Proceedings of the Eleventh International Conference on Urban Pests 2025
AF-Borgen, Academic Society, Lund, Sweden
William H Robinson, editor

EVALUATION OF WHOLE-HOME HEAT SYSTEMS FOR BED BUG, *CIMEX LECTULARIUS*, (HEMIPETERA: CIMICIDAE) ELIMINATION IN LOW-INCOME HOUSING

[1]TODD, D, B., [1]D. M. MILLER1, [1]M.M. WILSON AND [2]A. ARNESON
[1]Department of Entomology Price Hall Rm. 216A 170 Drillfield Dr. Virginia Tech University, Blacksburg, VA, 24061
[2]Department of Statistics Hutcheson Hall Rm 406A, 250 Drillfield Dr.,
Virginia Tech University, Blacksburg, VA, 24061

Abstract In the United States, whole home heat systems have been a frequently used method of bed bug (*Cimex lectularius L.*) "elimination" for more than a decade. However, there have been no evaluations of any of the known heat systems to determine their actual efficacy in the field. In this study three commonly used heat systems: the GreenTech Titan (propane), the Temp-Air Thermal Remediation (electric), and the Heat Assault (glycol), were evaluated in the field to determine their overall efficacy for bed bug control, and to determine the factors contribute to heat system success: the heat system itself, technician entries (for temperature monitoring and equipment positioning), heat sensors reaching lethal temperature, and treatment duration. Additionally, the clutter ratio in each home was measured to determine if high clutter levels were an impediment to heat treatment success. Sentinel bed bugs and remote heat sensors were also placed in each treated home to determine heat treatment efficacy. The mean bed bug sentinel mortality across all heat system replications ranged from 85.2% to 98.7% with no system achieving 100% across all replicates. The GreenTech system produced the lowest overall mortality and Heat Assault system produced the greatest mortality across all replicates. Logistic regression analysis revealed that the number of technician entries per hour was the most impactful factor for a successful heat treatment.

Key words Heat treatment systems, thermal death point

INTRODUCTION

Throughout history, the common bed bug, *Cimex lectularius* L. (Hemiptera: Cimicidae), has been a well-known pest of the human environment (Usinger 1966). Because of the bed bugs' reliance on human blood for growth and reproduction, the common bed bug has adapted to cohabitate with their hosts, even as the human habitation has evolved from rural agricultural villages into today's cosmopolitan cities. In Rukke's research article (2018), the author considers modern human homes to be the "natural habitat" for bed bugs and describes the bed bugs as being a true anthropochores. The bed bugs' ability to be transported and adapt to all human environments has resulted in their becoming established pests on every continent in the world except for Antarctica. The modern bed bugs' success can be attributed to several factors, including lack of predator pressure, their cryptic behaviors, and their malleable genetics which have allowed them to develop a variety of pesticide resistance mechanisms (Usinger 1966, Dang et al. 2017, Krinsky 2019).

Bed bugs were flourishing in the United States in the early 20th century (Ministry of Health 1934, Hartnack 1939, Mallis 1945, Potter 2011). However, their populations were severely reduced in the mid 1940's by the widespread use of dichlorodiphenyltrichloroethane (DDT) and other broad-spectrum insecticides (Potter et al. 2010, Potter 2011). However, bed bug populations were known to have developed resistance to DDT within five years of its use.

Between the years 1958 and 1968, organophosphates and carbamates replaced the use of DDT (Rafatja 1971, Potter 2018). Not surprisingly, the bed bugs began to develop resistance to organophosphate and carbamates as well, but by this time (Johnson and Hill 1948, Busvine 1958), bed bug populations had been almost completely eliminated from developed nations and many people assumed that bed bugs had been eliminated for good.

The resurgence of modern bed bugs that began in the 1990's caught many civilians by surprise. At first, the reason for the resurgence was completely unknown. But the resurgence is now thought to be the result of remnant bed bug populations in Africa being exposed repeatedly to pyrethroid impregnated bed nets. These bed nets are currently being used as mosquito control devices to reduce the malaria virus (Curtis et al. 2003, Kweka et al. 2009, Davies, T.G. et al. 2012). Because pyrethroids are one of the few remaining chemistries that are allowed to be used indoors in the United States after the Environmental Protection Agency's issuance of the Food Quality Protection Act (FQPA) of 1996, the United States, and the world, has been left with very few chemical options to address this resurgence of resistant bed bugs (Romero et al. 2007, Davies et al. 2012).

The modern bed bug (both the common and tropical) is known to have multiple resistance mechanisms that allow them to survive pyrethroid insecticide applications. These resistance mechanisms include target site insensitivity, increased metabolic detoxification, and reduced cuticular penetration (Lilly et al. 2016a, b; Romero and Anderson 2016; Dang et al. 2017). The ever-increasing levels of resistance to chemical spray insecticides has forced the pest management industry in the United States and throughout the world, to seek out and evaluate alternatives to spray formulation insecticides. Recent alternatives to spray insecticides have included the use of fumigation, steam heat, heat chambers, whole-home heat, frozen carbon dioxide, and entomopathogenic fungi (Kells and Goblirsch 2011, Olsen et al. 2013, Phillips et al. 2014, Barbarin et al. 2017, Kells 2018, Wang et al. 2018). One of the most widely used non-chemical methods for modern bed bug control has been the use of heat.

Heat treatments for bed bugs have been applied in a variety of ways. One of the earliest methods used for treating modern bed bugs was to apply steam to infested surfaces. Steam treatments have been quite effective when used properly. Puckett et al. (2013) determined the application parameters for steam treatment, which specify an application rate of 10 seconds per 30.50 cm of surface area. To generate significant mortality, the bed bugs must be located directly under the steamer head. Bed bugs that are in a position lateral to the steamer head may escape the treatment (Puckett et al. 2013). Also, if the technician moves too quickly, the steamer may not deliver enough heat to kill the eggs. Also, certain fabrics, such as leather (Wang et al. 2018), are known to protect the bed bugs hiding under them from treatment. Thus, it is important to note that the effectiveness of any steam treatment is dependent on the diligence of the technician.

Another method of bed bug heat treatment is the use of portable heat chambers. Heat chambers typically consist of portable tents that can be taken into a home and filled with infested furniture (depending on the size of the chamber) and belongings. The items in the heat chambers are heated and monitored for several hours while the rest of the home is typically treated with spray formulation insecticides. As of 2020, the use of heat chambers (portable trailers) has also become a methodology for treating bed bug infested vehicles (Howerton 2020).

Over the last decade, the use of whole home heat systems has been a widespread alternative to spray formulation insecticide applications. Bed bugs are known to harbor in hard-to-reach locations within a home, and like fumigation, heat treatments do not require that every bed bug harborage be located prior to treatment. Therefore, to the average consumer, whole home heat systems sound like a safe and ideal way of eliminating bed bugs throughout the house. However, although many types of heat systems have been marketed for bed bug control, not much is known about the efficacy of different types of heat systems or their actual ability to eliminate bed bugs from homes of different sizes. It is essential that the heat system being used is able to produce the required amount of heat needed to raise all hard to heat crack and crevices up to bed bug lethal temperature.

In 2011, Kells and Goblirsch determined that the lethal temperature for adult and nymph bed bugs was 47.7°C. However, they found that bed bug eggs required a temperature of 50°C to ensure mortality. Thus, every hard-to-heat crack and crevice inside a home must reach 50°C for all bed bugs to be killed. Needless to say, whole home heat treatments must be monitored rigorously to determine that all of the cubic footage, and all cracks and crevices achieve lethal temperature.

One of the common questions that our laboratory receives from bed bug infested consumers is “which is better heat or chemical?” Although this question may sound simple, it is not. There are currently a large variety of heat systems on the market, but up until this time there have been no efficacy studies to evaluate their performance under different household conditions. Yet, it is very important to know which of these heat systems have the potential to eliminate bed bug infestations in housing units of different cubic footage, different levels of household clutter (Catron et al. 2017), and that are infested with bed bug populations of different sizes. Therefore, it can be very difficult to say conclusively that a particular heat system will be able to eliminate all bed bugs under all conditions. Studies are needed to compare the different attributes of individual heat systems (which can range in price from $10K to $150K), that use different energy sources, pieces of equipment, and temperature monitoring devices for bed bug elimination in different housing units. Based on this current need, the purpose of this study was to compare, and evaluate, different whole home heat systems for their ability to eliminate bed bugs located in hard-to-heat locations in infested housing units. The heat systems evaluated were the GreenTech Titan® propane system, the Temp-Air Thermal Remediation® electric system, and the Heat Assault® forced convection glycol system.

MATERIALS AND METHODS

Heat Systems Evaluated

In this study, three professional bed bug heat systems were evaluated for their ability to eliminate infestations in low-income housing units. Each heat system required a different energy source (e.g. heated glycol, propane, or electricity) and specific installation procedures. The three systems were evaluated to compare their treatment time (set-up to takedown), required amount of equipment, temperature monitoring methods, as well as treatment efficacy and the price per system. After observing several individual heat treatments, it became obvious that the attentiveness of the heat treatment technician was also critical for the treatment success (efficacy). Therefore, technician activities were also monitored as part of this study.

The three bed bug heating systems that were compared in this study included the GreenTech Titan 800 (GreenTech Heat Solutions, Anaheim, California) propane heater, the Temp-Air Thermal Remediation system (Temp-Air Inc, Burnsville, Minnesota), and the Heat Assault 600X system (Tamarack Industries, Winnipeg, Manitoba; Table 1). Each system was evaluated in five field-site, low-income housing replicates.

GreenTech Heat Solutions designs, manufactures, and sells both electric and propane-based heat systems. The GreenTech Titan is a portable propane-powered heater that can be used to eliminate bed bugs and other indoor insect pests. There are two types of GreenTech Titans; the Titan 450 and the Titan 800 that produce 550,000+ and 990,000+ BTUs, respectively (GreenTech 2021). The GreenTech Titan is a "direct-fire" propane system that is set at the front door, and the heat is directed from the Titan to the specific rooms of the home using mylar tubing.

Temp-Air Inc. manufactures Thermal Remediation® bed bug heat treatment packages that are marketed to pest management professionals, hotels, universities, and property management companies. Temp-Air Heat packages can be purchased that contain different numbers of electric heaters, fans, power distribution boxes, cables, sprinkler head covers, and temperature monitoring equipment. Temp-Air also manufactures trucks and trailers that can be used to transport diesel generators as well as to store all of the heating equipment (Temp Air 2021).

The second system that researchers observed in this study, was the Temp-Air Thermal Remediation EBB-40KW trailer package. This electric heat system consisted of four 99.8 kg heaters (each one putting out 25,000 BTUs), and 12 fans that could be moved around the home to aid in the heating process. The electric power for this system originated from a diesel generator within the trailer that was then transferred through a power cable connected to a distribution box. The distribution box then distributed the electricity to the individual heaters through additional power cables.

The Temp-Air Company was the only manufacturer in this study that offered a temperature monitoring system for purchase. The temperature monitoring system consisted of 12 digital sensors that could be placed in hard to heat locations. The digital sensors displayed the local temperatures on computer monitor outside of the heated housing unit. This is so that the technician could constantly monitor the temperatures within different locations of the home. The constant temperature display would make the technician aware of locations that were failing to heat adequately, so that he/she could move the heat equipment into more focused locations if those locations were failing to reach bed bug lethal temperature.

The third heating system that was evaluated in this study was the Heat Assault system. Heat Assault is a Canadian company that sells diesel-powered heat systems (Heat Assault 300X and Heat Assault 600X). The Heat Assault website states that the 300X and 600X are able to produce 300,000 and 600,000 BTUs per hour, respectively. Both of the Heat Assault 300X and 600X packages include a trailer that contains the following equipment: heat exchangers/radiators, supply and return distribution manifolds, fans, and heat transfer fluid (glycol; Heat Assault 2021). For this study, the Heat Assault 600X system was evaluated.

The Heat Assault glycol system is unique in the fact that it uses what is called "forced convection technology". This refers to how the atmospheric air is put in contact with radiators heated by glycol and the heat expands to fill the treated home. This forced convection begins with heating the glycol prior to contact with the atmospheric air. The Heat Assault System basically consists of two closed loop systems: the "Heat Loop" and the "Field Loop." Within the Heat Loop, glycol from the glycol reservoir enters a heat exchanger. This heat exchanger is powered by burners fueled by a diesel generator. Within the heat exchanger, the glycol is heated to a temperature of 96°C. After reaching the desired temperature, the heated glycol is pumped into a reservoir. From the reservoir, the heated glycol can then be either returned to the exchanger for continued heating or pumped into the "Field Loop." Within the Field Loop, the heated glycol is pumped from the reservoir to the supply manifold within the treatment zone (apartment) using industrial-grade hoses. The supply manifold splits the heated glycol into different hoses that are each connected to individual radiators. These radiators are placed in multiple locations throughout the treated home. The glycol then heats the atmospheric air within each of the radiators. Fans are attached to the radiators in order to push the heated air into the treatment zone (apartment), thus increasing the temperature within the treated space. After heating the air, the spent glycol (from the different radiators) then moves into a return manifold. From the manifold, the cooled glycol completes the Field Loop by being returned to the reservoir to be reheated and reused throughout the multi-hour heating process.

Study Sites

All heat treatments were conducted in bed bug infested US HUD housing units. All five GreenTech System evaluations were conducted in the Richmond Rehabilitation and Housing Authority (RRHA) located in Richmond, Virginia. The Heat Assault treatment evaluations were conducted in Rocky Mount Housing Authority (RMHA) in Rocky Mount, North Carolina, and the Florence Housing Authority in Florence, South Carolina. The Temp-Air heat systems evaluations were conducted in both Richmond, Virginia, and in Rocky Mount, North Carolina.

Heat system evaluations were conducted in single or two-story apartment units with one to three bedrooms. One Heat Assault replicate was conducted in a free-standing housing unit. All units treated were slab-on-ground construction with cinderblock walls. The infested units within each treatment group varied in their cubic footage, clutter, and bed bug infestation levels.

The sentinel bed bugs used for this study were from the Richmond strain. The Richmond field strain was collected from a group home in Richmond, VA in 2008. The Richmond strain is currently maintained inside plastic rearing containers in the Dodson Urban Pest Management Laboratory (DUPML; Virginia Tech, Blacksburg, VA). All bed bugs are fed defibrinated rabbit blood once a week using an artificial feeding system. Bed bug colonies are kept in environmental chambers held at 28°C; 55% RH; and a photoperiod of 12:12 h L:D cycle. In 2017, the Richmond strain was one of ten bed bug field strains evaluated at Purdue University (West Lafayette, Indiana USA) for resistance to insecticide products containing chlorfenapyr or bifenthrin. The Richmond strain was found to be the most resistant of all field strains evaluated in that study (Ashbrook et al. 2017).

Sentinel Bed Bug Preparation

Five sentinel replicates of each bed bug life stage (eggs, nymphs, and adults) were prepared at the DUPML prior to each heat treatment. Each life stage replicate consisted of 10 bed bugs (150 bed bugs total). The bed bugs were placed on filter papers (35mm) inside of nylon stockings that were tied at the end. To prepare the eggs, adult female bed bugs were fed one week prior the scheduled heat treatment. The females were then placed in Petri dishes lined at the bottom with filter paper. Adult females were left to lay eggs on the filter paper *ad libitum*, so that there were at least 10 bed bug eggs laid on each filter paper in time for each heat treatment.

Resident Preparation Instructions

Heat treatments preparation instructions were provided to each resident by either the housing authority, or one of the heat treatment professionals. These instructions were typically provided a couple of days prior to treatment initiation. While the preparation instructions for each heat system were somewhat different, all of them focused on the removal of items that had the potential to be damaged by high temperatures. All houseplants, pets, candles, and combustibles (aerosol cans and cigarette lighters) were typically "required" to be removed. Preparation instructions also recommended that all electronics be disconnected from outlets and that televisions be removed or wrapped in blankets prior to treatment. In addition, all non-refrigerated foods, medications, stringed instruments, family heirlooms, and photographs were suggested to be removed to avoid any potential heat damage. It was also typically recommended that blankets, linens and towels be put through a dryer cycle prior to treatment, and that all clothes closets and drawers be opened prior to treatment to allow for heat access.

Clutter Ratio Determination

Each heat-treated apartment unit was measured to determine the cubic footage of each room. Measurements were made using measuring tapes ("15 ft" and "25 ft") and a Bosch® Professional GLM 40 measuring laser. The Bosch® laser was used to measure overall room size as well as clutter where appropriate. The measuring tapes were used exclusively for measuring clutter. The combined cubic footage of the entire apartment unit and the cubic footage of all personal items, appliances, cabinets etc. were used to determine the "clutter ratio" for each unit. This was so that we could determine the percentage of the apartment space that was filled (e.g. 10%; 30%, 50% etc.) with clutter or other items. If needed, we could later determine if this ratio influenced the time required for treatment, or the treatment efficacy (Catron et al. 2017). In addition, the space and clutter measurements were used to create a diagram of each treated apartment unit illustrating the amount of open space, the amount and location of the clutter, the locations of all heat the sensors and the locations of sentinel bed bugs.

Sentinel Bed Bug Placement

Sentinel bed bugs of each life stage were placed throughout each infested unit in hard-to-heat locations that would be challenging to get up to bed bug lethal temperature. Sentinel bed bug replicates were also placed in potential bed bug harborage locations. These included holes in the walls, between furniture cushions, inside closets, within clothes drawers, behind electrical outlet covers, and in gaps between the walls and baseboards. After the conclusion of a heat treatment, the replicates were collected and evaluated for mortality at the DUPML. Bed bug eggs were monitored for 14 days after treatment to determine egg mortality. Eggs that failed to hatch within this period were determined to have been killed by the heat treatment.

Temperature Monitoring During Heat Treatment

The researchers conducting this study used the Temp-Air Thermal Remediation wireless logger system to monitor each treated unit. The Thermal Remediation system includes 12 temperatures sensors, a repeater, and a laptop computer monitoring system contained within a case. The 12 temperature sensors were individually placed in hard to heat locations such as the corners of rooms, within hallway closets, along floor-wall junctions, on shelves, and within furniture. The repeater, which maintains the signal between the sensors and the monitoring device, was placed in the dining room or kitchen. The laptop computer monitoring system was placed outdoors in front of the apartment unit on a fold-out table. All sensor temperatures were recorded at 30-minute intervals throughout the heat treatment process.

GreenTech Heat Solutions Treatment Process

The GreenTech system evaluated in Richmond, VA, was the Titan 800. This heat system was owned and operated by Richmond Redevelopment & Housing Authority. To power the Titan 800, the technicians connected it to two 45 kg (≈100 lb) AmeriGas® propane cylinders that were confined to the bed of their work vehicle. The technicians placed two temperature resistant fans inside each apartment unit to circulate air. The technicians also had a Lasergrip® handheld infrared thermometer to monitor surface temperatures during the treatment.

During the setup phase of the treatment, the technicians placed the Titan 800 inside the doorway of the apartment unit's front door. They then connected mylar tubing to the front of the Titan 800 and extended the tubing to the uppermost floor (2nd floor if it was a 2-story unit). The two circulating fans were placed in locations near the mylar tubing outlet. The fans dispersed the heated air from the mylar tubing outlet into the treated room. During setup, the technicians removed any observed heat sensitive items to the outside of the unit.

After the mylar tube and the fans were in place, the technicians used clamps to secure a tarp over the unit's open doorway. After covering the doorway, the heat treatment was initiated. During the GreenTech heat treatment process, technicians entered the unit approximately every 1-3 hours to check surface temperatures. When a particular room reached lethal temperature (48.8°C), as determined by the technician (after testing multiple surfaces with the handheld thermometer), the mylar tubing outlet was either moved to another room or floor depending on the size and structure of the unit. Once all the rooms located away from the front door had achieved lethal temperature, the mylar tubing was disconnected from the propane heater so that the ground floor living room could be heated directly from the Titan heater itself.

Treatment completion was determined by the technicians. The criteria used by the technicians was either the time of day, or when all surface temperature measurements had reached ≈48.9°C (120°F), in each of the heated rooms. The RRHA heat treatment technicians were restricted by time, which required them to be finished treating every unit by 3:00 PM. When the treatment was concluded, all heat equipment was removed from the premises. Once the equipment was cleared, and sentinel bed bugs were removed, the RRHA technicians performed crack, crevice, and spot treatments using the spray formulation insecticide product CrossFire® (Clothianidin 4.0%, Metofluthrin 0.1%, Piperonyl Butoxide 10.0%; MGK, Minneapolis, Minnesota).

Temp-Air Thermal Remediation Treatment Process

Temp-Air heat treatments were conducted in both Richmond, VA and Rocky Mount, NC. The Temp-Air system used is owned by the Virginia Tech Maintenance facility. The system was housed in a trailer that contained a generator, four ≈99 kg (220 lb) electric heaters, 12 circulation fans, and 5 power cables (1 large, 4 small). The first two heat treatments were conducted by Virginia Tech Facilities personnel. The last three treatments were conducted by Dodson Urban Pest Management Laboratory personnel. The Virginia Tech Facilities personnel had their own temperature monitoring system, but it was non-functional at the time of these treatments. Therefore, they resorted to using a handheld temperature measuring device (model and manufacturer unknown) and the researchers' temperature monitoring system.

During the setup phase of the Temp-Air treatment, the technicians had to conduct a number of preparatory tasks. They installed covers over the overhead sprinklers used for fire prevention in each unit. They then inspected the home for items that could be damaged by the heat treatment. Finally, they sealed all exterior windows with aluminum tape to reduce potential heat loss.

After the apartment preparation tasks were completed, the technicians began moving heat treatment equipment into the apartment unit. Each of the four heaters was brought in by two technicians. Individual heaters were then placed in specific rooms, with upstairs bedrooms (highest priority) typically being treated first. At least one heater, if available, was also located downstairs at the beginning of the treatment. This heater was usually placed in either the dining area or living room. Once the heaters were in place, the power distribution box and the fans were brought into the unit. At least two fans were stationed next to each heater. Additional fans were stationed where needed, such as the living room or the kitchen. The distribution box was stationed in the living room. A large cable ran from the outdoor generator to the distribution box, and four cables ran from the distribution box to each of the heaters. Finally, a tarp was hung from the ceiling in the stairwell between the upstairs and downstairs corridor. This was to limit the movement of heated air from the downstairs to the upper level.

After all of the Temp-Air system elements were set up, the exterior generator was started. Each heater was manually set to the “blower” setting. This allowed the individual heaters to warm up. After approximately ten minutes, the heaters were put on the “heat” setting at 145° F. The fans remained turned off until the heater temperatures reached 37.8°C (100°F). After the heater temperatures reached 37.8°C (100°F), the fans were turned on to disperse and circulate the heat throughout the infested space. Once the fans were turned on, all doors to bedrooms that contained heat equipment were closed to confine the heat inside of that space.

Temperatures in the treated spaces were checked regularly throughout the Temp-Air heat treatment process. Temperatures were checked at least once every hour. During the temperature monitoring process, the technicians moved furniture, clothing, and other personal items around to increase their heat exposure. They also repositioned fans to re-focus the air flow when needed. When a bedroom was determined to have reached bed bug lethal temperature, the technician opened the door and moved the heater into the hallway to help heat the rest of the space upstairs. As the heat treatment came to completion (based on lethal temperatures being achieved) technicians moved all heaters into the living room. Once the living room was determined to have reached lethal temperature, the treatment was ended.

There were no specific time constraints on when the Temp-Air technicians needed to be finished therefore, once the treatment was determined by the technicians to be completed, the technicians began the breakdown process. To initiate this process, the technicians put all heaters on the “blower” setting again to cool them down safely. Then, the fans were unplugged and removed from the premises to be stored in the trailer. After the fans were removed, the heaters were shut down completely. The generator was shut down, and the power cables were disconnected from the heaters and power distribution box. Once the cables had been stored in the trailer, then the heaters and distribution box were removed from the home and placed into the trailer as well.

Heat Assault Treatment Process

Four heat treatments were performed using a Heat Assault 600x system that was owned and operated by Action Pest Control, of North Carolina. These four Heat Assault treatments were performed in the Rocky Mount Housing Authority in North Carolina. The fifth Heat Assault 600x treatment was performed in Florence, North Carolina in a single housing unit. This treatment was conducted by a maintenance technician who was employed by the Florence Housing Authority.

The two Heat Assault systems that were used in Florance and Rocky Mount were each contained in a single trailer. These trailers held the glycol reservoir (≈378.54 liters), and a pair of heat exchangers to heat the glycol. A diesel-powered generator activated the burners of the heat exchangers, as well as the pumps. A circulating pump drew the glycol from the reservoir and ran it through the heat exchangers. The heated glycol was returned to the reservoir via the pump and was then drawn out by a field pump through an industrial hose (2.54 cm width, 22.86 m length) to a supply manifold located in the apartment or housing unit that was to be heat treated. The supply manifold split the glycol into five smaller supply hoses (1.91 cm width, 7.62 m length) that then sent the glycol to the five radiators. The radiators put the ambient air in contact with the radiator heated by glycol and fans attached to the radiators pulled the heated air from the radiators out into the treatment zone (housing unit).

After the heated air was released from the individual radiators, the cooled glycol exited the radiators through return hoses (1.91 cm width, 7.62 m length). The return hoses then brought all of the used glycol together into the return manifold. From the manifold the glycol was sent through a larger return hose (2.54 cm width, 22.86 m length) back to the trailer reservoir where it was reheated and reused throughout the heat treatment process. At the end of the heat treatment, the pumps were shut down, but a compressor in the trailer was left on to return the glycol back to the reservoir.

To initiate the setup phase of the first four Heat Assault treatments, the Action Pest Control technician positioned the necessary equipment outside of the apartment unit that was to be treated. The technician then went indoors and checked the unit for infestations. He also removed any sensitive items (such as aerosols) from the apartment unit. In addition, he detached all socket plates from the electrical outlets. After the inspection, the technician began moving the heat equipment indoors. Each bedroom had at least one radiator (total of 10 radiators) that had a fan (total of 12) attached to it. The living room and dining room each had two radiators and fans. Five additional fans were placed throughout the upper and lower floor hallways, living room, and kitchen to circulate the heated air that was being produced by the radiators. The ground floor and upper floor of each apartment had a supply manifold (2) and a return manifold (2) located near the stairway. The technician connected the supply and return hoses (2.54 cm) to the trailer's glycol reservoir, and to the respective supply and return manifolds. The supply and return hoses (1.91 cm) were also connected between the manifolds and the appropriate radiators.

Once all of the equipment connections were completed and secure, the technician turned on the generator and began the heat treatment. Turning on the generator initiated the cycle of glycol moving through the hoses into the radiators and then back to the glycol reservoir. The fans were turned on to draw the heat out from the radiators and circulate it into the surrounding air. The technician then began to check surface temperatures every twenty minutes for the duration of the heat treatment using a FLIR handheld thermometer (FLIR systems Inc, Portland, Oregon, US). Halfway through the heat treatment, the average temperature reached ≥50°C (≥120°F). At that time, the technician began to move the furniture and other belongings to suddenly expose hiding bed bugs to the high heat. This exposure process included flipping mattresses and leaning them on their sides against the wall; displacing and flipping couch cushions, standing couches up on their end, and pulling drawers out from the dressers and other cabinets. Clothes on the floor were shifted around and clothes in bags were pulled from the bag and draped across furniture to expose the bed bugs to high heat.

Each glycol heat treatment had a duration of approximately six hours. The technician determined the heat treatment was completed once the lethal temperature was held for a sufficient amount of time (approximately 3 hours). When this determination was made, the technician went outside to shut off the trailer pump. The technician then turned on the compressor to send air through the glycol supply lines to return the remaining glycol back into the reservoir. Once it was determined that the lines were clear, the technician shut off the compressor and went back inside the treated apartment unit to turn off the fans. The hoses were then disconnected from the radiators and manifolds and moved out of the apartment. After removing all of the heat equipment, the technician returned all furniture items back (more or less) to their original positions.

While the first Heat Assault technician was a trained pest management professional, the Florence maintenance technician was not. Although the Florence technician was effective at setting up the heat system, he did not inspect the home for items that could be damaged. This was because resident had been provided with preparation instructions, so it was assumed that all at-risk items had been removed. In addition, all furniture and mattresses had been stood on end and all cabinets, closets, and drawers were open. Thus, the home was already considered prepared. The Florence technician also did not regularly monitor interior temperatures, instead he moved equipment in this single-story home on an hourly basis. Treatment duration was therefore, dependent on the number of rooms that were heated.

Statistical Analysis

Wilcoxon signed-rank tests were used to compare the quantified bed bug mortality for each heat treatment system in the field. A non-parametric method was chosen over an ANOVA, because the distributional assumptions of an ANOVA test are not met when the mortality values are near 100%. The Wlicoxon tests were performed for each life stage and were conducted using JMP Pro 16 (SAS Institute Inc., Cary, NC). Since five replicates for a specific life stage of sentinel bed bugs were placed at each treatment site, the mortality data for the five replicates at each treatment site were aggregated. This is because treating each sample replicate as an independent test would artificially inflate the sample size for this analysis (psuedoreplication).

The probability of a treatment resulting in 100% mortality was modeled for each life stage using mixed-effect logistic regression. This was done in lieu of a direct model of bed bug mortality, because true success of a treatment entails complete mortality. Separate logistic regression models were fit for the egg, nymph, and adult life stage outcomes. Each model included the heat system, clutter ratio, treatment duration, the proportion of temperature sensors that reached the desired temperature, and the number of technician entries per treatment hour, as fixed effects. The model included the replicate (treatment site) as a random effect. The treatment duration times included in the data set ranged from ≈4.4 to ≈10.6 hours. The quantitative predictor variables were standardized to allow for direct comparison of effect sizes of predictor variables using the formula:

$$\frac{observed\ value\ -\ minimum\ observed\ value}{maximum\ observed\ value\ -\ minimum\ observed\ value}$$

The models were fitted using the ‘glmmTMB’ package in R (Brooks et al. 2017). Overall model fit and distributional appropriateness was evaluated using tools in the ‘DHARMa’ package in R (Hartig 2021). Stepwise regression using the Bayesian Information Criterion (BIC) as the determining criterion was performed on the full models using the ‘stepAIC’ function in R to select the most important predictors of treatment success (100 % mortality) in each life stage (Venables and Ripley 2002). Predictor addition and elimination was allowed at each step.

Because the proportion of temperature sensors that reached the lethal temperature (50C) was retained in all of the lifestage models described above, and was consistently correlated with successful treatments, a logistic regression model was also used to predict the proportion of temperature sensors that would reach the lethal temperature of 50°C (122°F) for each treatment. The system, clutter ratio, treatment duration, and the number of technician entries into the building per treatment hour, were included as fixed effects in this model and the housing replicate was again used as a random effect.

RESULTS

Sentinel Bed Bug Mortality

Bed bug mortality by life stage and total sentinel bed bug mortality for each heat system is provided in Figure 1. Total mortality ranged from 85.2% to 98.7%, with no system alone reaching 100% total bed bug mortality across all trials, though each system reached 100% mortality in specific housing units. Statistical differences were not found in the overall bed bug mortality across the three systems (*Chi-square* = 3.622*, df* = 2*, p* = 0.1635).

Treated and control mortality for egg, nymph, and adult life stages for each whole-home heat system is presented in Figure 1. Overall, each heat treatment system produced ~80% to 100% mortality for each bed bug life stage. No statistical differences were detected for bed bug nymph (*Chi-square* = 3.973, *df* = 2, *p* = 0.1372), adult (*Chi-square* = 1.231, *df* = 2, *p* = 0.5404), or egg mortality (*Chi-square* = 5.749, *df* = 2, *p* = 0.0564) mortality among the three systems.

Logistic Regression of Whole-Home Heat System Factors that Predict Bed Bug Mortality

Data ranges for the whole-home heat system factors can be found in Table 2. The logistic regression evaluates which factors best predict bed bug mortality for each life stage. After a stepwise regression was conducted, the heat system used for treatment was not retained in any of the models (egg, nymph, or adult). It should be noted that there was complete mortality in the egg life stage for all Heat Assault system trials. This 100% egg mortality for the Assault Heat system created a statistical anomaly in the data that may be why the stepwise selection process excluded the system from the egg life stage model. The proportion of temperature sensors reaching the bed bug lethal temperature (50°C) was retained as a predictor of mortality for all life stages (Table 3). In addition, treatment duration was found to be an influential predictor in the nymph and egg life stage mortality models, though it was not a significant predictor of adult bed bug mortality (Table 3).

Logistic Regression of Whole-Home Heat System Factors that Predict Proportion of Temperature Sensors Reaching Lethal Temperature

Since the proportion of temperature sensors reaching lethal temperature was retained in all of the models of sentinel mortality, another logistic regression analysis was performed to determine the factors that contributed to the proportion of sensors reaching lethal temperature. In the lethal temperature sensor model, only the heat treatment system, and the number of technician entries per hour were retained after stepwise regression. Both were considered significant predictors of the proportion of temperature sensors reaching lethal temperature (Table 4). Tukey-adjusted pairwise comparisons of the heat systems showed that the Heat Assault and GreenTech systems performed significantly better than the Temp-Air system in terms of the proportion of temperature sensors that reached the bed bug lethal temperature of 50°C. It was also found that the number of technician entries per hour had a positive effect on the proportion of sensors that reached lethal temperature (Figure 2 & Table 4).

DISCUSSION

While this study determined that heat treatments, in general, could kill a large number of home infesting bed bugs, there are a number of variables that may challenge or contribute to heat treatment success. During this study we found that the Temp-Air system was used to treat units of the smallest size but with the highest overall clutter ratios (Table 2). The Temp-Air system also had the longest average heat treatment time (>8 hours). The Heat Assault system treated units had the overall lowest clutter ratios, and that during the Heat Assault heat treatments, all temperature sensors reached lethal temperature with the exception of two treatments. For one of those treatments, two sensors in different closets and one sensor within a living room table drawer did not reach 50°C. For the second treatment (Florence), only five sensors (of the 12) reached lethal temperature, which could be attributed to the technician's low number of entries (Figure 2).

Table 1. Functional properties of each whole-home heat system. The heat source used, the amount of heat produced (BTUs), and the equipment used to operate each system are shown.

Properties	**GreenTech**	**Temp-Air**	**Heat Assault**
Heat Source	Propane	Electric	Glycol (heated)
Reported BTUs	≈990,000+	≈24,880 (per heater)	≈600,000
Equipment	1 heater 1 mylar tube, divided 2 propane tanks 2 fans	4 portable heaters 5 power cables 1 power distribution box 12 fans	4-6 radiators, 10-14 hoses, 2-4 supply/return manifolds 14-15 fans

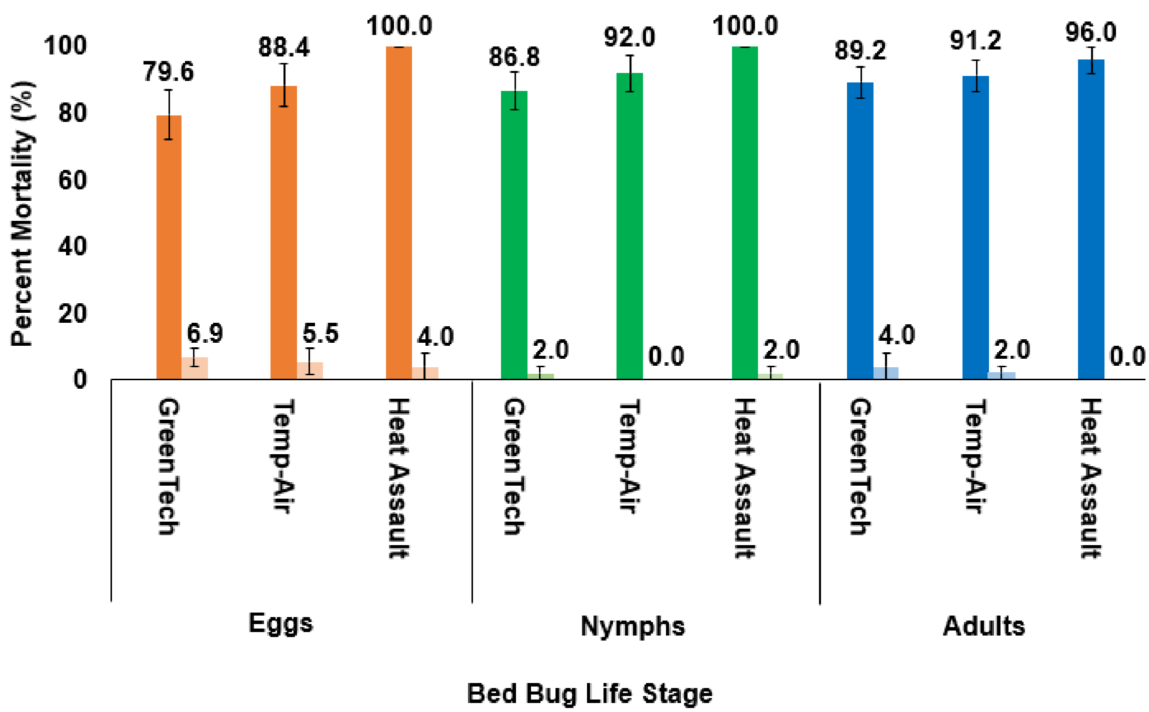

Figure 1. Bed bug average percent mortality (± SE) separated by life stage for each whole-home heat system calculated from the raw data. Darker colored bars represent treated bed bug mortality. Lighter shaded bars represent control bed bug mortality. Nonparametric pairwise comparisons using Wilcoxon's method were used to compare observed mortality within life stage. No pairwise differences were detected within any life stage or overall, when life stages were combined.

Table 2. Data ranges for each variable measured during treatments. Observed ranges for the number of sensors that reached lethal temperature, treatment duration, treated apartment size, the amount of clutter and clutter ratios for the treated apartment, and the range of technician entries across all treatments are listed as potential variables contributing to heat treatment success.

Variables	GreenTech	Temp-Air	Heat Assault
Sensors (12) Reaching Lethal Temperature	4.60 average (4 - 5) range	5.00 average (0 - 8) range	10.0 average (5 – 12) range
Average Treatment Duration (min)	Setup: 24.8 Treatment: 249.6 (4.2 h) Breakdown: 11.8	Setup: 45.6 Treatment: 441.4 (7.4 h) Breakdown: 20.2	Setup: 71.4 Treatment: 334.6 (5.6 h) Breakdown: 34.8
Apartment Size Ranges (m^3)	131.08 - 233.78	84.23 - 247.87	131.39 - 232.01
Clutter Amounts (m^3)	4.63 – 49.19	13.68 – 68.36	1.61 – 53.00
Clutter Ratios (Clutter/Apartment Size) (%)	2.93% - 37.53%	9.51% - 34.25%	1.02% - 22.84%
Range of Technician Entries across all treatments	2.00 – 6.00	8.00 – 16.00	4.00 – 21.00

Apartment size and raw clutter were not used in analysis. These variables were used to generate the clutter ratio (m^3, %) that was used in the analysis.

Table 3. Significant predictors of mortality for each bed bug life stage after stepwise regression. Logistic regression models of whether or not complete mortality was achieved during a given trial were fit to the data from each life stage separately. The models initially included treatment duration, proportion of temperature sensors reaching lethal temperature, clutter ratio, technician entries per treatment hour, and the heat system, as fixed effects. Stepwise regression in both directions using BIC as the selection criteria was performed to select the most meaningful set of predictors for each model. The table includes the set of predictors and their associated model coefficients that were retained in each model after stepwise selection.

Egg Life Stage	Estimated coefficient[b]	Standard Error	*P*-value
Intercept[a]	-4.87	2.73	0.074
Treatment Duration	8.13	4.80	0.091
Proportion of Sensors Reaching 50°C (122°F)	14.28	6.46	0.027
Nymphal Life Stage	Estimated coefficient	Standard Error	*P*-value
Intercept	-2.29	1.99	0.250
Treatment Duration	6.52	3.38	0.054
Proportion of Sensors Reaching 50°C	7.31	4.63	0.115
Adult Life Stage	Estimated coefficient	Standard Error	*P*-value
Intercept	0.258	0.709	0.717
Proportion of Sensors Reaching 50°C	3.54	1.59	0.026

a. Mean level of response variable (i.e. egg mortality) when other variables (i.g. treatment duration) equal zero.
b. Linear parameter estimates in terms of log(odds). Estimates can be compared as effect sizes.

Table 4. Significant predictors of temperature sensors reaching lethal temperature (50°C) after stepwise regression. A logistic regression model was fit to the proportion of temperature sensors in the home that reached lethal temperature. The original model included heat system, technician entries into the building per treatment hour, clutter ratio, and treatment duration. Stepwise regression in both directions using BIC as the selection criteria was used to select the most meaningful set of predictor variables. The table includes the set of predictors and their associated model coefficients that were retained in each model after stepwise selection.

Proportion of Sensors Reaching 50°C	Estimated coefficient[b]	Standard Error	*P*-value
Intercept[a]	-1.44	0.363	<0.0001
Heat System (Compared to Temp-Air)			
Heat Assault System	1.213	0.400	0.0023
Green Tech System	1.290	0.291	<0.0001
Technician Entries per Treatment Hour	1.919	0.300	<0.0001

a. Mean level of response variable when other variables equal zero.
b. Linear parameter estimates in terms of log(odds). Estimates can be compared as effect sizes.
c.

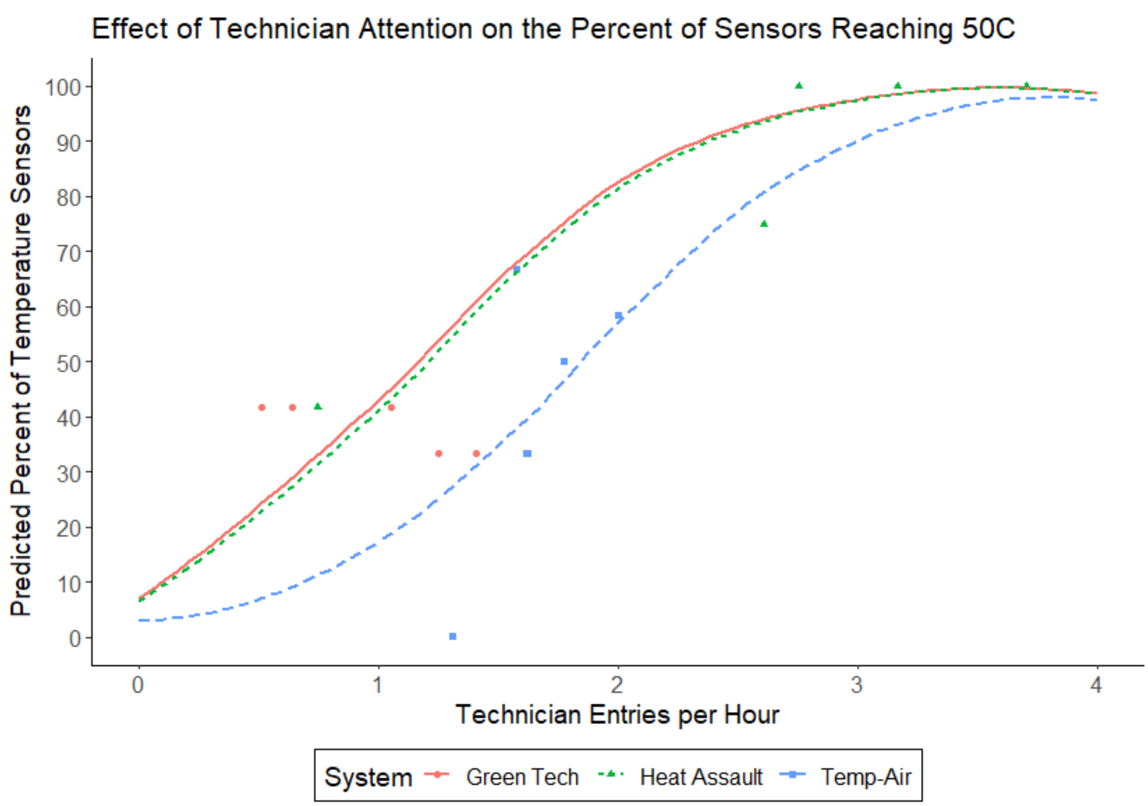

Figure 2. Predicted effect of technician entries per hour on the proportion of temperature sensors reaching lethal temperature when other modeled variables (heat system) were held constant. These proportions were estimated using a mixed effect logistic regression model of whether each sensor reached lethal temperature (50 C).

Overall, when the number of technician entries were evaluated, it was found that technicians using the GreenTech system consistently conducted the least entries, while the Heat Assault technician (with the exception of the Florence technician) consistently conducted the most entries (Table 3). Technicians of the Temp-Air systems had varied amounts of entries, which ranged from eight to sixteen entries throughout the treatments. Even with relatively low technician entries with the GreenTech system, total bed bug mortality for that system was 85.2% (Fig 1). The Heat Assault system produced the highest total bed bug mortality (98.7%), although this difference was not statistically significant. The total bed bug mortality (across all replicates and heat systems) indicates that all systems were able to kill a large amount of the sentinel bed bugs within the units' hard-to-heat locations, however, no system was able to eliminate every bed bug within the treatment zone.

The question of whether or not bed bugs might develop resistance to heat treatments has been investigated due to the widespread observation of heat treatment failures. However, Ashbrooke (2019) found that bed bugs only have a limited ability to develop significant levels of heat resistance. Ashbrooke (2019) determined that susceptible-strains and insecticide-resistant field-strain bed bugs were equally susceptible to heat stress. Benoit (2009) also found that bed bugs are not known to display effective "heat hardening". This is when heat shock proteins are produced to protect other proteins from destruction due to heat exposure. Therefore, concerns of resistance development to heat treatments should remain reasonably low. This study confirms that bed bug survival after a heat treatment is not due to resistance but is most likely due to some aspect of heat treatment failure.

It has been documented that bed bugs can detect heat increases at close range (10-30 mm; Devries 2016: 25.4 mm; Berry III 2021). Therefore, temperature increases may induce an escape response during a heat treatment. Bed bugs have been observed moving to cooler locations (including outside of windows, personal observation) during heat treatments. If it were to take a long amount of time to heat a home or if the home is insufficiently heated over time, bed bugs might seek out cooler environments to escape and shield themselves from heat within hard-to-heat locations (Loudon 2017). Under more extreme circumstances, bed bugs may also attempt to escape a treated apartment entirely and enter a different apartment unit (Raab 2016). Given that our study had surviving sentinel bed bugs (that had been placed in hard-to-heat locations), we now know that heat treatments cannot be expected to deliver complete elimination without rigorous technician attention, and that reinfestations may occur in the future after a heat treatment is conducted.

While some bed bugs may survive heat treatment, there can be biological consequences to the heat exposure. Bed bug heat treatment survivors can suffer effects from sublethal temperatures, which can include reduced offspring production, reduced molting, and egg hatching (Rukke 2018). Ashbrooke (2019) also found that sublethal heat exposure caused reduced feeding and inhibited bed bug development. In spite of these sublethal consequences, heat treatment survivors can still feed post-treatment, which in consumer evaluations, can greatly reduce the value of heat treatments for bed bug control. Given that bed bug survivors can be less "fit" after being exposed to sublethal temperatures, it would be beneficial to consistently apply supplementary treatments such as dusting and insecticide spray applications post-heat treatment.

Logistic regression analysis was unable to determine if the Heat Assault system would perform differently from the GreenTech system if technician attention during the treatment were equal, given that Heat Assault had a high level of technician entries while GreenTech entries were consistently low (Table 2). Thus, we are unable to discern if Heat Assault's superior performance in killing bed bugs was due to technician entries or due to the system itself. However, Temp-Air's performance remained relatively similar even as technician entries increased. Therefore, we were able to determine that the Temp-Air system was relatively less effective than the Heat Assault system. That being said, it is possible that the GreenTech system may have produced greater bed bug mortality if the technicians had entered the treatment site more often and conducted more interventions (Figure 2). GreenTech's technicians were constrained by time and had the shortest treatments on average (Table 2), which may also have been a contributing factor to bed bug heat treatment survival (Table 3). It would be beneficial for future studies to investigate the impact of different numbers and types of technician interventions (checking temperatures and/or moving furniture) and to compare heat system efficacy while controlling for technician entries as much as possible.

The most important predictor of heat treatment success, as suggested by the magnitude of the associated linear estimate in all of the life stage models, was the proportion of temperature sensors that reached 50°C (122°F). Because of this, the analysis of what factors impact how many temperature sensors reach lethal temperature was very important. A logistic regression analysis revealed that the number of technician entries per treatment hour was the most impactful factor for treatment success! Having lethal temperatures reached by sensors in hard to heat locations is positively correlated with the number of times a technician enters the treatment site to check temperatures, adjust equipment, and move furniture (Figure 2). Sensors in hard-to-heat locations reaching lethal temperatures is important given that stepwise regression indicated that the factor was influential in the mortality of all bed bug life stages. Consequentially, the importance of technician diligence during the heat treatment process cannot be understated and we hope that this result will help pest management professionals in learning how to conduct effective heat treatments.

Based on this study, the reason for bed bug survivors ("heat treatment failure") appears to be a due to certain cracks and crevices failing to reach bed bug lethal temperature. In spite of the deficiencies in heating all cracks and crevices, overall bed bug mortality was high (Figure 1). Yet, given the fact that not all bed bugs were eliminated in this study brings into question whether or not reinfestations are really the fault of residents bringing bed bugs back in after the treatments are conducted. The results of this study indicate that it would be unfair to accuse residents of bed bug reintroduction when bed bug survivors are known to occur even when the most conscientious technician is using a high-tech system. This study aids in dispelling any myths that heat treatments are a silver bullet. There is no question that supplementary forms of control should be applied after a heat treatment to address any potential survivors.

REFERENCES CITED:

Abbott W. S. 1925. A method of computing the effectiveness of an insecticide. *J. Econ. Entomol.* 18: 265-267.

Ashbrook, A. R., M. E. Scharf, G. W. Bennett, and A. D. Gondhalekar. 2017. Detection of reduced susceptibility to chlorfenapyr- and bifenthrin-containing products in field populations of the bed bug (Hemiptera: Cimicidae). *J. Econ. Entomology*. 110: 1195-1202. https://doi.org/10.1093/jee/tox070.

Ashbrook, A. R., M. E. Scharf, G. W. Bennett, and A. D. Gondhalekar. 2019. Bed bugs (*Cimex lectularius* L.) exhibit limited ability to develop heat resistance. *PloS One.* 14: e0211677. https://doi.org/10.1371/journal.pone.0211677.

Barbarin, A. M., G. S. Bellicanta, J. A. Osborne, C. Schal, N. E. Jenkins. 2017. Susceptibility of insecticide-resistant bed bugs (*Cimex lectularius*) to infection by fungal biopesticide. *Pest Manag. Sci.* 73: 1568-1573. DOI: 10.1002/ps.4576

Benoit, J. B., G. Lopez-Martinez, N. M. Teets, S. A. Phillips, and D. L. Denlinger. 2009. Responses of the bed bug, *Cimex lectularius*, to temperature extremes and dehydration: levels of tolerance, rapid cold hardening and expression of heat shock proteins. *Med. Vet . Entomol.* 23: 418-425. DOI: 10.1111/j.1365-2915.2009.00832.x

Berry III, R. 2021. The behavioral response to heat in the common bed bug, *Cimex lectularius* (Hemiptera: Cimicidae). *J. Med. Entomol.* 58: 1626-1637. DOI: 10.1093/jme/tjab020

Brooks, M. E., K. Kristensen, K. J. van Benthem, A. Magnusson, C. W. Berg, A. Nielsen, H. J. Skaug, M. Maechler, and B. M. Bolker. 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. The R Journal, 9: 378-400.

Busvine, J. R. 1958. Insecticide-resistance in bed-bugs. *Bull. World Health Organ*. 19: 1041–1052.

Catron, K. A., M. S. Wilson, and D. M. Miller. 2017. Treatment efficacy of thermal remediation for bed bug (Hemiptera: Cimicidae) control in apartments with different clutter levels. *In* W.H. Robinson and D. Bajomi (eds.), Proceedings, 9th International Conference on Urban Pests, 9-12 July 2017, Birmingham, England.

Curtis, C. F., B. Jana-Kara, and C.A. Maxwell. 2003. Insecticide treated nets: Impact on vector populations and relevance of initial intensity of transmission and pyrethroid resistance. *J. Vector Borne Dis.* 40: 1-8.

Dang, K., S. L. Doggett, G. V. Singham, and C. Y. Lee. 2017. Insecticide resistance and resistance mechanisms in bed bugs, *Cimex.* Spp. (Hemiptera: Cimicidae). *Parasites & Vectors*. 10: 318.

Davies, T. G. E., L. M. Field, and M. S. Williamson. 2012. The re-emergence of the bed bug as a nuisance pest: implications of resistance to pyrethroid insecticides. *Med. Vet. Entomol.* 26: 251–254. DOI: 10.1111/j.1365-2915.2011.01006.x

Devries, Z. C., R. Mick, and C. Schal. 2016. Feel the heat: activation, orientation and feeding responses of bed bugs to targets at different temperatures. *The Journal of Experimental Biology.* 219: 3773-3780. DOI: 10.1111/j.1365-2915.2011.01006.x

Environmental Protection Agency of the United States. 1996. Summary of the Food Quality Protection Act.1996. EPA, Washington, DC. http:// epa.gov/laws-regulations/summary-food-quality-protection-act.

GreenTech Heat Solutions. 2021. "One Bed Bug Heat Machine. Many Pests." *The Best Bed Bug Heat Machine Equipment for Sale: Titan Heaters*, https://www.greentechheat.com/titan.php.

Hartig, F. 2021. DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. R package version 0.4.4. https://CRAN.R-project.org/package=DHARMa

Hartnack, H. 1939. 202 common household pests of North America. Hartnack Publishing Co., Chicago, IL.

Heat Assault. 2021. "Heat Assault Equipment." *Heat Assault Bed Bug Equipment*, https://www.heat-assault.com/equipment.

Howerton, M. 2020. Dallas bed bugs expert says he treats 5 to 10 rideshare vehicles per week. https://wfaa.com/article/news/bed-bugs-expert-says-he-treats-5-10-rideshare-vehicles-per-week/287-d8d2170b-bcd1-4e78-a589-4db280302360.

Johnson, M. S., and A. J. Hill. 1948. Partial resistance of a strain of bedbugs to DDT residual. Med. News Lett. 12: 26–28.

Kells, S. A. 2018. Chapter 28. Non-chemical control, pp. 257–272. *In* S. L. Doggett, D. M. Miller, and C. Y. Lee (eds.), *Advances in the biology and management of modern bed bugs*. Wiley Blackwell, Oxford, United Kingdom.

Kells, S. A., and M. J. Goblirsch. 2011. Temperature and time requirements for controlling bed bugs (*Cimex lectularius*) under commercial heat treatment conditions. *Insects*. 2: 412-422. DOI: 10.3390/insects2030412.

Krinsky, W. L. 2019. True Bugs (Hemiptera). M. Gary & D. Lance, *Medical and Veterinary Entomology.* Elsevier, pp. 107-127. doi.org/10.1016/B978-0-12-814043-7.00008-X

Kweka, E. J., B. J. Mwang'onde, E. E. Kimaro, S. Msangi, F. Tenu, and A. M. Mahande. 2009. Insecticides susceptibility status of bedbugs (*Cimex lectularius*) in a rural **area of** Magugu, Northern Tanzania. *J. Glob Infect Dis.* 1(2) 102-106; DOI: 10. 4103/0974-777X.56252

Lilly, D. G., K. Dang, C. E. Webb, and S. L. Doggett. 2016a. Evidence of metabolic pyrethroid resistance in the common bed bug (Hemiptera: Cimicidae). *J. Econ. Entomol.* 109: 1364–1368. DOI: 10.1093/jee/tow041

Loudon, C. 2017. Rapid killing of bed bugs (*Cimex lectularius* L.) on surfaces using heat: application to luggage. *Pest. Manag. Sci.* 73: 64-70. DOI: 10.1002/ps.4409

Mallis, A. 1945. Handbook of pest control. Mac Nair-Dorland Company, New York, NY.

Ministry of Health. 1934. Report on the bed-bug. Reports on Public Health and Medical Subjects. No. 72. His Majesty's Stationary Office, London.

Olson, J. F., M. Eaton, S. A. Kells, V. Morin, and C. Wang. 2013. Cold tolerance of bed bugs and practical recommendations for control. *J. Econ. Entomol*. 106: 2433-2441. DOI: 10.1603/ec13032

Phillips, T.W., M. J. Aikins, E. Thoms, J. Demark, and C. Wang. 2014. Fumigation of bed bugs (Hemiptera: Cimiciade) effective application rates of sulfuryl fluoride. *J. Econ. Entomol.* 107: 1582-1589. DOI. 10.1603/ec13471.

Potter, M. F. 2011. The history of bed bug management- with lessons from the past. *Am. Entomol.* 57: 14-25. doi.org/10.1093/ae/57.1.14

Potter, M. F. 2018. Bed bugs throughout history, pp. 9-25. *In* S. Doggett, D. M. Miller, and C. Lee (eds.), *Advances in the biology and management of modern bed bugs.* John Wiley and Sons, West Sussex, United Kingdom.

Potter, M. F., B. Rosenburg, and M. Heinricksen. 2010. Bed bugs without borders: executive summary: defining the global bed bug resurgence. Pestworld (September/October): pp. 1–12.

Puckett, R. T., D. L. McDonald, and R. E. Gold. 2013. Comparison of multiple steam treatment durations for control of bed bugs. *Pest. Manag. Sci.* 69: 1061-1065. DOI 10.1002/ps.3467

Raab, R. W. J. E. moore, E. L. vargo, L. Rose, J. Raab, M. Clubreth, G. Burzumato, A. Koyee, B. McCarthy, J. Raffaele, C. Schal, and R. Vaidyanathan. 2016. New introductions, spread of existing matrilines, and high rates of pyrethroid resistance result in chronic infestations of bed bugs (*Cimex lectularius* L.) in lower-income housing. *PloS ONE* 11(2): e0117805. DOI: 10.1371/journal.pone.0117805.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org

Rafatja, H. 1971. The problem of resurgent bed-bug infestation in malaria eradication programmes. *J. Trop. Med. Hyg.* 74: 53–56.

Rittman, E. 2020. KC experts treat rideshare vehicles to get rid of bed bugs. https://www.kctv5.com/news/local_news/kc-experts-treat-rideshare-vehicles-to-get-rid-of-bed-bugs/article_7390d3a0-5e88-11ea-814c-c33f6ba83016.html

Romero, A., and T. D. Anderson. 2016. High levels of resistance in the common bed bug, *Cimex lectularius* (Hemiptera: Cimicidae), to neonicotinoid insecticides. *J. Med. Entomol*. 53: 727–731. DOI: 10.1093/jme/tjv253

Romero, A., M. F. Potter, D. A. Potter, B. C. Haynes. 2007. Insecticide resistance in the bed bug: a factor in the pest's sudden resurgence? *J. Med. Entomol.* 44: 175-178. doi.org/10.1093/jmedent/44.2.175

Rukke, B. A., R. Sivasubramaniam, T. Birkemoe, A. Aak. 2018. Temperature stress deteriorates bed bug (*Cimex lectularius*) populations through decreased survival, fecundity and offspring success. *PloS One*. 13: e0193788. doi.org/10.1371/journal.pone.0193788.

SAS Institute Inc. 2004. SAS/STAT. 9.1 User's Guide. SAS Institute Cary, NC.

Temp Air Thermal Remediation. 2021. "Commercial Bed Bug Heaters and Equipment." *Thermal Remediation*, https://www.thermalremediation.com/bed-bug-equipment.html.

Usinger, R. 1966. *Monograph of Cimicidae (Hemiptera – Heteroptera)*. The Thomas Say Foundation. Vol VII.

U.S. Department of Agriculture. 1875. Report of the Commissioner of Agriculture. Washington, DC.

Venables, W. N. and B. D. Ripley. 2002. Modern Applied Statistics with S. Fourth Edition. Springer, New York. ISBN 0-387-95457-0

Wang, D., C. Wang, G. Wang, C. Zha, A. L. Eidan, and R. Cooper. 2018. Efficacy of three different steamers for control of bed bugs (*Cimex lectularius* L.). *Pest Manag. Sci.* 74: 2030-2037. DOI: 10.1002/ps.4933