was found to be useful for destruction of certain susceptible insects on hardy plants, weevils in nuts, and pests in dried fruits, beans, and peas. The germination of most seeds was not affected when sufficient heat was applied to kill insects working in the seeds.

Back (1923) reported fabric pests were controlled effectively by heat and that most were killed in a short time when rooms were heated to a temperature of 54 C and kept at this temperature long enough for all articles in the room to be thoroughly penetrated by the heat. Data reported from these experiments indicated that all larvae exposed to 53.2 C, 49 C, and 43.2 C were killed in 6, 11, and 31 minutes, respectively. The method of eradication is very useful when clothes are to be freed of pests and stored for the summer.

Back and Cotton (1924) studied the effects of high temperatures on the rice weevil, Sitophilus oryza (L.), and the granary weevil, Sitophilus granarius (L.), and found that they were able to kill the rice weevil in nine days when using heat in the temperature range of 35 C to 37 C. All of the adults of the granary weevil were found to be dead at the end of 13 days at the same temperature. In another test, these workers found that a temperature of 49 C killed adults of both species in three hours and a temperature of 54.3 C was lethal in 30 minutes.

Harned and Allen (1925) conducted two experiments on the effectiveness of superheating rooms for the control of C. lectularius in the dormitories of the Mississippi Agricultural and Mechanical College. Superheating of the infested rooms was accomplished by closing the rooms and turning on the steam heat during hot summer weather. At temperatures of 49 C and above, absolute control was secured by treatment in 63 to 87 hours.

A high mortality in the insects was obtained at temperatures averaging 43.3 C when maintained for two or more days.

Grossman (1931), working with the rust-red flour beetle, Tribolium ferrugineum (Fab.); the rice weevil, S. oryza; and the slender-horned flour beetle, Gnathocerus maxillosus (Fab.), reported that these species were killed when exposed to 50 C for one hour. An exposure to a temperature of 42 C for 200 hours was also lethal for all species studied. The pupae of these insects resisted a given temperature for a longer period of time than did the larvae, which in turn were able to withstand longer exposures than did the eggs or the adult stages.

Cressman (1933) conducted a test in the library of the United States Circuit Court of Appeals in the Post Office Building, New Orleans, Louisiana, using heat to control the cigarette beetle, Lasioderma serricorne (Fab.). Previous to the treatment, the cigarette beetle had infested the leather bindings of books in all parts of the library. A gas burner with a heat capacity of 2 1/2 cubic feet per minute was installed for the source of heat. The temperature used in the test was 60 C to 63 C, which was maintained for six hours. Electric fans were used to insure an even distribution of heat in a room which measured 100 by 21 by 15 feet. All of the books were placed apart from each other to allow the hot air to circulate freely among the volumes. There was no evidence of damage to the wooden desks and tables or to books bound in sheepskin. An inspection of the premises at 3- and 37-day intervals revealed no evidence of the insect in any stage of development.

Pepper and Strand (1935) investigated the importance of surface temperatures in heat sterilization. In their tests they determined

that it would take eight hours to raise the temperature at the surface of the floor to 49 C, but it would take only two hours to raise the temperature at the 1/4-inch level to 49 C. The temperatures at the 1- and 2-inch levels above the floor surface were found to be very similar to the 1/2-inch level. The results of this experiment indicate that heat stratification in the air very close to the floor is a very important factor to consider when using heat as a control of insects.

Thomas and Shepard (1940) found that when adults of the saw-toothed grain beetle, Oryzaephilus surinamensis (L.), and the confused flour beetle, Tribolium confusum (Duval.), were exposed to a temperature of 44 C at 30% relative humidity, 50% of the flour beetles were killed in approximately four hours while at 46 C at 50% relative humidity, approximately 40 minutes were required to kill the beetles. At 42 C, 50% of the saw-toothed grain beetle were killed in 34 hours, while at 44 C 50% were killed in approximately 4.5 and 5.7 hours at 30% and 75% relative humidity, respectively.

Kenaga and Fletcher (1942) demonstrated an interesting example of the effect of a high temperature on various insects. They increased the temperatures from a normal of 27 C to 41 C over a 64-hour period and demonstrated that for B. germanica, C. lectularius, and T. confusum, all developmental stages were unaffected at these temperatures; for Periplaneta americana (L.), 40% of the immatures and 99% of the adults were killed; for Attagenus piceus (Oliv.), 50% of the immatures and 90% of the adults were killed; for

Dermestes spp., 50% of the immatures and 50% of the adults and 100% of the eggs were killed; and for Tineola bisselliella (Hum.), 90% of the immatures and 100% of the adults were killed.

Busvine (1944) found that heat was completely ineffective in controlling insects when a room was heated by its regular furnace. This was due to the poor distribution of heat. In a test with the "Millbank Disinfestor," the results obtained indicated a 100% control of the insect population in rooms where this apparatus was used. The English army adopted this apparatus during the Second World War because the air was circulated by a forced draft. Busvine conducted a test by placing louse eggs at various spots among the rugs, bedding, and clothing of a storage area in which hot air was allowed to circulate for half an hour. This period of time was long enough to obtain a temperature of 101 C at the top and in the center of the room and 55 C at the floor surface at the farthest point from the heater. This treatment successfully killed all lice eggs at the top and bottom levels and at other various points in the room.

Bare, Tenhet, and Reed (1946) investigated the effects of the "Thermal-Vacuum Process" on insects in stored tobacco. They found that the thermal-vacuum treatment for conditioning tobacco is effective in destroying insects. The maximum temperature attained in the treated tobacco was in range of approximately 77 C to 80 C. Approximately 16 minutes was required to produce 100% mortality in all developmental stages of the insects found in the tobacco.

Godkin and Cathcart (1949) demonstrated that infra-red heat offers a rapid and effective means of eliminating surface infestation

of all developmental stages of stored products insects in finished packaged products. They used an infra-red exposure temperature of approximately 260 C, which they determined was capable of heating the surface of a finished packaged product to 60 C to 66 C within 20 seconds. This short time treatment was found to be sufficient for killing any insect infestation present in the package without altering the food product or damaging the cellophane packaging materials.

Rawle (1951), in his experiments, found that all stages of T. biselliella can be destroyed at 41 C in four hours; but at 39 C, it would take one day to kill the eggs, three hours to kill the larvae, and four hours to kill the adults.

Knipling and Sullivan (1958) studied the thermal death points of several species of insects and determined that 100% mortality was obtained after 15 minutes' exposure at 45 C to Culex pipiens (L.) and Anopheles quadrimaculatus (Say); at 50 C to Epilachna varivestis (Muls.) larvae and Aedes aegypti (L.); and at 55 C, E. varivestis adults, Musca domestica (L.), Popillia japonica (Newm.), Dermacentor variabilis (Say), and T. confusum. They found it took 60 C to kill grasshoppers and Leptinotarsa decemlineata (Say).

The Effects of Heat and Relative Humidity on Insects

Beattie (1927) determined the thermal death point of the blow fly to be definitely influenced by the factor of relative humidity. In his test, relative humidity in the range of 60% to 80% was found to be more favorable for survival at high temperatures while a relative humidity of 70% was found to be the optimum point. Saturated

and dry air had the effect of lowering the thermal death point. He concluded that death in saturated air was due to the inability of the flies to regulate their body heat by evaporation of moisture.

In a 24-hour experiment in moist air, Mellanby (1932) found that various species of insects died at temperatures between 36 C and 39.5 C. Their death presumably was caused by the high temperature. In dry air, insects not able to conserve their water were found to have a higher death rate at lower temperatures. The causes of death at high temperatures were: (1) When the air temperature was over 40 C, insects died from the effects of the heat. (2) Below 36 C, all the insects experimented with were able to survive for at least 24 hours in moist air; but, in dry air, the insects died from desiccation. In hot air, over 40 C, certain large insects such as the American cockroach were able to survive longer in dry air than in moist air.

Mellanby attempted to calculate the amount of water which must be evaporated from an insect if its body is to be kept cooler than the environmental air. He used Preston's (reference unknown) constants from his theory of heat. These constants could not be applied to water loss in insects, but Mellanby was able to obtain an indication as to how much water was lost.

Cooling of an insect - Mellanby (1932) reported that an insect, in hot air, may be cooled by evaporation of water from the tracheal system even though it is exposed to heat continuously over its entire exoskeleton. The heat may penetrate into the body proper, but the effect will be neutralized by the cooling effect of the evaporation of water. The amount of heat received by the insect will depend on

the difference of temperature between its body and the temperature of the environment.

The nature of the body surface of the insect was a very important factor and can vary considerably; but, for the purpose of this thesis, an average figure can be assumed. This figure can be determined by assuming that for every square centimeter of body surface and for every degree centigrade with which the body temperature is lower than the environmental temperature, an insect will absorb 0.00025 calories per second (figure from Preston in Mellanby, 1932). This amounts to roughly one calorie per hour.

For an insect to maintain its body at a lower temperature than that of air, the absorbed heat must be eliminated; and it was assumed that this is accomplished through the evaporation of water. At 40 C, every gram of water evaporated required almost 600 calories. Therefore, provided that the cooling mechanism in an insect is very efficient, for every calorie of heat absorbed, about two milligrams of water will have to be evaporated if the body is to maintain a constant temperature.

In order for a cockroach weighing one gram and having a surface area of about eight square centimeters to maintain its body temperature 5 C cooler than the air temperature for one hour at an environmental temperature of 45 C, it will have to absorb about 40 calories and evaporate 80 milligrams of water or about 8% of the insect's weight. This figure is well within the range reported by Mellanby. He determined that an insect could lose body water by evaporation amounting to 13% of its body weight.

Gunn and Notley (1936) concluded that moist air was more favorable for cockroaches than dry air when the body exposure to high temperatures was for a long period of time. They reported death to occur in dry air from desiccation even though the temperature was not high enough to be fatal. They also concluded that dry air was more favorable than moist air for a short body exposure due to the fact that the evaporation of water lowered the body temperature.

Frankel and Herford (1940) found that the oxygen consumption of blow fly larvae at sub-lethal and lethal high temperatures, at the beginning of a test period, was dependent on the oxygen pressure; but, after approximately one hour at 42 C, oxygen consumption was higher at 20% and 10% partial pressure of oxygen than at either 100% or 5%. They determined that death at high temperatures was not due to a lack of oxygen but may be due to the accumulation of acid waste products of metabolism in the body of the insect. They also determined that the basal oxygen consumption remained unchanged for some time after the organism had been irreversibly injured by high temperature.

In tests with Calliphora erythrocephala (Meig.) and Phormia terra-norae (R. D.) larvae, Frankel and Hopf (1940) found that the amount of heat adaptation of both species developed to such a degree that larvae cultured at temperatures of 18 C higher than normal culture temperatures will be able to withstand at least one degree higher air temperature for the same time of exposure as those bred at the lower level.

The degree of unsaturation of the phosphatides in the body of these larvae measured by iodine values was dependent upon the temperature of culturing only. A difference was observed between those

cultured at high and low air temperatures. A role of these phosphatides in the mechanism of heat adaptation of insects was suggested; but closely allied species of flies, bred at the same temperature and having the same iodine value for the fatty acids of their phosphatides, were found to have different resistances to heat. This indicated that a physical breakdown of the fatty substances cannot be the direct cause of heat injury.

Hopf (1940), in his experiments with C. erythrocephala and P. terra-norae at abnormally high temperatures, reported that high temperatures caused an increase in the lipoid phosphorus, the inorganic phosphorus, and the adenylpyrophosphate-phosphorus of the haemolymph. The function of the two latter components were connected with buffering and coenzymic activity, respectively. The increase was more pronounced for a long exposure to low lethal temperatures (15 hours at 38.5 C or 42.5 C) than for short exposures at a high lethal temperature (one hour at 46 C) except in the case of the adenylpyrophosphate-phosphorus, which increases equally in both cases and was assumed to be liberated at an early stage.

Beament (1944), working with the cuticular lipoids of insects, showed that a membrane waxed with insect lipoids exhibited a sudden increase in permeability at a critical temperature. The waxes were found to undergo a crystalline transition at this temperature in which their molecules became mobile resulting in the disorganization of the oriented layer. He demonstrated that the waxed surface in the presence of water becomes more hydrophilic at the transition point, and the molecules are permanently oriented in this state.

Jefferson (1945) suggested that the mitochondria of the fat bodies was the possible site of heat injury. This conclusion was based on his work with Calliphora larvae. He found that when larvae were treated with high temperature, the globules of fat were small and discrete; whereas, the ones in the control groups maintained at lower temperatures had globules which were generally larger and often aggregated into clumps.

The influence of temperature upon the respiration and heart activity of Thermobia and Grylloblatta was investigated by Edwards and Nutting (1950). They tested the oxygen consumption, heart rate, and activity at various temperatures between -5.0 C and 51.8 C. The data from their tests indicated that the heart rate and respiration rate were practically identical at all levels of temperatures checked.

Roan (1952), in his work with the oriental fruit fly at high temperatures and at various humidity levels, demonstrated that the time for 100% kill from heat ranged from 20 seconds at 50 C to 15 minutes at 43 C. The results of his tests indicated that at temperatures above 43 C with dry conditions, survival is favored; whereas, at lower temperatures, dry conditions appeared inimical to survival. He attributed these differences to cooling by water loss at the higher temperatures. Thermocouple measurements indicated a body temperature lower than the environmental temperature at low relative humidities; whereas, at high relative humidities, the body temperature rapidly approached environmental conditions. But he did not attribute the more rapid increase in body temperature at high humidities to latent heat of condensation.

Munson (1953) stored groups of P. americana at different temperatures and at different time intervals which were sufficiently long

to insure different iodine numbers for the different temperatures. Results of his tests showed that there was no difference in the resistance of these cockroaches to high lethal temperatures under the experimental condition used. This investigation did not prove or disprove the "Lipoid Liberation Theory" which suggests that lipids play a vital role in the resistance of animals to high temperatures (Frankel and Hopf, 1940).

The effects of humidity and other factors on the upper thermal death point of the chinch bug Blissus leucopterus (Say) were studied by Guthrie and Decker (1954). These workers subjected chinch bugs to eight temperature levels ranging from 41 C to 55 C and to five different levels of relative humidity ranging from 10% to 92% for each temperature tested. They concluded that at temperatures below 50 C survival of the chinch bug occurred at a high rate when the relative humidity was high, while at temperatures above 50 C, the bug survived at a high rate when the relative humidity was low. Chinch bug body water losses were determined at these different temperature levels. At 45.2 C at low relative humidity, death occurred when the bug had lost body water amounting to approximately 32% of its original weight. More weight was lost by insects held at 48.8 C and at low humidity than by those held at 48.8 C in high relative humidity. The data obtained by Guthrie and Decker indicated that the amount of water lost when chinch bugs were exposed to different conditions of temperature and humidity for various periods of time might be a primary cause of death at 45.2 C. At 50.2 C water loss was not great enough to account for death by desiccation.

Mead-Briggs (1956) worked on the effects of temperature on the permeability of the arthropod cuticle to water. In experiments with P. americana, he determined that the cuticle became progressively more permeable when the temperature was raised from 30 C to 55 C. In addition, he found that the progressive change in cuticle permeability was dependent on the presence of cuticular wax.

The effects of thermal conditioning and the degree of saturation of dietary lipids on resistance of an insect to high temperatures were explored by House, Riordan, and Barlow (1958). They demonstrated that the resistance of larvae of Pseudosarcophaga affinix (Fall.) to a high temperature was increased by thermal conditioning and by changes in the dietary lipids. Data from these experiments indicate that an exposure time of 130 minutes at 45 C was required to produce 50% mortality of larvae that had been reared at 23 C on pork liver. If these larvae were preconditioned for two hours at 39 C before this exposure, an exposure time of 200 minutes was required to produce 50% death loss. These workers reported results of other experiments in which larvae were exposed to a temperature of 45 C where larvae were reared on chemically defined diets; 50% mortality occurred after an exposure of 177 minutes for those on a diet containing unsaturated fatty acids, 184 minutes for those reared on an intermediate mixture of saturated and unsaturated fatty acids, and 218 minutes for those reared on a diet that contained a high proportion of saturated fatty acids. These results indicated that the degree of saturation of body lipids was directly influenced by the degree of saturation of the dietary lipids.

METHODS AND MATERIALS

Test Animals and Rearing Techniques

Ten different species of common household insect pests were used in the laboratory tests. Colonies of these species were started from colonies maintained at the Oklahoma State University Entomology Department Insectary; the United States Department of Agriculture Research Laboratory at Gainesville, Florida; or were collected from homes in the Stillwater, Oklahoma, area.

Periplaneta americana and Blattella germanica colonies were established from laboratory reared females from colonies available at the Entomology Department Insectary at Oklahoma State University. Nymphs and male and female adults were maintained in glass aquariums and fed on a dog food diet.

Blatta orientalis (L.) that were used to start a colony were collected during the summer of 1963 from a garage which was located in Stillwater. Nymphs and male and female adults were used in the tests. They were reared on dog food and kept in glass aquariums.

Supella supellectilium (Serville) were collected during the summer of 1963 from the Insectary of the Department of Entomology at the Oklahoma State University. Nymphs and male and female adults were used in the tests. They were reared and fed in the same manner as the above named roaches.

Anthrenus verbasci (L.) larvae and Trogoderma veriscolor (Cruetz) adults and larvae were used in the tests. They were collected from an infestation found in an old box of dog food. The colonies were reared in quart jars, and the diet of dog food was continued for it seemed to provide sufficient nutritional ingredients for growth and reproduction.

Thermobia domestica (Pack.) and Lepisma saccharina (L.) were collected during the summer of 1963 from buildings on the Oklahoma State University campus, and a colony has been maintained since that time. The colony has continued to increase in numbers providing sufficient numbers of each species for testing purposes. This colony is being reared in a glass aquarium which contains a small quantity of dog food plus scraps of paper and four pieces of 3/8 by 1 1/2 by 5 inch wooden laths. The wooden laths are dampened every three to five days and are kept in the aquarium to provide an abundance of organic debris for the animals to feed on. The colony is maintained in a constant temperature cabinet at 29.5 C.

Cimex lectularius adults were obtained in August, 1963 from the United States Department of Agriculture Research Laboratory located in Gainesville, Florida. Nymphs and adults were used in the tests. These insects have been maintained by allowing them to feed for 20 to 25 minutes weekly on the blood of a rabbit. To facilitate the feeding procedure, fur was clipped from the skin of the abdomen of the rabbits in a 3 square inch area. The colony was reared in a 2 by 6 by 6 inch plastic box that had a 3 square inch hole cut in the top. This hole was covered with a double thickness of nylon netting to prevent the nymphs from escaping through the

holes. The outer layer of the cover material was very fine nylon netting and the inner layer was nylon hose. This covering allowed the bedbugs to feed on the rabbit while they were still inside the box. This method appeared to be a very easy and effective feeding procedure.

Constant Temperature Cabinet Tests

A test was designed to determine the lethal time period for each of four temperatures, 42.2 C, 44.5 C, 46.8 C, and 48.9 C, for the ten species of insects used in this study. The time periods for 10% and 100% mortality were recorded for each species at each of the four temperatures. Five replications using four individuals of each species in each replication were employed to determine the death point for the following species of insects: each of the four species of roaches, both species of carpet beetle larvae, and the group of carpet beetle adults. Two individuals in each replication were used for the bedbugs, silverfish, and firebrats. The test groups of insects included 50% adults and 50% immatures except for the carpet beetles, in which case the larvae and adults were kept separate.

The cabinets that were used for the constant temperature tests had a double pane window for observation purposes. The heat source for the cabinets was electric lights which were located in the sides of the cabinets. To overcome heat stratification, an electric fan was installed in the back of the cabinet to circulate the air. This fan was operated by the thermostat that controlled the lights.

The temperature level used for each test was checked by three thermometers which were placed in the test cabinet. One thermometer

was placed in the middle and the other two were placed at each end of the test cages. Temperatures were maintained within 1 C at a given location but were found to vary as much as 2 C in other parts of the cabinet. The placement of the test animals was important because of the variation in temperature inside the test chamber. To avoid variation in the test procedure, the test insects were placed in the same position during the trials carried out at each temperature. Placement of the test animals' cages was randomized for each of the tests. The test cages were made of glass tubes one inch in diameter and five inches long with both ends open. Nylon net was glued over one end, and the other was covered by a single thickness of nylon hose which was held in place by a rubber band.

It was necessary to cool all roaches except S. supellectilium for ease in handling. This was accomplished by placing them in a refrigerator at 7.2 C for 20 minutes. After the correct number of insects were placed in their test cages, they were left at room temperature, 29.5 C, for 30 minutes to allow the cooled insects to resume normal activity before placing them in the test cabinet.

The time required to determine the 10% and 100% mortality rates was recorded for each test group. These ratios were obtained by recording the shortest and longest period of time required to kill individuals within each test group. The time required to produce 50% mortality in the test groups could not be determined because in this type of test procedure, only the first and last insects to die could be determined accurately.

Peet-Grady Chamber Heat Tests

The Peet-Grady heat test was set up to check the practicality of using heat as a method of controlling various household pests. An effort also was made to determine whether the ten groups of test animals would react to heat in the same manner in a more natural situation as they did in the constant temperature test.

A Peet-Grady chamber, 6 by 6 by 6 feet, was converted into a heat chamber by installing a 110 AC, 1,500 watt thermostatically controlled electric heater with fan inside the chamber. The walls of the chamber had holes which were originally used for applying insecticide sprays but which were used in this test for the insertion of thermometers. Two thermometers were placed in the chamber so that the bulbs were located six inches from the top while two others were placed on the floor of the chamber. Temperatures were recorded from the thermometers during each of the tests. In addition, the probes of two spring controlled soil thermographs were placed diagonally on the floor to determine temperature occurring in the corners of the chamber.

The chamber door was the only possible avenue of escape for the test animals. Petrolatum jelly was applied to a four-inch area completely surrounding the door to keep the test animals from crawling out the door when it was opened for purposes of obtaining data.

The electric heater, placed in the center of the chamber facing the door, took approximately 20 to 25 minutes to warm the test chamber to the desired temperature. After the temperature

was reached, the time interval varied from 10 to 15 minutes between stops and starts of the heater depending on the temperature being used. Heat stratification was a problem in the chamber. When the floor temperature averaged 48.9 C, the average temperature at the top of the six-foot cube was 64.5 C with a range of 59 C to 68 C. The average floor temperatures of the other two tests were 43.2 C and 46 C; whereas, the temperatures in the top averaged 53.9 C and 58.9 C, respectively.

The chamber was prepared to simulate as nearly as possible the natural habitats of the insects used in each trial. A six-drawer file cabinet was placed against one wall, and the drawers were left open during each test. In addition, a wool sweater was placed flat on the floor (one thickness) behind the heater near the back wall. In one corner, an 11-ounce army fatigue jacket was placed on the floor. The jacket was folded to provide four thicknesses so the insects could be placed between the folds of the jacket to determine how long it would take to kill the insects under these conditions. A coat made of 75% wool, 15% nylon, and 10% cashmere with a rayon quilted lining was hung 36 inches above the floor level. The two species of carpet beetle larvae were placed in the pockets.

In each test, 30 nymphs and 30 adults of P. americana, B. orientalis, B. germanica; 60 adults and larvae of T. versicolor; 60 larvae of A. verbasci; and 15 adults and 15 numphs of C. lectularius, T. domestica, L. saccharina, and S. supellectilium were exposed to the high temperatures. About ten minutes before

each test, the insects were placed in the test chamber. The larger insects, four species of roaches, firebrats, silverfish, and carpet beetle adults, were turned loose; and the smaller ones, bedbugs and two species of carpet beetle larvae, were placed in glass tubes. In addition, a check group of ten S. supellectilium and five each of T. domestica and L. saccharina were placed in the glass vials. This procedure made it possible to observe the habits of the larger insects when exposed to high temperatures since they were able to move about in the test chamber. Glass test cages of carpet beetles were placed in three locations, one on the floor without protection, one in the pocket of the coat on the wall, and one under the folded fatigue jacket. Cages of C. lectularius, S. supellectilium, T. domestica, and L. saccharina were placed in all locations except in the coat.

Temperature tests were designed to be checked alternately at 6- and 12-hour intervals. The percentage of kill was recorded at the end of each time interval for each group at each temperature being used. The insects that appeared to be dead in the chamber were removed, placed in cardboard carton lids, and counted after one hour to determine how many were dead. These counts were used to estimate the percentages of insects killed after each test period. The percentages are only estimates and should be considered plus or minus 5% except for the final percentages because the counts were made by picking up all the dead insects in the test chamber without moving the file cabinet and some of the insects possibly were overlooked until the end of the test when the file cabinet was removed and taken apart to recover the test animals.

Relative Humidity Test with P. americana

This test was conducted to determine the effects of relative humidity (10% through 90%) on P. americana nymphs and male and female adults at a constant temperature of 44.5 C. This test was carried out in the constant temperature cabinet described under the constant heat test.

The test cages used were 250 milliliter jars with screw-on tops. Inside the jars, cages were built in such a manner so as to prevent the roaches from falling into the KOH solution used to maintain the various relative humidity levels used in the test. The cages were made of plastic screening cloth and were placed about two inches from the top of the jars.

Technical potassium hydroxide was used to maintain the relative humidity levels in the tests. The amounts of KOH and water necessary to obtain the various percentages of relative humidity were taken from Peterson (1953). The KOH solution was placed in the jars just before the roaches were put into the test cages. Roaches were inactivated by cooling to facilitate counting, sexing, and lotting. When all roaches were in the jars, they were left at room temperature, 29.5 C, for 20 minutes before being placed in the test chamber.

The data obtained from each relative humidity level for each group in the test were based on five replications with four individuals in each replication. The data indicate the length of time necessary to kill the different insect groups at each relative humidity level.

Observations were made continually to determine when the test animals died. The movement of the roaches during the tests was very erratic, and no set pattern was observed. When the test animals' movement ceased, they were removed and placed in a 1/2-gallon cardboard carton lid. They were observed for one hour to see if any had survived the test.

Temperature check jars were placed between the test jars in the test chamber. The check containers contained the same percentage of salt solution as the test jars. The test jars were arranged in a semi-circle around the light bulb with each jar being the same distance from the source of heat.

Body Temperature Test with P. americana

The surface temperature of the body of adult male American roaches was compared to the atmospheric temperature in close proximity of the roach under the following relative humidity levels: 90%, 70%, and 50%. The surface temperature was obtained at each humidity level from a thermocouple that was taped under the wings of the roach. The temperature of two roaches at each of the relative humidity levels was determined and a determination of the air temperature inside the test jars was made by inserting another thermocouple through the cap of the jar. The jars, test chamber, and KOH solutions used were described in the relative humidity test.

Finished Surface Test with Heat

Heat tests on finished surfaces were designed to ascertain the effects of heat on six common surface finishes; namely, outside white paint, high-gloss enamel, rubber base paint, flat varnish, high-gloss

varnish, and low-gloss varnish. These finishes were applied to 3/8 by 4 by 10 inch plyboard panels. Two coats of each finish were applied by dipping the panels in the various finishes and was completed at least 30 days before the test period. Three panels of each surface finish were made so one could be used as a check and the other two could be used in the test.

The tests were conducted in the modified Peet-Grady chamber at the average temperature of 46.1 C at the floor level and 58.9 C at the top level. One test panel of each finished surface was placed at the floor level and one each at the ceiling level. The panels were removed after 24 hours in the heat chamber and compared with the checks. They were again examined for damage due to heat 24 hours later. After eight months, the same panels were subjected to a 48-hour test period at the temperatures used previously.

RESULTS AND DISCUSSION

Considering the results obtained in the different tests with high temperatures, it would seem feasible to use heat as a method of controlling some of the common household insect pests. However, if heat is to be used as a possible method for control of insects, one must be aware of the various environmental factors that can affect the control of insects with heat. Studies were made and data were collected on these factors that were considered to influence the use of high-temperature methods to control insects. Results of these studies are summarized and discussed along with the conclusions that were reached.

Constant Temperature Cabinet Tests

Ten groups of common household insect pests were subjected to four different high temperatures, and the time required for 10% and 100% mortality was determined for each group at each of the four temperatures. The results of these tests are shown in Table I. These data indicate that there is a great deal of variation in the effectiveness of heat in killing the different species of insects commonly found in the home. Data collected from the constant temperature cabinet tests indicate that at the temperature of 42.2 C there was a wide variation in the time required to kill 10% of the insects tested. *Cimex lectularius* were killed most quickly (90 minutes); whereas, *T. versicolor* were able to withstand

TABLE I

Results of experiments to determine the length of time, in minutes, required to kill 10% and 100% of ten species of insects that were exposed to the effects of four temperatures, centigrade, at a relative humidity of 22%.

Species of Insects	Temperatures	Time Required to Produce a Mortality of	
		10%	100%
P. americana	42.2	105	150
	44.5	61	77
	46.8	43	70
	48.9	23	38
B. germanica	42.2	100	160
	44.5	42	56
	46.8	27	52
	48.9	17	44
B. orientalis	42.2	125	195
	44.5	55	83
	46.8	35	75
	48.9	25	40
S. supellectilium	42.2	110	210
	44.5	35	72
	46.8	30	41
	48.9	18	34
T. domestica	42.2	3,240	5,400
	44.5	720	1,200
	46.8	360	540
	48.9	45	125
L. saccharina	42.2	420	550
	44.5	53	90
	46.8	32	72
	48.9	20	45
C. lectularius	42.2	90	185
	44.5	20	27
	46.8	17	25
	48.9	15	25
T. versicolor adults	42.2	180	420
	44.5	25	60
	46.8	20	48
	48.9	20	43
A. verbasci larvae	42.2	1,260	7,200
	44.5	300	720
	46.8	120	240
	48.9	40	80
T. versicolor larvae	42.2	3,600	14,400
	44.5	540	1,500
	46.8	360	1,380
	48.9	60	130

the same temperature for approximately 3,600 minutes. The difference in time required to produce 100% mortality was much greater; 150 minutes for P. americana and 14,400 minutes for T. versicolor. Kenaga and Fletcher (1942) reported a similar conclusion from their tests with high temperatures on various insects in the home and stored products, but Back (1923) reported that most fabric pests could be controlled in a room heated uniformly to a temperature of 54 C. Howard (1917), in his tests with B. germanica, found that a 100% kill could be obtained in 20 minutes at temperatures between 50 C and 60 C. This conclusion agrees with the data obtained from the tests that were conducted during this investigation.

Results of experiments to determine the comparative susceptibility of ten species of insects are presented in Table II. It is apparent that only three species of the test animals—T. domestica, T. versicolor, and A. verbasci larvae—were able to withstand temperatures of 44.5 C and 46.8 C for more than 100 minutes. All of the test animals were killed in less than 130 minutes at 48.9 C, and only three groups—T. domestica, T. versicolor, and A. verbasci—required more than 60 minutes. At temperatures of 44.5 C, 46.8 C, and 48.9 C, C. lectularius required less than 30 minutes to produce 100% mortality. These data indicate that most of the common household pests could be controlled if the entire area of the home were heated to 48.9 C for a brief period.

Peet-Grady Chamber Heat Tests

Tests were conducted in the Peet-Grady chamber to determine how effective heat is for control when insects are free to select a place

TABLE II

Results of experiments to determine the comparative susceptibility of ten species of insects that were exposed to the effects of four temperatures, centigrade, at a relative humidity of 22%.

Species of Insects	Time Required to Produce 100% Mortality			
	0-30 Minutes	31-60 Minutes	61-100 Minutes	over 100 Minutes
P. americana				42.2
			44.5	
			46.8	
		48.9		
B. germanica				42.2
		44.5		
		46.8		
		48.9		
B. orientalis				42.2
			44.5	
			46.8	
		48.9		
S. supellectilium				42.2
			44.5	
		46.8		
		48.9		
T. domestica				42.2
				44.5
				46.8
				48.9
L. saccharina				42.2
			44.5	
			46.8	
		48.9		
C. lectularius				42.2
	44.5			
	46.8			
	48.9			
T. versicolor adults				42.2
		44.5		
		46.8		
		48.9		
A. verbasci larvae				42.2
				44.5
				46.8
			48.9	
T. versicolor larvae				42.2
				44.5
				46.8
				48.9

to hide. The results obtained from these tests were of more practical value than those obtained from the constant temperature cabinet tests.

Tests performed at 43.2 C - It is apparent that after 24 hours at an average floor temperature of 43.2 C, only 10% of the four species of roaches and adult carpet beetles were killed; whereas, none were killed in the other groups except for C. lectularius. Forty per cent of this species was killed under these test conditions. When T. versicolor and A. verbasci larvae were placed in the pockets of a garment 36 inches from the floor, 24 hours were required for a 100% kill for A. verbasci larvae and 36 hours were required for T. versicolor larvae. These data are summarized in Table III.

After 54 hours C. lectularius showed 100% kill, and after 84 hours S. supellectilium showed 100% mortality; whereas, only 30% of T. versicolor were killed after 96 hours. Six groups had a mortality rate of 90% or more at the end of the test. They were P. americana B. germanica, B. orientalis, S. supellectilium, C. lectularius, and L. saccharina. The mortality rates of the four remaining groups, T. versicolor larvae, T. domestica, A. verbasci larvae, and T. versicolor adults were 30%, 40%, 50%, and 60%, respectively.

Tests performed at 46 C - Results of tests conducted at 46 C average floor temperature and a relative humidity of 20% indicate that somewhat faster kills, and in some cases, a higher percentage of mortality occurred at this temperature than at 43.2 C. The relative humidity for both tests was 20%. These data are summarized in Table IV. After 24 hours, three species, P. americana, B. orientalis, and B. germanica, showed 20% mortality; whereas, 75% of S. supellectilium, 30% of L. saccharina, and 100% of C. lectularius

TABLE III

Results of experiments to determine the cumulative per cent kill in ten species of insects that were exposed to a relative humidity of 20% and a temperature of 43.2 C for different time periods.

Species of Insects	Per Cent Killed at 43.2 C and 20% Relative Humidity										
	6 Hours	12 Hours	24 Hours	30 Hours	36 Hours	48 Hours	54 Hours	60 Hours	72 Hours	84 Hours	96 Hours
P. americana	0	0	10	10	10	25	30	40	65	85	95
B. germanica	0	5	10	10	10	25	35	40	75	80	90
B. orientalis	0	0	10	10	10	20	35	45	75	90	93.4
S. supellectilium	0	0	10	20	40	60	70	70	90	100	-
A. verbasci larvae	0	0	0	0	0	0	0	0	0	40	50
T. versicolor larvae	0	0	0	0	0	0	0	0	0	30	30
L. saccharina	0	0	0	0	0	0	50	70	80	90	90
T. domestica	0	0	0	0	0	0	0	0	0	30	40
C. lectularius	0	0	40	70	80	80	100	-	-	-	-
T. versicolor adults	0	0	10	10	10	20	20	30	60	60	60
A. verbasci larvae (36-inch level)	0	0	100	-	-	-	-	-	-	-	-
T. versicolor larvae (36-inch level)	0	0	25	75	100	-	-	-	-	-	-

TABLE IV

Results of experiments to determine the cumulative per cent kill in ten species of insects that were exposed to a relative humidity of 20% and a temperature of 46 C for different time periods.

Species of Insects	Per Cent Killed at 46 C after Given Times							
	6 Hours	12 Hours	24 Hours	30 Hours	36 Hours	48 Hours	54 Hours	60 Hours
P. americana	0	5	20	35	65	75	88	98.3
B. germanica	0	6	20	40	60	75	94	96.7
B. orientalis	0	6	20	40	75	85	92	100
S. supellectilium	15	60	75	100	-	-	-	-
A. verbasci larvae	0	0	0	10	30	35	60	85
T. versicolor larvae	0	0	0	0	10	15	15	35
L. saccharina	0	10	30	50	80	100	-	-
T. domestica	0	0	0	0	0	0	40	70
C. lectularius	20	75	100	-	-	-	-	-
T. versicolor adults	0	0	0	10	20	20	30	30
A. verbasci larvae (36-inch level)	0	100	-	-	-	-	-	-
T. versicolor larvae (36-inch level)	0	60	100	-	-	-	-	-

were killed under these conditions. None of the following species, T. versicolor larvae, A. verbasci larvae, and T. versicolor adults, were killed at this temperature after 24 hours.

At the 36-inch level where only two species were tested, 100% mortality was reached in A. verbasci larvae after 12 hours; whereas, after 24 hours, a 100% kill was obtained in T. versicolor larvae at this level. Upon completion of the test (60 hours), B. orientalis, S. supellectilium, L. saccharina, C. lectularius, P. americana, and B. germanica showed a mortality in excess of 90%; while the more resistant insects at the floor level, A. verbasci larvae, T. domestica, and T. versicolor larvae and adults, ranged from 85% down to 30%.

Tests performed at 48.9 C - Experiments were conducted to determine the lethal effect of conditions when the average floor temperature was 48.9 C and a relative humidity of 20%. Data collected from these tests are summarized in Table V.

It is apparent from these data that a higher percentage of all groups was killed. After 12 hours at 48.9 C, all of the bedbugs and A. verbasci larvae at the 36-inch level were killed. At the end of 24 hours, all S. supellectilium, L. saccharina, and T. versicolor larvae held at the 36-inch level were killed. At the end of the test only small numbers of P. americana, B. germanica, A. verbasci larvae, T. domestica, and T. versicolor larvae and adults at the floor level remained alive.

The results of these tests indicate that if high temperatures are used for control of insects in buildings, it is very important that all of the areas in the building be heated to a temperature above the critical temperature. Dean (1913) found that insects

TABLE V

Results of experiments to determine the cumulative per cent kill in ten species of insects that were exposed to a relative humidity of 20% and a temperature of 48.9 C for different time periods.

Species of Insects	Per Cent Killed at 48.9 C After Given Times					
	6 Hours	12 Hours	24 Hours	30 Hours	36 Hours	48 Hours
P. americana	0	10	40	65	95	98.3
B. germanica	0	10	40	60	80	87
B. orientalis	0	10	45	65	95	100
S. supellectilium	0	75	100	-	-	-
A. verbasci larvae	0	0	50	60	70	96.7
T. versicolor larvae	0	0	15	20	35	71.7
L. saccharina	0	0	100	-	-	-
T. domestica	0	0	20	20	30	40
C. lectularius	20	100	-	-	-	-
T. versicolor adults	0	10	30	55	65	75
A. verbasci larvae (at 36-inch level)	0	100	-	-	-	-
T. versicolor larvae (at 36-inch level)	0	75	100	-	-	-

that bred in inaccessible places were killed more easily by a high, constant temperature than by any fumigating materials. Bacot (1914) concluded from data obtained in his tests with C. lectularius that a temperature of 45 C for 15 hours killed all of the test insects. Harned and Allen (1925) found that effective control of C. lectularius could be obtained by superheating rooms to 48.9 C and above for 63 to 87 hours. The longer time period was required due to the fact that test animals were placed between mattresses.

During the Peet-Grady tests, the movement patterns and habits of the larger insects were observed. When the temperature inside the chamber began to rise about ten minutes after the start of each test, some of the insects tended to move to the floor area where they sought shelter or remained still; whereas, before the temperature was increased, they had been crawling all over the test chamber.

Some of the insects that were free to move about sought shelter from the heat in the coat, sweater, or file cabinet. These insects remained inactive after the first hour of the tests.

The possibility of using heat for the control of household insects has been studied and the results obtained have been discussed. Such factors as: (1) The time required to kill each species at each temperature level being used, (2) The habits of the different insects, (3) The source of heat, (4) The area considered for control, should be considered in any control program along with

the fact that in a home many more of the pests would be able to escape because they could find a number of places to escape from the heat.

Relative Humidity Test with P. americana

Several experiments were conducted to determine the effect of relative humidity on the mortality rate of P. americana at 44.5 C. The results obtained are shown in Figure 1. It is apparent that at the two lower relative humidity levels, all development stages were killed in 17 to 30 minutes. The nymphs were most resistant and adult males were least resistant. Survival time of all stages lengthened as the relative humidity increased until the 70% or 80% level was reached; at higher relative humidities, the survival rate was greatly reduced.

The results are similar to the observations made by Beattie (1927) from his experiments with blow flies at high temperatures and at different relative humidity levels. He determined that the thermal death point of the blow fly was definitely influenced by relative humidity. His tests indicated that saturated and dry air had the effect of lowering the thermal death point of the blow fly. Gunn and Notley (1936) concluded from their experiments on the cockroach that moist air was more favorable for insect survival during long exposures to high temperatures, and dry air was more favorable than moist air during short exposure to high temperature for cockroach survival. This variation, they assumed, was due to the fact that evaporation of water lowers the body temperature. Guthrie and Decker (1954) reported that B. leucopterus

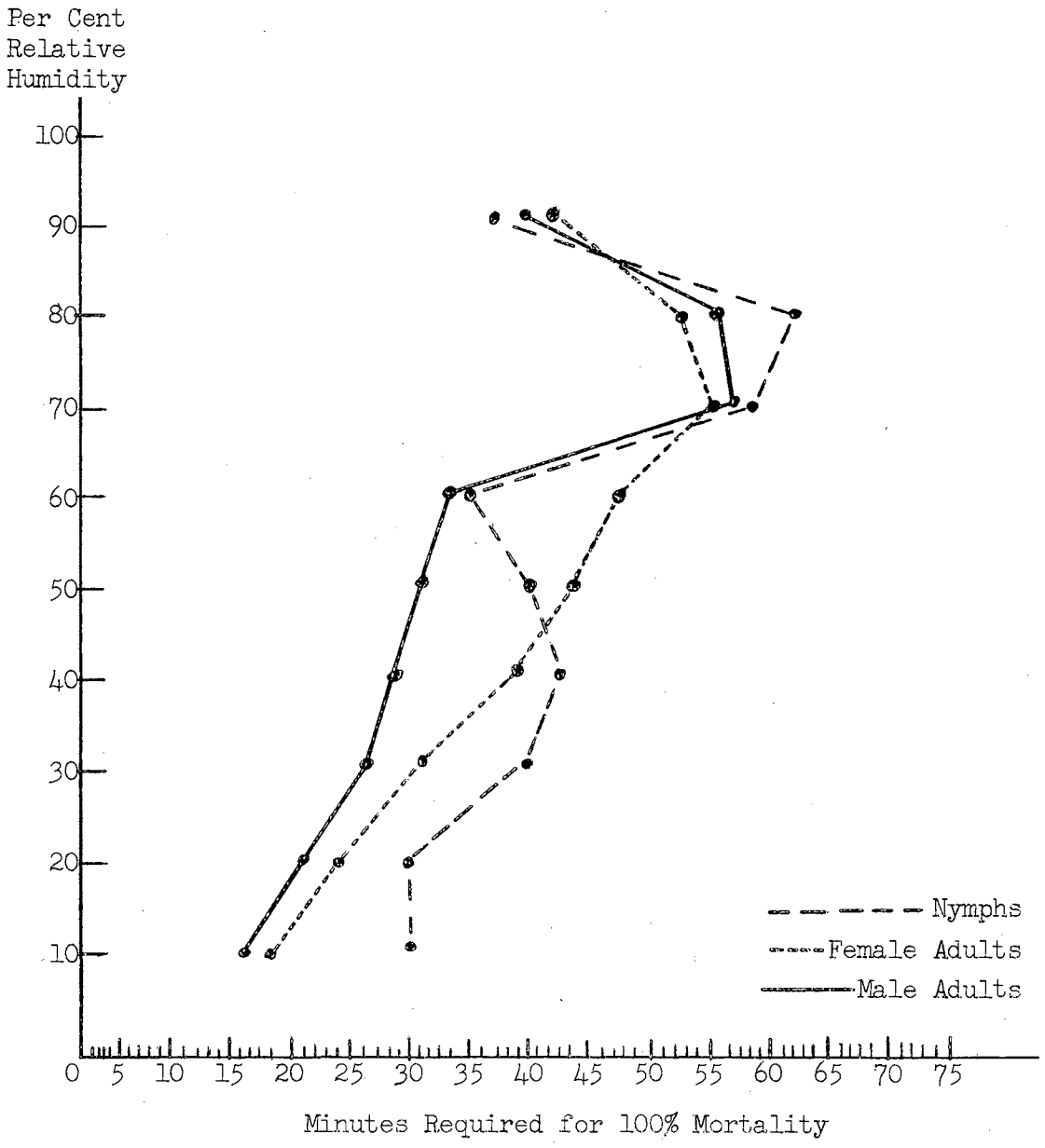

Figure 1. The effect of humidity on the time required to reach 100% mortality of the P. americana held at 44.5 C.

survived longer at temperatures above 50 C when the relative humidity level was high.

Body Temperature Test with P. americana

The data obtained in this test (Table VI) indicate that the body temperature of the adult male roach at high temperatures tends to be very similar to the environmental temperature within the test chamber. At the end of the 10 minute test period, the temperatures of the roaches were approximately 1 C lower than the surrounding environmental temperatures at the three relative humidity levels used. At the end of the 20 minute test period, data obtained indicated that the body temperature of the roach was almost the same as the adjacent environmental temperature with the biggest difference being .6 C at the 90% humidity level. After 30 minutes, body temperatures of the roaches were the same as the environmental temperature at the 50% and 70% levels; but, at the 90% level, it was 1 C lower than adjacent environmental temperatures.

TABLE VI

Results of experiments to determine the comparison of body temperatures of P. americana adult males and adjacent atmospheric temperature at three relative humidity levels and a temperature of 39.5 C.

Per Cent Relative Humidity	Time Intervals					
	10 Minutes		20 Minutes		30 Minutes	
	Body Temp C	Atm Temp C	Body Temp C	Atm Temp C	Body Temp C	Atm Temp C
50	36.1	37	39.5	39.9	39.5	39.5
70	35.6	36.6	39.5	39.5	39.5	39.5
90	35.6	36.6	38.3	38.9	38.9	39.5

Finished Surface Test with Heat

An attempt was made to determine the effect of high temperatures on common surface finishes usually found in the home. The results of these tests indicated that most of the common finishes found within the home were not affected by a temperature of 58.9 C when maintained for 48 hours or less. The only damage observed after 48 hours was on the test panels which were painted. The paint appeared to be cracked, probably caused by the loss of moisture; but no damage was observed after 24 hours at room temperature of 29.5 C.

SUMMARY AND CONCLUSIONS

The literature was reviewed and a series of experiments were conducted under controlled conditions on the effect of high temperatures on the survival and activity of P. americana, B. germanica, B. orientalis, S. supellectilium, L. saccharina, T. domestica, C. lectularius, A. verbasci larvae, and T. versicolor larvae and adults.

Confined insects maintained under test conditions were used to determine the thermal death point of the ten species of household pests. At the 48.9 C level, the time required to produce 100% mortality rate was less than 100 minutes for seven of the species, P. americana, B. germanica, B. orientalis, S. supellectilium, L. saccharina, C. lectularius, and T. versicolor adults. The shortest time necessary to kill all C. lectularius at 48.9 C was 25 minutes, while the time necessary to kill all T. versicolor larvae at 42.2 C was 14,400 minutes.

The results of the simulated room conditions tests indicated that insects that were free to move about sought protected areas where the heat was less intense. From these data, it was concluded that a sufficiently high temperature must be maintained for effective control of insect pests within a confined space. After 96 hours at an average chamber floor temperature of 43.2 C, more than 90% of P. americana, B. germanica, B. orientalis, S. supellectilium, L. saccharina, and C. lectularius were killed. The

per cent of individual insects killed of T. domestica, T. versicolor larvae, A. verbasci larvae, and T. versicolor adults ranged from 30% to 60% after 96 hours at 43.2 C. When the average floor temperature was maintained at 46 C for 60 hours more than 90% of P. americana, B. germanica, B. orientalis, S. supellectilium, L. saccharina, and C. lectularius were killed. The mortality rates of T. domestica, A. verbasci larvae, and T. versicolor larvae and adults ranged from 30% to 85% at the same temperature. In experiments where the average floor temperature of 48.9 C was maintained for 48 hours, the number of individuals killed of P. americana, B. orientalis, S. supellectilium, A. verbasci larvae, L. saccharina, and C. lectularius were 90% or more. The mortality rate for B. germanica, T. domestica, and T. versicolor larvae and adults was in the range of 40% to 87%.

The results obtained in the relative humidity tests with P. americana at a high temperature indicated that for best control, the relative humidity level should be very low or extremely high.

The comparison of the body and adjacent environmental temperatures of P. americana adult males maintained in three relative humidity levels and at a temperature of 39.5 C indicated that the roaches' body temperatures were very similar to the adjacent environmental temperatures at the various humidity levels checked. The roaches' body temperatures were never found to be more than 1 C lower than the surrounding environmental temperature.

The only observable damage in the high temperature tests on six of the common finishes found in the home was to the plywood panels which showed cracks that were caused by loss of moisture. These cracks disappeared after 24 hours at normal room temperature.

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