The Influence of Thermal and Physical Characteristics of Buildings on Overwintering Brown Marmorated Stink Bugs (*Halyomorpha halys*)

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ABSTRACT

Building design, maintenance, and management can have significant impacts on accessibility and suitability for pest species. The brown marmorated stink bug, *Halyomorpha halys* (Stål), causes household nuisance pest problems because of its habit of using human homes as winter refuges. Studies were conducted to understand behaviors and characteristics relevant to this problem, including response to gravity, ability to pass through openings, responses to heat, and mortality estimations in wall assemblies. In the lab, winter shelter seeking bugs were shown to exhibit upward movement, and field observations of bugs on building exteriors gave similar results. In experiments testing the size limits on openings through which bugs could pass, height limited tests excluded most females at 4 mm, and all bugs at 3 mm. Pronotum width limited tests excluded most females at 8 mm and nearly all bugs at 7 mm. Accompanying measurements of over 900 bugs found an average female pronotum width of 8.33 mm and height of 4.03 mm, and male pronotum width of 7.47 mm and height of 3.50 mm, with minimum sizes indicating that only a small percentage of bugs will pass the smallest openings tested. Heat response experiments of shelter seeking bugs were first piloted outdoors, and then modified to be a forced choice indoor test. In outdoor tests on a flat plane wall section with alternating heated sections, bugs did not respond to thermal contrast but rather immediately walked off of the wall. In the indoor forced choice test, a box of four cavity walls was used. Bugs did not respond to the heated sections in either the adjacent or opposite configuration. Thermal simulation modeling was used to evaluate the possible effects of varying wall assembly materials and configurations on cold-related mortality of bugs overwintering in the cavity space behind cladding. Simulation results indicated that bugs electing to overwinter in the space between cladding and sheathing were at risk of freezing deaths, with mortality expectations increasing in better insulated buildings. The results of these studies will inform future control measures and impact studies in buildings.

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GENERAL AUDIENCE ABSTRACT

Building design, maintenance, and management can have significant impacts on accessibility and suitability for pest species. The brown marmorated stink bug, *Halyomorpha halys* (Stål), is a household pest because of its habit of using human homes as winter refuges. This research investigated the ability of these bugs to enter homes, and what happens once inside. This included responses to gravity and heat, studies of the body size and the ability to enter openings in building envelopes, and estimations of mortality due to freezing in wall assemblies using thermal simulation modeling. Bugs were shown in the laboratory and on the sides of buildings to consistently move upward. Bugs were given the ability to move along alternatingly heated and unheated sections of walls in search of winter shelter. The heated sections of walls did not elicit any response, suggesting that warmer portions of walls are not impacting the search for structure entrances. Bugs were shown to not pass through 3 mm tall or 7 mm wide openings, though female bugs tend to require even larger holes. Males are consistently smaller than females, at an average of 3.50 mm tall and 7.47 mm wide to the females' average 4.03 mm height and 8.33 mm width. Thermal simulation modeling suggested that increasing the insulation in a building may influence the expected mortality rate of bugs that overwinter in the space between sheathing and cladding. These findings will help to create and target pest control methods, by helping design exclusion methods, identifying what openings need treatment, and indicating better orientations of traps. The thermal modeling results suggest possible effects of building design choices on the spread of *H. halys*, as well as possible problems associated with increased mortality within wall assemblies.

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Contributions of Authors

While the bulk of this work was done by Benjamin Chambers, the committee made meaningful contributions throughout the process, including guidance and input during conceptualization, experimental design, and interpretation of results. Everyone also contributed to the editing of each manuscript. Additionally, Georg Reichard provided the wall assembly models used in Chapter 5. Accordingly, all four committee members will be listed as co-authors on any resulting publications.

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1. Introduction and Background

For ages, humans have been constructing buildings to suit their needs. The specifics of construction all vary with time, climate, region, material availability, need, and purpose. Material choices, layering, assemblies, geometry, and other design decisions are driven by these factors. Apertures for windows, doors, or ventilation may also vary, but tend to be present in one form or another, as are cavities, crevices, and corners on and within the structure, and all across history, these features have created opportunity or habitat for other species.

Some may come seeking food or a home, others for temporary shelter. Some people employ extensive pest control methods to keep them out, while others do not mind sharing space with a few insects and spiders. However, even the most generous, passive humans can become unhappy when the numbers of these visitors become too high. It ceases to seem like a few cute, bumbling bugs on the wall, and becomes an infestation. This line has been crossed for many people by a winter visitor, the brown marmorated stink bug, *Halyomorpha halys* (Stål), which is the focus of this dissertation.

Pest control is approached in a variety of ways. Pests may be killed or trapped and removed. Buildings may be made less appealing to the pest by reducing comfort level with repellants or changes in physical features, or food supply by changing processes and behaviors of human users. Where possible, pests are prevented from even entering the building with appropriate barriers or design features. The specifics of all of these vary by pest species. A species' biochemistry, food sources, environmental preferences, general behavior, and entry methods must all be understood to effectively control it.

Sometimes, the easiest, safest, and most effective way of dealing with a problem is to design a system to prevent it. These higher-order prevention through design controls are used in several fields, including structural pest control. These methods are particularly dependent upon understanding the behavior and physical characteristics of the pest species. They also depend upon understanding the design and function of the building elements with which the pest species interacts.

In the case of shelter seeking insects like *H. halys*, the first part of a building to be interacted with is the envelope, that which separates the outside from the inside. The design and characteristics of the envelope vary, but knowledge of how they work inside and out helps to understand what the invading insects encounter and interact with as they assess the structure. Naturally, apertures are needed to allow for the exchange of air, light, and people. The location, function, design, and physics of these holes indicate how and where a pest insect can enter, as well as the environmental conditions around the opening. In addition to providing access, these features are often a path of least resistance for heat transfer between conditioned spaces and the outside, potentially creating thermal contrast.

Other apertures may exist in an envelope that don't connect to the conditioned interior space, but rather provide ventilation for cavities within the walls to prevent moisture problems. Knowledge of where these holes typically are placed and what sizes and characteristics they need to function helps to understand where and how a pest might enter a structure. It also reduces the risk of accidental disruption of function during exclusion feature installations. Depending on movement patterns, physical features may prevent a bug from even encountering a hole. For *H. halys*, the first step in identifying access points on buildings of various design is to figure out how these insects are actually moving on the surfaces of buildings as they evaluate them.

Another way to improve and target exclusion methods is to understand what characteristics *H. halys* uses to evaluate the suitability of the structure as shelter. For instance, if they are seeking a way to survive the winter cold, then the thermal properties of a structure matter for survival. This suggests the possibility that *H. halys* could be responding to warm spots such as thermal bridges as they seek thermally safe winter sites.

Once a suitable opening is found, whether it is intentionally present, or the result of some failure of the envelope, a pest has to be able to physically fit through. Various rules of thumb and design guidelines exist for other pests. For pests using vents to enter unconditioned spaces for shelter, exclusion methods need to be fine enough to keep the pest out, while allowing sufficient airflow to continue through the vent. Finding this balance for *H. halys* requires knowledge of the physical size of the insects and their ability to move through holes.

When exclusion methods fail or are not used at all, bugs may enter wall cavities. Although there is a chance that their presence may lead to secondary pest infestation, the real concern there is whether or how they might affect the function of that cavity. Knowledge of these cavities and the requirements for a certain amount of ventilation area suggest that their corpses could cause moisture problems. Checking under cladding for their presence might be expensive, so a first step is to determine whether those cavities provide sufficient protection for overwintering *H. halys*.

The rest of this chapter explores these ideas in more detail. First, best practices for pest control relevant to *H. halys* are described. This is followed by a discussion of building envelopes and the types of holes they have. Once pest control, exclusion, and building envelopes are understood, the state of knowledge about overwintering aspects of the lifecycle of *H. halys* are discussed. Finally, a set of objectives for the rest of the dissertation are outlined.

Pest Control

When infestations occur, or when people simply do not want any invaders in their buildings, they may do something about it. These structural pest control methods typically include some combination of chemical and mechanical efforts, such as insecticides, repellants, traps, or barriers. Monitoring, process changes, behavior modifications, and other management efforts may also be used. In the United States, this is big business, with the industry surpassing $8 Billion in revenues in 2016 (Specialty Consultants 2017).

Insects frequently seek entry to buildings for shelter or food. Food-seekers such as cockroaches, ants, and termites get a lot of attention, as they may contaminate human food stores or cause damage to structures. However, although *H. halys* is anecdotally reported feeding indoors on fruits, vegetables, and house plants, this is not known to be a primary motivator for its entry. In the case of shelter seeking insects, hymenopterans like paper wasps and yellow jackets looking for places to establish their nests are generally of greatest concern because of their tendency to sting people who disturb them. Such insects frequently move in and out of the structure as they forage. There are a number of other species that enter solely for purposes of finding sheltered locations to enter diapause and ride out the winter in the same way as *H. halys*.

This discussion of pest exclusion and management in buildings focuses on those practices relevant to *H. halys*, and largely excludes literature focused on treatment for subterranean pests like termites, adequate sanitation to eliminate food sources for roaches, or impedance to the movement of bed bugs, as those methods are largely irrelevant to *H. halys*. Rather, of concern are above-grade exclusion, landscape management, and the removal of shelter for those individuals that make it past the outer shells of buildings.

Pest control practices for insects that are attempting entry generally relies on some combination of chemical or mechanical means. Killing of insects is achieved by application of traps or deadly substances. These substances may be pesticides or desiccating agents such as diatomaceous earth. These methods are regularly used, and may be effective, depending on the insect. Pesticide soaked netting and applications to window frames have been shown to prevent *H. halys* invasion (Watanabe et al. 1994b). However, pesticides do not always work for overwintering insects. Boxelder bugs, for instance, may still be present in homes even after treatment with liquid insecticides (Robinson 1999).

Mechanical methods of pest control are of particular interest for *H. halys*, specifically exclusion. Exclusion methods simply mean blocking entrances. The particulars vary by hole and pest type. Holes created for utilities usually are caulked, though when rodents are involved, metal screen may be impregnated in the surrounding wall. Plastic or metal screens are placed over or inside of other holes as appropriate, but the size, material, and gauge may vary with expected pest species.

General exclusion guidelines above grade typically focus on the ¼ in rule-of-thumb, which is based on exclusion of mice (Geiger and Cox 2012). In this, any hole larger than ¼ in (6mm) should be treated, as holes much larger than this can be squeezed through by field mice, whose passage is limited only by the size of their skulls. In the case of larger holes, ¼ in hardware cloth is recommended. Some other guidelines indicate treating smaller openings and the use of finer mesh for exclusion of insects. In the case of ladybird beetles, 1/16 in (1.6mm) is presented as the maximum allowable size (Layton 2014). This sizing is supported by a study of minimum opening sizes accessible by these beetles (Nalepa 2009), which bottomed out at 2mm. Guidelines for dealing with wasp invaders discuss the application of mesh over all holes (Around the Clock Pest Control 2015; Beyond Pesticides 2015; Eartheasy 2015).

The strength of exclusion methods is that they translate well to construction and building design. In construction as well as pest control, designing to avoid a problem is desirable. In the construction field, prevention through design most often references safety (NIOSH 2018) or thermal performance (Passivhaus 2018), but it is also applied to integrated pest management. Of particular note to this review is a guide commissioned by the city of San Francisco that reviews building design for pest prevention (Geiger and Cox 2012). This document provides much generally useful information, and is well worth reading.

Building Envelopes

Effective exclusion and management starts with an understanding of building envelopes. Building envelopes tend to be very complex systems, with multiple materials used on the exterior as well as interior, and there is significant variation between buildings as well. For example, some houses may be sided with brick, others with vinyl, and others with woods such as cedar. Lighting, shading, and temperature of exteriors vary with the time of day, time of year, and the weather. Many intentional structural openings may exist for ventilation, lighting, or entrance and exit. Other unintentional openings may also be present, due to poor construction, settling, or temperature changes. These openings, along with material and construction choices as well as interior climate control methods, dictate the thermal characteristics and temperature profiles within walls.

Openings and Cavities

Openings exist for a variety of reasons. Some are intended or required, while others result from failures during construction or operation. In addition to people, pets, air, and moisture, pests such as *H. halys* use these openings to enter buildings. Successful exclusion requires understanding the openings that need to be there so that function is not interrupted by insect barriers. It also requires awareness of the types of unintended openings that occur, so they can be addressed, prevented, or accounted for. Openings between conditioned and unconditioned spaces are of particular interest to energy efficiency efforts, and have been inventoried for purposes of preventing air infiltration (EPA 2015).

Intentional Openings

For convenience of discussion, intentional opening types have been classified (Table 1.1). Penetrations are holes in the envelope intended for the passage of utilities like cable or electric lines. Penetrations are typically sealed around the utility. Apertures, such as doors and windows, are intended for passage of things and people through the envelope, and typically open and close as needed. These apertures may have screens, and if weatherized, have seals or brushes around their edges to prevent air or pests from passing around their edges. Exhaust vents from conditioned spaces carry through in order to remove smoke, steam, or odors from the structure. Exhaust usually connects to bathrooms, kitchens, and laundry rooms. Exhaust vents often have dampers or some other control measure to reduce or prevent air leakage when not in use. However, damper location varies with purpose and design, and openings may carry well into the envelope before the damper is encountered. Exhaust vents may be screened, but the necessary effective vent area for function must be considered, as does any matter carried with the exhaust air. For instance, dryer vents can clog with lint, reducing their efficacy and potentially creating a fire hazard.

Table 1.1: Classifications of intentional building envelope openings.

Opening Type	**Open Period**	**Purpose**	**Examples**
Vent	Always	Ventilation for moisture control	Soffit vent, attic vent, wall cavity vent
Exhaust	Always, but usually dampened	Ventilation	Bathroom or stove exhaust, chimney flue
Aperture	Sometimes	Moving air, things, or people in and out	Window, door, mail chute
Penetration	Never	Resealed opening for utilities	Cable, phone line, gas, or electric service entrance

Other intentional openings are vents, and these typically do not carry through to conditioned spaces within the buildings. These vents help to regulate temperature and prevent damaging moisture accumulation within attics and wall assemblies, and therefore must always be open. This requirement makes them good candidates for mesh or screen. However, designers and operators must be careful about selection of screens, as they reduce the effective area of a vent, particularly with fine meshes. The size of vent openings dictates its functionality. In the case of attics, building codes require the ratio of attic vent area to floor area to be between 1:150 and 1:600, depending on climate and design choices (Lstiburek 2006).

Vents also exist for regulation of moisture within exterior walls. Cladding or rainscreen systems can require a vented cavity between them and building sheathing (Lstiburek 2010). This is because water can find its way under the cladding, and needs to be removed before it causes rod, warping, or corrosion. These vented cavities allow drainage of hydrostatic pressure, as well as airflow for drying. For air to flow, vents must be present both near the tops and bottoms of cavities. Such vents can be screened, or designed as small, regular holes created during the cladding manufacturing process, as with some kinds of vinyl. In the case of brick cladding, vents must be built in, either with weep holes, air bricks, wicks, or other specially designed items. These systems also typically incorporate some sort of catchment to prevent mortar in the cavity from falling down and blocking the vents and drainage.

Unintentional Openings

Failures at any stage in the lifecycle of a building can lead to the presence of other unintentional openings, which for convenience of discussion, have been classified (Table 1.2). During construction, mistakes can occur due to human error, inexperience, or sloppiness. Materials may not be well connected, and separate during or after construction, or they may not be aligned well, creating a space through which air or pests can pass. Construction methods also typically involve multiple subcontractors or trades, creating opportunities for miscommunication about tasks and responsibility. When trades expect that a penetration will be used or filled by another trade, they will leave it open. If no trade takes responsibility, the penetration will remain open. For example, sewage outlet penetrations may be left by builders for plumbers, who may expect sealing to be a task for one of the finishing teams.

During the operational life of a building, a variety of factors can create gaps or holes. Holes can be actively created by biological agents, such as rodents or woodpeckers in search of food, termites or ants creating nests in wood, or people, be they well-intentioned DIYers, or children with destructive streaks. Moisture can get in through other holes, or compound from breakdowns in wall systems. Water is destructive, and interacts differently with different materials. Corrosion can occur in concrete or steel, and wood warps. In either case, material separations and openings can be created. Finally, weather and outside factors can cause openings in a variety of ways. Thermal expansion and contraction occurs as temperatures change, and in cases where materials with different thermal properties are joined, they can expand or contract at different rates. This can create deformities and disconnections, and thus openings. Sun, water, and heat can all degrade materials used to seal around intentional openings, such as window weather stripping.

Table 1.2: Classifications of unintentional building envelope openings.

Cause	**Phase**	**Example**
Mistake	Construction	Uneven material connection
Miscommunication	Construction	Plumbing access
Moisture	Operation	Water warped wood
Biological	Operation	Rodent chewing, woodpecker hole, ant hole, child damage
Weather	Operation	UV degraded window seal, material separation from thermal expansion

Thermal Characteristics

Buildings are often designed to create thermally protected spaces and protect their contents from the elements. When designed and maintained appropriately, indoor spaces are cool in summer and warm in winter. This is achieved with multiple materials and layers. Indoor spaces are usually finished with a clean barrier like gypsum board. Insulation slows heat transfer, providing thermal protection. Structure and support is provided in a variety of ways, including wood or steel framing. Outside of framing an insulation, sheathing provides more structure and a place to attach cladding. Vapor barriers or other membranes may be added to reduce condensation or airflow within the wall. On the outside, some sort of cladding is placed to improve thermal performance, protect the wall from weather, and to improve aesthetics. A vented cavity space is typically created between sheathing and cladding, which can be an essential part of keeping the inside of the wall dry (Lstiburek 2010).

Characteristics of wall design such as insulation choices and thermal bridging are very important in the thermal performance of walls (Capozzoli et al. 2013; Kaynakli 2012). These characteristics, along with air leaks, can dictate the temperature gradient across wall assemblies. When interior conditions are comparable, poorly insulated buildings will typically have overall warmer wall assemblies than well insulated buildings. In winter, that means that insulation choices may determine the degree of thermal protection for any *H. halys* that have worked their way inside a wall assembly.

Thermal effects and heat transfer through walls depend on geometry, material, and location. However, windows and framing are responsible for energy loss through a building envelope (Bjarløv and Vladykova 2011; Cappelletti et al. 2011; Christian and Kosny 1996; Kosny et al.

2014; Theodosiou and Papadopoulos 2008). Even modern high-performance windows tend to show higher thermal conductivity than the rest of a building's exterior (Cuce and Riffat 2015).

Higher thermal losses around these features occur for a variety of reasons. The various connections between glazing, framing, and installation systems provide thermal bridges, conducting heat through the wall. Radiant heat loss occurs through glass. Weatherstripping and seals around apertures can degrade through exposure to UV, heat, or moisture, as well as simple wear and tear. When these seals break down, air may leak through them. High energy loss through window assemblies can occur because of these air leaks (Younes et al. 2012), and the air exfiltration can create even more thermal loss than conduction in some situations (Cuce 2017).

Because of their high thermal losses, these apertures are commonly targeted in energy efficiency retrofits. They also have become significant parts of guidelines for new energy efficient construction. This sealing or re-sealing of openings also has the potential benefit of excluding invading *H. halys*.

Thermal and hygric performance of walls is often analysed with thermal simulation modeling software (De Boeck et al. 2015). This allows estimation of energy requirements and conditioning costs. It also allows system designers to avoid moisture and condensation problems. Design can determine power bills and moisture repair costs over the operational life of the building. It may also affect the accessibility and suitability of a building for winter guests like *H. halys*.

The Brown Marmorated Stink Bug (*Halyomorpha halys*)

The brown marmorated stink bug, *Halyomorpha halys* (Stål), (Figure 1.1) is a generalist plant eating (polyphagous) insect originating in Asia. The species was accidentally introduced into the United States sometime in the 1990s, and was first identified in Pennsylvania (Hoebecke and Carter 2003). It has rapidly spread through the eastern U.S., becoming a serious agricultural pest (Leskey et al. 2012). It has also become a nuisance in the colder months, as it has a tendency to invade households and commercial buildings in search of overwintering sites (Hamilton 2009; Inkley 2012).

Figure 1.1: The brown marmorated stink bug.

Many lay people have been discussing their experiences with *H. halys* in both crops and buildings on a variety of websites. Of particular note are those run by the USDA (http://www.stopbmsb.org/), Rutgers University (http://njaes.rutgers.edu/stinkbug/) and Pennsylvania State University (http://www.Stinkbug-info.org).

The existing literature on this insect has been reviewed. Leskey et al. (2012) reviewed literature on *H. halys* as a pest, focusing on agricultural concerns, with some discussion of home nuisances. In the native range of *H. halys,* it has long been an important pest. This led to the creation of a significant body of literature in China, Japan, and Korea, which Lee et al. (2013) reviewed. Rice et al. (2014) followed this with a general review. Continued range expansion and significant research activity inspired a general review focusing on North America and Europe by Leskey and Nielsen (2018). Because of these extensive reviews, the literature presented in this dissertation provides important general background information, and includes information germane to overwintering behavior organized sequentially.

Invasion and Spread

In North America, *H. halys* was first reported in Allentown, Pennsylvania. In the mid 1990s, a large number of these bugs began aggregating on building exteriors, prompting investigation, identification, and the beginning of North American *H. halys* research (Hoebeke and Carter 2003). It is thought that bugs settled in shipping containers for diapause, and were thus transported to the US (Hamilton 2009). The Eastern US population of *H. halys* has been genetically traced back to an area outside of Beijing, China (Xu et al. 2014). Dispersal patterns within the US find strong correlation with railroad shipping lanes (Wallner et al 2014), and shipping containers remain a risk for the continued spread (Aigner and Kuhar 2016).

As of 2017, *H. halys* has been found in 43 US states and four Canadian provinces (Northeastern IPM Center 2017), and climate analysis suggests further expansion (Zhu et al. 2012). In Europe, it has become established in several countries (Haye et al. 2015). Further international expansion of the range of *H. halys* is expected through international travel and trade (Kriticos et al. 2017), and is now present in much of Europe, most recently in Slovakia and Spain, and has also spread to South America, being reported in Chile (Reviewed in Leskey and Nielsen 2018). Cargo shipment treatments are hoped to slow the spread (Aigner and Kuhar 2016).

Nomenclature

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is also commonly referred to as BMSB. Due to their prevalence in the region, when the public says “stink bugs”, it is usually in reference to this species. In the scientific literature, the identity of the species was finalized in 1978 (Hoebeke and Carter 2003). A mis-identification as *Halyomorpha picus* appears in several papers, and the old classification *Halyomorpha mistus* persisted in the Japanese literature into the 1990s.

Description of *H. halys*

Adult *H. halys* are shield shaped, with brown and tan marmorated backs. Abdomens are characterized by white bands along their edges, and antennae have similar white bands. Undersides are cream or tan. Adults are generally between 12 - 17 mm long and 7 - 10 mm wide (Hoebeke and Carter 2003). Females are typically larger than males.

When disturbed, *H. halys* release defensive chemicals including the foul-smelling volatile E-2-decenal (Baldwin et al. 2014, Harris et al. 2015, Solomon et. al 2013). The smell is described as reminiscent of cilantro, but the chemicals taste considerably worse. It also has a tendency to stain human skin for several days. Bug excreta appears as brown liquid streaks along walls and curtains, which may also stain some materials.

Lifecycle

Life for *H. halys* begins as eggs laid on the undersides of tree leaves. Development times range from four to 22 days, depending on temperatures (Nielsen et al. 2008). After hatching, nymphs go through five instars over the next 38 to 122 days, progressing faster in warmer temperatures. In the upper mid-Atlantic United States and Canada, there is typically only one generation per year, but Virginia, West Virginia, and North Carolina are warmer, and thus *H. halys* is typically bivoltine in these states. In their native range in Asia, voltinism is also influenced by temperature (Lee et al. 2013). Fujiie (1985) suggested that the end of oviposition is related to photoperiod and temperature, after observing it ending in lower latitudes at a 14 hours light to 10 hours dark period, and a 15 hours light and 9 hours dark period in higher latitudes.

As oviposition ends and fall arrives, *H. halys* begins to move away from feeding grounds in search of overwintering sites. The timing of this appears to vary geographically, from August to November (Lee et al. 2013, Hoebeke and Carter 2003). Triggers may include temperatures and photoperiod. Arrival at buildings has been reported as beginning when daily low temperatures fell below 15 °C and highs were around 25 °C (Watanabe et al. 1994a). Photoperiod has been shown to influence diapause in the lab, with a cycle of 11 hours light and 13 hours dark having a significantly larger effect than a 16 hours light and 8 hours dark cycle at a temperature of 20 °C (Niva and Takeda 2003). Toyama et al. (2006) also triggered diapause with a 12 hour light and 12 hour dark cycle at 15 °C.

In spring, as diapause ends, bugs exit their winter shelters. The timing of this is highly varied, but typically it occurs as temperatures consistently begin to exceed 10 °C, between March and May (Lee et al. 2013). Emergence has also been linked to nutritional states and the depletion of fat body (Funayama 2012). After emergence, adults begin to feed. Ovarian development then completes, and mating and egg laying begins.

Overwintering Habits

This section of the review collects the overwintering research that has been published to date, and presents it in a manner that may be useful for targeting specific types of interactions between these bugs and overwintering structures. To better understand the overwintering behavior of *H. halys*, it has here been broken into distinct steps based upon needs, triggers, and influencing factors, adapted from those described for *Harmonia axyridis* by Nalepa et al. (2005). Some of these steps may overlap temporally, and bugs may revert to previous steps. However, in any given year, each step will first occur in the order presented. These steps are outlined in this section, along with scientific and anecdotal evidence relevant to each.

When overwintering behavior begins, a bug will leave its feeding grounds to search for structures that may provide shelter for the winter. Once a structure is found and approached, the bug will assess it for general suitability. If the structure is deemed attractive, the bug will begin to search the structure for settling sites. When a settling site is found in the structure, the bug will assess its potential as a spot to spend the winter. If the site is deemed suitable, the bug may then settle down for the winter. Eventually, physiological or environmental factors will interrupt diapause, and the bug will become active and mobile. If the bug is ready to end diapause, it will search for an exit to the structure, that it may begin its active cycle. In simplified form, the steps defined for this review are:

1. Initiation of overwintering behavior
2. Search for overwintering structures
3. Assessment of structures
4. Search for settling sites
5. Assessment of settling sites
6. Interruption or end of diapause
7. Search for structure exit

Initiation of Overwintering Behavior

At some point in the fall, adult *H. halys* begin to search for structures in which to spend the winter. The timing of this varies by region. This process has been described as beginning as early as late August (Hoebeke and Carter 2003), and running as late as November (Lee et al. 2013), with higher numbers in mid-October. In the eastern United States, the period of searching and settling used in scientific study has been assumed mid-September to mid-October, with a peak of activity observed between September 30 and October 2 (Hancock et al. 2015). In the experience of researchers at Virginia Tech, this mid-September to mid-October period is typical. In one Japanese study, overwintering bugs began arriving at structures when daily temperature lows dropped below 15 °C with highs around 25 °C. Peak numbers were recorded when daily lows dropped below 10 °C (Watanabe et al. 1994a). These numbers align with an *H. halys* temperature-related behavior profile that indicated that they slow down at 23 °C, with flight ceasing below 20 °C, and most individuals becoming inactive below 9 °C (Li et al. 2007). It is possible then that local climate patterns may be an important factor in the timing of structure search. There are certainly regional climate effects on other aspects of the lifecycle of *H. halys*, such as the number of generations in a given year.

Photoperiod is also implicated as a factor in triggering diapause. A daily cycle of 11L:13D (11 hours light to 13 hours dark) for *H. halys* in the lab has been shown to lead to diapause at 20 °C (Niva and Takeda 2003), with significantly more insects entering this state than those kept at a 16L:8D cycle. This information has been used in other studies to trigger diapause at 15 °C and a 12L:12D cycle (Toyama et al. 2006). In both of these studies, diapause was confirmed by examining the development of gonads, which is inhibited in diapausing bugs (Niva and Takeda 2002). Further discussion of photoperiod is provided in a Japanese oviposition study, where oviposition ended in higher latitudes at 15L:9D, and 14L:10D in lower latitudes (Fujiie 1985).

Search for Overwintering Structures

When overwintering behavior is triggered, *H. halys* begin to leave feeding grounds in search of overwintering structures. This search appears to be related to visibility from feeding areas. One study of structures reported that they were more present in structures in elevated areas with open views, visible from breeding areas (Kobayashi and Kimura 1969). A trapping study on one building similarly found that more bugs appeared in traps facing downhill than traps facing uphill (Watanabe et al. 1994).

Visibility does not appear to be the only important factor. The first study of structural characteristics did not find any correlations in building materials used in the siding or roof (Kobayashi and Kimura 1969), however, the sample sizes were small and many of the buildings compared had at least one unknown material. Another study found that wood and stone residential structures had higher *H. halys* counts than other materials, as did brown or grey coloration (Hancock et al. 2015). This study also found that north-facing and east-facing sides had significantly higher counts than south-facing sides. These results conflict with the conventional wisdom that the insects are more prevalent on white, south-facing sides of structures, and another report in the literature of insects aggregating more on west-facing sides (Qin 1990). It is unknown whether the orientation of the side the bugs are found on is indicative of bugs moving from that direction, or of bugs moving to that side of the structure after locating it.

The range of searching is not known, but it may not be limited to what is immediately visibly apparent from whatever feeding grounds are occupied when bugs are triggered to begin their search. Overwintering *H. halys* have been shown to be capable of flying tens of kilometers on flight mills in the laboratory, and are capable of longer distance flights in this step than during the summer (Wiman et al. 2015). However, long flights come at the cost of depletion of fat body, so they are probably not preferable.

Assessment of Structures

Once a structure is located, *H. halys* begin to examine it for suitability. Researchers from Virginia Tech have observed bugs flying back and forth between buildings and surrounding trees and bushes, which may indicate structures being assessed and found unsuitable. There is also some indication that these flights involve a final round of waste elimination before settling, but this has not been tested yet. In the case of natural structures, *H. halys* settling in trees have been studied, and they prefer dead trees such as oak and locust that have thick bark (Lee et al. 2014).

Search for Settling Sites

If a structure is selected, *H. halys* will begin to search on and in it for settling sites. They will crawl all over the structure in search of access points. How much of the search is dependent upon sensory information as opposed to incidental location during random wandering is not known. They are, however, searching for holes large enough to fit through, or piles of objects into which they can insert themselves. Preferred characteristics, such as the size or conformation of an entrance, are not yet known.

Outside, they have been observed all over foundations, outer wall surfaces, eaves, and window and door frames (Hoebeke and Carter 2003). Inside, they have been seen moving around on roof wall surfaces, window glass, floors, and ceilings. After flying around inside, they have been seen moving to sites heated either by the sun or other sources (Kobayashi and Kimura 1969). In that account, they entered crevices, closets, paneling, clothing, mattresses, documents, and various clutter items. In trees, bugs may search for tree holes or leaf litter (Qin 1990).

On the exterior of structures, a comparison of trap colors in six traps on one building over four years found more bugs nesting in brown or white traps than black ones, suggesting that searching bugs may be more attracted to reflected ultraviolet light than infrared (Watanabe et al. 1994a). However, those authors wondered whether the results reflected the fact that the black traps were much hotter, suggesting future research.

Whether there is a tendency towards or away from geotaxis during site searching is unclear. A test of four traps on one structure over two to four years (depending on the trap) found much higher trap counts on the ground than under eaves or on roofs (Watanabe et al. 1994b). Another study involving surveying students living in two college dormitories over one winter indicated that the fourth floor had significantly more activity over the course of the winter than the first floor (Cambridge et al. 2015). Additionally, in trees, cavities above ground contained more overwintering individuals than did fallen logs or leaf litter (Lee et al. 2014).

Assessment of Settling Sites

Once potential settling sites are found, *H. halys* enter and investigate them to determine whether the conditions inside are suitable. Light, moisture, size, temperature, and presence of conspecifics have all been implicated as factors. Impacts of humidity and material qualities have not been investigated.

There is a clear preference for dry surfaces shown in the study of dead trees (Lee et al. 2014). Other in-progress studies (J. Cullum, Personal Communication) also seem to support the desire for dry conditions. Internal temperatures sought are unclear. Cool temperatures are supported by that tree study and the previously mentioned lower numbers in black traps (Watanabe et al. 1994a), but warm temperatures are suggested in anecdotes from older literature (Kobayashi and Kimura 1969). Other anecdotal evidence from researchers at Virginia Tech place overwintering *H. halys* in sunrooms and attics, which can easily reach temperatures of 30C on warm days. However, those individuals in the warm sunrooms were very active during the day, and were observed feeding on house plants, and thus, were likely post-diapause.

Negative phototaxis has been demonstrated in overwintering bugs, particularly at lower temperatures (Toyama et al. 2011). Therefore, dark or dark-colored spaces are suspected to be preferable. This goes hand in hand with tight spaces, which have not been demonstrated scientifically as preferable, but anecdotally overwintering *H. halys* are overwhelmingly thigmotactic, seeking touch on all sides.

H. halys exhibit a desire to aggregate in settling sites. Anecdotally, they have been observed clustering in corners more than alone, and in the field filling up spaces, sometimes piling into holes in numbers ten bugs deep. Bugs are less responsive to some identified aggregation pheromones at this time of year (Funayama 2008, Morrison et al. 2017), but still clearly aggregate. Studies of this aggregation behavior indicate that it is partially aided by the presence of illumination, highly dependent upon the use of antennae, and largely independent of temperature (Toyama et al. 2006).

Even if a suitable site is found, *H. halys* may exit and continue looking. A marking study found that of 100 bugs marked in one trap, only 46 marked bugs remained in the trap a week later (Watanabe et al. 1994a). Of the others, 18 were in a neighboring trap, 11 were on a nearby wall, one was in a further removed trap, and 24 were never found.

Interruption or End of Diapause

Eventually, bugs will select a location and settle in for the winter. Once this has happened, they are unlikely to exit unless their fat body is depleted (Funayama 2012). This nutritional state has previously been measured as the ratio of pronotum width to live body mass (Funayama 2008, 2012, 2015). Whether the nutritional state can be improved when bugs leave settling locations over the winter is unclear. Cannibalism has been anecdotally noted by researchers at Virginia Tech. It is not discussed in the literature, other than a note in an article describing rearing methods that suggests separating *H. halys* in different life stages to avoid cannibalism (Medal et al. 2012). Anecdotes from various sources suggest adults in houses may feed on houseplants and fruits and vegetable that have been left out. They have also been witnessed in multiple buildings drinking water in and around sinks and other available sources.

Bugs are noticed throughout the winter in houses by their intended occupants. Some anecdotes put the bugs more commonly active during afternoons on warm days. However, various light-baited traps are successful at night (Aigner and Kuhar 2014). This positive phototaxis may be related to nutritional state, as a mechanism for exit finding, as nutritional state is implicated in the spring exodus from refugia (Funayama 2015). Anecdotally, bugs that have left shelters in homes often disappear again, and are presumed to have resettled. This resettling behavior has also been successfully utilized in several experiments (Toyama et al. 2006, 2011).

It is unknown whether nutritional state is the only trigger for exiting diapause. In the lab, *H. halys* have been induced to exit diapause by subjecting them to temperatures around 26 °C and a 16:8 hour daily light/dark cycle (Medal et al. 2012). In the wild, they may exit overwintering sites anywhere between late March or mid May (Lee et al. 2013). Two papers indicate temperature may have an effect on exits. In one, adults left overwintering sites when ambient temperatures reached an average of 10 °C (Qin 1990). Another study suggested that high temperatures in March and April resulted in adults exiting overwintering sites about a month earlier one year than in previous years (Kiritani 2007).

Search for Structure Exit

When diapause has ended, bugs will search for an exit to their settling sites and structures. As previously mentioned, it is possible that this involves positive phototaxis, as evidenced by the success of light traps (Aigner and Kuhar 2014). The anecdotal presence of bugs around windows adds support to this hypothesis, but it has not been tested yet. Exit size, height, or color may also be important as bugs seek food sources.

Objectives

The characteristics of buildings influence the winter behavior and survival of *H. halys*, and people who do not wish to share their spaces with these insects need to understand both for proper management. This chapter explored pest control best practices with respect to *H. halys*, as well as relevant building characteristics. The state of knowledge about the overwintering habits was then described.

The research in this document combines these bodies of knowledge and experience to investigate *H. halys* as they move on and into structures during their fall shelter seeking period. Several potentially fruitful areas of interest were identified. The movement directions of bugs on building exteriors may influence which openings are encountered, and how. Bugs seek thermally protected winter refuges, and thermal contrast can be coincident with potential paths to the interior of a structure. Upon finding an entrance, the size and shape of openings dictates whether *H. halys* can enter a space. Once bugs are inside a wall, they need to survive the entire winter. These ideas suggest the following research objectives to help define and address *H. halys* overwintering behaviors as they seek shelter in buildings:

1) Identify movement directions of *H. halys* on building exteriors

2) Determine the influence of thermal contrast on winter shelter seeking *H. halys*

3) Identify limits on the size of openings through which *H. halys* can pass

4) Estimate the mortality rates of *H. halys* overwintering in wall assemblies

Each of these objectives is explored in its own chapter. These chapters contain more detailed reviews of pertinent concepts and literature, as well as research methodologies and discussions of results.

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2. Negative Gravitaxis in Brown Marmorated Stink Bugs (*Halyomorpha halys*) Seeking Winter Shelter

Abstract

Brown marmorated stink bugs (*Halyomorpha halys*) are significant domestic pests, known in their range for aggregating in large numbers on home exteriors in the fall, and seeking winter shelter inside as they enter diapause. This research sought to characterize gravitactic responses during this behavioral period. An observational study of bugs moving on several building exteriors during fall afternoons found that a large portion of movements had an upward component, and directly upward movement was observed more frequently than movement with horizontal components. Laboratory studies of gravitaxis in overwintering bugs showed that in controlled conditions in darkness to remove the effects of daylight and weather, bugs also exhibited negative gravitaxis. It is concluded that overwintering *H. halys* tend to exhibit negative gravitaxis during and following shelter seeking behavior.

Introduction

The brown marmorated stink bug, *Halyomorpha halys* (Stål), is a significant pest, both domestically and agriculturally (Leskey et al. 2012, Rice et al. 2014). Each fall, these bugs arrive in large numbers at house and buildings throughout their range, seeking safe places to spend the winter. Infestations in single homes can reach numbers in the tens of thousands (Inkley 2012). Once in a safe space, the bugs attempt to settle until spring.

For those people who do not wish to share their homes with *H. halys*, pest control options exist. Traps have been tested on building exteriors (Watanabe et al. 1994b). Exclusion methods provide physical barriers that keep bugs from entering the house. Pesticide applications meant to kill bugs before they can get in have been tested (Watanabe et al. 1994b) and are recommended by many structural and urban pest control companies in the U.S. Moreover, insecticide treated window screens can both exclude and kill stink bugs that walk on them (Aigner et al. 2016). Nonetheless, control methods can be expensive or difficult to install, particularly if they require exterior access to upper story features like soffits or vents. Furthermore, when pesticides are used, appropriate contact times must be achieved for insects to be killed. This means that targeted application requires some knowledge of bug behavior in order to be effective. By better understanding how and where these bugs move when they are seeking entry to structures, control methods can be applied in targeted, efficient ways, and directional traps can be properly oriented. For instance, features like vent covers with downward facing openings might be more visible to bugs moving upwards than those moving downwards.

On the outsides of houses, reports of movement patterns and responses to stimuli include observational anecdotes and a few experiments. Hoebeke and Carter (2003) described *H. halys* as being found on foundations, outer walls, eaves, and window and door frames. Watanabe et al. (1994a) compared traps of different colors, suggesting that bugs preferred nesting in brown or white traps to black ones. It was not clear whether this was a response to color, reflectivity, or the thermal characteristics of the traps.

A simple question of movement is whether the bugs tend to move up or down once they land or walk onto the side of a building. The movement response to gravitational force is called gravitaxis, though older literature typically refers to it as geotaxis (Beckingham et al. 2005). Specifically in regards to height and possible gravitaxis in overwintering *H. halys*, several relevant studies have been published. In the first study, an experiment with several traps on a single two-story structure found higher capture rates in ground traps than in those under eaves and on roofs (Watanabe et al 1994b). In contrast, the second study surveyed two college dormitories over a single winter and found that the four story buildings had significantly more *H. halys* activity inside on the fourth floor than on the first floor (Cambridge et al. 2015). Likewise, a third study of bugs overwintering in natural structures found more in tree cavities above ground than in fallen logs or leaf litter (Lee et al. 2014). It is unclear why one study found more bugs at ground level, and the other two found more up high. However, we suspect that the type and proximity of vegetation may be a factor.

Gravitaxis in other parts of the life cycle of *H. halys* has been studied. Second instar nymphs (the second of five phases of development) have been shown to exhibit strong negative gravitaxis, which is to say, they moved upwards (Acebes-Doria et al. 2016), and nymph traps opening towards the ground are more effective because they were designed to capture these upward-moving bugs. Adults during feeding season also appear to cause the most damage to fruit in the upper canopy of trees in border rows of orchards and in the least in the lower canopy in the interior of an orchard block (Joseph et al. 2014), though it is unknown whether bugs have a tendency to move upwards on an object they have flown to, or prefer to land higher up on it.

Understanding how *H. halys* interacts with buildings and arrives at the upper floors may help to improve control methods. Movement patterns and tendencies indicate information such as angle of approach, and what environmental or visual cues bugs could be exposed to as they search for entry. In service of characterizing the role of gravitaxis in the behavior of *H. halys* seeking entry to buildings for winter shelter, an observational study was conducted on several buildings in Blacksburg, VA. Controlled laboratory tests of gravitaxis were also performed to validate field observations.

Methods

In a field study, adult *H. halys* were observed as they moved on building exteriors in fall during shelter seeking season. Overwintering adult *H. halys* were also tested for gravitaxis, in a laboratory experiment based closely on one used by Acebes-Doria et al. (2016) to test gravitaxis in *H. halys* nymphs.

Observation of Movement: Sites

Potential observation sites within southwest Virginia were initially selected based on researcher experience, previous exposure, accessibility, and convenience sampling, as well as participation solicited through a neighborhood listserv. Southwest Virginia is in the range where the agricultural and nuisance status of *H. halys* is classified as severe (Leskey et al. 2012), and the Blacksburg area is the site of a significant amount of research on this insect. The houses participating in the neighborhood listserv anecdotally had high activity and abutted a community garden for which gardeners complained of *H. halys* pest pressure. The participation call asked for a reply if the home occupants had noticed many bugs and were willing to have researchers take observations. Each site was explored at least once as a possible measurement site. Because of the short duration of this shelter-seeking behavior, sites were not revisited if little or no *H. halys* activity was observed ($n < 10$).

While over twenty structures were visited, and movement measurements were taken at ten, only two sites had sufficiently high pressure, one being a single-story home in the neighborhood, and the other being a five-story academic building on the campus of Virginia Tech. Because of the disproportionate sample sizes, results presented in this chapter are only from those two sites. There were not many commonalities between these structures, either in nearby vegetation, sun exposure, material, or otherwise, although nearly all activity recorded was on the southwest facing walls of the house. Similarly, data taken on the academic building was on the southwest side, which also had the greatest activity. *H. halys* site selection preferences for side of building preferred are anecdotally inconsistent, and appear to be a result of a variety of factors, though preliminary results suggest that color and orientation matter, with a preference for northern sides and brown colors (Hancock et al. 2015). However, experimental determinations of those factors are left to future research.

Observation of Movement: Procedure

Over the course of September and October 2015, subject buildings were visited between 2pm and 5pm on non-rainy days. This is the date range and time period indicated by previous research as having the highest overwintering site searching activity (Hoebeke and Carter 2003, Lee et al. 2013, Hancock et al. 2015). At each site, a researcher visually scanned an exterior wall, starting from the top left corner, and moving back and forth until the entire wall had been examined. As adult *H. halys* moving on the wall were observed, their directions in the vertical plane were recorded as a tally on a compass rose on the data sheet (Figure 2.1). For the sake of discussion, directional bins in this chapter are also given letter signifiers A-H, clockwise starting from up-left. Researchers visually estimated in which of the eight 30 degree arcs the bugs were moving to select one of the eight tally boxes. If a bug was closer than approximately 10 cm from a geometrical discontinuity that would impede movement, such as the underside of a window sill, that bug was ignored. Only bugs on vertical planes were considered. No bug was counted twice, and scans were limited to 5 minutes to prevent accidental double counting.

↖ A	↑ B (up)	C ↗
← H		D →
↙ G	↓ F	E ↘

Figure 2.1: Vertical plane compass for movement data collection.

Gravitaxis Experiment: Test Specimens

Following the field observation study, test specimens were adult *H. halys* collected from overwintering structures in the fall and winter of 2015-2016. Bugs were kept in containers full of paper and foam insulation pieces in darkness at 10 ºC until the time of the experiment, in their overwintering state. This method has previously been used in unpublished experiments with *H. halys* at the USDA and Virginia Tech. Immediately before the experiment, sufficient bugs of each sex for all repetitions were removed from storage and placed into a mesh holding cage under the same conditions, in order to provide easy access to the researcher while reducing the potential for bug escapes. No bugs were reused.

Gravitaxis Experiment: Apparatus

The apparatus used was closely based upon that by Acebes-Doria et al. (2016) to test gravitaxis in *H. halys* nymphs. Experiments were performed in a dark room with no windows, kept at 15 °C to simulate conditions where *H. halys* might find itself after locating a site for overwintering. In that room, three wooden dowels 13 mm in diameter were vertically suspended (Figure 2.2). Each dowel was marked at a center release point and at response points 315 mm above and below the release point.

Figure 2.2: Vertically suspended dowels for gravitaxis experiments on *H. halys* adults.

Gravitaxis Experiment: Procedure

The trial room overhead light was turned off, and a dim red light was turned on so that the experimenter could see the bugs. For each trial, a bug was removed from the holding cage and placed onto a strip of paper. The paper was held perpendicular to the release point on a dowel until the bug moved onto the dowel, which typically happened within a few seconds. Paper strips were also held such that bugs were facing sideways rather than up or down when they were released onto the dowel, to ensure that directional choices were made on the dowel. Once a bug crossed a response point, the up or down response was recorded and the bug was removed. All bugs completed the test with a definitive response in less than five minutes. After each trial, the dowel was wiped down with a damp cloth and allowed to dry before reuse, to avoid the influences of odors deposited by previous subjects. A total of 30 bugs were tested, with half male and half female to check for sex effects, matching that used by Acebes-Doria (2016).

Analysis

Data were analyzed using JMP Pro 13 statistical software (SAS Institute, Inc., Cary, NC). Chi-squared tests were performed on movement data for the hypothesis of an equal distribution of 12.5% per bin. For gravitaxis experiments, chi squared tests were run for the hypothesis that the binomial proportions of each photoresponse test were significantly different from a probability of 50% by using the standard normal approximation (Ott and Longnecker 2010). This same binomial proportion test was also applied to the building movement measurements with vertical components.

Results

Gravitaxis in adult *H. halys* was tested in the laboratory, and movement patterns of bugs in situ on the vertical planes of building exteriors in the fall were observed. This section collects the results.

Observation of Movement

A total of 202 data points were gathered over 15 sessions on the two high-activity buildings. Data were pooled for analysis. Of the 202 bugs observed moving, 66% of the directions had upward components, as shown by summing the top row of the rose (Figure 2.3). Only 13% of bug movements had a downward component, shown by summing the bottom row of the rose. Assuming a random distribution of movements in the eight directions (with equal arcs), a chi-squared test with estimated 12.5% probability for each direction was performed. There was a significant difference in movements ($\chi^2 = 136.1086$, DF = 7, P < 0.0001). Comparing the vertical axis movements of the 158 records with a vertical component against a 50% expected binomial proportion in a chi-squared test confirms a negatively gravitactic response ($\chi^2 = 81.0311$, DF = 1, P < 0.0001). Further tests indicate that direct upward movement surpassed movement to the sides and upwards, which surpassed any direction with a downward component.

↖ A	**11%**	**↑ B**	**42%**	**C ↗**	**13%**
← H	**9%**	**⇧ Up ⇧**		**D →**	**12%**
↙ G	**3%**	**↓ F**	**7%**	**E ↘**	**3%**

Figure 2.3: Percentages of initial movement directions (n = 202 observations) of adult *H. halys* that flew onto sides of the two highest activity buildings during September and October 2015.

Gravitaxis Experiment

In this experiment, of the 30 bugs tested, 25 bugs (83%) moved upward, and the other 5 (17%) moved downward. A two-sided chi-squared test against an expected 50% proportion showed a significant difference ($\chi2 = 14.5552$, DF = 1, P = 0.0001). A chi-squared test showed no difference between sexes (N = 30, $\chi2 = 2.288$, DF = 1, P = 0.1304). Therefore, we conclude that *H. halys* seeking overwintering sites tend to exhibit negative gravitaxis, with no difference between sexes.

When considering the 202 records with a vertical component alone, approximately 84% of these showed upward movement, and 16% had downward movement. This tracks closely with the gravitaxis results (Table. X).

Table 2.1: Comparison of percentages of bug movements with vertical components in observational and laboratory studies.

	Observations on Structures, vertical movements only (n=158)	Gravitaxis Experiment (n=30)
% with upward component	84	83
% with downward component	16	17

Discussion

Both experimental and observational results indicate that adult *H. halys* walking on and in buildings during winter shelter seeking have a tendency towards negative gravitaxis. This appears to occur even in the absence of light. Nymphal *H. halys* also exhibit negative gravitaxis in the absence of light (Acebes-Doria et al. 2016).

The choice of walking directions may be affected by a tendency of bugs to drop rather than walk downward, as Acebes-Doria et al. (2016) suggested their nymphs did. However, that was in the context of food-seekers rather than shelter-seekers. The nature of the search for hiding spaces could discourage dropping, perhaps due to the scarcity of suitable hiding places relative to food sources for this polyphagous insect, or the time pressures of coming cold nights. This idea is supported by the field study, in which we observed very few bugs dropping off of the structures during this study, unless they had been disturbed by us on those days when counting was followed by collection. However, these ideas require future research to further explore.

Movement patterns may also be influenced by the direction in which bugs are facing when they first arrive at a building. Bugs were observed walking from the ground onto the sides of buildings, which would start them off facing upwards. Additionally, *H. halys* in flight anecdotally tend to have their abdomens hanging down below their heads, as a result of weight distribution and wing placement. When landing, this may result in the bugs initially facing upwards. Exploring patterns in initial directions faced and their influence on movement patterns is left to future research.

The tendency to move upward suggests a preferred orientation for trapping measures on the exteriors of structures. Various trap configurations for bugs walking up and down trees have been tested (Acebes-Doria et al. 2016), and for bugs walking on the exterior of buildings searching for winter harborage (Watanabe et al. 1994). If movement is primarily upwards, as our results suggest, then it follows that downward-facing trap entrances may be more effective, and that obstructions limiting upward movement towards those traps could potentially reduce their efficacy.

Alternatively, obstructions could possibly be used to guide bugs away from untreated openings or towards traps. Observations on buildings and pilot tests of path obstructions suggest that there may be a depth or shape of obstruction that bugs will move towards and along, rather than climbing over, though future research is needed to test this. Bugs allowed to crawl freely past response points on the gravitaxis experimental apparatus were seen to go to the top of the dowel, then down to the bottom, then back up again. This suggests tests of protruding structures to turn bugs facing downwards, or invite them to fly away.

Our observations on buildings were taken in the late afternoon. Anecdotal evidence has previously suggested that this is the time of highest activity. Initially, we attempted to take data at other earlier times in the day, but did not observe any bugs. It is unclear whether the warmth of the afternoons trigger this activity, or why this time of day correlates with greater activity levels. We do note that virtually all of the activity we recorded was on southwest-facing walls, and although both structures were shaded by trees, this side of a structure tends to be warmer in the afternoons in the northern hemisphere. However, this is contradicted by Hancock et al. (2015), in which citizen scientists found more activity in afternoons on the northern sides of houses than the southern sides. Future research should examine and confirm the times of day when bugs are most active on buildings, and whether there are specific time or temperature ranges during which they are most likely to actually enter shelters. Watanabe et al. (1994) showed that bugs may leave shelters again during the settling period, and speculated that the effects of time and temperature could be relevant to that behavior. Future research is needed to explore refuge enter and exit patterns and their relationship with temperature and time of day.

We noticed that at the structure and side where most observations were taken, many more bugs appeared to be walking onto the building from the ground than were flying to it. For context, this was on a side of the house where a hedgerow of evergreen trees were planted approximately 2m from the building, with branches extending to within 1m (Figure 2.4). The bottom 0.75m of the wall was built from concrete masonry, with a thin concrete veneer (Figure 2.4). While no data concerning the specific location of the individual insects on the wall were taken, the relative number of bugs appeared to be relatively high. As the insects are moving upwards once on the building, the starting point on the wall may determine the access point. Bugs alighting higher on a wall should be more likely to reach elements in the walls and eaves such as soffit vents, due to the shorter distance from landing points than from the ground. On the other hand, bugs walking up onto a building from the ground may encounter overhangs where cladding begins. In the case of this specific house, that overhang included an opening to the space beneath the cladding which many of these bugs were observed entering. This anecdotally supports the original experiment by Watanabe et al. (1994) that found more bugs in trap shelters on the ground than under eaves on their two-story building. Therefore, we suggest future research into how *H. halys* approaches and moves onto buildings, including comparisons between the proximity, height, and type of vegetation.

Figure 2.4: (Left) The opening under the cladding at the joint between it and the masonry, at the corner of a basement window. (Right) The high activity side of the house with adjacent trees.

Movement patterns may also be relevant to moisture concerns. Studies of overwintering *H. halys* in natural locations like trees found them exclusively in cool and dry locations (Lee et al. 2014). Future studies of cavity material moisture content and humidity could answer these questions.

In summary, we conclude that *H. halys* has a tendency to exhibit negative gravitaxis during overwintering shelter seeking. This potentially has significant implications for control methods, including pesticide, trapping, and exclusion. Future research is needed to determine how the bugs tend to actually arrive on buildings, including pathways and comparisons of the features of the surrounding area.

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3. Exploring thermal contrast in walls as a possible factor in the winter shelter seeking behavior of the brown marmorated stink bug (*Halyomorpha halys*)

Abstract

The brown marmorated stink bug (*Halyomorpha halys*) is known for its habit of overwintering in human structures, where it can be a nuisance pest for occupants. Every fall, these insects aggregate on the sides of structures in search of entry to overwintering sites. The windows and doors that they use to enter living spaces can show contrasting signatures in the infrared spectrum compared to the rest of building exteriors, depending upon environmental conditions. This paper discusses experiments that were designed to test whether those thermal contrasts provide navigational cues to *H. halys* while walking on walls in search of winter refugia. A pilot experiment with an outdoor open-faced wall panel with alternating heated sections was performed with various design iterations, but bugs consistently elected to quickly leave the wall face rather than select between heated and unheated sections. The apparatus was re-designed as a forced choice arena consisting of four framed cavities arranged to create a box. This forced choice experiment was conducted first with the heated walls opposite, and then repeated with the heated walls adjacent. Bugs were released in the center, and initial selection of the heated or unheated wall sections was recorded, as was movement between walls. Statistical analysis indicates no correlation between thermal contrast and wall selection, suggesting that higher thermal contrast areas on walls does not influence the shelter seeking behavior of *H. halys*.

Introduction

Brown marmorated stink bugs, *Halyomorpha halys* (Stål), are significant agricultural pests, as well as household nuisance pests (Leskey et al. 2012; Rice et al. 2014). These chill intolerant (Cira et al. 2016), temperate insects seek protected places to overwinter, which they enter as they begin diapause in the fall. These sites can be in natural features such as cliffs and dead standing trees (Lee et al. 2014), but houses, sheds, and other human-made structures are also commonly used (Hoebeke and Carter 2003; Kobayashi and Kimura 1969). The winter infestations can reach numbers of bugs in the tens of thousands in a single home (Inkley 2012).

Each fall, as days grow shorter and temperatures begin to drop below 15 °C (Watanabe et al. 1994a), *H. halys* begin to move away from their feeding grounds in search of winter shelter, leading to eventual infestation of buildings. Observers may note bugs covering the eaves, foundations, doors, windows, and crawling over most available surfaces (Hoebeke and Carter 2003). The windows and door frames of structures have repeatedly been suggested as points of entry (Cambridge et al. 2015; Kobayashi and Kimura 1969) and candidates for infestation control (Aigner et al. 2016; Watanabe et al. 1994b), although typical spatial distributions of bugs on buildings have yet to be characterized.

The thermal characteristics of *H. halys* overwintering sites are important factors for survival, and have been observed or discussed several times in the literature. Winter temperature averages have been correlated with mortality rates (Kiritani 2007), as have winter low temperatures (Cira et al. 2016). Population levels after lethally extreme cold events in 2014 confirm that many of these bugs are in fact utilizing thermally protected refugia (Cira et al. 2016). Shelters where bugs have been found were described as cool and dry (Lee et al. 2014; Leskey et al. 2012). These descriptions contradict Kobayashi and Kimura (1969), which described preferred refugia in houses as warm, indirectly heated by the sun or stoves. Watanabe et al. (1994a) compared refugia of several colors, typically finding more insects in brown and white refugia than black. They also noted that the black refugia were considerably warmer than the others, which might have been reducing numbers, but that after a temperature drop one year, those warmer black refugia contained more bugs than the white and brown ones. That suggests the possibility of refugia temperature comfort zones. None of those descriptions involved temperature measurements. A more recent unpublished study by (J. Cullum, Personal Communication) with temperature measurements found no difference in occupation between heated and unheated shelters, but had a narrow temperature range. Since these studies show the importance of thermal conditions, it follows that *H. halys* could benefit from response to thermal stimuli during shelter seeking.

Thermosensilla in insects have long been studied, and positive thermotaxis and the ability to distinguish between targets and ambient temperature has been described in heteropterans, though these were in relation to host location in hematophages. Bed bugs (*Cimex lectularius*, Cimicidae) responded in an experiment to relative differences in temperature between feeder apparatuses and ambient, but positive thermotaxis only occurred at a proximity less than 3 cm (DeVries et al. 2016). Kissing bugs (*Rhodnius prolixus*, Reduviidae), also respond to host surfaces when they are higher than ambient temperature, though that also may be at close distances (Fresquet et al. 2011).

Multicolored Asian ladybeetles (*Harmonia axyridis*, Coccinellidae) are also well known for their habits of overwintering in buildings, and thermotaxis has been implicated as a factor in their navigation to overwintering sites, as has thigmotaxis, chemotaxis, phototaxis, hygrotaxis, and geotaxis [gravitaxis] (Reviewed by Hodek et al. 2012). In layman's terms, touch, smell, light, water, and gravity may all influence where they go. Studies of *Harmonia axiridis* (Coccinellidae) suggest that small scale visual contrast is relevant in deciding what portions of a surface on which to land (Nalepa et al. 2005). That experiment involved dark strips on a white background, which provided a flat plane with clear visual contrast. It should be noted that though they were laminated and therefore somewhat reflective, the placement of those colors in direct afternoon sunlight could have led to considerable thermal contrast. This possible thermal contrast was not discussed in that paper, but it is worth noting here in this exploration of thermotaxis as a possible factor in overwintering behaviors.

While navigating building exteriors in search of refugia, the design, age, and maintenance of those buildings influence the presence and strength of possible thermotactic navigational cues. The windows and doors that *H. halys* seem to use for access to living spaces are of particular interest. In addition to the obvious visual contrasts, even modern high-performance windows typically show relatively high thermal conductivity when compared with the rest of a building exterior (Cuce and Riffat 2015). The higher thermal losses are a result of the reduced thickness of these building components along with additional thermal bridges around the various connections between the glazing, frame, and installation system. Ultimately, the overall performance changes based on the utilized glazing and frame materials, In addition to this high conductive loss, radiant heat loss also occurs through glass. While thermal effects are very much dependent upon geometry, material, and location, windows and framing are nonetheless responsible for a major portion of a building's energy loss (Bjarløv and Vladykova 2011; Cappelletti et al. 2011; Christian and Kosny 1996; Kosny et al. 2014; Theodosiou and Papadopoulos 2008). This higher heat-transfer rate means that windows and the areas right around them can be perceived as thermally contrasting from the rest of the exterior if there is a significant enough temperature difference between interior and exterior climate. Weatherstripping and seals around windows and doors can degrade for a variety of reasons, and the material discontinuities inherent in their design and construction are susceptible to separation and distortion from thermal expansion and contraction or moisture, creating spaces through which air exchange can occur. They are therefore common and easy targets for energy efficiency retrofits in existing buildings, as well as significant parts of guidelines for energy efficient new construction.

In buildings with openings that connect conditioned interior spaces with the unconditioned outside, the stack effect causes cool air to enter lower in the building, and warm air to exit from higher holes. Significant energy loss through window assemblies can also be caused by this air exchange through leaks (Younes et al. 2012). Air exfiltration in some situations can actually create significantly more thermal loss than conduction (Cuce 2017). Escaping warm air would only add to the thermal contrast around windows on the building exterior. Thus, many of the openings on buildings most likely to be accessible to *H. halys* in search of overwintering sites may also be thermally contrasting from the rest of the structure. The experiments presented here were designed to test whether positive thermal contrast influences the navigation of *H. halys* as they walk along walls in search of refugia.

Methods

We hypothesize that thermal contrast is a relevant factor for *H. hays* navigating to suitable refugia. An experiment was designed to test the response of *H. halys* adults to thermal contrast in walls during winter shelter seeking. The geometry and material of a structure can have significant effects on thermal imaging, due to the material's emissivity (reflections) and shading (Vollmer and Möllmann 2010). To prevent geometry or reflectivity related issues with monitoring of the apparatus using thermal imagers, the bug interface portions of the apparatuses were smooth, flat planes of plywood. This was considered an acceptable material, as *H. halys* are commonly found in simple rough wooden sheds, and move easily on the surface.

The pilot design involved a large wall panel section placed outdoors, meant to mimic an exterior wall. This design resulted in bugs leaving the panels. This behavior necessitated redesign of the experiment as a forced choice test. The methods used for both studies are described in the following subsections.

Test specimens

All test specimens were collected from the sides of homes in southwest Virginia at the beginning of October 2016, when bugs were seeking and moving into structures. Specimens were stored in mesh cages with leaf litter and moisture, in darkness at 10-15 °C and undisturbed until experimentation in mid-late October. They were removed five at a time for each repetition.

Wall Panel Apparatus Pilot Test

A large apparatus was used to mimic a portion of an exterior wall, close to a story in height. Because the test was outdoors and open sided, a location was needed that was somewhat protected, and which had easy access to power for the space heater. There was such a space in a loading dock area on Virginia Tech’s campus (Figure 3.2). On three sides, buildings reduced wind load and provided consistent shading. While there was some foot and vehicle traffic, there was less than many other places. The apparatus was built on a sidewalk against one of the buildings with northeastern exposure, with its back against a wall where wild BMSB had been observed.

The apparatus was built using standard cuts of 12.7 mm (0.5 in) thick plywood and 2x4s. It consisted of four framed cavities, each 610 mm wide by 2438 mm tall (2 ft x 8 ft), to mimic the general construction of a wood-framed house (Figure 3.1). Front and rear faces were covered with plywood sheathing. A box frame was built around the arena, extending 914 mm (3 ft) out from the face of the apparatus, to the edge of the sidewalk. Holes were cut into the bottom of each cavity for the insertion of space heaters. Black fiberglass screen was stapled to the frame to create a cage to hold in bugs and obscure views outside, including a screen floor 610 mm (2 ft) up from the ground. The screen was hoped to reduce the influence of pedestrians and other activities nearby. The trial face consisted of eight sheets of plywood 610 mm x 1219 mm (2 ft x 4 ft). These sheets were flush with each other, but some warm air escaped the seams. For later trials, 25.4 mm (1 in) wide strips of plywood were screwed into the face to cover these seams. As pilot testing progressed, shading ridges were added to provide motivation for bugs to move toward the top of the apparatus, so a 2x4 was attached at the top of the face. Later, 610 mm (2 ft) sheets of plywood were attached over the roof to create even more overhang shading. In a later attempt to direct movement of bugs toward the wall, cardboard refugia 610 mm (2 ft) wide were attached to the wall at the tops of each cavity. In later trials, a screen bag was attached to the center of the apparatus just above the screen floor to encourage bugs to make contact with the wall.

Figure 3.1: Pilot wall panel apparatus with seam cover strips.

Figure 3.2: Pilot wall panel apparatus surroundings.

For each trial, two of the cavities were heated with space heaters inserted into the holes at the bottom. As the air in each cavity heated, convection would cause it to circulate and heat the entire cavity. The aim of the test was to create alternating sections of wall with significant thermal contrast. An infrared temperature measuring device was used to monitor the cavities as they warmed up (Figure 3.3). Surfaces did not reach uniform temperatures due to differences in thermal mass and conductivity of the materials plus air exchange with the ambient environment. When the heated and unheated wall sections had at least a 3 °C temperature differential along the entire surface of the arena, the screen flaps were lowered down to enclose the apparatus and keep in test subjects. The apparatus was then considered ready. All trials were done between 2:00 PM and 6:00 PM, when the most stink bug activity has anecdotally been observed on the sides of houses by the researchers. Groups of 20 bugs were then released into the arena. Several release points and methods were tested to determine what would be most effective. At first, bugs were placed in the center of the screen floor of the arena. Later, they were released from a container resting on the floor and leaning up against the center of the wall. Finally, screen bags were attached to the center of the wall, and left open such that the bugs would crawl out of the bags directly onto the wall. Bug movements and locations were monitored and recorded.

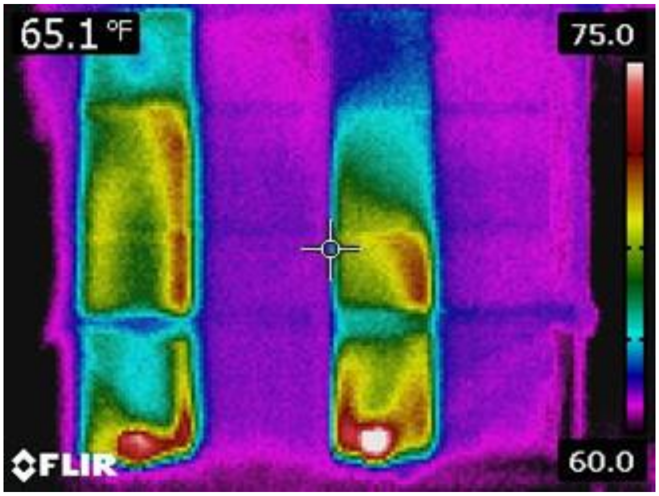

Figure 3.3: Thermal image of two heated panels as the apparatus warmed up.

The outdoor wall panel design resulted in unexpected behavior, rather than intended. Groups of 20 bugs were released into it, and each time all but two or three of the bugs had moved off of the wall face within 30 minutes. As shown in Chapter 2, bugs tend to move straight up when unobstructed, as is their general preference. When the plywood strips were installed over the seams, bugs walked up to them and then moved to the screen side walls, and frequently attempted to get between the screen and the wood, either against the wall or against the frame. This illustrated the importance of having a continuous surface when testing for gravitaxis.

Bugs also stopped moving once they reached the ceiling or highest overhang (Figure 3.4), or moved away from the wall and sought exit from the arena on the open side. The few bugs that remained on the panel mostly stayed directly adjacent to the underside of the plywood strips. No bugs entered the cardboard shelters at the top of the apparatus when they were installed. None of the trials resulted in anything resembling desired aggregating behavior, resulting in eventual discontinuance of the study and revision of the apparatus to require forced choice. Each modification to the apparatus was made when, after two or three trials, it became obvious that the bugs chose not to remain on the wall. At the conclusion of the pilot tests, there was not sufficient data for significance testing. At this point, due to difficulty in motivating bugs to move toward the wall, this apparatus and setup was abandoned and the forced choice arena was designed and built.

Figure 3.4: Bugs on the screen ceiling of the wall panel apparatus.

Forced Choice Apparatus

Using the lessons learned during the wall panel pilot test, a new apparatus was designed using four framed cavities (Figure 3.5), arranged to form a box (Figure 3.6). Each cavity was 610 mm wide by 1220 mm tall (2ft x 4ft standard panels), with side walls made of cut 2x4s and panels cut from 12.7 mm (0.5 inch) thick plywood screwed to both faces. The exterior faces had a cut out section small enough to accommodate a small space heater, thus eliminating the need for apertures within the arena, which could pave been a distraction to bugs. The panels were arranged around a 610 mm square (2 ft x 2 ft standard) piece of plywood which served as a floor and brace. Off-gassing of volatiles used in manufacturing of plywood were considered negligible due to ventilation and material age. Panel surfaces showed wood grain, with some small differences, but were unpainted due to time constraints.

The panels were attached to each other outside of the arena with two brackets at each corner. All interior corner edges were covered with tan masking tape, similar in color to the unfinished plywood, to cover the places where the walls did not fit perfectly together and minimize visual discontinuity. Each wall was topped with a cardboard refugium, which provided a small cavity to enter, and a 12.7 mm (0.5 in) overhang that shadowed each edge, to mimic the conditions found on the exterior wall of a building. The arena was located in a space kept at a constant ambient temperature of 15 °C, and centered under a daylight compact fluorescent bulb such that the refugia shadows were even and level. This ambient temperature of the space was similar to the average temperature around which bugs typically begin to seek shelter (Lee et al. 2007).

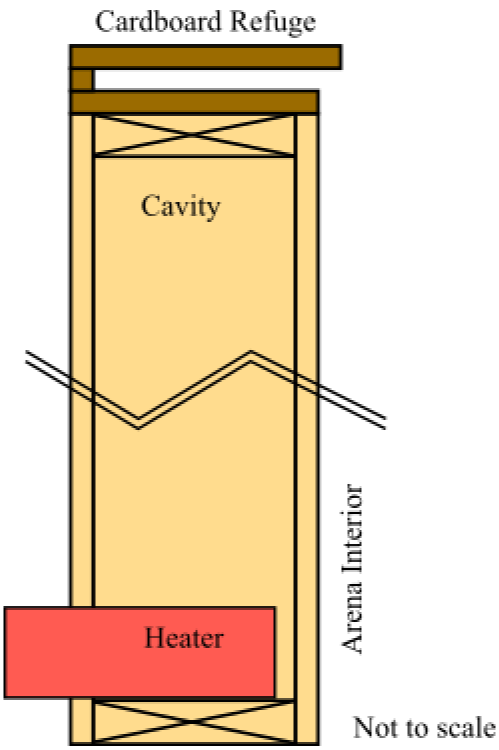

Figure 3.5: Heated cavity wall diagram


Figure 3.6: Left: Forced choice arena, and Right: entry chute.

Forced Choice Procedure

Before each trial, the apparatus was allowed to reach the ambient temperature of 15 °C. Two of the walls in each trial were heated with space heaters. The space heaters were placed into the holes in the exterior faces and switched on. An infrared measurement device was used to monitor the interior faces of the walls (Figure 3.7). When there was a minimum difference of 3 °C between the surface of the heated and unheated walls, meaning the coolest part of the unheated wall panels were at least 18 °C, the apparatus was considered ready for action. The coolest spot was always in the center, and the warmest spots were in front of the heaters and along the top edges. The heaters were left on throughout the trials. For the first set of trials, the heaters were placed in opposite walls. For the second set, the heaters were placed in adjacent walls. Between each trial, the shelters were rotated to control for subtle differences between them. After each complete rotation, the apparatus was allowed to cool, and the heaters were rotated.

The experiment required a small enough group of bugs per trial that each bug could be individually tracked by the experimenter by eye. Groups were also intended to be small enough to reduce the likelihood that bugs would visually influence each other's movements, but still large enough that all trials could be done in a reasonable time frame. After pilot testing, a group size of five was selected.

For each trial, five bugs were removed from their cages and placed into an ethylene tetrafluoroethylene (ETFE) coated cup to be transferred into the apparatus all at once (Figure 3.6). To place the bugs in the center of the arena, an ETFE coated funnel made of a plastic bottle was taped to the end of a PVC pipe. The pipe was held centered in the arena so that bugs would be deposited equidistant from all four possible wall choices, and the bugs were dropped in.

The first wall that each bug climbed up onto was recorded. After twenty minutes, each trial was concluded and final positions of each bug were recorded. A total of eight trials with 40 bugs were completed for the adjacent heater arrangement, and eight trials with 40 bugs for the opposite heater arrangement.

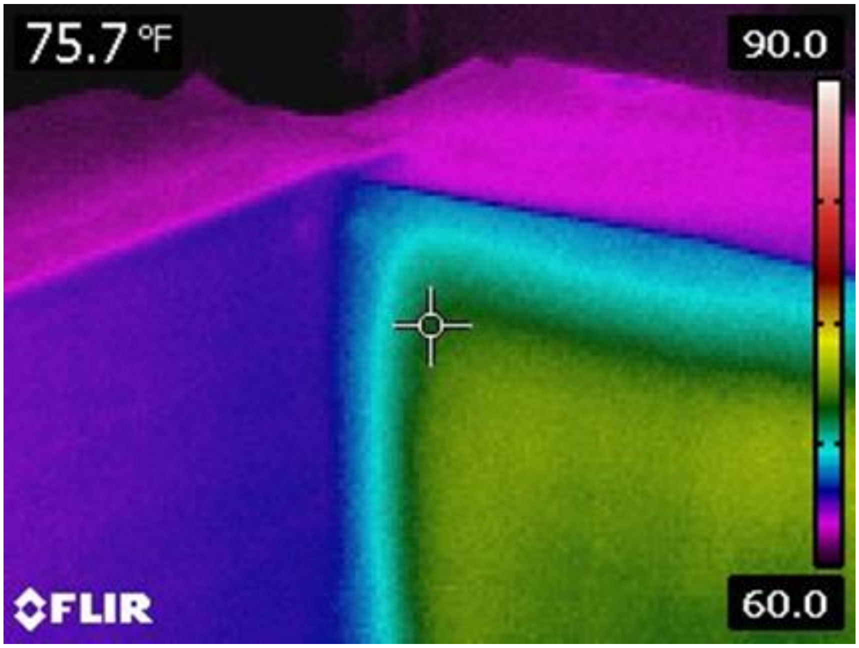

Figure 3.7: Edge between heated and unheated wall in forced choice arena.

Analysis

Statistical analysis was performed using JMP Pro 13 (SAS Institute, Inc., Cary, NC), in which we ran chi-squared tests of the hypothesis that the binomial proportions of bugs responding to heated and unheated walls were significantly different from a probability of 50% by using the standard normal approximation (Ott and Longnecker 2010). Contingency analysis was performed to test for effects of orientation, wall, and shelters. Tests were considered significant when $P < 0.05$.

Results

For the most part, bugs deposited in the center of the arena paused briefly and then moved towards a wall to climb. They moved up, pausing periodically, and some moved towards corners to climb. A small percentage became very active, horizontally circumnavigating the arena. Some climbed into the shelters and stayed there, while others climbed out and on top of them.

Only one of the 90 bugs tested in the forced choice arena never left the floor, and was therefore removed from the adjacent heated walls trial data. For both initial and final wall selection in both heater configurations, the binomial proportion was tested against an expected 50% using the standard normal approximation. No effect was found in any case (Table 3.1). Contingency analysis was performed to test the effects of shelter, wall, and orientation. In the case of the opposite wall trials, an effect on initial wall selection was suggested for shelter ($\chi^2 = 8.178$, DF = 3, P = 0.0425), and for orientation ($\chi^2 = 9.116$, DF = 3, P = 0.0278), but no effect was found on final selection. No effect was found in the adjacent heated wall trials, nor when all trials were combined.

Table 3.1: Responses to Heated Walls

	Opposite Heated Walls, Initial	Opposite Heated Walls, Final	Adjacent Heated Walls, Initial	Adjacent Heated Walls, Final	Combined, Initial	Combined, Final
n	50	50	39	39	89	89
% Heated	54.0	40.0	43.6	48.7	49.4	43.8
χ^2	0.3203	2.0136	0.6424	0.0256	0.0112	1.3630
P	0.5714	0.1559	0.4227	0.8728	0.9156	0.2430

*Responses differed ($P < 0.05$) by testing that the binomial proportion was significantly different from P = 50% using the standard normal approximation.

Discussion

The pilot design of an outdoor arena was used expecting to mimic conditions on the sides of buildings. In any building, there are a variety of competing stimuli from the surroundings. There is wind and sun, and there is movement from wind, cars, people, and other animals. In neighborhoods or wooded areas, there are other structures competing for attention. The use of a screen in this apparatus design could have dulled these competing stimuli, but also may have been a distraction in itself. Either way, there may just have been too many competing variables. The forced choice boxes offered a much more controlled system with regards to confounds such as air movement, visual distractions, and ambient temperature. However, it also created a more enclosed space, which may introduce additional confounds, as they are already in an enclosure. Future research could adapt these designs to create a tighter enclosed space to mimic the cavity behind building siding in order to learn whether thermal contrast is a cue to bugs once they are inside more tightly enclosed spaces.

While the outdoor wall experiment did not answer the intended question, it did suggest some interesting new ones. It is unclear why the bugs moved off of the wall so quickly. In observing the bugs on the sides of structures, they frequently move. They do stand still periodically, and do appear to cluster around windows and doors, which are the warm spots that suggested this research in the first place. However, it’s possible that what looks like static aggregations is actually a very mobile group of bugs. The amount of movement versus stationary time on the sides of structures may need to be studied. Bugs may actually be actively searching for hiding places or means of ingress the entire time they’re on the sides of buildings. This would be consistent with the rapid movement off of the wall apparatus and the attempts to get into cracks on the sides of the structure, as well as the bugs that stayed under the plywood strips covering the panel seams. It is also not clear why other bugs moved to and stayed on the ceiling, the outer wall, or tried to leave. Future research could explore this phenomenon, including responses to unsuitable structures or other outside environmental cues received through the screen.

As bugs often began to move sideways when hitting the overhangs, but have been observed moving over similar overhangs created by building siding materials, there may be a characteristic of the overhang that determines whether the bugs will climb over it or move alongside. This could be related to material, depth of overhang, or angle. In this apparatus, all materials were plywood, with 90 degree angles and a ½ in. overhang. Building exterior features involving larger overhangs could possibly be directing bugs to enter joints around windows or corners and get behind siding or into window frames, instead of allowing bugs to move straight up and into eaves and soffits, and entering attic spaces. Overhangs and shadows may also be important cues. The overhanging refugia in the forced choice arena were added after choice arena pilot tests where bugs were not leaving the floor of the arena. Once the overhangs were added, twenty minutes were sufficient to allow the bugs to select walls and begin moving upwards. Future research should explore the impact of overhangs and shadows on movement and shelter seeking.

The results of the contingency analysis suggested the possibility that shelter and wall had an effect on initial wall choice in opposite heated wall trials. It is unclear why this occurred, as the effect was not present in other arrangements. It is possible that small coloration differences in the unfinished wood surfaces, smoothness of cut edges of cardboard, or unnoticed slight irregularities in the shadow created this effect. It is possibly also a random effect. Future replication could clarify this.

The ambient temperatures used in this experiment were kept at 15 °C. This is warm enough that bugs will move, and fly, though below this point flight is limited (Lee and Leskey 2015) and movement slows down as temperature drops (Li et al. 2007), and activity increases with temperature. The addition of heat to the arena therefore had the potential to increase activity. Nalepa (2009) used decreasing ambient temperatures to encourage winter shelter seeking *Harmonia axiridis* to enter refugia. As H. halys were most often observed on houses in late afternoon (Chapter 2), and temperature tends to begin falling in late afternoon, there is the possibility that ambient temperature changes influence this behavior. In our study, ambient was kept constant, though some warming would be expected due to the use of the space heaters. Future research should explore the effects of changing ambient temperature on shelter seeking and settling in *H. halys*.

The temperature ranges explored in this experiment were limited to a small range with warmer than ambient surfaces. The temperature of spaces within the natural structures these bugs evolved with may be cool and constant, unless warmed by decomposition. Additionally, the humidity of cavities may differ from that outside, depending on a wide variety of factors. Whether *H. halys* will move towards sections cooled below ambient temperature, or whether thermal contrast needs to be coupled with other stimuli such as humidity or air currents is left to future research.

In the forced choice arena, there was no significant difference between heated and unheated walls either for initial or final locations of bugs. Future research could explore possible conditions under which bugs prioritize finding shelter and safety over assessing surface temperatures. However, given the lack of response in both experiments, we conclude that thermal contrast from heated sections of walls alone likely does not influence where *H. halys* move on the sides of structures while seeking overwintering shelter. This suggests that weatherizing or insulating buildings to reduce thermal contrast may not interrupt navigation to shelter.

Acknowledgements

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4. Preparing for Exclusion of Bugs from Buildings: Size Restrictions on the Passage of *Halyomorpha halys* through Holes

Abstract

Intentional and unintentional openings in a building's envelope provide opportunities for unwanted pests to enter buildings. Brown marmorated stink bugs, *Halyomorpha halys* (Stål), are one such pest, causing a significant domestic winter nuisance in many locations. One important means of pest control is exclusion, or blocking openings through which they can enter, although some openings are intentional and cannot be completely blocked without putting a building at risk. In support of safe application of exclusion methods, adult *H. halys* ready for overwintering were driven out of heated boxes through holes designed to limit passage by lateral and dorsoventral dimensions of the bugs. Protonum-limited holes 8 mm were passed by only one female, and no females and only one male passed through 7 mm wide holes. For dorsoventrally limited holes, few females passed through 4 mm high slits, and no bugs passed through 3 mm high slits. Bug heights (dorsoventral) and pronotum widths of 930 bugs collected in Virginia were measured. Females were consistently larger, with pronotums averaging 8.33 mm wide to the males' 7.47 mm, and heights at the point of leg movement restriction averaging 4.03 mm to the males' 3.50 mm. Based on experimental data and size data, we conclude that most *H. halys* individuals will be excluded by holes smaller than 3 mm by 7 mm.

Introduction

The brown marmorated stink bug *Halyomorpha halys* (Stål) is a major agricultural pest and a significant domestic nuisance pest (Leskey et al 2012, Rice et al. 2014). It has achieved its domestic nuisance status because of its habit of using human-built structures as refuges while in winter diapause. Every fall, these bugs arrive at houses and sheds. They crawl around the exteriors, searching for entry points. Once inside, they find safe places to hide and settle down for the winter. In spring, they exit, triggered at least in part by the depletion of their fat bodies (Funayama 2008). Throughout the colder months, individuals may exit their hiding places and move around houses. This can be disturbing to homeowners, particularly in the cases of large infestations, as there can be tens of thousands of bugs in a single house (Inkley 2012).

There are many methods used to try to reduce domestic pest pressure in buildings, and several have been applied to *H. halys* control. Indoors, a variety of light traps are commercially available, though a simple setup of a lamp over a pan of soapy water may be most effective (Aigner and Kuhar 2014). The application of pesticides and the use of traps on building exteriors has been shown to help (Watanabe 1994). Pesticide-treated screens applied to windows may also reduce pressure (Aigner et al. 2016). However, with the exception of treated screens, these methods are inherently distinct from the building itself, and even treated screens are aftermarket. Likewise, improperly used pesticides pose potential uncertainties in terms of health, safety, and environmental impacts, making them less desirable when other approaches can be used instead.

In many fields, designing a system to avoid a problem entirely is considered an ideal solution, since it minimizes the possibility of the problem occurring in the first place. In the occupational safety and health field, the technique of Prevention through Design (PtD) is employed during the design and construction phases of a building's lifecycle to mitigate or eliminate hazards that would be encountered by workers and occupants in later lifecycle phases (Lorent 1987). For instance, tie-off points for fall protection may be included as part of the design of a roof in recognition that future maintenance personnel will be at risk of falling while on the roof doing maintenance, or equipment requiring maintenance can be placed at ground level (e.g., Behm and Pearce 2017). In energy efficiency efforts, the idea has been expanded into building standards like Pasivhaus (Passivehouse 2018) and applied to other aspects of sustainable construction as well, such as designing to avoid unwanted ecological impacts on site or waste generated during construction (Pearce et al. 2018). In pest control even, design standards are included in some Integrated Pest Management solutions, and a design guide for pest control in green buildings has been written (Geiger and Cox 2012).

The exclusion method applies both to new construction and existing buildings, although one must be careful to understand the origin and utility of openings, since some are necessary. However, unintended or undesired openings in building envelopes often exist, serving as points of ingress for pests. These may occur as a result of mistakes made during construction, or due to moisture and temperature-related distortion of materials as buildings age. These openings are typically good targets for exclusion sealing. Those that provide pathways between conditioned and unconditioned spaces should be considered for sealing anyway, to save on heating and cooling costs. However, some envelope openings are critical to ensure the proper ventilation of layers of building enclosure systems or accomplish other functional purposes, including weep holes in masonry veneer walls, vents for exhausting or intake of air, and rainscreens that create capillary breaks between planes of exterior walls so that water cannot migrate into inner layers of the wall (e.g., Brown et al. 1991). The work presented in this chapter is meant to inform design and maintenance decisions for appropriate treatment of openings in the building envelope to exclude pests while maintaining proper building performance.

Background

Exclusion as a design method of control has been studied and presented as a part of efforts to manage other pests. Sealing or screening off entry points is an effective and important part of general pest control (Geiger and Cox 2012). Below ground, openings are treated to exclude termites, and even the smallest holes need to be treated where the smaller species of termites are present. Above ground, exclusion methods are often meant for rodents, and maximum untreated hole sizes are accordingly larger at ¼ inch, though wasps and bees are mentioned in some guidelines, described in more detail in Chapter 1. The asian ladybird beetle (*Harmonia axyridis*) is a winter nuisance pest in similar ways to *H. halys*, and the sizes of these insects relevant to exclusion have been studied. Nalepa (2009) found that *H. axyridis* was unable to traverse 2 mm openings, but mostly passed through 3 mm openings. This information has found its way into some exclusion guidelines, which recommend 1/16 inch mesh installation over openings in houses that suffer ladybird beetle infestations (Layton 2014). In some places, similar screens can be seen to stop *H. halys* ingress (Figure 4.1).

Figure 4.1: Metal screen inside an attic gable vent in Blacksburg, VA, with trapped dead *H. halys* illuminated by the flash. The vent on the other end of the building had no screen.

There are two dimensions of a bug likely to limit its passage through a hole (Figure 4.2). While several previous papers have discussed dimensions of *H. halys*, they have not discussed dorsoventral dimensions or the ability of these bugs to navigate through holes. The North American redescription of the species gave a length range of 12-17 mm and a width across humeral angles of 7-10 mm (Hoebeke and Carter 2003). Another paper gave the lengths of laboratory reared adults (n = 30 for each sex) as 14.35 mm (range 12.8-15.5 mm) for females and 11.97 mm (range 11.1-13.5 mm) for males (Medal et al. 2013). Pronotum widths have been reported in several studies of the nutritional statuses of Japanese *H. halys* populations, which also included live body weights (Funayama 2008, 2012, 2015). These studies indicated seasonal and annual fluctuations in sizes, but pronotum width means were all between 7-8 mm in males and 8-

9 mm in females, with standard error extending beyond those ranges in very few cases. No published work was found discussing the actual heights (dorsoventral dimensions) of *H. halys*. This is a difficult dimension to measure, due to body and leg morphology and the lack of rigidity of the exoskeletons in this dimension compared to lateral or anterior-posterior dimensions. The flexibility of *H. halys* in this dimension can be observed by watching a bug walk on a surface, then lightly squeezing it under a plane until the dorsal plane is forced to make light contact with the bottom surface. The legs become splayed, but observers will note that the bugs are still able to push themselves along.

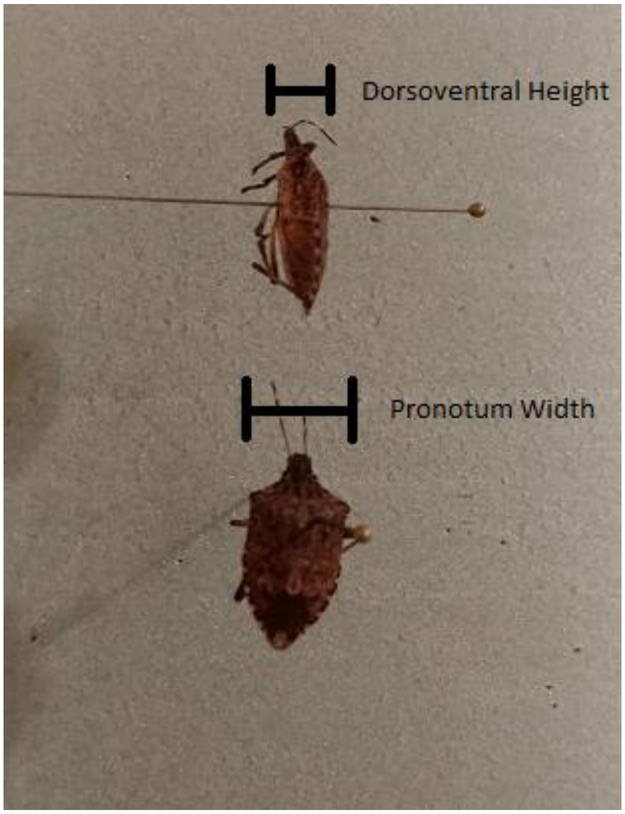

Figure 4.2: Dimensions of *H. halys* relevant for exclusion.

Some openings are necessary for proper function of a building envelope, and should not be sealed. These gaps, holes, and vents help to regulate temperature and to prevent moisture accumulation that could damage a building. These are the candidates for screen or hardware cloth installation. In building envelope systems, gaps between cladding and sheathing systems can be essential (Lstiburek 2010). Water can find its way between cladding and sheathing, and needs to be removed, lest it cause rot, warping, or corrosion. Creating a cavity can allow drainage to reduce hydrostatic pressure, and airflow to help dry. For these to be effective, there needs not only to be that cavity, but openings for the air and moisture to escape.

In some cases, the size of the opening is very important. For instance, the ratio of attic vent area to floor space is regulated by building codes to be between 1:150 and 1:600, depending on design choices and climate factors (Lstiburek 2006). Installing screens can significantly reduce the amount of actual vent area, particularly when fine meshes are used. Other vents, such as appliance exhaust and bathroom fans, can have similar problems. This means that screening and sealing efforts require calculation, or at least basic knowledge and awareness of how the envelope of the structure in question functions. It also bears noting that unintentional blockages can cause the same problems. For instance, in brick cladding systems, techniques have long been in place to prevent mortar and other residue from blocking weep holes (Conway 2016). Dryer vents need to be cleaned periodically to prevent fires. Likewise, animal nests and remains can potentially block vents and other openings, depending on their relative size and abundances.

It is useful to understand what the minimum size hole that a pest can fit through is, so that pest control measures can be designed to exclude pests without causing building failures. That way, bugs can be kept from entering through holes that are unnecessary, and can be kept from blocking necessary holes. The work presented here seeks to further characterize the dorsoventral and pronotum dimensions of *H. halys* critical to its passage through building envelopes, and tests the species' actual ability to traverse openings that limit access by these dimensions.

Methods

Adult *H. halys* were placed in boxes with small openings cut into the lids designed to restrict escape either laterally or dorsoventrally. Boxes were placed into mesh cages, and then heated to drive the bugs out. Afterwards, bug heights and pronotums were measured.

Test Subjects

Subjects were adult *H. halys* collected from trees and the sides of buildings in Blacksburg, Virginia, during September and October. Collected bugs were kept in mesh cages outdoors until use. Cages were shaded from sun and wind. Bugs were provided branches and foliage of assorted plants, and provided with apples, carrots, and water-soaked cotton. No bugs were reused.

Apparatus

Minimum opening size boxes were laser cut from 3.175 mm (1/8 in.) hardboard. Pilot testing indicated that bugs would have no difficulty walking on this material, even on the undersides of lids. Pieces were designed to interlock, and lids were meant to be easily interchangeable. Assembled boxes were 200 mm cubes with completely removable lids. Boxes were placed inside larger screen cages (Figure 4.3). Outside edges were secured with blue masking tape, then completely blacked out with black electrical tape. Cages were placed directly on top of a DeLonghi SafeHeat circulating oil space heater set to medium-4. No temperature measurement device was used, but pilot tests indicated this provided sufficient stimulus for bugs to exit the boxes. The apparatus was placed directly under an illuminated light bulb to help bugs locate the exit.

Figure 4.3: Box in mesh cage atop a space heater.

Two lid styles were used for the boxes, one designed to limit exit by dorsoventral dimensions (height), and the other by lateral pronotum dimensions (width). Laterally limited exit lids each had four laser-cut circular holes (Figure 4.4). The multiple holes were provided to reduce the impact of competition for egress and blockage by bugs that were too large to fit, but refused to give up. The circular holes ranged from 7 mm diameter to 10 mm diameter, in intervals of 1 mm (Figure 4.5). Lids with dorsoventrally limited holes each had one laser-cut rectangular hole. Rectangular holes were 150 mm in length, and had widths ranging from 3 mm to 5 mm, in intervals of 1 mm. To-scale drawings have been included for reference Figure 4.6). Boxes were empty except for test subjects, and all six inner surfaces were free of obstruction.

Figure 4.4: (a) Laterally limited circular holes, and (b) dorsoventrally limited rectangular hole.

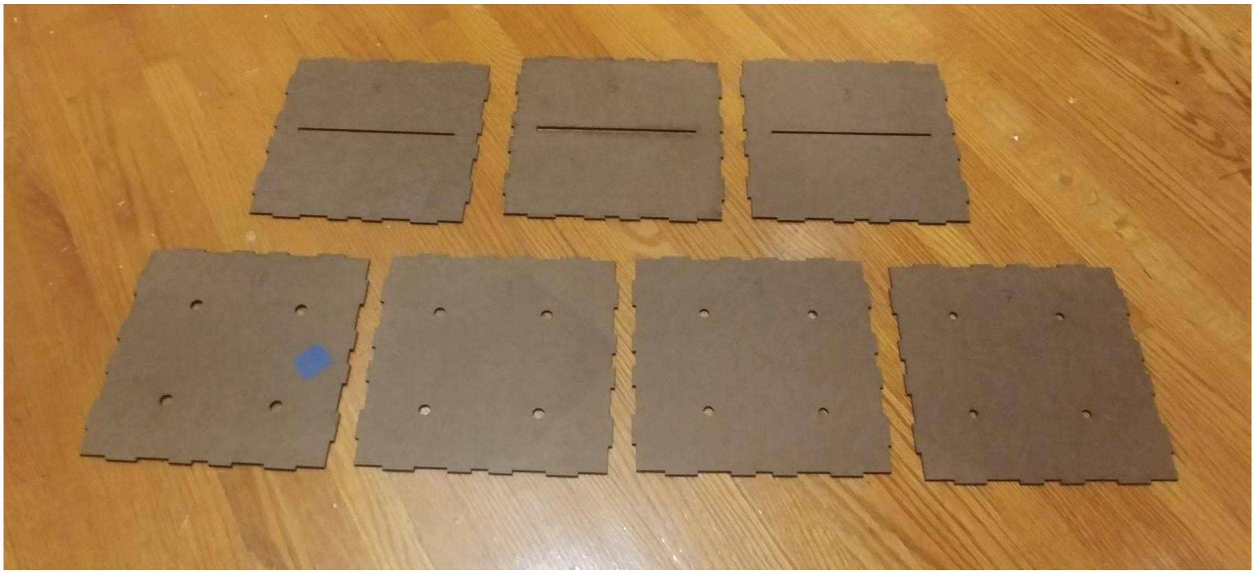

Figure 4.5: Lids. Top row: Rectangular openings, 5 mm restriction on left to 3 mm on right. Bottom row: Circular openings, 10 mm on left to 7 mm on right.

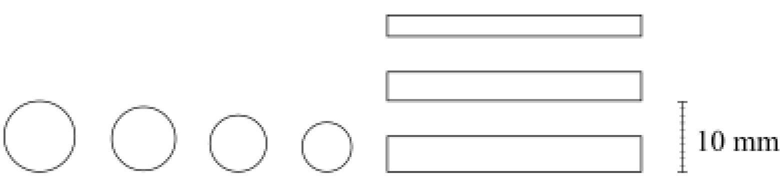

Figure 4.6: Holes and slits. Left: Pronotum limited 10 mm, 9 mm, 8 mm, 7 mm. Right: Dorsoventrally limited 5 mm, 4 mm, 3 mm (Slit widths shortened from 150 mm for demonstration).

Procedure

Before each trial, a total of 60 individuals, half male and half female, were collected from the outdoor cages and chill-stunned in a refrigerator at about 2 °C for 30 minutes. Afterwards, they were placed in the box and the lid was put on. The lid was then secured and top edges blacked out with strips of black electrical tape. The box was then put into the mesh cage and placed on top of a pre-heated space heater. A light bulb on the ceiling above the apparatus was lit to help bugs find the exits. Other environmental conditions were considered negligible due to the strong negative response of *H. halys* to the heat stimulus during pilot tests. After five hours, the boxes were moved into separate mesh cages to separate those bugs that had not exited from those that had. The experiment was performed with n = 60 bugs per treatment and a total of 420 bugs altogether.

Bug Dimension Measurement

Bugs were measured with a digital caliper (Figure 4.7). The pronotums of *H. halys* are laterally rigid enough for easy and consistent measurement, but they are slightly dorsoventrally compressible. Therefore, dorsoventral (height) dimensions were taken at the point of compression at which the legs ceased to be able to freely move, confirmed by a light finger tap on the bug's abdomen. The same measurement procedure was performed on both bugs used for pilot tests as well as bugs in the final experiment, and all measurements were included in the height and width summary statistics for a total of 930 bugs. All 930 measurements included are from bugs collected in late September and early October of 2015 in Blacksburg, VA. Bugs used in experiments were only measured after use.

Figure 4.7: Digital caliper measuring dorsoventral dimension.

Results

Bugs were encouraged to pass through size-restricted holes. Results were sorted by sex. Bugs were also measured for lateral and dorsoventral dimensions, again sorted by sex.

Restricted Passage Results

More bugs escaped through larger holes, and more males escaped, consistent with their smaller size. Pronotum width limited holes allowed the passage of steadily fewer bugs (Figure 4.8), as did dorsoventrally limited slits (Figure 4.9). While relatively high numbers of bugs escaped the boxes through 9 and 10 mm holes and 5 mm slits, 8 mm holes and 4 mm slits excluded most females. Only one male passed through the 7 mm diameter holes, and one female through the 8 mm holes. No bugs passed 3 mm slits. Means of limiting dimensions for each sex were not significantly different from the means of the remainder of the population for the 7 mm and 3 mm trials (Table 4.1). The pronotum dimensions of the males exiting the 8 mm hole were significantly different from those remaining within the box (respective means 7.31, 7.56 mm) ($F = 5.3120$, $df = 1$, $P = 0.0285$). Similarly, the dorsoventral dimensions of the females exiting the 4 mm slit were significantly different from those remaining within the box (respective means 3.78, 4.09 mm) ($F = 15.3$, $df = 1$, $P = 0.005$).

Table 4.1: Comparison statistics between groups and the rest of the test population of *H. halys.*

Opening Size	Limited	Sex	F	dF	P
7 mm	Pronotum	M	0.2309	1, 215	0.6313
7 mm	Pronotum	F	0.0598	1, 214	0.8070
3 mm	Dorsoventrally	M	0.8467	1, 215	0.3585
3 mm	Dorsoventrally	F	1.9356	1, 214	0.1656

Heights and Widths of *H. halys*

A total of 930 bugs were measured, half male and half female (Table 4.2). Females measured an average of 8.33 mm wide across the pronotum and 4.03 mm high. Males averaged 7.47 mm wide and 3.50 mm high. The smallest dimensions were a 6.00 mm wide pronotum and 2.41 mm high, both in males. Males were consistently smaller than females, both in terms of pronotum width (Figure 4.10), and dorsoventral height (Figure 4.11). Dorsoventral dimensions significantly differed between sexes ($F = 1191.648$, $df = 1, 928$, $P < 0.0001$), as did pronotum widths ($F = 1364.274$, $df = 1, 928$, $P < 0.0001$).

Figure 4.8: Percentages of *H. halys* adults escaping through each pronotum limited lid hole size.

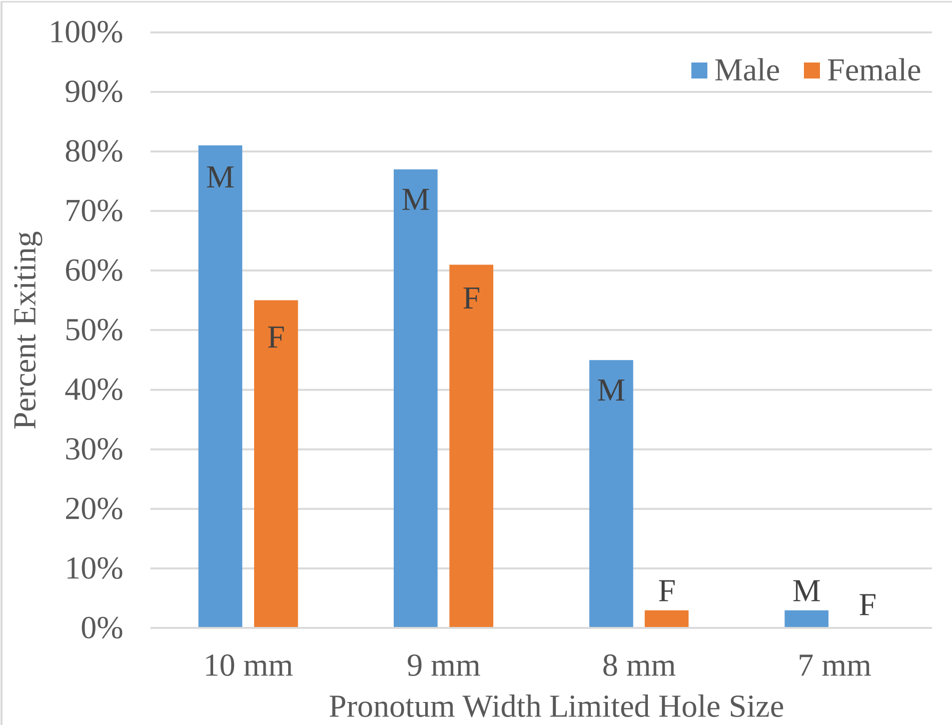

Figure 4.9: Percentages of *H. halys* adults escaping through each laterally limited lid slit size.

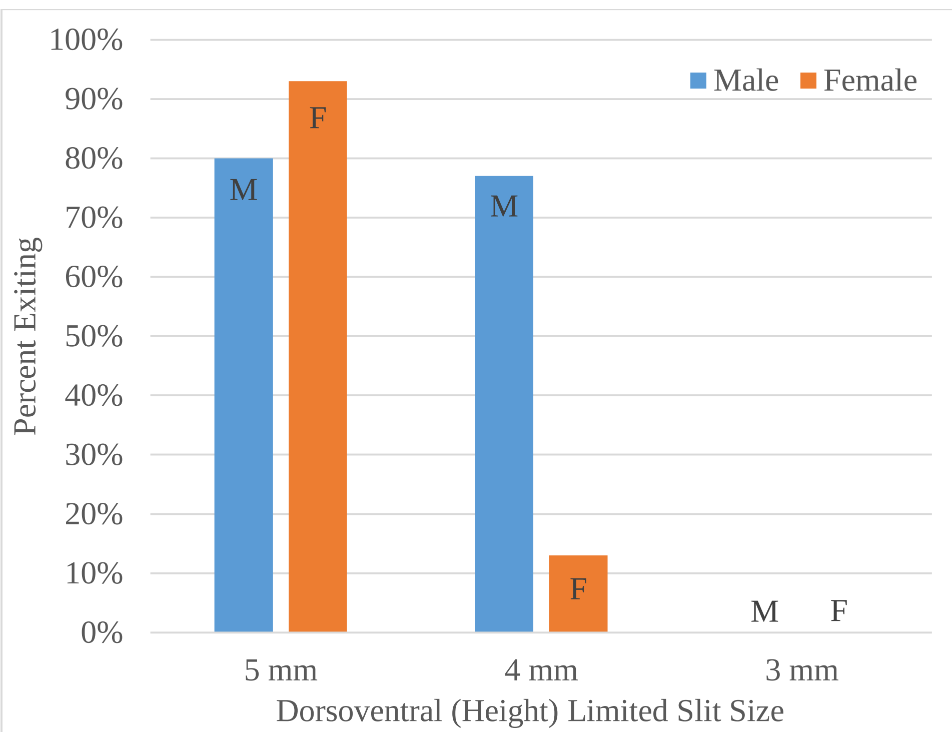

Table 4.2: Dimension summaries from adult *H. halys* measurements.

	Female	**Male**
Number Measured	465	465
Pronotum (Width)		
Average (mm)	8.33	7.47
SEM (mm)	0.02	0.02
Standard Deviation (mm)	0.40	0.36
Maximum (mm)	9.43	8.25
Minimum (mm)	7.04	6.00
Dorsoventral (Height)		
Average (mm)	4.03	3.50
SEM (mm)	0.01	0.01
Standard Deviation (mm)	0.23	0.20
Maximum (mm)	4.60	4.00
Minimum (mm)	2.99	2.41

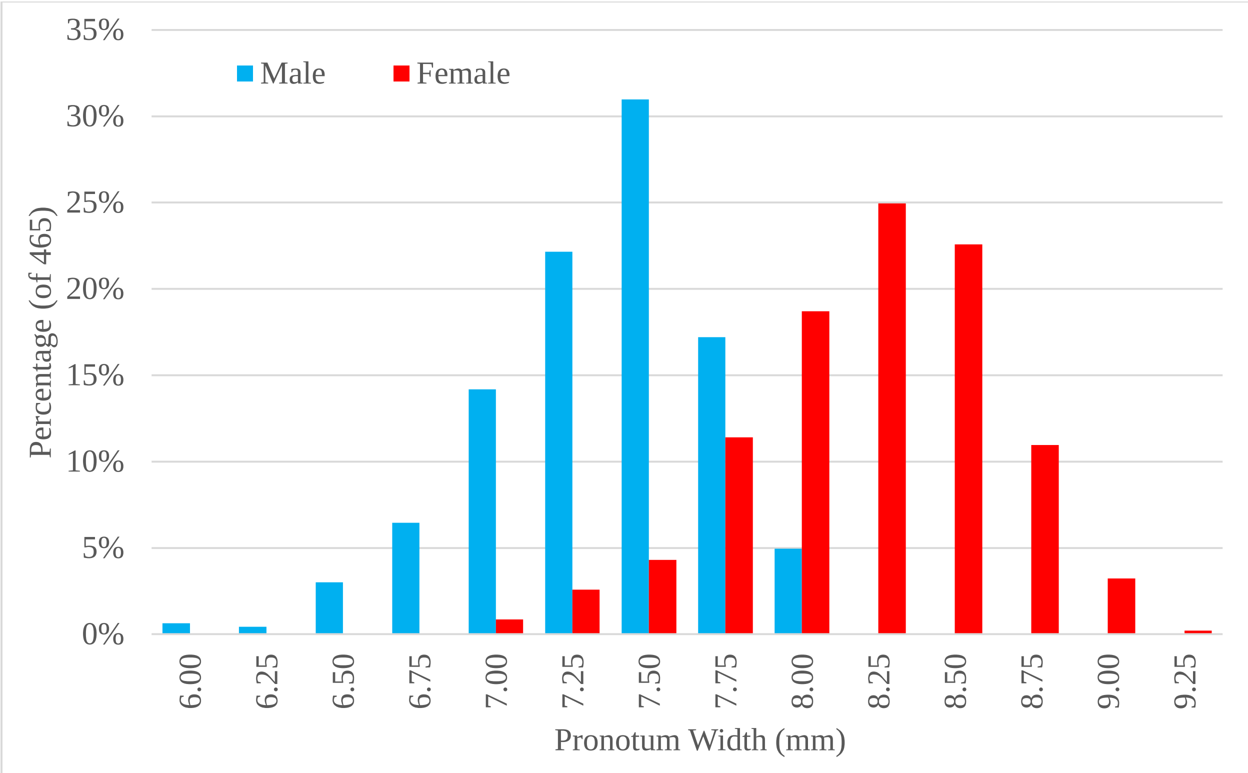

Figure 4.10: *H. halys* adult pronotum width (lateral size) distributions by sex.

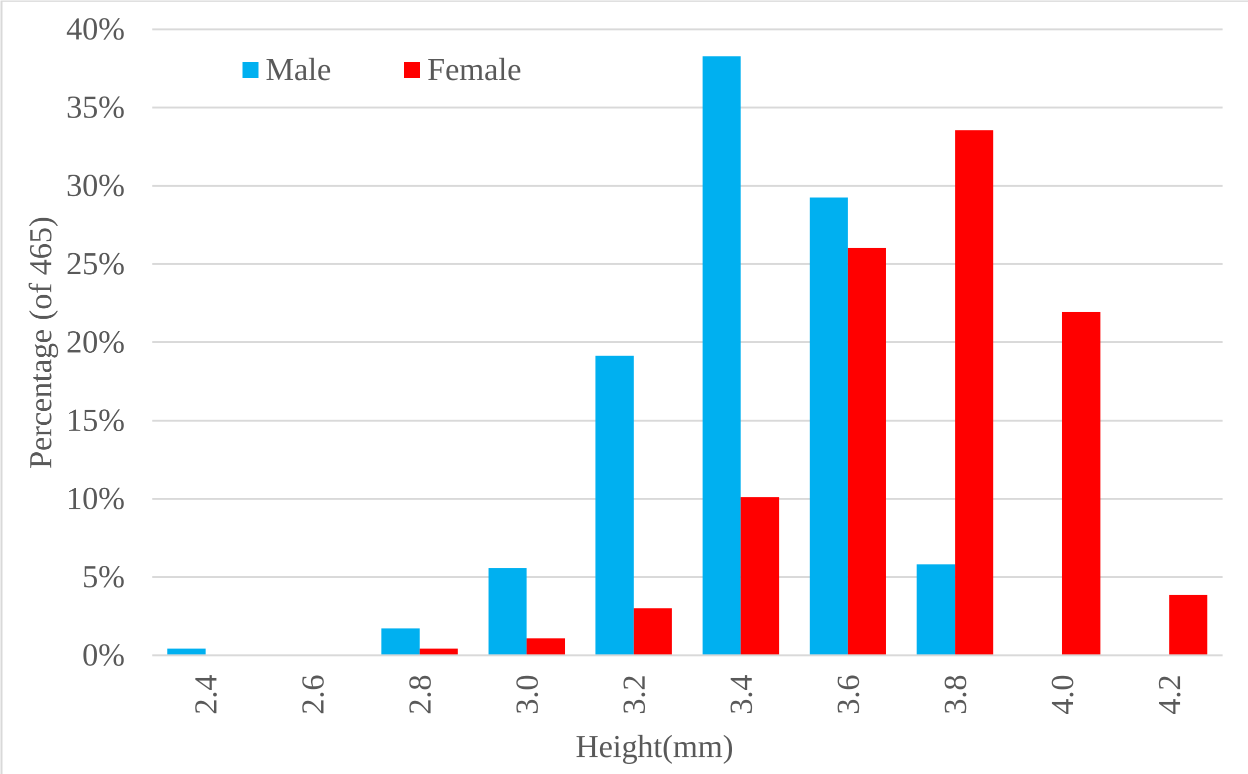

Figure 4.11: *H. halys* adult height (dorsoventral size) distributions by sex.

Discussion

The average pronotum widths and standard deviations are comparable to those measured in Japan by Funayama (2008, 2012, 2015), with averages within 0.5 mm (6%) and similar variance. Though Funayama found that size varies from year to year, the variation was small enough that for exclusion related purposes, our findings are generalizable.

Rodent exclusion typically calls for steel mesh, ¼ inch (6.35 mm) grid hardware cloth (Geiger and Cox 2012). The diagonals of this grid are approximately 9 mm, which may be sufficiently wide for most adult *H. halys* to pass through. However, the difficulty of walking on and passing through this material should be evaluated in future research. How tightly affixed the mesh has been attached at the edges is also important, as bugs have been seen attempting to crawl under it (Figure 4.1).

The fact that a portion of bugs were measured at shorter heights than the exclusion slits is not overly surprising, as heights were taken at the point at which bugs could no longer move their legs. In order to move into a hole perpendicular to a surface, and to effectively move through that hole, bugs need some room to maneuver. The softness and flexibility of materials as well as the configuration of the opening relative to the surface the bugs move along may be important, but that is left to future research. However, in spite of the results, given that roughly 10% of the total measured males were less than 7 mm wide at the pronotum, it is possible that 7 mm limited openings will not provide perfect exclusion, unless other factors are at play. Similarly, a small number of males were less than 3 mm dorsoventrally, and thus this 3 mm limiters may not provide perfect exclusion. It is possible, though, that these smaller individuals are underdeveloped, and may not be relevant to population dynamics, as fat body has implications for both winter survival (Funayama 2012) and spring dispersal (Lee and Leskey 2015).

Pilot tests indicated that bugs would try to get out through any crack with light, and stay there for the duration of the test, even if it was far too small. Blackout tape was used so that bugs would only attempt to leave through the holes they were meant to. It is unclear why bugs did not abandon these cracks in favor of the larger ones through which they could actually fit. Some bugs continued to stay in the corners after the blackout tape was installed. This suggests future research on interactions between heat and light on stress responses of *H. halys*.

For curiosity's sake, a GoPro camera was trained on the box opening for several iterations of the experiment. Bugs moved through the openings sideways or shoulder first, and typically walked forward to the edges of boxes before leaving. In one interesting moment, a bug crawled forward away from the hole, paused, and then backed up. Once it had moved its abdomen over the hole, it defecated. This was a small amount of fluid, but excretion has the potential to influence the dorsoventral compressibility of a bug, so future research may explore excretion patterns during shelter seeking.

Results show that there are differences in the ability of males and females to pass through both types of holes. This is expected, given the results showing males as smaller than females in both measured dimensions. There are some morphological differences in males and females (Medal et al. 2013), but the influence of those on the ability of bugs to physically navigate holes of different configurations and rigidity is left to future research.

These results provide dimensions to consider when treating structures for exclusion of *H. halys*. Any slit opening less than 3 mm (about 1/8 in) is unlikely to permit the passage of many bugs. Similarly, rigid holes or screen less than 7 mm (about 9/32 in) wide should not suffer much entry. If *H. axyridis* are also a concern, the suggested use of 1.6 mm (1/16 inch) mesh is more than sufficient. In building systems, some materials are softer or more flexible, and therefore could shift with temperature, moisture, or sheer brute force of the bugs, so this should be considered when designing or retrofitting for exclusion. Likewise, as mentioned in the literature review, care needs to be taken that added screens do not reduce the effective area of a necessary opening, lest moisture problems occur, particularly in buildings where vents are small and few in number.

Acknowledgements

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5. Using Thermal Simulation Modeling to Evaluate the Effects of Insulation on Cold-Related Mortality of Overwintering Brown Marmorated Stink Bugs (*Halyomorpha halys*) in Cavities Under Cladding

Abstract

Building thermal simulation modeling software is typically used to assess thermal and hygric performance of wall assemblies. However, the thermal performance of a building affects more than just energy bills. Walls may be home to insects seeking shelter through the winter, including brown marmorated stink bugs, *Halyomorpha halys* (Stål). This research used HTflux to simulate thermal profiles in walls during winters in Blacksburg VA. Results were used to estimate freeze-related mortality of *H. halys* overwintering in cavities between sheathing and cladding for a variety of wall assemblies typical of single-family residential buildings. Results indicate that these cavities reach temperatures low enough to kill *H. halys*, with increased mortality in colder times or with better insulation.

Introduction

Buildings are often meant to protect us from the elements. When they are properly designed and maintained, they keep out the heat in summer and the cold in winter. This is accomplished with wall assemblies consisting of layers of different materials. Some layers provide barriers, clean views, and structure, such as gypsum board. Insulation layers provide thermal protection by slowing the flow of heat. Outside the insulation, sheathing provides a structure to which other materials can be applied. Depending on the climate, thin vapor barriers or other membranes may be applied to reduce the risk of condensation forming within the wall. Finally, on the outside, there is some sort of cladding to improve the thermal performance, keep off the weather, and make everything look nice. Between the sheathing and cladding, there is often a cavity space. This cavity can be essential to the function of the building (Lstiburek 2010), providing airflow and drainage to keep the inside of the wall dry.

Thermal simulation modeling software is commonly used to evaluate wall assembly designs for thermal and hygric performance (De Boeck et al. 2015). This provides the ability to estimate energy requirements and conditioning costs. It also allows for prediction of moisture and condensation problems. Through good design, building owners can save money on power bills, and repair costs on moisture damaged buildings. However, thermal performance affects other things. There are a variety of animals that take up residence around and inside of homes, and accessible cavities and attics can provide shelter throughout the winter for diapausing insects.

The brown marmorated stink bug, *Halyomorpha halys* (Stål), is an invasive pest, causing significant agricultural damage, as well as nuisance problems for the public due to its habit of aggregating in human homes for winter shelter (Leskey et al. 2012; Rice et al. 2014). These bugs have been spreading successfully, and their range is expected to continue to expand in the US and internationally (Haye et al. 2015; Zhu et al. 2012).

In fall each year, *H. halys* arrive in large numbers on structures, and seek entry. Once on buildings, they crawl on outer walls, seeming to focus on door frames, windows, eaves, and foundations (Hoebeke and Carter 2003). Windows have been explored as critical points for treatment (Aigner et al. 2016; Watanabe et al. 1994). Bugs also enter eaves, and can get into attics and crawl spaces. There can be tens of thousands of bugs in a single building (Inkley 2012). Most will wait until the end of winter to leave, possibly triggered at least in part by the depletion of their fat stores (Funayama 2012), with the end of diapause triggered by photoperiod (Nielsen et al. 2017). Some wake up early because of nutritional needs or disturbances. Those in living spaces are noticed by human occupants, to varying levels of distress, as they make messes with their excreta and corpses, disturb people with their movements and smells, and possibly feed other pests. This has created a market for indoor traps, and research with citizen-scientists (Aigner and Kuhar 2014).

Some issues related the presence of *H. halys* in buildings have been reported or suggested. Aggregations of *H. halys* are also reported to have created blockages in vents and ducts (Haye et al. 2015). Crushed bug corpses were shown to be a potential significant allergen in lab tests conducted after some patients reported rhinitis and conjunctivitis when coming in contact with them (Mertz et al. 2012). Corpses of insects in walls may lead to secondary infestations of dermestid beetles, as has been suggested with ladybird beetles (*Harmonia axyridis*) (Nalepa 2009). Bugs may also be providing food for rodents, as Virginia Tech colonies have been raided by field mice.

As *H. halys* are being found overwintering in attics and crawl spaces, it is not a great leap to assume that they are aggregating in wall cavities and voids as well. The authors have repeatedly observed winter shelter seeking *H. halys* moving up under exterior cladding and into the cavities there, as well as through cracks in old window frames. These spaces may seem secure to the bugs, but they are not well insulated.

Mortality rates may be influenced by the thermal characteristics of the walls in which they settle. *H. halys* are chill intolerant, meaning they may die well before their bodies actually freeze (Cira et al. 2016), though reaching the supercooling point where their hemolymph freezes will kill any that remain. Mortality rates increase as annual winter low temperatures drop (Kiritani 2007). Thermally protected refugia such as buildings clearly play a significant role in the ability of these insects to maintain populations through extreme weather events and to expand their range into colder regions (Cira et al. 2016).

This research sought to determine the risk of freeze-related *H. halys* mortality in wall cavities, where their deaths have the potential to cause ventilation and moisture problems. Thermal simulation software was used to model a variety of single-family residential home wall assembly designs to estimate the coldest temperatures reached in the cavities between sheathing and cladding. These temperatures were then compared to a supercooling distribution curve to estimate the mortality rates of *H. halys* overwintering in these cavities.

Methods

Several wall assemblies potentially susceptible to infestation of overwintering *H. halys* were identified. Thermal simulation software was used to estimate the coldest temperatures reached in the cavities underneath cladding. These temperatures were applied to an existing supercooling model to estimate freeze-induced mortality rates.

Wall Assemblies

Building envelope configurations modeled were based on several configurations for stick-framed single-family residential buildings. These configurations were selected because they include cavities with ample space for *H. halys* between sheathing and cladding for regulation of moisture. These assemblies also require ventilation near the top and bottom of the cladding system, providing access points for overwintering *H. halys*.

A total of eight well-constructed assembly cross sections were modeled. Each model was simplified as a 30.48 cm (12 in) high cross section in the center of a wall, between studs. For convenience of discussion, each has been assigned a configuration type identifier (Table 5.1). All assemblies used stick-frame construction, with either 2x4 studs or 2x6 studs, and common material thicknesses (Table 5.2). Insulation between studs was assumed to be glass wool, assumed to be the thickness of the studs, 88.9 mm (3.5 in) for 2x4 studs and 139.7 mm (5.5 in) for 2x6 studs, with a thermal conductivity $\lambda = 0.0332$ W/m.K, based on ASHRAE 3.5 inch mineral fiber batting. For comparison, two cases using integrated insulated sheathing systems that utilized 25.4 mm (1 in) thick extruded polystyrene (XPS) in addition to the glass wool batting were also tested. Interior walls in all assemblies consisted of 12.7 mm (0.5 in) gypsum board. Sheathing in all cases was 12.7 mm (0.5 in) oriented strand board (OSB). Cladding options were 6.35 mm (0.25 in) softwood shingle, 2.54 mm (0.1 in) vinyl (PVC), and 88.9 mm (3.5 in) thick brick and mortar. Material properties were based on ASHRAE handbook materials or HTFlux standard materials.

Table 5.1: Building envelope insulation configurations modeled.

Type	**Framing**	**Cladding**	**Insulation**
A	2x4	Brick	Glass Wool
B	2x4	Softwood Shingle	Glass Wool
C	2x4	Vinyl	Glass Wool
D	2x4	Vinyl	Glass Wool, XPS
E	2x6	Brick	Glass Wool
F	2x6	Softwood Shingle	Glass Wool
G	2x6	Vinyl	Glass Wool
H	2x6	Vinyl	Glass Wool, XPS

Table 5.2: Material thicknesses

Material	**Thickness**	**Thermal Conductivity λ** (W/m.K)
Gypsum Board	12.7 mm (0.5 in)	0.1601
Glass Wool Batting 2x4	88.9 mm (3.5 in)	0.0332
Glass Wool Batting 2x6	139.7 mm (5.5 in)	0.0332
XPS	25.4 mm (1 in)	0.039
OSB	12.7 mm (0.5 in)	0.13
Softwood Shingle	6.35 mm (0.25 in)	0.1298
Vinyl (PVC)	2.54 mm (0.1 in)	0.17
Brick	88.9 mm (3.5 in)	0.40
Cement Mortar	88.9 mm (3.5 in)	1.00

Temperature Data

At the supercooling point, the hemolymph (essentially, blood) of an insect begins to freeze, killing it. The estimations in this research were based on this freeze point, and the supercooling point needs only to be reached once to kill the insect. Therefore, winter minimum temperatures were used for exterior conditions.

Temperature data from Blacksburg, VA, were selected for thermal simulation. Temperature data in this area were the basis for creation of the supercooling model used. Selecting the same area is important because Cira et al. (2016) also found a location-based acclimation effect, suggesting that regional climate conditions or weather events could affect the supercooling model. This area is also in the range of severe agricultural pressure and nuisance *H. halys* infestation (Leskey et al. 2012).

Winter data were gathered from an internet weather data service (Weather Underground 2017). This service provides a variety of statistics on winter lows. Data were gathered from each of the ten winters beginning from 2006 to 2016, and then averaged. Although longer term data exists, the use of long term weather and climate data averages in building thermal simulation has been criticized because of the effects of climate change (Kegel 2017). Additionally, this range approximately matches the known presence of *H. halys* in Virginia (Rice et al. 2014).

Low temperature data include an all-winter recorded low temperature, indicating the coldest temperature reached that year. These data were averaged over the ten-year period to give an expected annual coldest recorded temperature of -15.6 °C. Data for the days with the coldest average temperatures of each of the ten years were also averaged, to give an expected average temperature for the coldest day of the year of -11.5 °C. This provided a more conservative estimate.

Temperatures for the interior space and conditioned side of modeled walls assumed the ASHRAE standard interior wall temperature of 20 °C.

Thermal Simulation

HTflux software was used to estimate two-dimensional temperature profiles of the eight wall assemblies. HTflux was selected for several reasons. Unlike some other thermal simulation packages, HTflux allows for the use of layers, saving time in comparison between multiple similar assemblies. It also has post processing and visualization tools that permit the creation of the descriptive images provided in the results section of this chapter.

Most importantly, HTflux has strong cavity modeling capabilities, and this research was interested in the presence of *H. halys* in those cavities. Cavities are complex and difficult to model, particularly when they are slightly ventilated, as the cavities modeled must be to allow for entry of *H. halys*. Ultimately, the cavity model selected for this simulation was ISO 10077-2:2012, which considers some convective properties and stratification in these types of cavities.

After running simulations, temperatures were gathered. In these models, cavities were the only spaces within the walls large enough for *H. halys*, and it was assumed that the bugs would likely be on the warmer, internal sides. Therefore, temperatures were taken on the outside surfaces of sheathing within those cavities. This included average, maximum, and minimum surface temperatures.

Supercooling Curve

Cira et al. (2016) produced a supercooling curve (Figure 5.1) based on data from southwest Virginia, USA, showing the points at which insects begin to freeze. This allows prediction of freeze-induced mortality, and Cira et al. used it to successfully predict bug deaths in the field. That study found *H. halys* to be a chill-intolerant species, indicating that chronic exposure, desiccation, and other winter mortality causes will consistently cause higher actual mortality than the curve predicts. The curve is a Weibull cumulative distribution curve (Eq. 1), the equation for which was omitted from that publication, but which was kindly provided by the lead author (Cira, personal communication). For this distribution, most of the mortality increases fall between a relatively small temperature range. The slope is steepest (above 10%/°C), between -12 and -17 °C.

(1) $F(x, \alpha, \beta) = 1 - e^{-(-x/\beta)^{\alpha}}$, where $\alpha = 5.886122$and $\beta = 15.0527663$

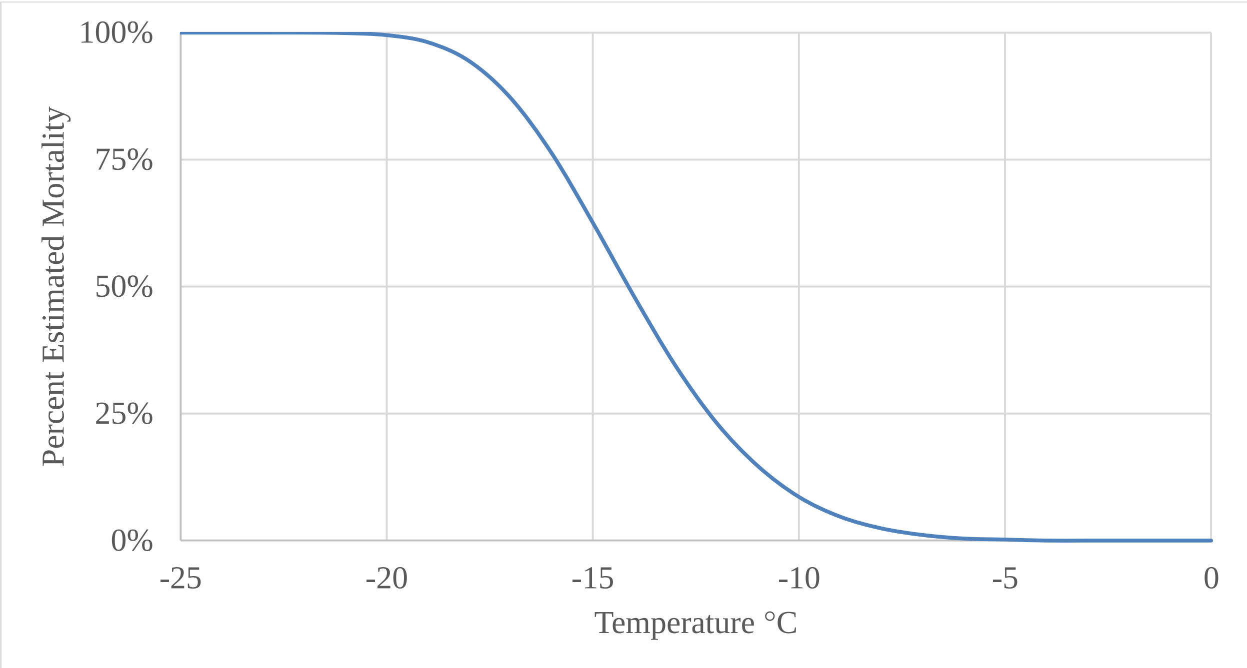

Figure 5.1: Supercooling cumulative distribution curve

Analysis

After running thermal simulation in HTflux, temperatures were taken on the outside surfaces of sheathing within the modeled cavities, where *H. halys* might be present. It was assumed that any entering bugs would be on the sheathing surface, for conservative estimation, as this is the warmest point in the cavity. Sheathing surface temperatures may vary with the geometry of cladding, particularly when vinyl is attached directly to it. It is unknown where *H. halys* might cluster within a cavity, so the minimum, maximum, and average temperatures were all collected from each simulation. These temperatures were then put into the supercooling equation to estimate mortality.

Results

Estimated mortality rates based on freezing of body fluids of *H. halys* overwintering on the surface of sheathing in the cavity under cladding was calculated. This was done by using thermal simulation software to determine sheathing surface temperatures, using the average of the daily averages of the coldest days in the winters of 2006-2016 in Blacksburg, VA (Figure 5.2), as well as with the average of the coldest recorded temperatures of those ten winters (Figure 5.3). Mortality rates were conservative estimates, as *H. halys* tend to die before freezing. Numbers for temperatures and mortality rates for each case are contained in tables in Appendix A.

In no cases were *H. halys* completely protected from freezing. Softwood shingles or bricks provide warmer cavities than does vinyl. The addition of additional XPS insulation and/or an additional ~51 mm (2 in) of insulation provided by the thicker glass wool batting between 2x6 studs creates colder cavities and increased estimated mortality. These differences are much larger when considering coldest recorded temperatures than the coldest daily averages. For instance, for the coldest daily outdoor average temperature, assembly C with 2x4 studs and vinyl siding expects an average estimated mortality of 10.8% vs the estimated mortality of 13.9% in assembly H with 2x6 studs, additional XPS, and vinyl siding. By comparison, the coldest recorded temperature model gives assembly C 52.4% estimated mortality vs 61.1% in assembly H. Colder temperatures also created larger differences between assemblies. The overall ranges of case A-H are 3.0 - 14.7% from the coldest daily averages, and 22.3 - 64.0 % for the coldest recorded temperatures.

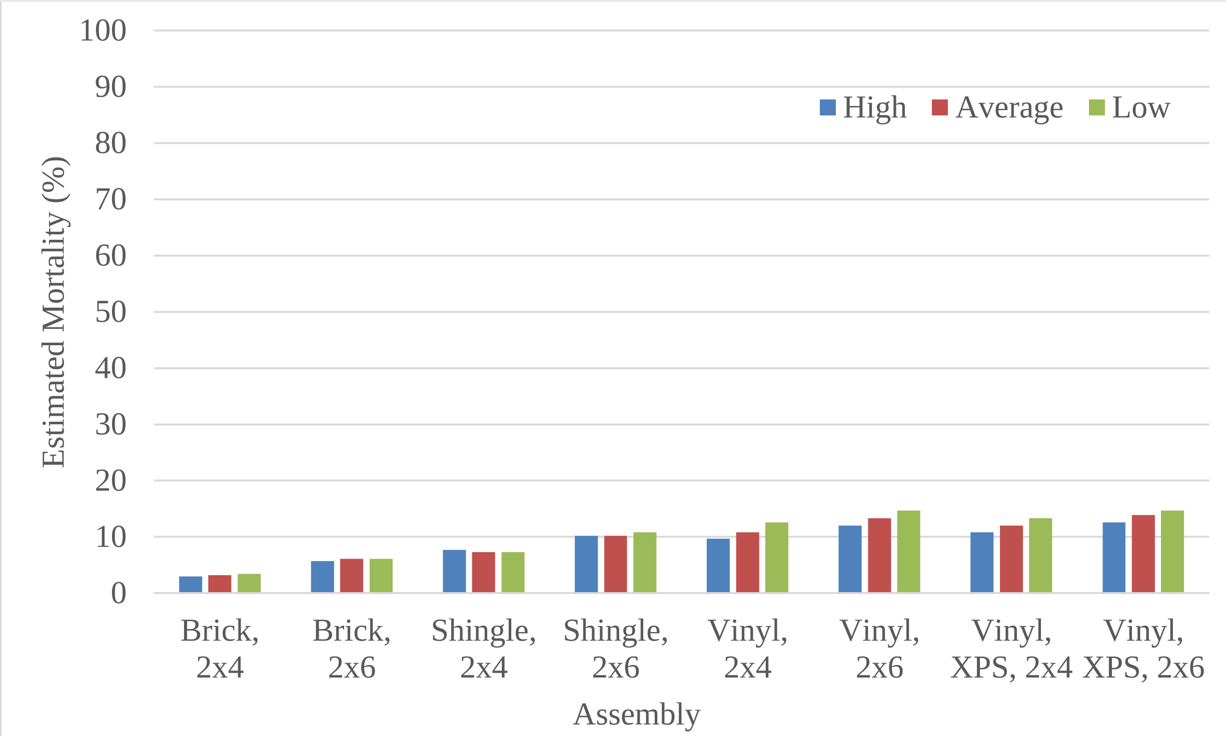

Figure 5.2: Estimated mortality results for expected coldest daily average (-11.5 °C)

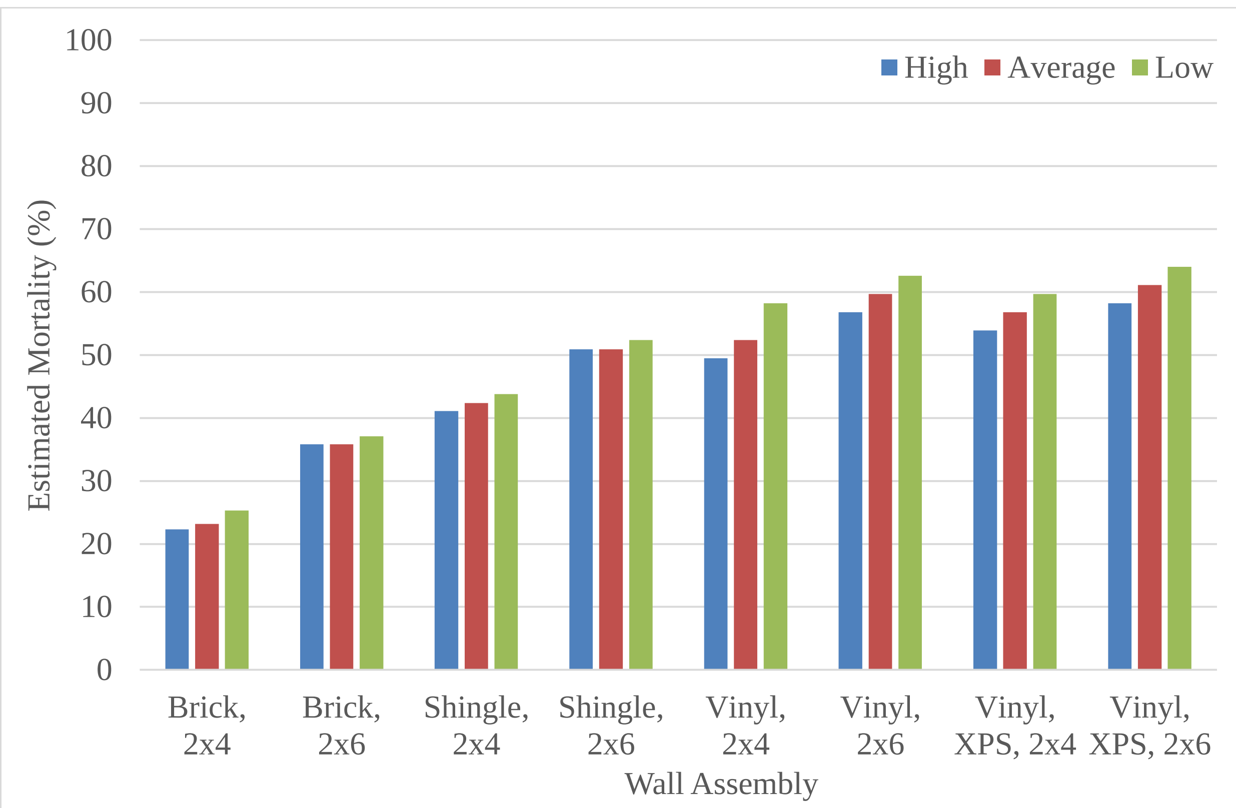

Figure 5.3: Estimated mortality results for expected annual coldest recorded temperature (-15.6 °C)

Outputs from HTflux indicated temperature profiles through each idealized wall case. In this chapter, case D, with vinyl siding, 2x4 framing, and additional XPS is included. All assembly visualizations are included in Appendix B. For each assembly, visualizations include an image of the configuration of materials in the assembly (Figure 5.5), a key for which is in Figure 5.4. Visualizations also include temperature maps of the assembly for the coldest daily average outdoor temperature -11.5 °C (Figure 5.6) and the coldest recorded outside temperature -15.6 °C (Figure 5.7). Temperature maps are scaled from red to yellow to white, with red indicating -18 °C, the point where freeze mortality rises above 95%, and white as temperatures approach -9 °C, the point at which freeze mortality of *H. halys* is expected to drop below 5%. This cutoff was selected because the slope of the mortality Weibull curve is small beyond that point, taking an additional 5 °C to approach 0%. Locations warmer than this in Figure 5.6 and Figure 5.7 are filled with hatching.

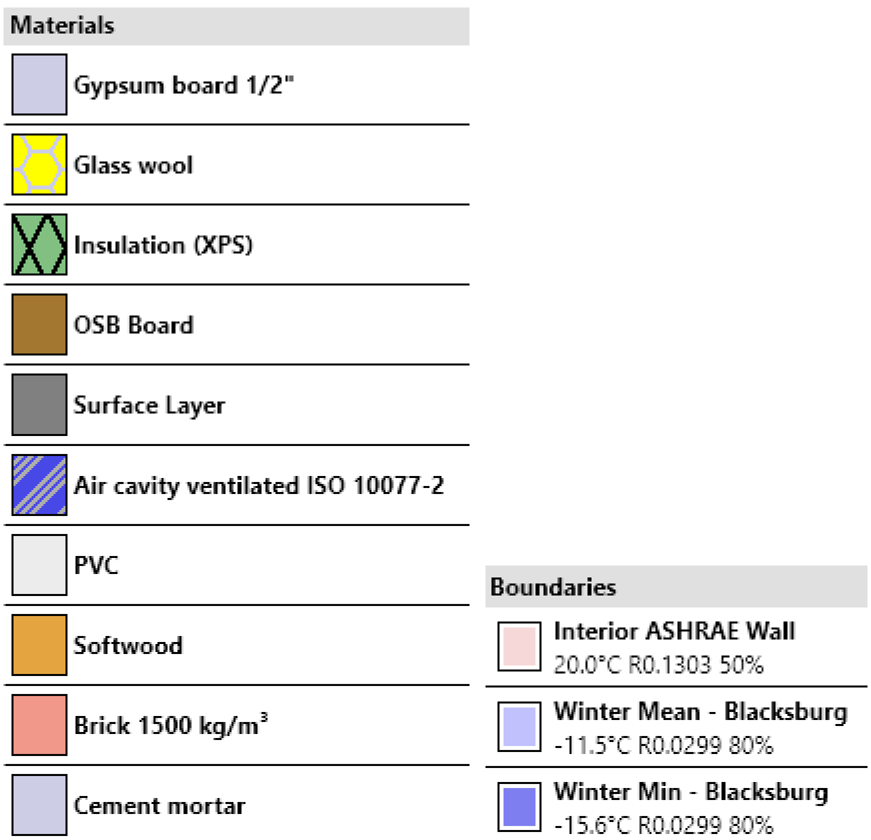

Figure 5.4: Configuration Key

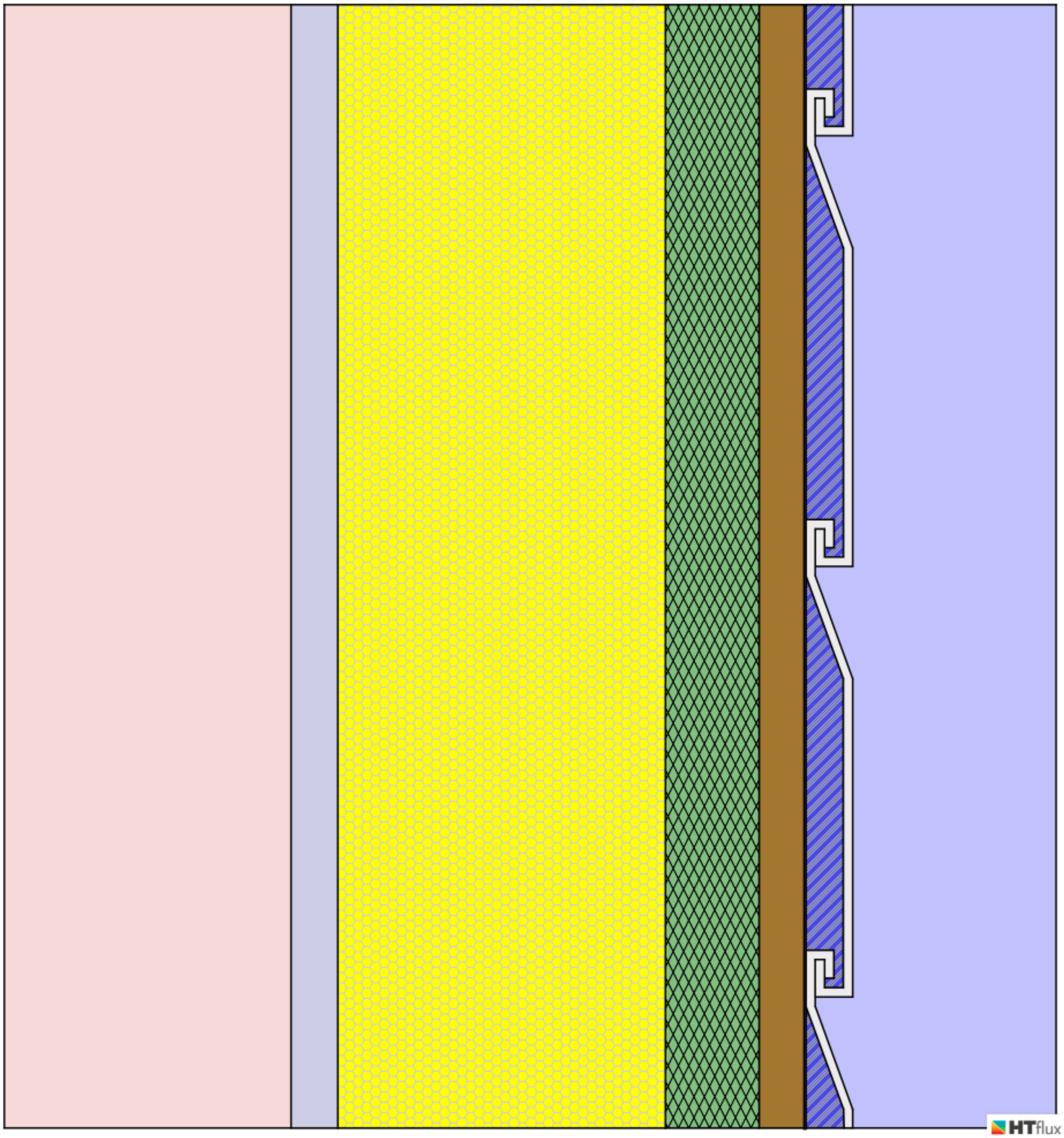

Figure 5.5: Assembly D model, with 2x6 framing, XPS, and vinyl siding.

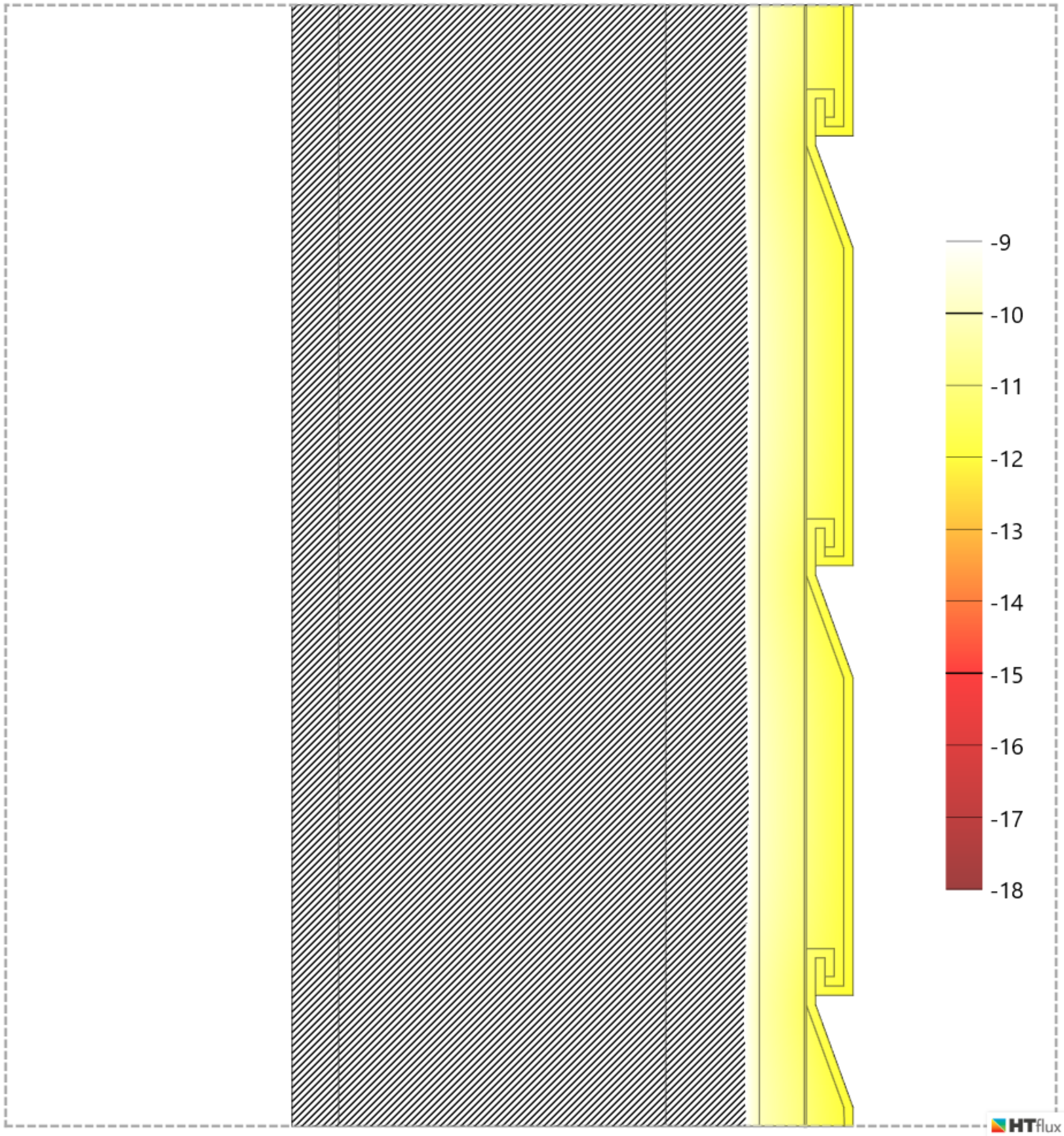

Figure 5.6: Assembly D simulation with coldest day average outside temperature of -11.5 °C.

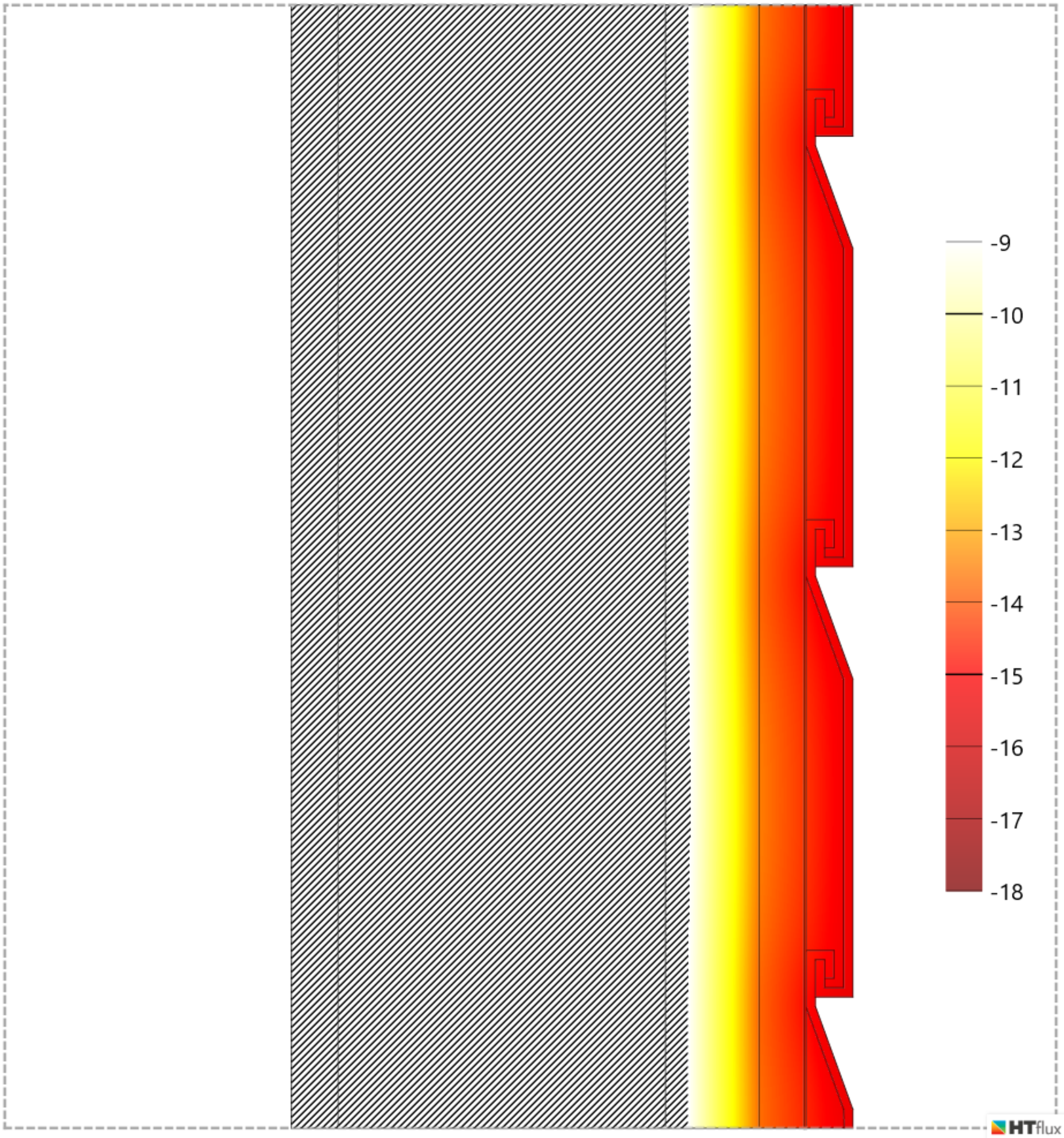

Figure 5.7: Assembly D simulation with coldest expected outside temperature of -15.6 °C

Discussion

When considering the results, it is important to remember that the supercooling-based estimated mortality curve is conservative. It shows the expected percentage of bugs whose bodily fluids will freeze at those temperatures. As Cira et al. (2016) found, *H. halys* are chill intolerant. That means that they consistently die before temperatures drop to the supercooling point. The specifics of those death mechanisms are unknown, and future research should investigate a variety of possible factors, such as the effects of humidity, desiccation, and prolonged cold exposure, and the effects these have on mortality curves. This discussion focuses on supercooling mortality only.

As Cira et al. (2016) noted, *H. halys* exhibit regional acclimation in cold tolerance, as some seasonal mean supercooling points were lower for bugs acclimated in Minnesota than in Virginia, though there was no statistical difference between winter supercooling points in these two locations. Because of this, specific predictions made using the Virginia-based curve cannot necessarily be applied to other areas. However, Weibull cumulative distribution curves have that same sigmoidal shape, so there will still be a temperature at which the portion of the population freezing begins to increase dramatically. This suggests that the basic relationships will exist, that is, there is a point at which a small decrease in cavity temperature could lead to significant increases in mortality. Future research is required to determine how the parameters of these distribution curves vary with locality, weather, climate, and climate change.

These simulations were idealized models, and did not consider the possible effects of thermal bridging. Simulations ignored studs, which are also breaks in the insulation, and furring or other structures allowing connections between sheathing and cladding, which may also act as thermal bridges. Such elements may have warmer surfaces, or affect the thermal properties of their locations within cavity. In reality, bugs have the ability to move vertically or laterally within these cavities until they encounter these edges or warmer locations, and so have the potential to be more thermally protected than these results suggest. Air infiltration and exfiltration through improperly sealed envelopes may also create warmer or colder zones.

There is a critical range in the distribution curve (Figure 5.1) where small changes in temperature can potentially have a large impact. In the range between -12 °C and -17 °C, estimated supercooling increases by at least 10% per drop of 1 °C. The expected coldest daily average of the year was warmer than this (-11.5 °C), so when analyzing the thermal simulation results for that temperature, the cavities in all of the simulated assemblies remained relatively protected, though still cold enough that as much as about 15% of bugs would be expected to freeze. However, it is not the prolonged cold of the coldest day that guarantees death, but rather the instantaneous coldest temperature, as their body fluids need only freeze once to kill them. Moving ~4 °C colder to the expected coldest recorded temperature (-15.6 °C) (Figure 5.3) changed the results dramatically. At that temperature, all assembly cases fell within the sweet spot, with estimated mortality reaching as high as 64%. The additional ~50 mm (2 in) of glass wool insulation in cases E-H over A-D lowered the temperature on the sheathing surface enough to increase estimated mortality by ~4 - 12%. Despite the outside temperature being 3° into the critical range, assembly A barely brought the sheathing surface temperature down into that range. It follows that once the outside temperature reaches the critical range, wall construction and material choice could have a significant impact on supercooling mortality rates.

Cladding choices in buildings appear to have potentially significant effects on mortality. Vinyl is typically much less thick than brick or softwood shingles, and for the material properties used in these simulations, also has a higher thermal conductivity. This led to the highest estimated mortality being in vinyl clad assemblies, and the lowest estimated mortalities in brick assemblies. As previously stated, when the outdoor temperatures begin to enter the critical range, this can make a significant difference in estimated mortality.

If bugs die in large numbers behind wood or vinyl cladding systems as the predictions suggest, there are potentially several concerns that future research may need to investigate. Secondary infestations of other pests, such as dermestid beetles, may occur. These beetles are much smaller than *H. halys*, and a population explosion could potentially make its way into the living spaces, where they might eat things the occupants do not wish to be eaten. Similarly, in the course of our other research, we have observed evidence of field mice eating live overwintering *H. halys*, and possibly dead ones as well. Large accumulations of bugs potentially provide incentive for mice to come inside the walls. Lastly, the vents for the cavities in the modeled wall assemblies are necessary for the proper function of these walls. The presence of corpse accumulations could interfere with this necessary ventilation, causing moisture or mold problems. This suggests that there is a need for future research to confirm the anecdotal evidence of *H. halys*' use of these cavities for winter shelter. This may be done with surveys of cladding professionals, insertion of cavity cameras, and physical removal of siding.

The simulations suggest that bugs that reach the spaces behind brick cladding systems are not completely protected from freezing. Brick cladding is common in some areas of severe infestation, particularly in Pennsylvania and West Virginia. This is important because brick clad assemblies may have more limited ventilation and moisture elimination systems than other cladding types. In assemblies where weep holes are used, there are only small spaces through which moisture can drain. If bugs were to enter the space behind the brick, then die, their corpses could potentially block drainage, causing moisture problems. Future research should investigate brick buildings in high infestation areas to determine if this is indeed happening.

There are many arguments for the adoption of measures to increase the thermal performance of buildings. These results offer yet another. If bugs do indeed die at higher rates in higher performance building systems as the model suggests, then they offer an additional means of control of the population and spread of *H. halys*, but also other consequent negative possibilities as described previously. Furthermore, regional building choices may affect the range expansion of these insects. In colder climes, high performance insulation systems are more desirable. Future research should compare bug populations in areas with high proportions of newer or tighter buildings versus areas with high proportions of older or leakier buildings. If a difference is found, that could also suggest future longitudinal studies of acclimatization effects on supercooling to determine whether improved thermal performance could select for increased cold tolerance, again affecting range and population size, particularly as climate pattern changes allow range expansion in other ways.

While these simulations only considered a typical interior temperature of 20 °C (68 °F), a commonly promoted method of reducing power bills is to turn the thermostat down a few degrees in winter. This is not much, but would lower the temperature inside the wall. As previously discussed, if outside temperatures are in the critical zone, this little change could kill a lot of bugs. For this reason and the previously explored effects of insulation and thermal performance, we conclude that efforts to reduce heating costs, both through improving wall thermal performance and through reducing interior temperature settings during the heating season are also likely to assist in the control of *H. halys*.

Acknowledgements

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6. Summary and Conclusions

The response of the brown marmorated stink bug (*Halyomorpha halys*) to gravity and thermal cues during winter shelter seeking were evaluated, as well as its size distribution and ability to pass through small openings. Additionally, thermal modeling software was used to estimate how building insulation choices affect freeze-related mortality of bugs taking refuge within wall assemblies between cladding and sheathing. The results could be useful for the development of control measures, and suggest some future research. This chapter summarizes the results, and describes the lessons learned.

Methodology Notes for Future Research

In the course of performing this research, a number of observations were made that may be useful for future research. These are anecdotal, and have not been scientifically tested, but were significant enough to the author and committee that they should be captured.

For stink bug behavioral research, large numbers of test subjects are typically needed. In some cases, researchers have triggered diapause in lab colonies (Niva and Takeda 2003, Toyama et al. 2006). Others recover wild bugs (Lee et al, 2014). We opted for the latter option, quite successfully. There are many good sources of bugs in fall and winter. In fall, right before the bugs moved to houses, we found them in abundance on red maples around town. Later, we collected them from the sides of houses. Once it was properly cold out, we began to collect them from barns and sheds, particularly those with a lot of clutter. Gloves and masks were necessary due to the large amount of dust and rodent droppings. Tarps were easy and safe sources of bugs. Piles of wood often contained a lot of bugs, but they are harder to sift through, and it is easy to accidentally crush bugs. We suggest that researchers with access to regularly infested sheds plant extra tarps to help collect bugs. Future research should be done to determine optimal materials and placement, as tarps were not consistently full of bugs.

This winter collection is best done in the cold. Disruption of diapausing colonies can trigger stress and alarm pheromone release. Collections taken during colder days seemed to release fewer defensive compounds and to have higher survival rates. Rotating through multiple containers during collection also seemed to help.

We stored our bugs long term most years in buckets full of pipe insulation, which worked well provided that air holes were drilled and covered with screen. Lids needed to be broken in, as new ones created a lot of noise and disruption during removal. Lid removal tools may help. Bugs tended to climb up to the top of the buckets, and shaking the insulation was necessary to remove those that did not try to run, so stunning the bugs down with cold weather helped during retrieval. Mesh cages were also used, with paper used as a substrate. They provided much easier and less disruptive to use, but had several downsides. They exchanged air much more easily than the buckets, putting the bugs at risk of desiccation death. They developed mildew and mold on dead bugs more easily in humid environments. They were also vulnerable to rodents, and the stock of one container in a shed was completely eaten.

The minimum opening size experiments were designed for and built with a laser cutter. This made the several iterations of prototyping easy and inexpensive (Figure 6.1). Hardboard was ultimately selected for these experiments, for price and ease of cutting. It is not a good material for longer term experiments, though, because humidity can warp it. Thicker materials or structural reinforcement may be necessary in some cases. Additionally, the thickness of the material is an important consideration. When interlocking parts are used, it is easier to design around units of thickness of the material. This potentially is a source of error and confusion in complex builds, so future researchers should consider unit choices carefully at the beginning of the design phase, and always double check for mistakes before cutting.

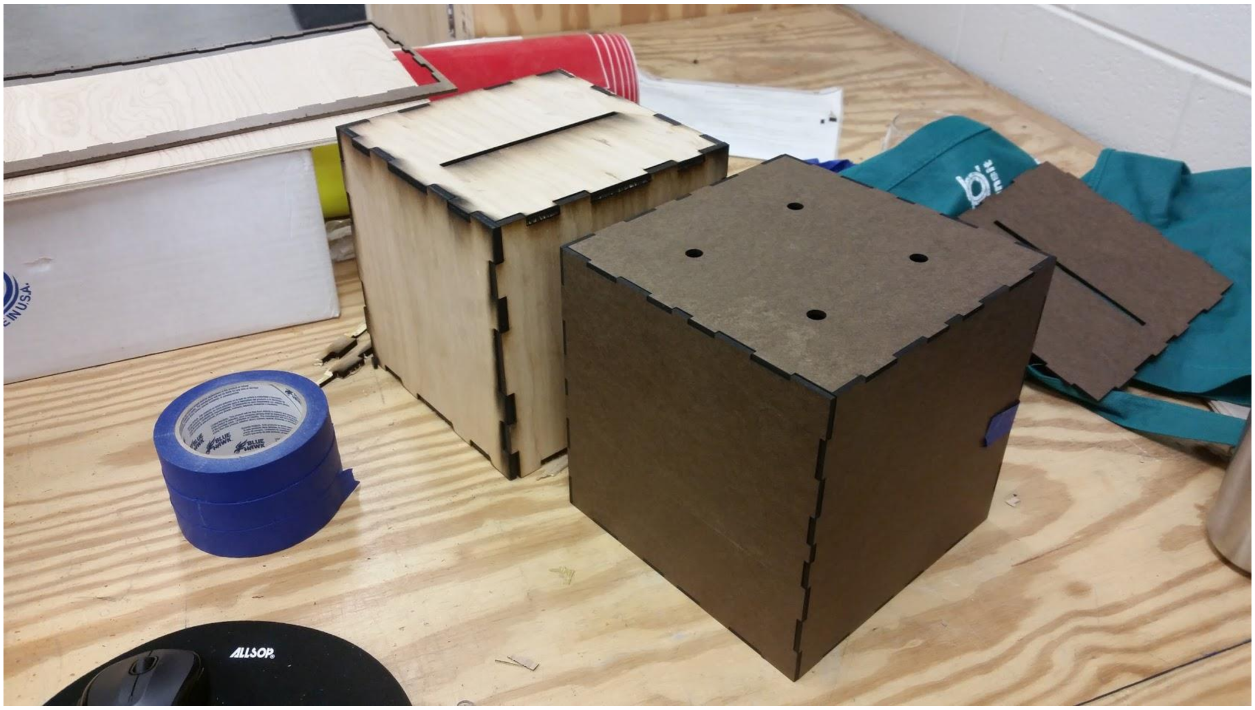

Figure 6.1: Prototyping minimum opening size boxes.

The thermal contrast experiments began outside, with a flat wall section on one side, and screen on all others and the roof. Bugs in cages, containers, and our gravitaxis studies have a tendency to move upwards. We expected this in the outdoor thermotaxis experiment, and bugs did indeed move upwards. However, we had hoped for horizontal movement and arrestment on the contrasting walls. Instead, bugs moved as far to the side as they could, settling in the folds of screen or moving upwards to the ceiling on the screen. When designing experiments that take place inside cages with several screen walls, it may be important to remember the tendency of *H.*

halys to climb up the sides and walk on the ceilings. Forcing choices and eliminating apparatus parts that allow non-participation are design choices that should be considered early on in the design process.

Contributions

In field observations, *H. halys* tends to move upward on the sides of buildings. Even horizontal movement occurs more than downward movement. Laboratory tests of gravitaxis to validate these results showed that adult *H. halys* tend to exhibit negative gravitaxis during winter shelter seeking, and suggest that this response is independent of light. Therefore, we conclude that *H. halys* will most often approach holes in buildings from below.

Experiments suggested that while *H. halys* are moving along walls in search of harborage, they do not respond to wall sections whose temperatures have been raised above ambient. This suggests that leakage of warmth through lesser insulated or poorly sealed elements of building envelopes is not an important factor in shelter seeking.

Adult *H. halys* during shelter finding time were forced to exit boxes that limited passage by height or pronotum width. These tests suggest that most adult female *H. halys* will be excluded by holes less than 4 mm high or 8 mm wide, and that nearly all bugs will be excluded by holes less than 3 mm high or 7 mm wide. A large sample of bugs from Virginia was also measured, indicating average pronotum widths and heights for that year. Females were consistently larger than males, with pronotums averaging 8.33 mm and heights at the point of leg restriction averaging 4.03 mm, compared to the males' 7.47 mm and 3.50 mm, respectively. We conclude that exclusion pest control methods can succeed if treatment reduces any openings to dimensions of a maximum of 3 mm by 7 mm.

Thermal simulation software was used to estimate supercooling-related mortality of *H. halys* in wall assemblies in Blacksburg, VA. Simulations indicate that the cavities between sheathing and cladding are not sufficiently thermally protected to ensure winter survival. Increased insulation levels increased estimated mortality, and if the temperature drops into a critical range, mortality may increase significantly. As their corpses have the potential to interrupt necessary cavity ventilation in some assembly designs, we conclude that future research about their presence in these cavities and the actual effects is needed. For people who would like to contribute to control of *H. halys*, we suggest that reducing their heating costs, through improving wall performance or reducing interior temperature settings, may have an impact.

Limitations and Future Research

While observations of the movements of adult *H. halys* seeking winter shelter were taken at a number of buildings over several days, the vast majority of data points were taken from a single side of a single building. It is possible that visual cues from structural elements influence movement patterns of walking bugs, so future experiments could isolate visual cues as a variable to test this. These observations also only considered moving bugs and took movement data once from each bug. Future research should consider longer term movement patterns of individuals, the length of movement and stationary periods, and the influence of other individuals and groups.

Exterior movements were only recorded in the afternoon. Data collection was attempted at other times, but as expected by anecdotes from homeowners and other researchers, we did not actually find bugs outside of the late afternoon. While bugs were observed entering crevices in the wall assembly during this time, it is unclear when actual building entry most often occurs, or whether there is similar activity during the night. Future research could examine the timing of exterior movement during a 24 hour period, and should investigate the times of entry and exit. Temperature should also be considered in future experiments.

The original design for an outdoor thermal contrast experiment simulated a wall, and as such was exposed to multiple external variables. Screen was installed to hold bugs in and dull other stimuli, but it could have created confounding factors itself. Given that the experiment was redesigned before sufficient data for meaningful statistics were taken, this effectively only influenced a supporting anecdote. Future research would benefit from an investigation of reasons why these bugs seem to tend to move to the tops and sides of cages in this and other experiments.

The forced choice thermal contrast experiment isolated the temperature of walls as a variable, so it should be noted that air leakage has not yet been tested. The wall temperature experiment required redesign as a box, whose wall sections at 610 mm by 1220 mm were considerably smaller than most actual walls. It is possible that panel size is a factor in behavior, as could be ground material, or means of access and exposure to buildings. Similarly, though the bugs almost all made it to shelter or out of the arena in 20 minutes, it is possible that behavior is different in longer time frames than this, or the approximately one or two hour window of afternoon activity.

Minimum opening size experiments utilized rigid materials. While some openings in a building envelope may be similarly rigid, there are other softer seals and brushes that could conceivably be pushed apart. Future research could investigate whether *H. halys* are willing or able to go through these flexible materials, in order to determine any different needs for exclusion treatments. Similarly, the conformation of a hole and the type of even rigid material surrounding it could influence the ability of *H. halys* to maneuver through. Of particular interest is the ¼ inch hardware cloth often used for rodent exclusion.

Those minimum opening experiments also used heat to drive bugs through the openings. Light sources shone through openings at the tops, and tape was used to black out the seams, but some bugs still seemed to orient towards the seams and corners, and stay there instead of moving towards the escape holes. It is not clear why movement eventually became arrested at these locations. Future research should investigate whether photoresponse and movement varies with stress stimuli.

Height measurements of bugs were taken by squeezing them with a digital caliper until they were unable to move their legs. While it is possible to get fine detail with that instrument, and all data were taken by a single person for consistency, there was some room for interpretation and human error.

In experiments and observations of bugs moving in the vertical plane, it appeared that horizontal structural characteristics influenced movement, either by possibly being attractive due to shadow creation, or by providing a physical feature that encouraged bugs to move horizontally. Future research should investigate the influence of shadows, as well as the size and configuration of obstructions at the point where movement is arrested or shifts from vertical to horizontal. These features could lead bugs to seam openings in cladding assemblies that they might not otherwise find.

Estimates of supercooling mortality in typical wall assemblies were based on mortality curves from another researcher. Those estimates were conservative, and do not consider slower deaths from starvation, desiccation, or long-term cold exposure. No observations of bug mortality in situ were taken, so future research is needed to confirm what is suggested by our study.

Thermal models of wall assemblies used were simplified and idealized, and the presence of bugs in large numbers could influence actual temperatures, so this should be considered in future experiments. Climate change and extreme weather events may further distort future mortality expectations. Our models used cold weather events from the last ten years to estimate contemporary exposure, but this may change in the future. The data we used were also only from Blacksburg, VA. The range expansion of *H. halys*, which may acclimate to an area, may include other areas with somewhat different weather and climate patterns and extremes, and construction choices also shift regionally. Therefore, the models and methods we presented in that chapter should be considered a starting point and methodology for estimating mortality in other places and justifying more involved investigation. In Blacksburg, the results suggest that taking observations of bugs inside of wall assemblies is an important next step for research.

Practical Applications

Many people are interested in hearing how to get rid of their stink bugs. This research does not answer that question, but it does move the state of knowledge closer to that goal. Movement direction studies suggest that trapping systems on building exteriors should face downward, and should be at points of movement obstruction, such as under eaves or where foundation blocks transition to cladding. Thermal contrast experiments did not reject the null hypothesis that thermal contrast has no effect on bug behavior, but suggest future research that could improve exclusion and control methods. Minimum opening size results will inform exclusion efforts, by showing what size holes are worth the effort and expense of treating, or designing to avoid. Mortality models provide yet another case for using more effective insulation and building envelopes. They also suggest the need to investigate the possibility of bug corpse accumulations, and any possible problems that could be caused by their presence.

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Toyama, M., Ihara, F., and Yaginuma, K. (2006). "Formation of aggregations in adults of the brown marmorated stink bug, *Halyomorpha halys* (Stål) (Heteroptera: Pentatomidae)." *Applied Entomology and Zoology*, 41(2), 309–315.

Appendix A: Thermal Simulation and Mortality Estimation Tables

Table 0.1: Simulation Results for Expected Coldest Daily Average

Type	**Description**	**High Temperature on Sheathing**		**Average Temperature on Sheathing**		**Low Temperature on Sheathing**	
		°C	**% Mortality**	**°C**	**% Mortality**	**°C**	**% Mortality**
A	2x4, Brick	-8.3	3.0	-8.4	3.2	-8.5	3.4
B	2x4, Shingle	-9.8	7.7	-9.7	7.3	-9.7	7.3
C	2x4, Vinyl	-10.2	9.7	-10.4	10.8	-10.7	12.6
D	2x4, XPS, Vinyl	-10.4	10.8	-10.6	12.0	-10.8	13.3
E	2x6, Brick	-9.3	5.7	-9.4	6.1	-9.4	6.1
F	2x6, Shingle	-10.3	10.2	-10.3	10.2	-10.4	10.8
G	2x6, Vinyl	-10.6	12.0	-10.8	13.3	-11.0	14.7
H	2x6, XPS, Vinyl	-10.7	12.6	-10.9	13.9	-11.0	14.7

Table 0.2: Simulation Results for Expected Coldest Recorded Temperature

Type	**Description**	**High Temperature on Sheathing**		**Average Temperature on Sheathing**		**Low Temperature on Sheathing**	
		°C	**% Mortality**	**°C**	**% Mortality**	**°C**	**% Mortality**
A	2x4, Brick	-11.9	22.3	-12.0	23.2	-12.2	25.3
B	2x4, Shingle	-13.5	41.1	-13.6	42.4	-13.7	43.8
C	2x4, Vinyl	-14.1	49.5	-14.3	52.4	-14.7	58.2
D	2x4, XPS, Vinyl	-14.4	53.9	-14.6	56.8	-14.8	59.7
E	2x6, Brick	-13.1	35.8	-13.1	35.8	-13.2	37.1
F	2x6, Shingle	-14.2	50.9	-14.2	50.9	-14.3	52.4
G	2x6, Vinyl	-14.6	56.8	-14.8	59.7	-15.0	62.6
H	2x6, XPS, Vinyl	-14.7	58.2	-14.9	61.1	-15.1	64.0

Appendix B: Thermal Simulation Results

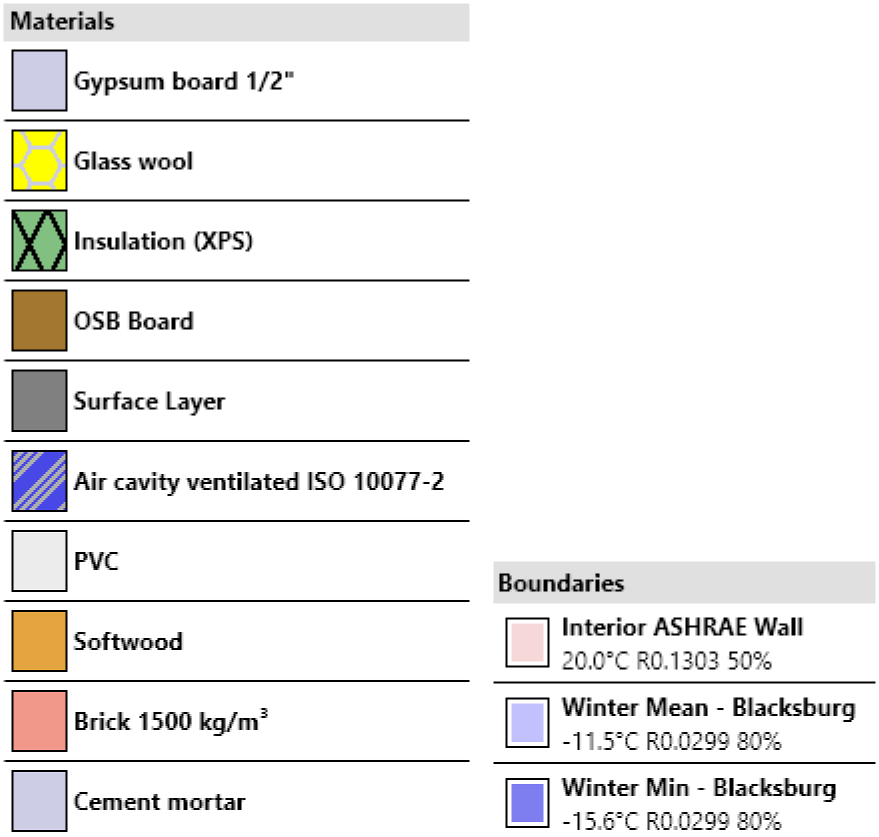

Figure 0.1: Configuration Key

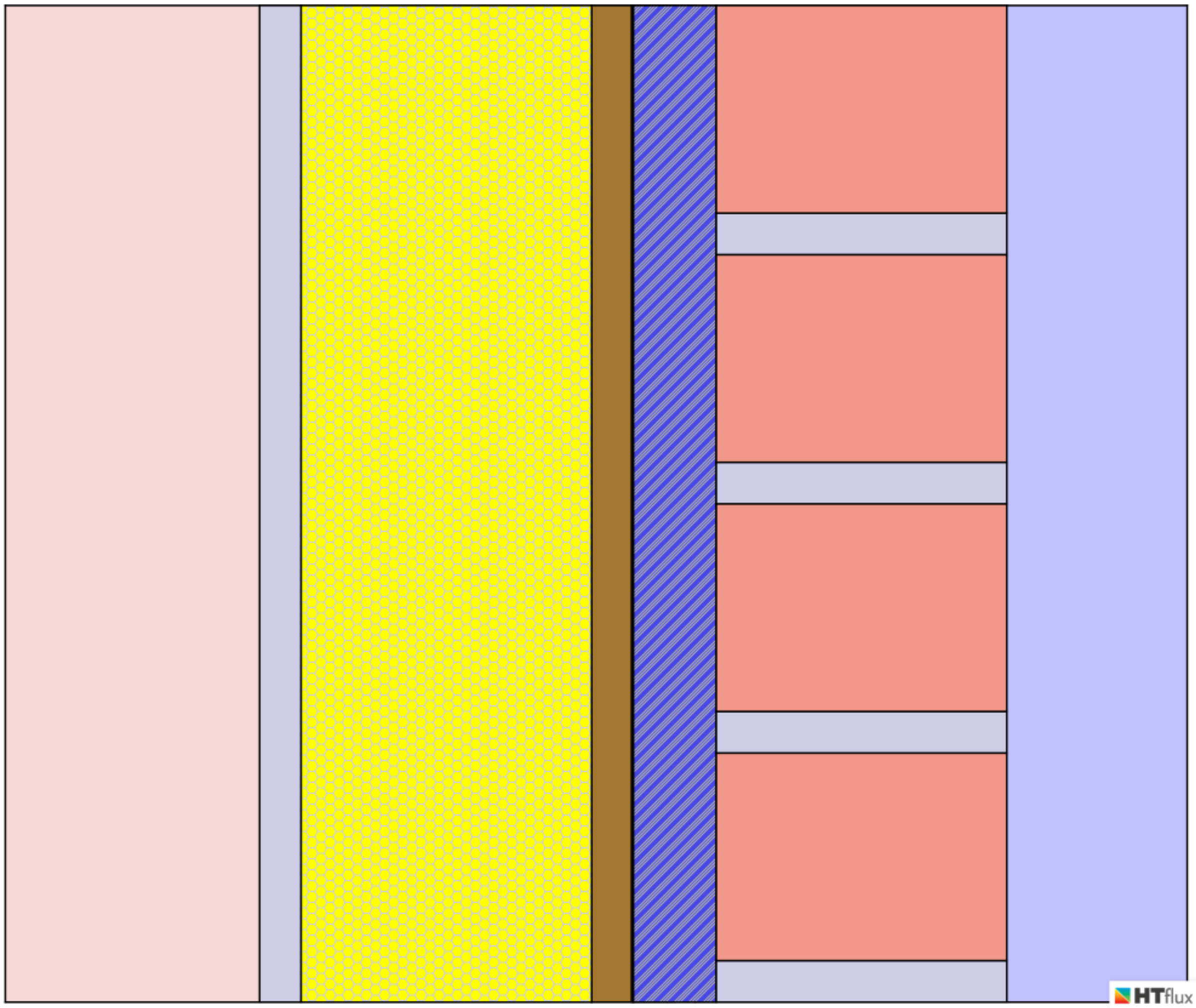

Figure 0.2: Assembly A model, with 2x4 framing and brick cladding

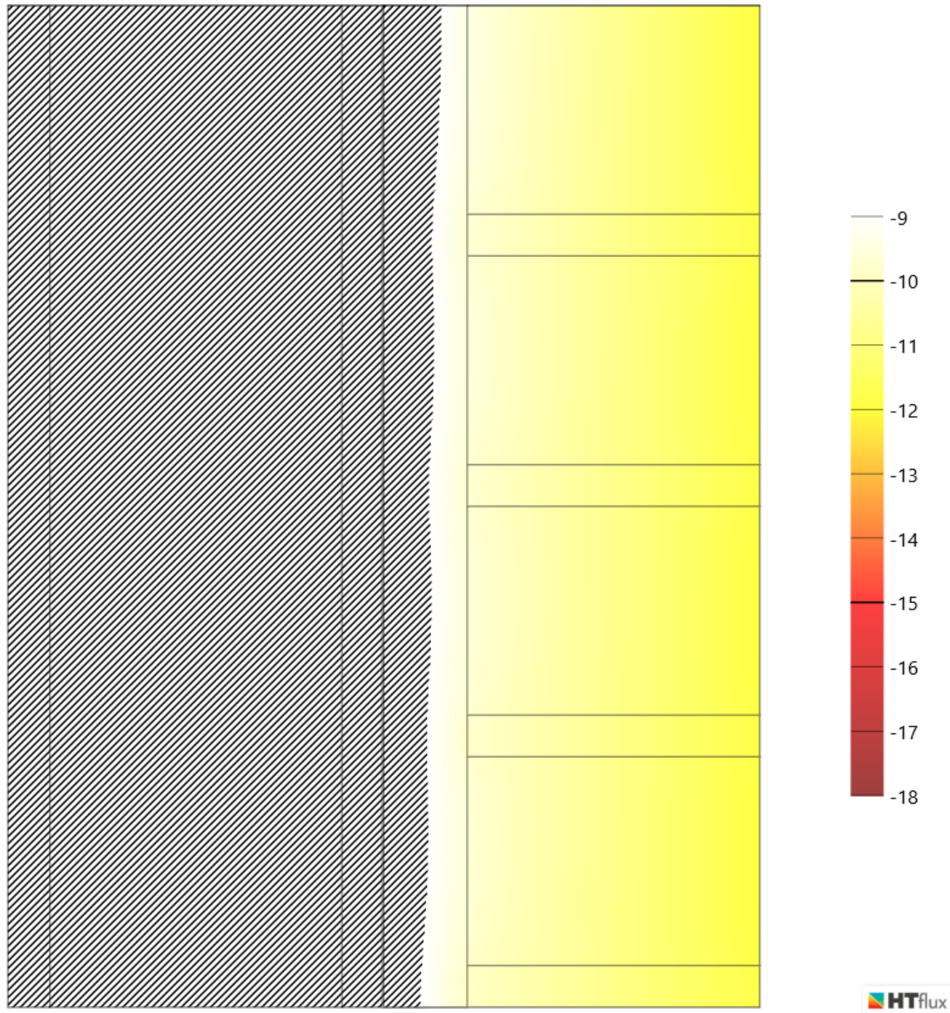

Figure 0.3: Assembly A simulation with coldest day average outside temperature of -11.5 °C.

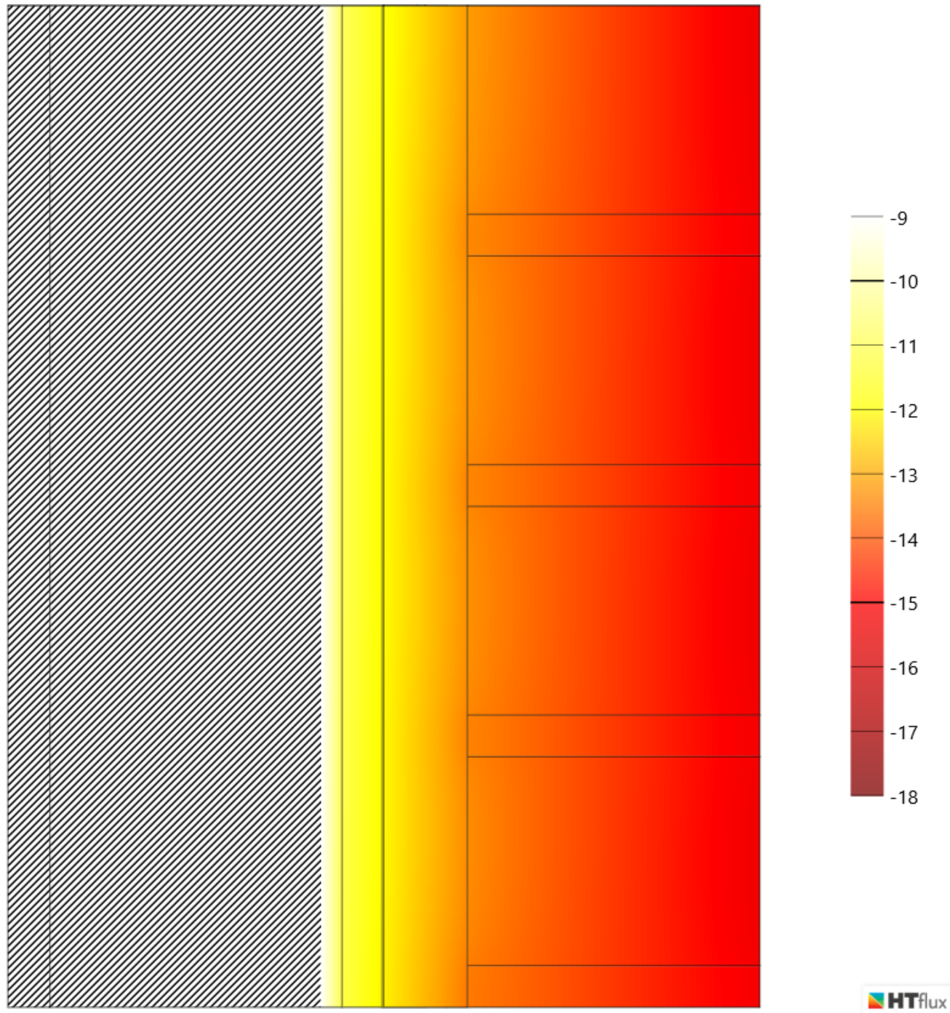

Figure 0.4: Assembly A simulation with coldest expected outside temperature of -15.6 °C

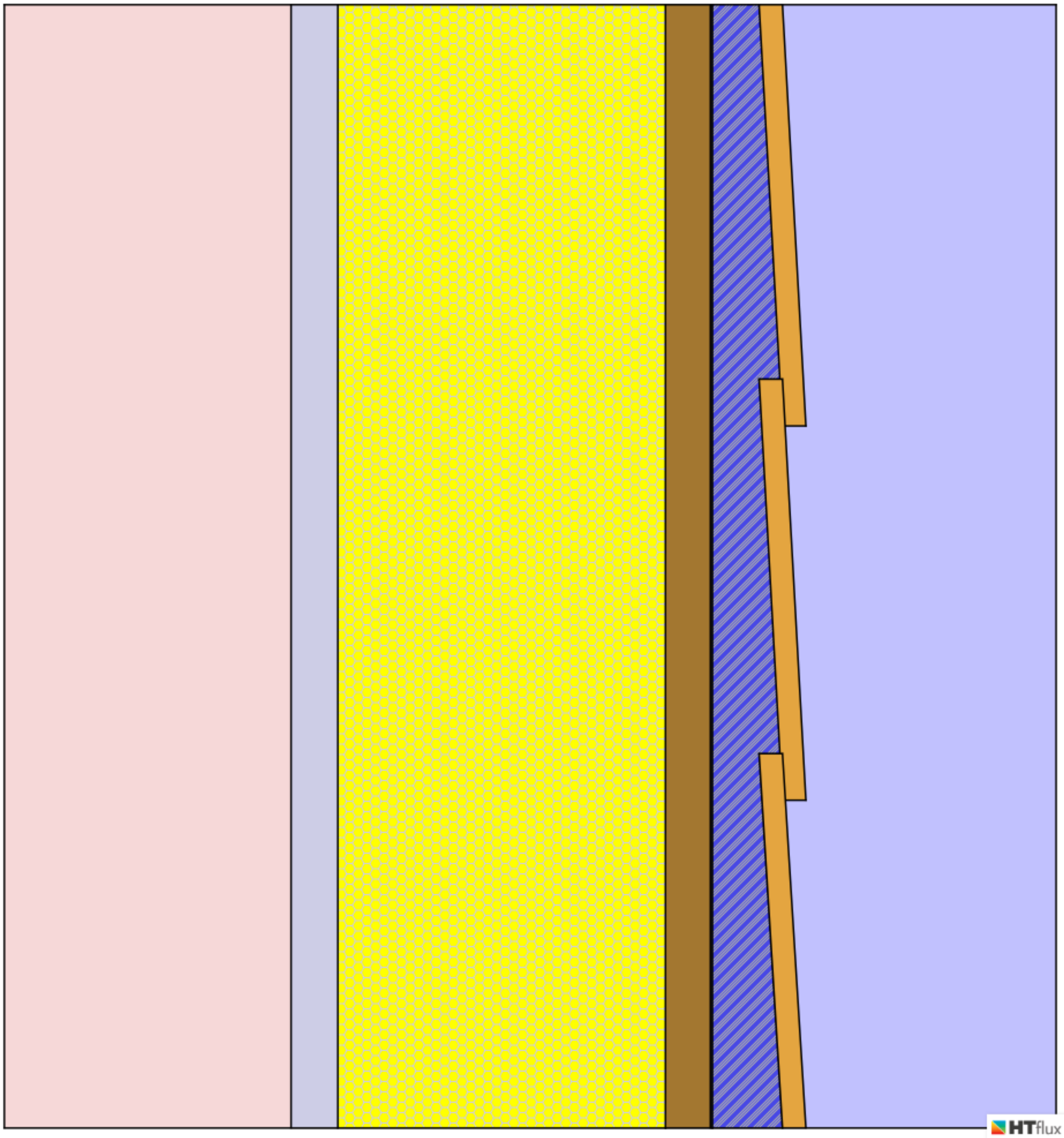

Figure 0.5: Assembly B model, with 2x4 framing and softwood shingles

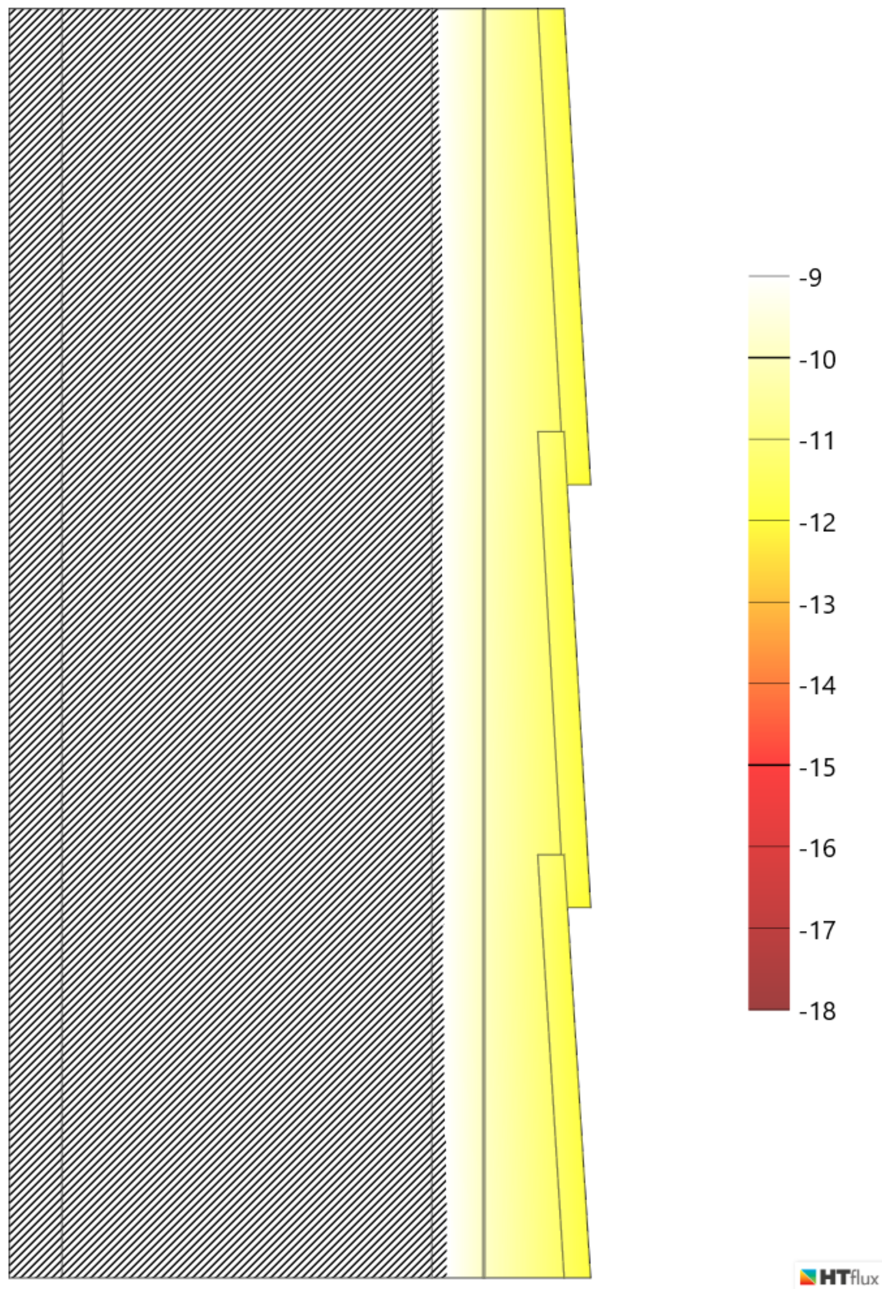

Figure 0.6: Assembly B simulation with coldest day average outside temperature of -11.5 °C.

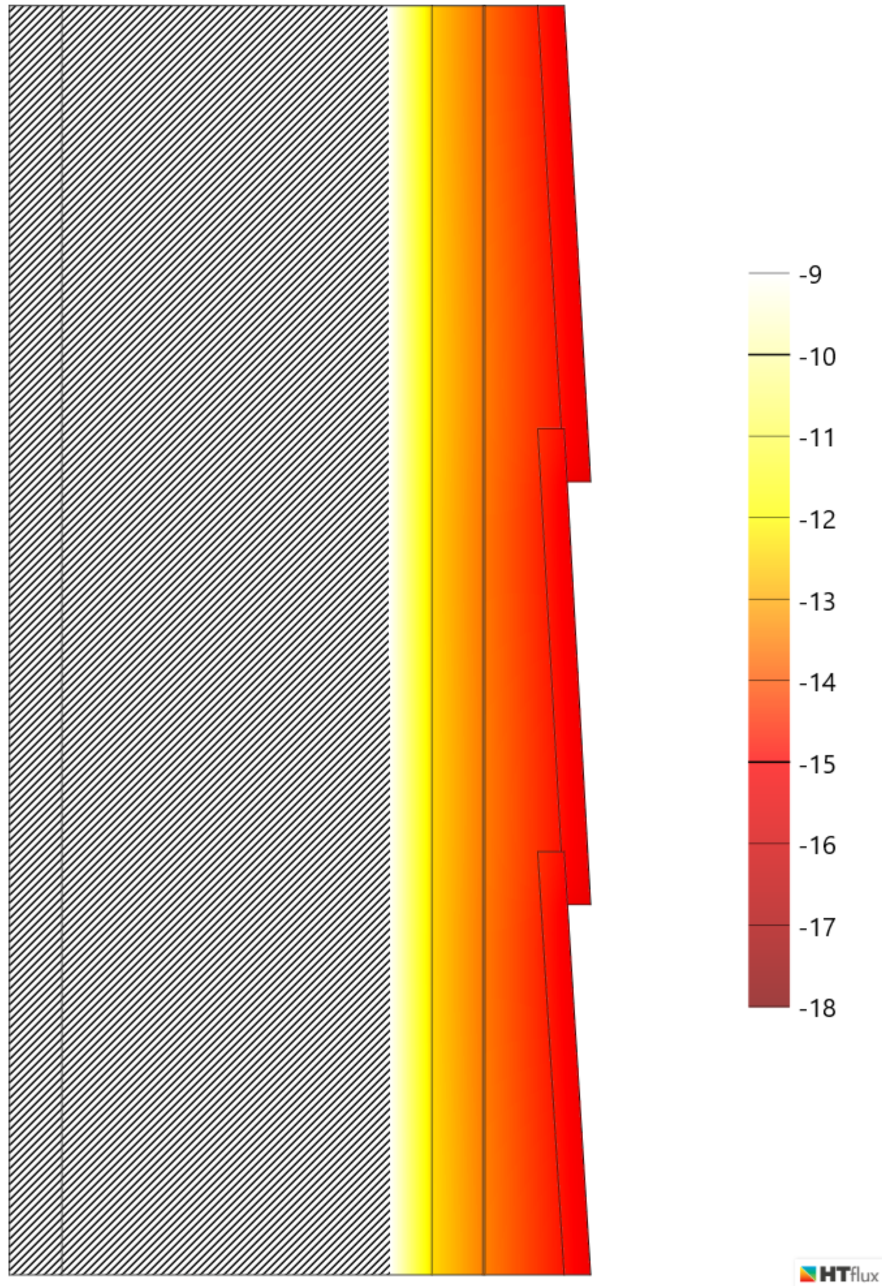

Figure 0.7: Assembly B simulation with coldest expected outside temperature of -15.6 °C

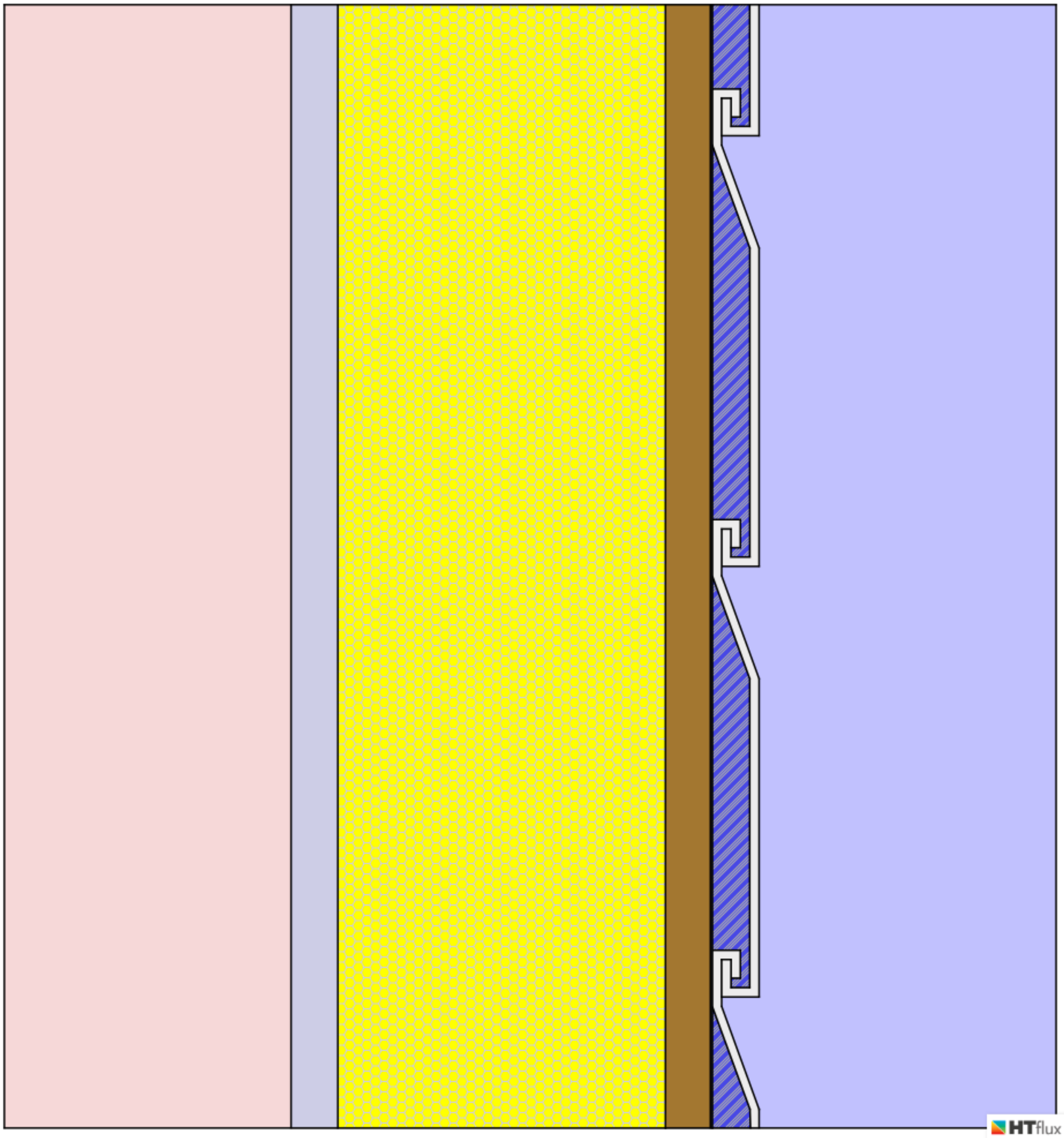

Figure 0.8: Assembly C model, with 2x4 framing and vinyl siding

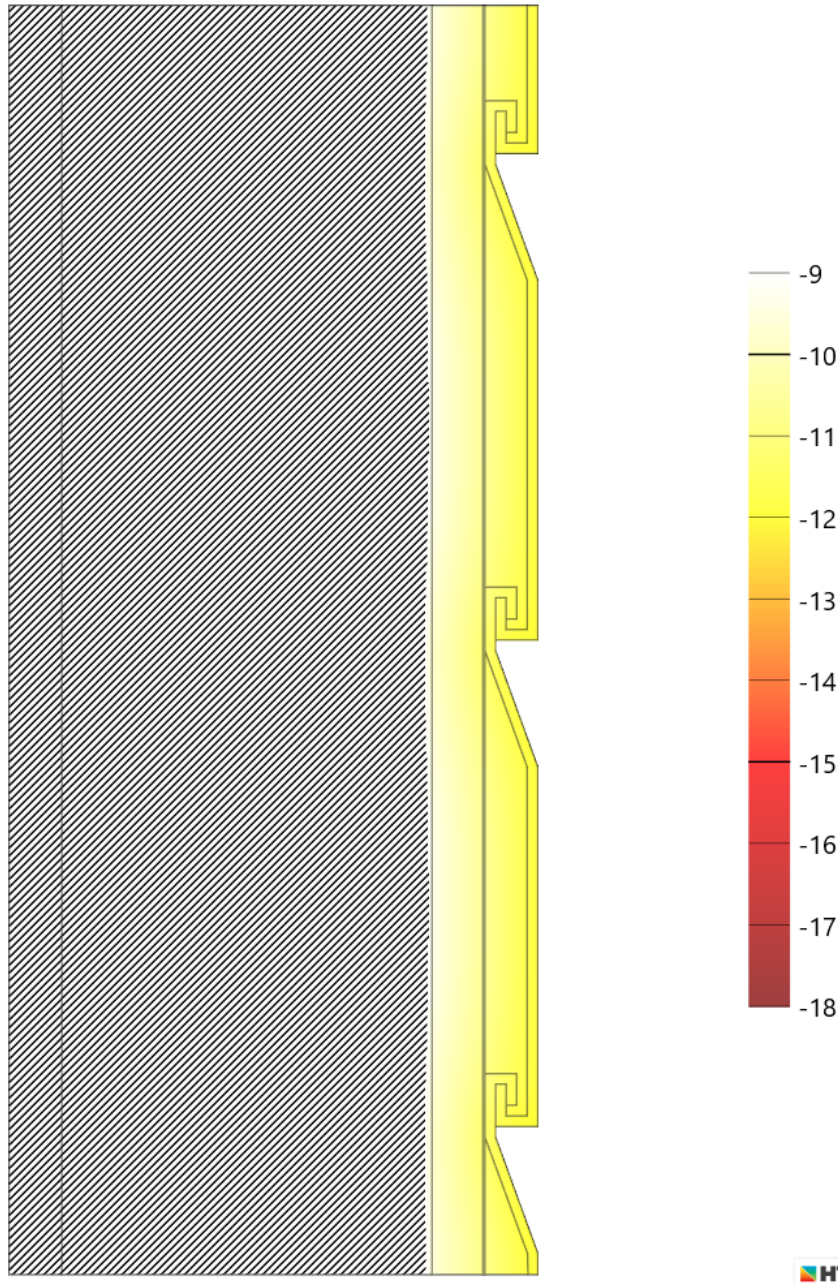

Figure 0.9: Assembly C simulation with coldest day average outside temperature of -11.5 °C.

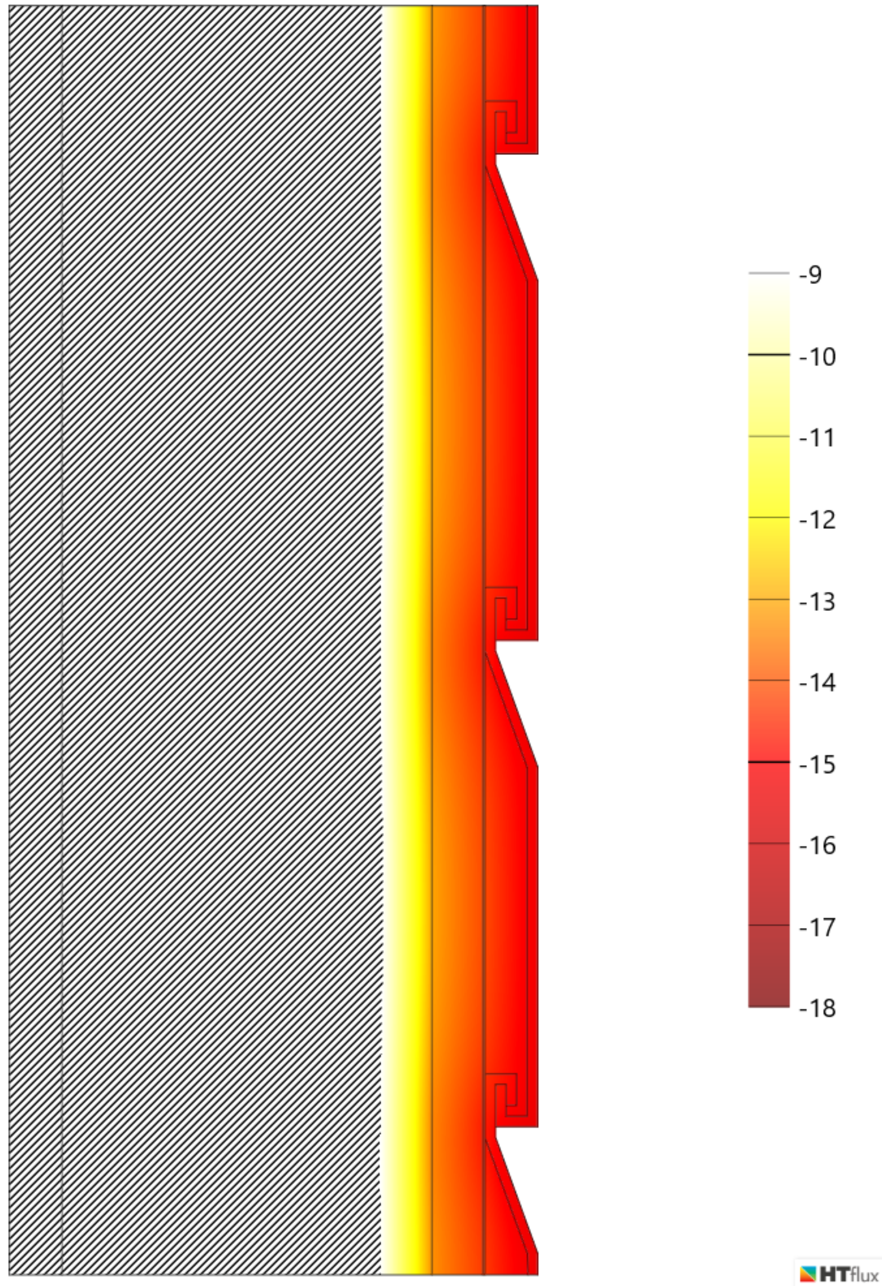

Figure 0.10: Assembly C simulation with coldest expected outside temperature of -15.6 °C

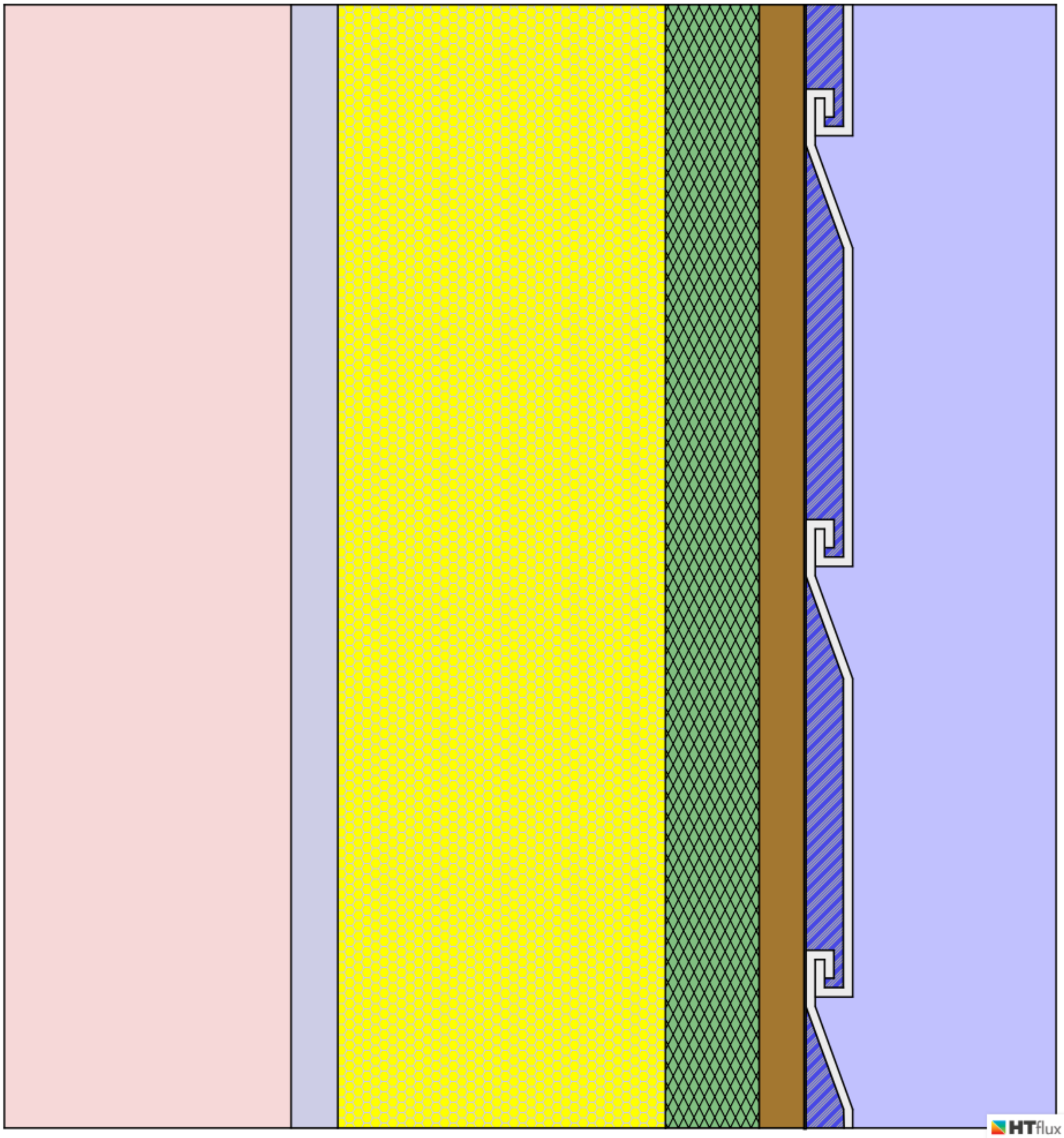

Figure 0.11: Assembly D model, with 2x4 framing, XPS, and vinyl siding

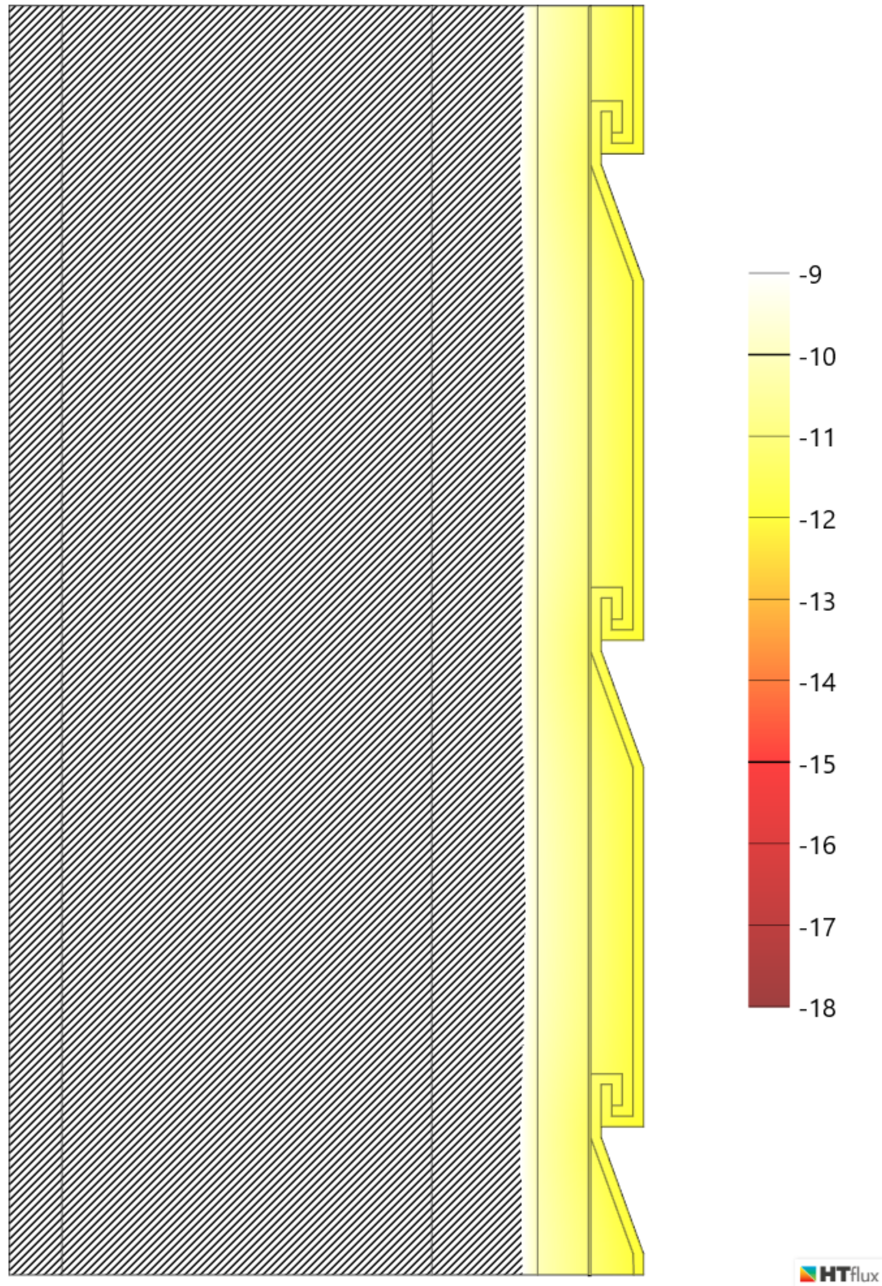

Figure 0.12: Assembly D simulation with coldest day average outside temperature of -11.5 °C.

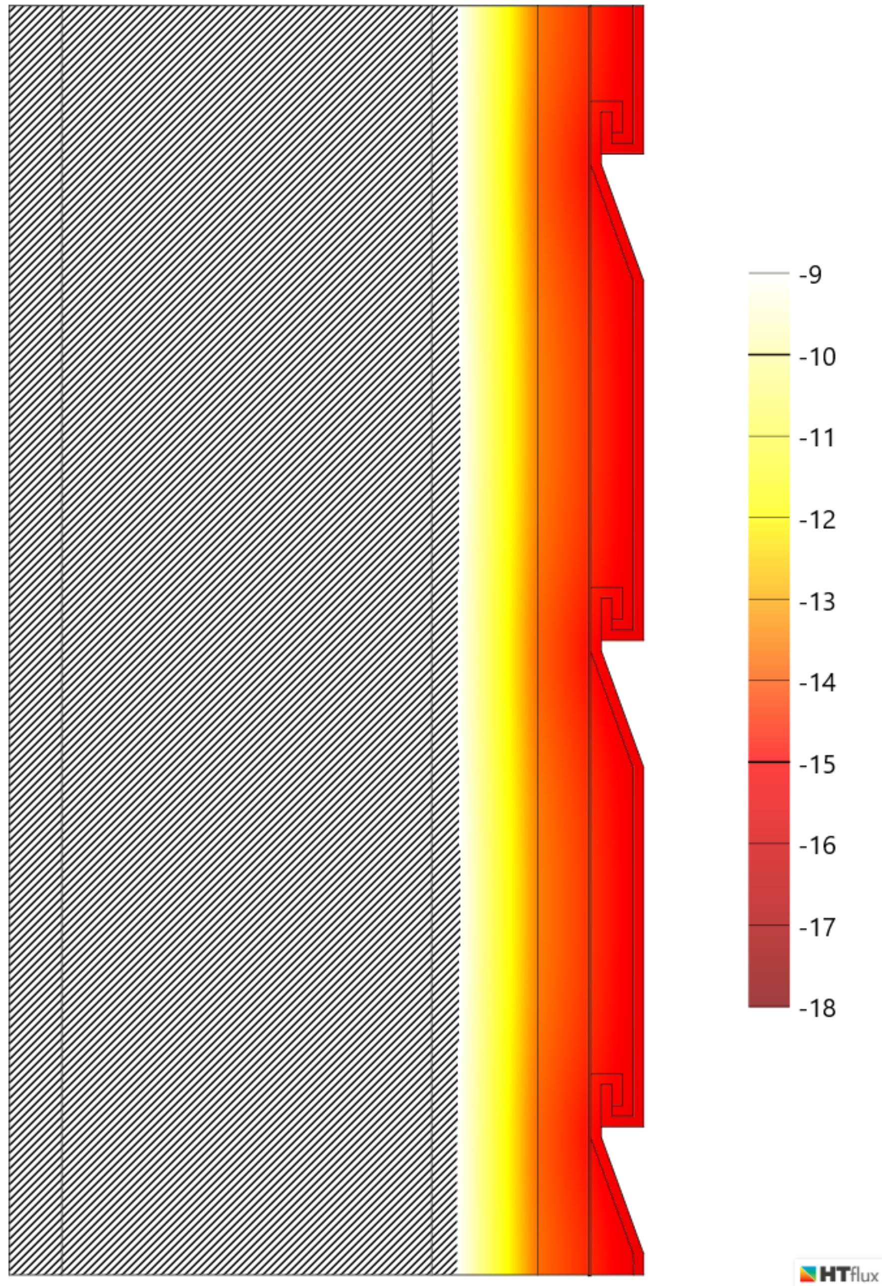

Figure 0.13: Assembly D simulation with coldest expected outside temperature of -15.6 °C

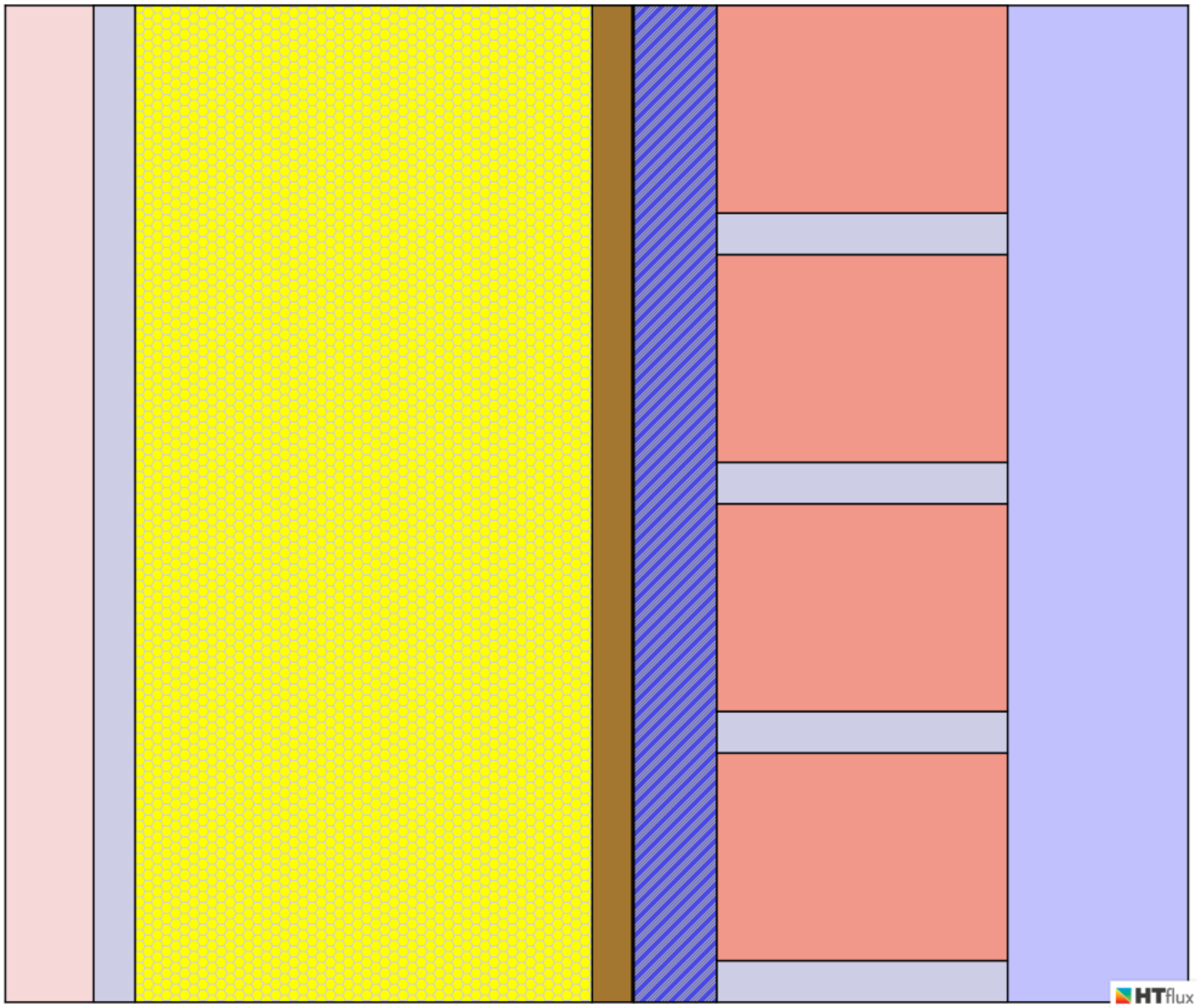

Figure 0.14: Assembly E model, with 2x6 framing and brick cladding

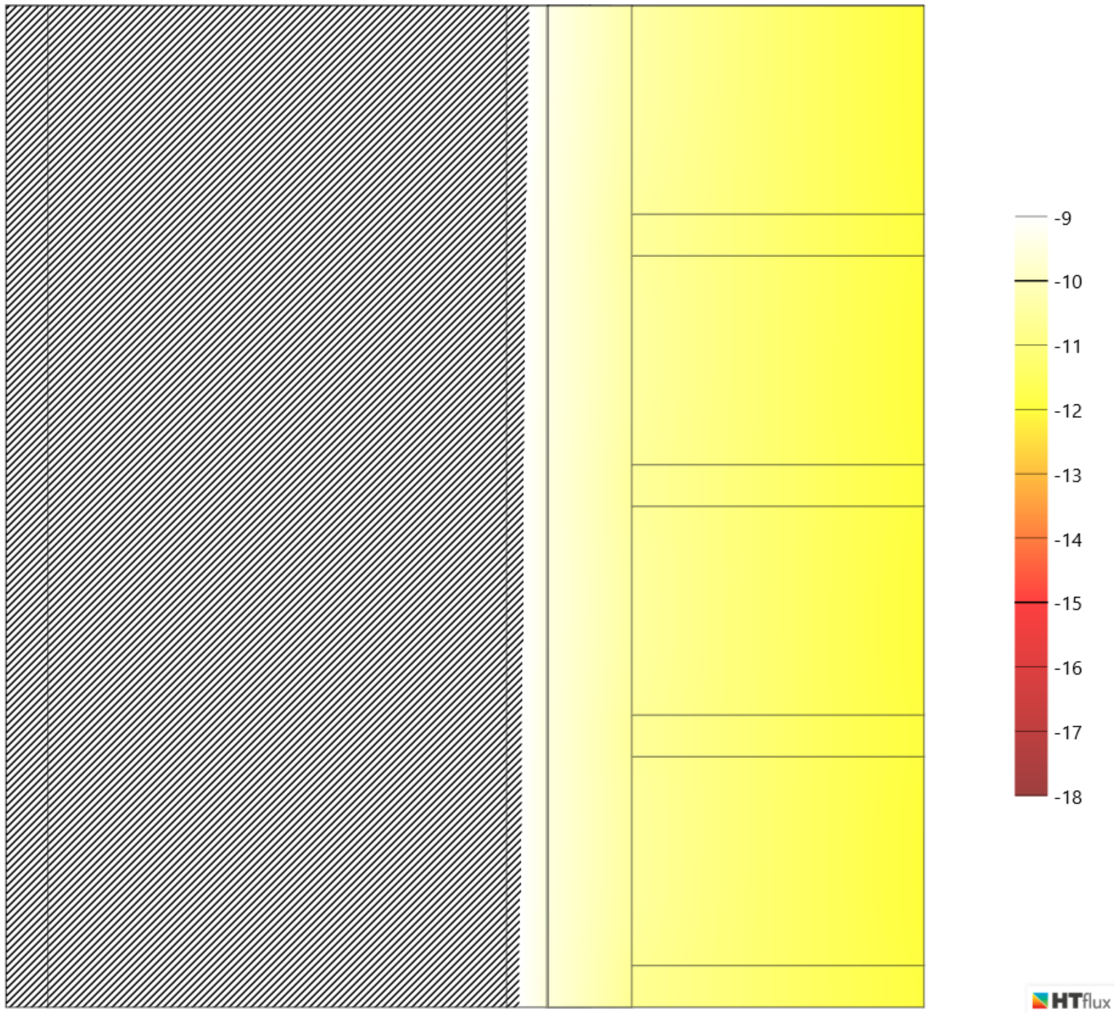

Figure 0.15: Assembly E simulation with coldest day average outside temperature of -11.5 °C.

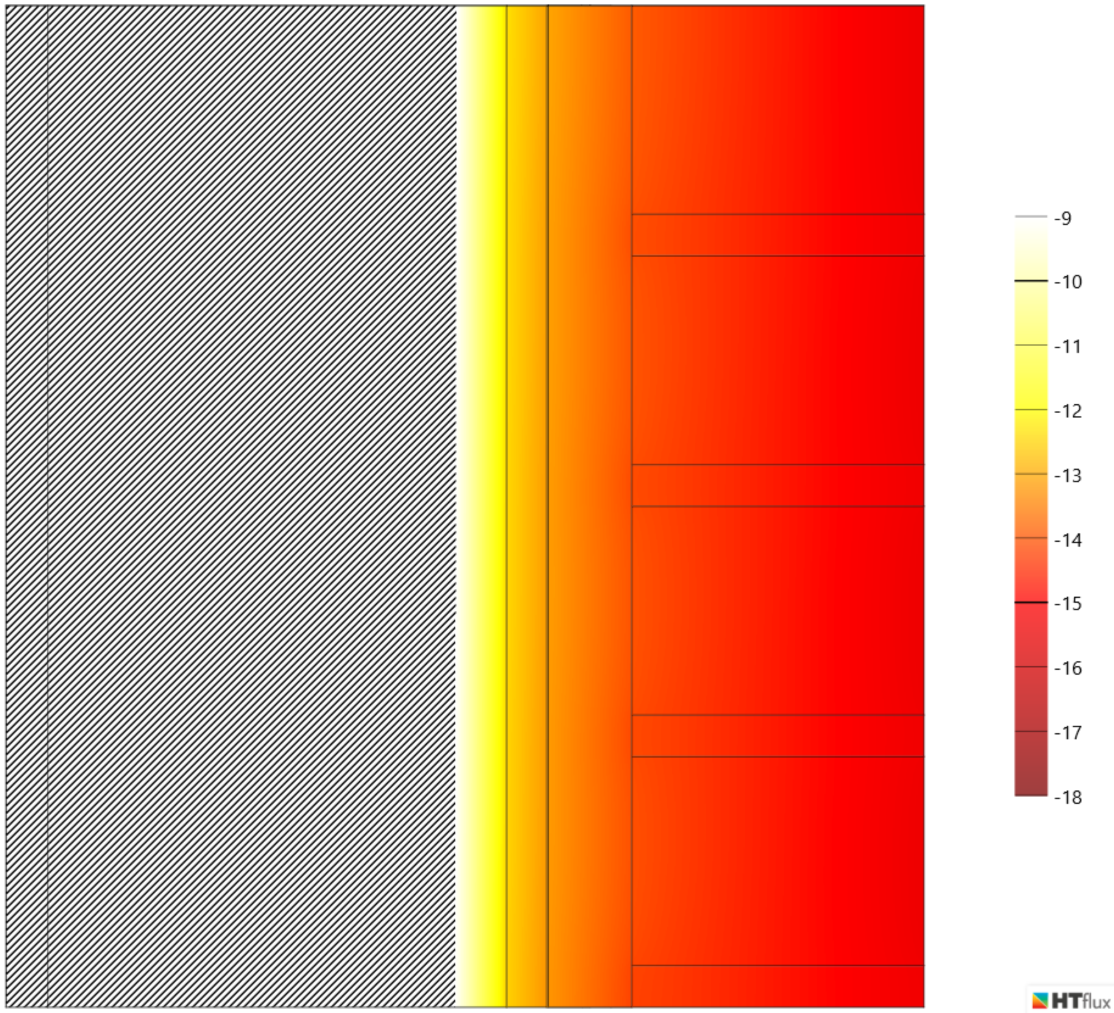

Figure 0.16: Assembly E simulation with coldest expected outside temperature of -15.6 °C

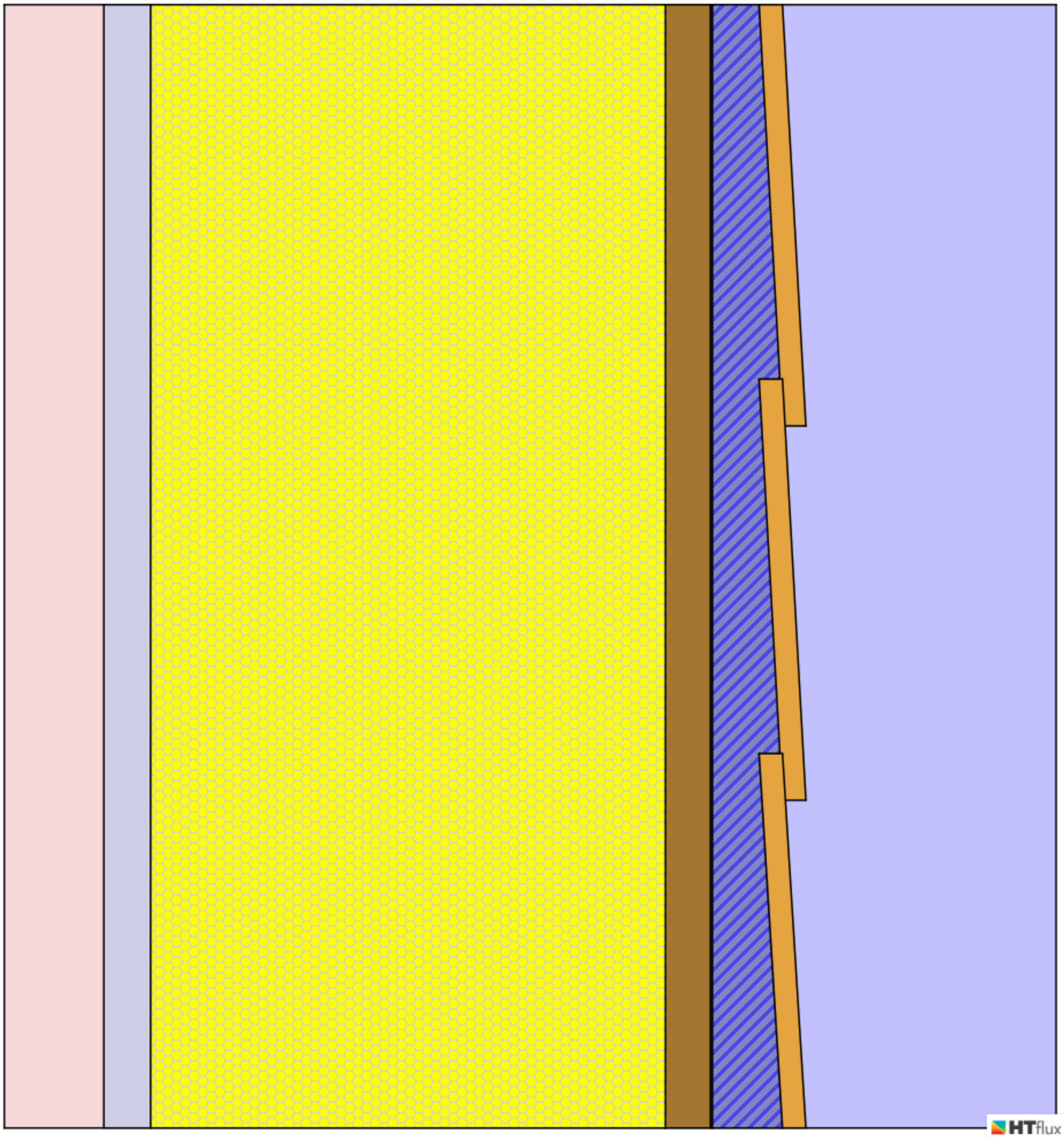

Figure 0.17: Assembly F model, with 2x6 framing and softwood shingles

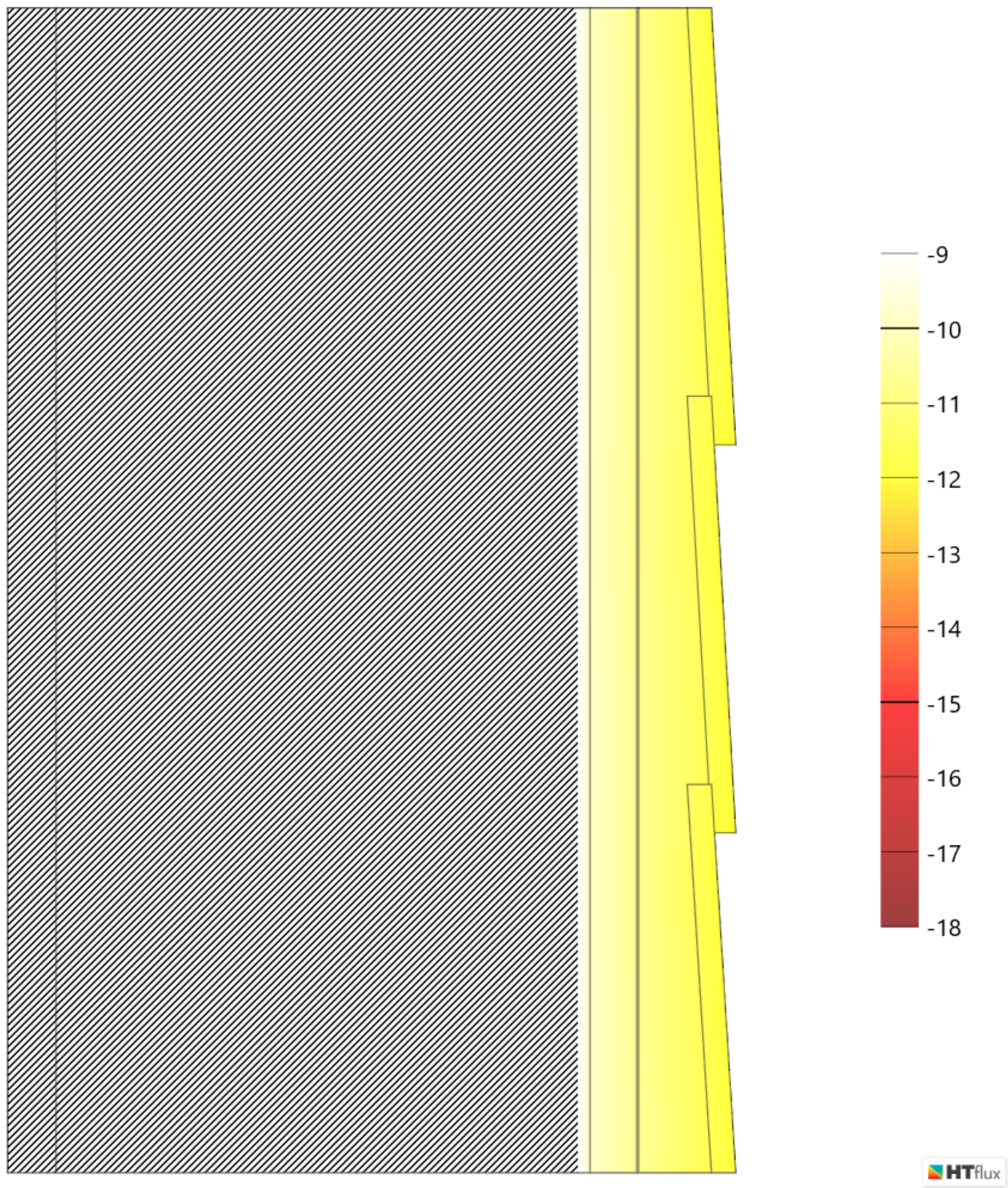

Figure 0.18: Assembly F simulation with coldest day average outside temperature of -11.5 °C.

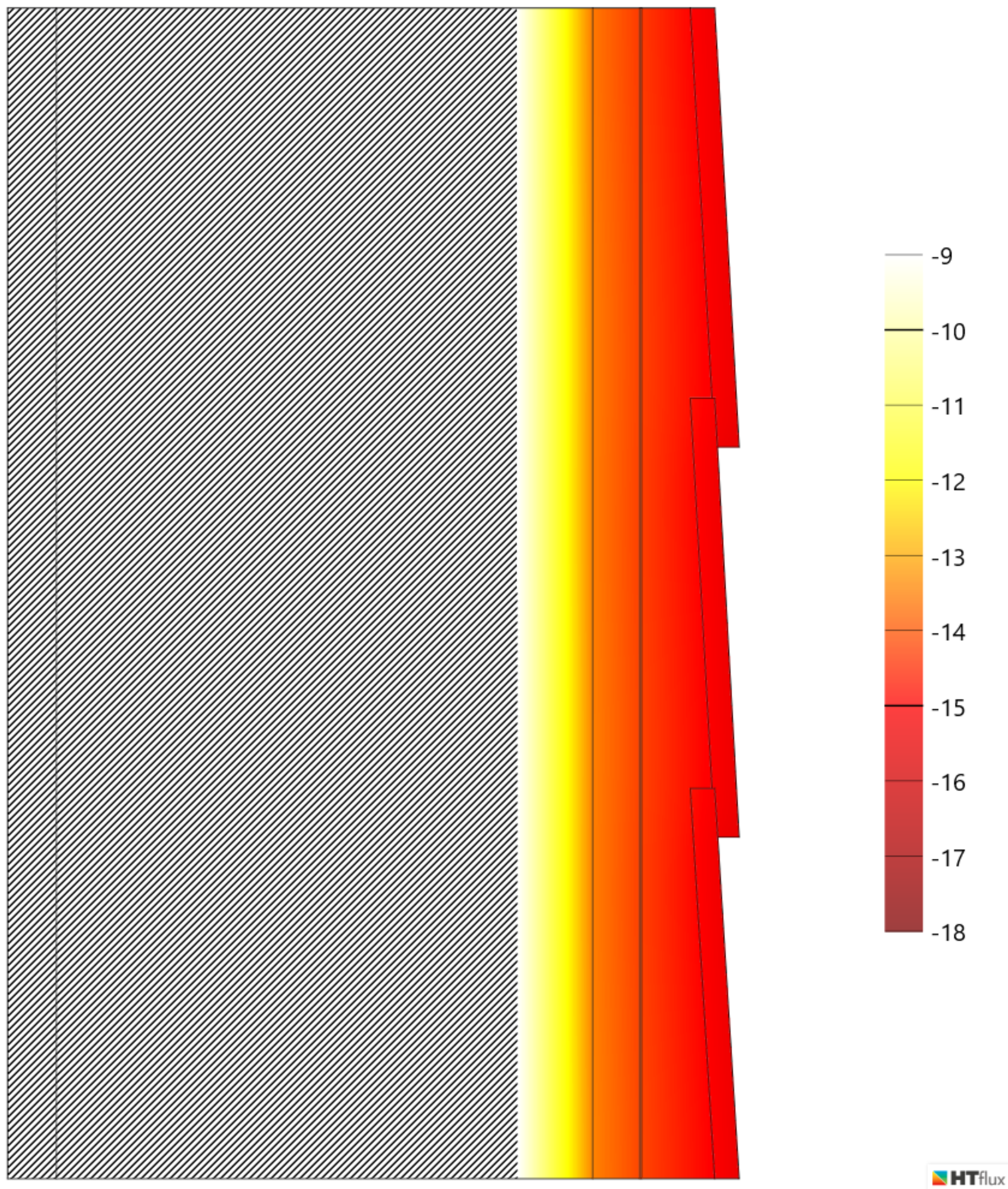

Figure 0.19: Assembly F simulation with coldest expected outside temperature of -15.6 °C

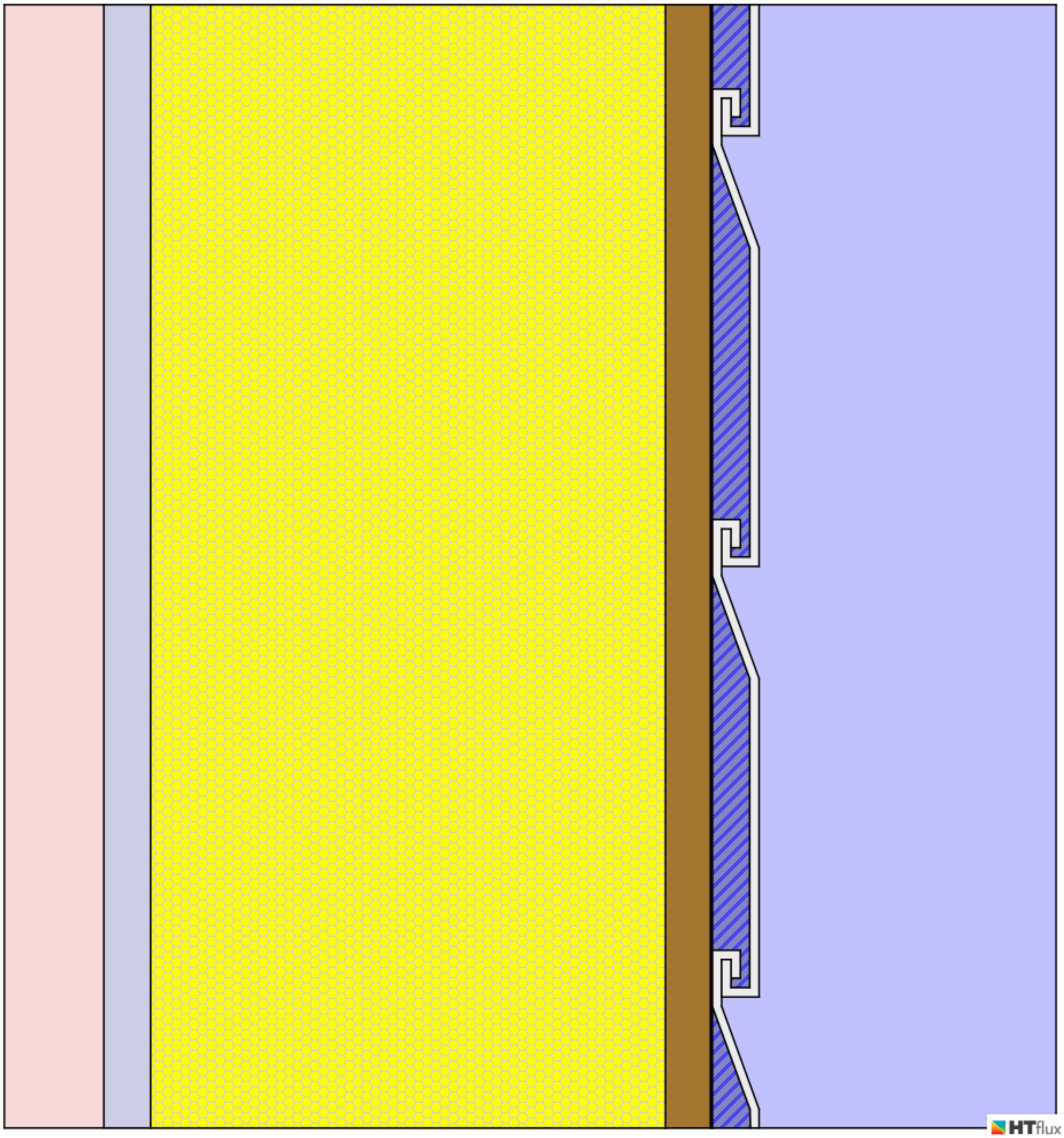

Figure 0.20: Assembly G model, with 2x6 framing and vinyl siding

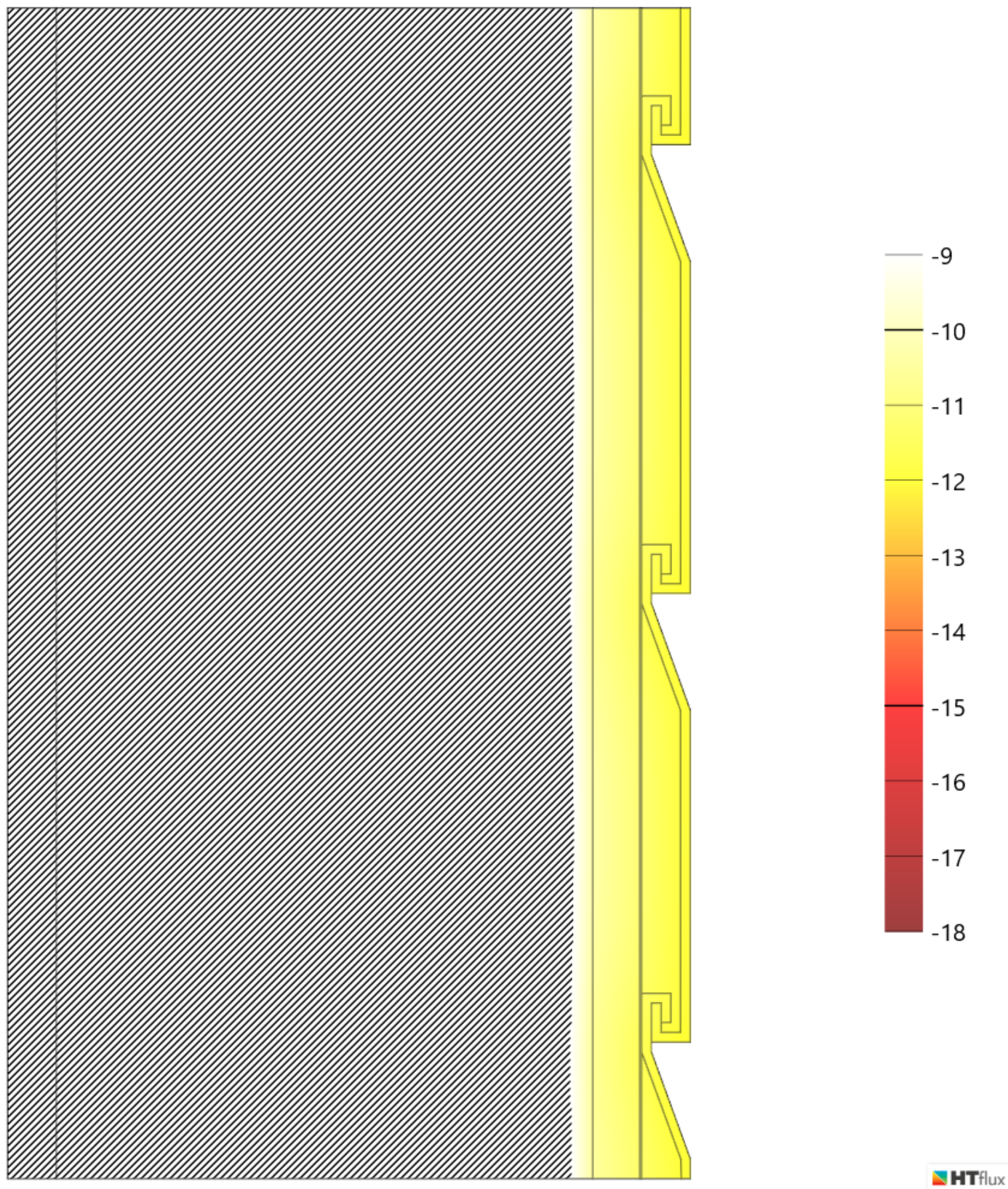

Figure 0.21: Assembly G simulation with coldest day average outside temperature of -11.5 °C.

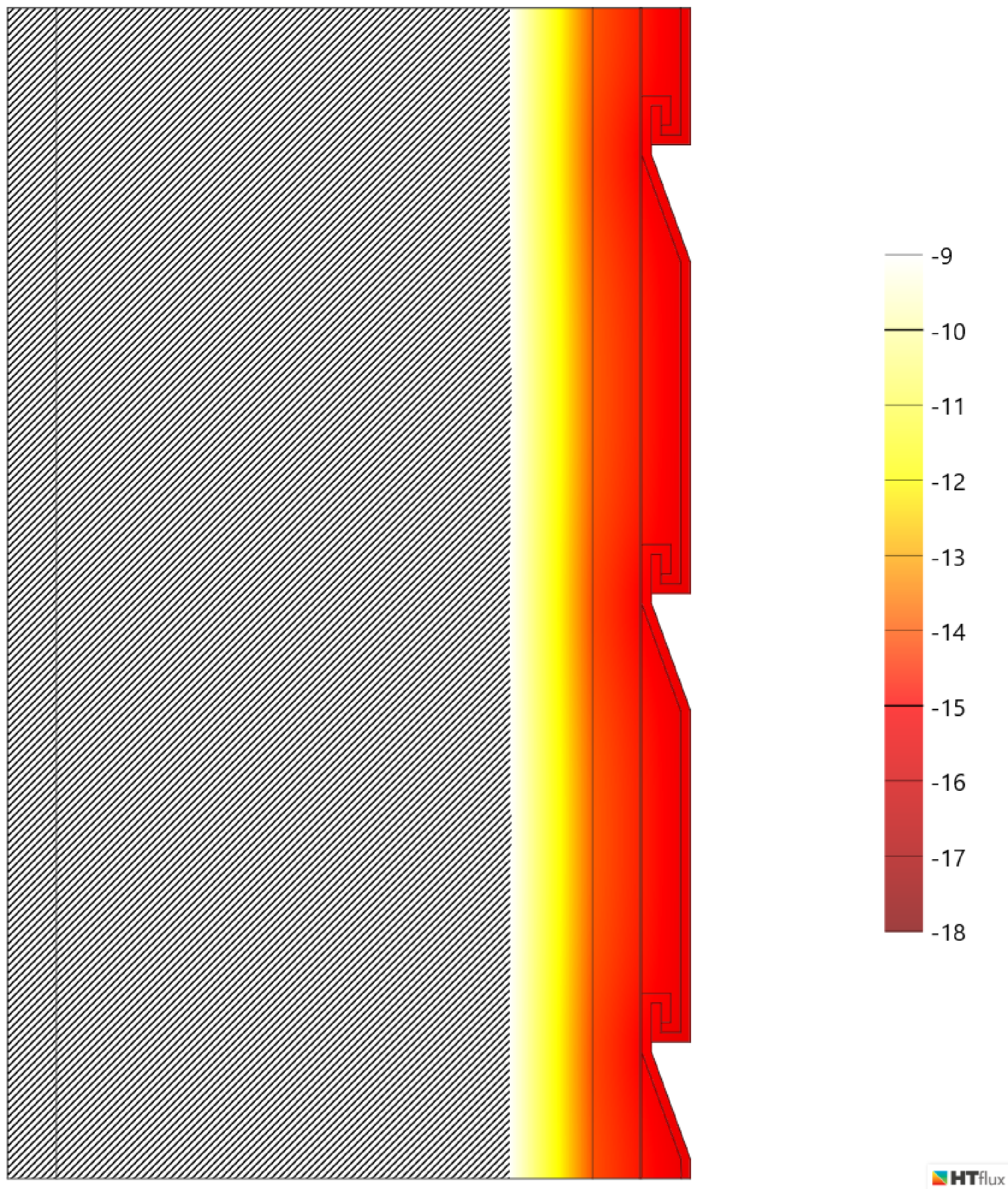

Figure 0.22: Assembly G simulation with coldest expected outside temperature of -15.6 °C

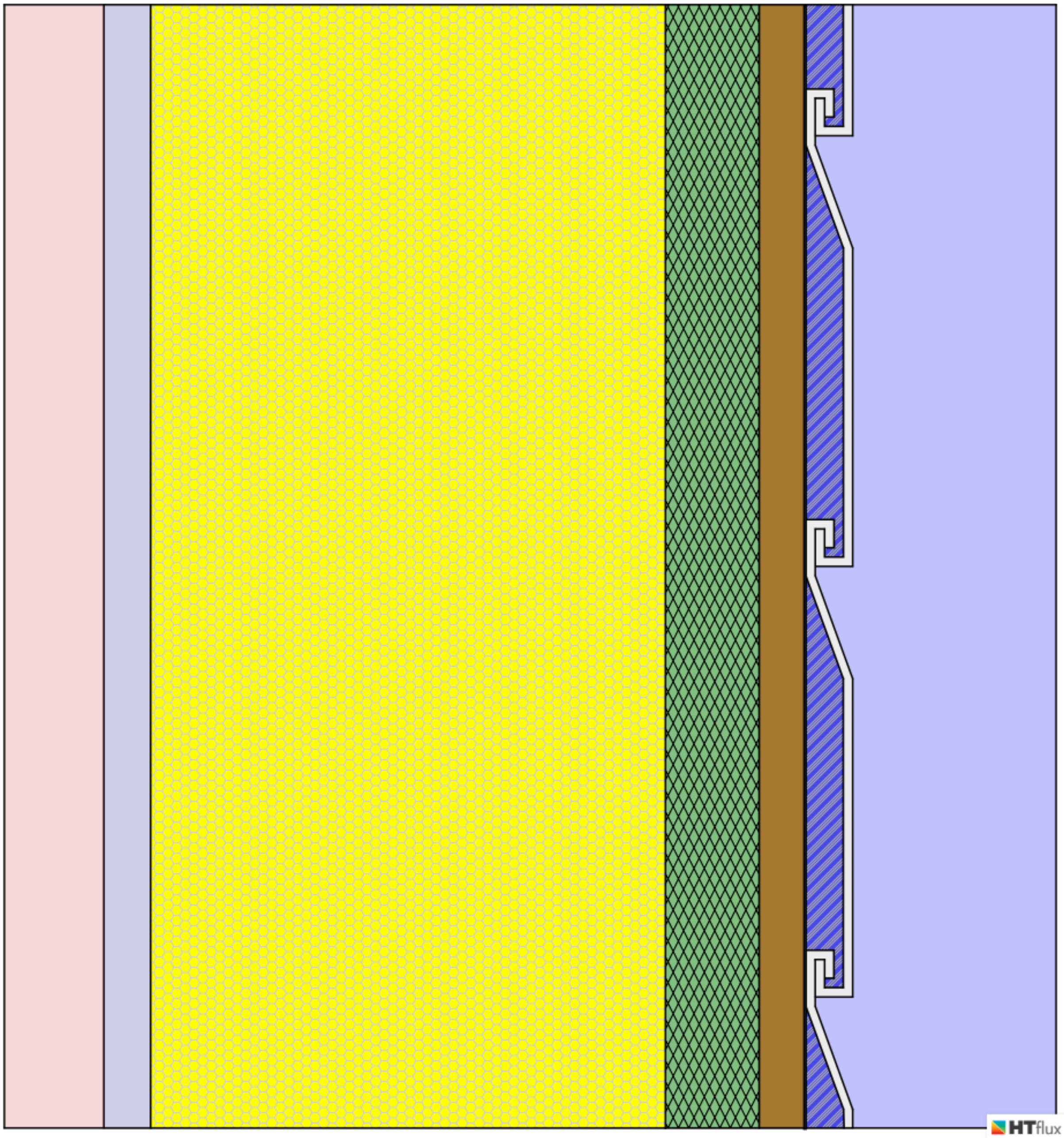

Figure 0.23: Assembly H model, with 2x6 framing, XPS, and vinyl siding

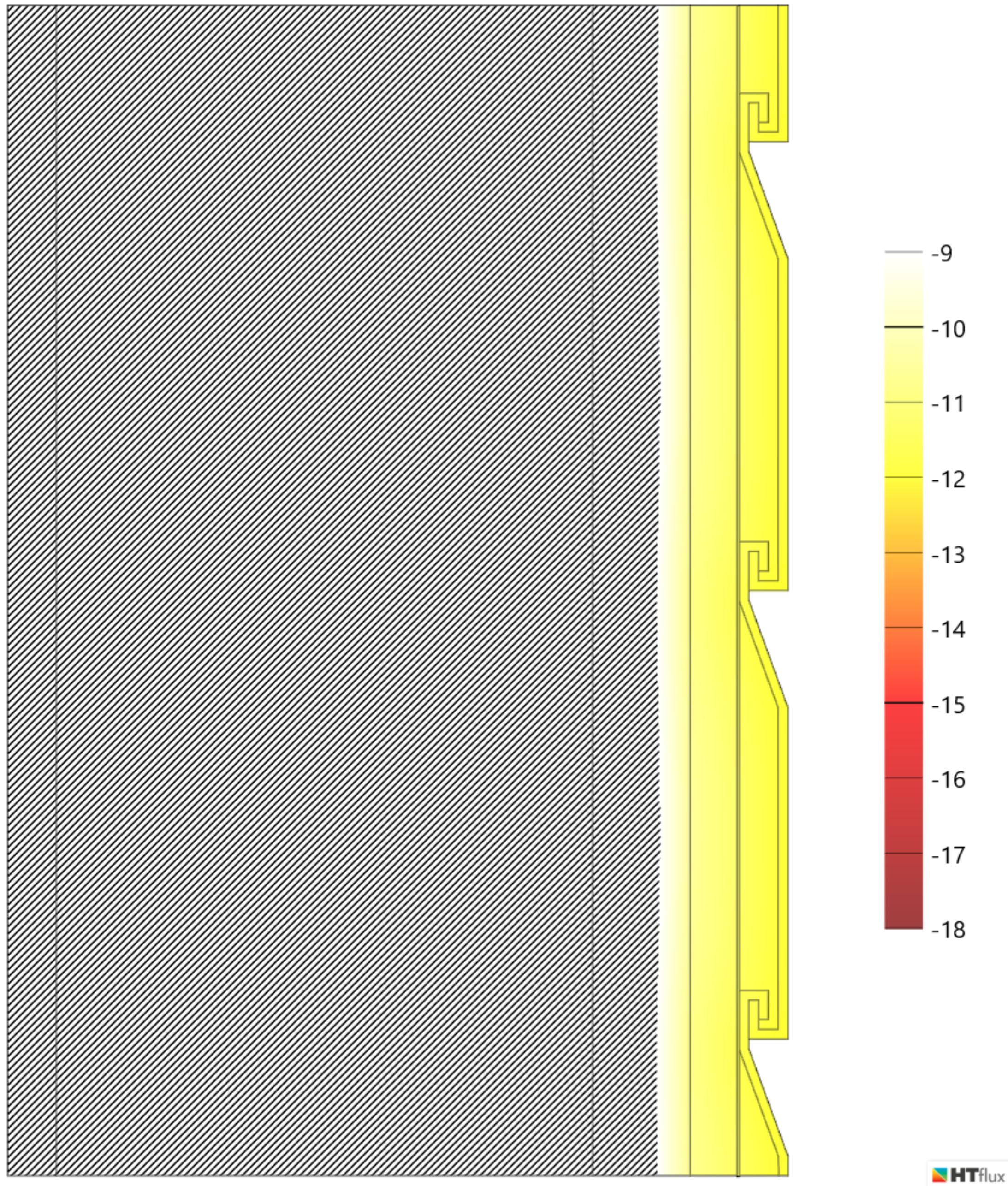

Figure 0.24: Assembly H simulation with coldest day average outside temperature of -11.5 °C.

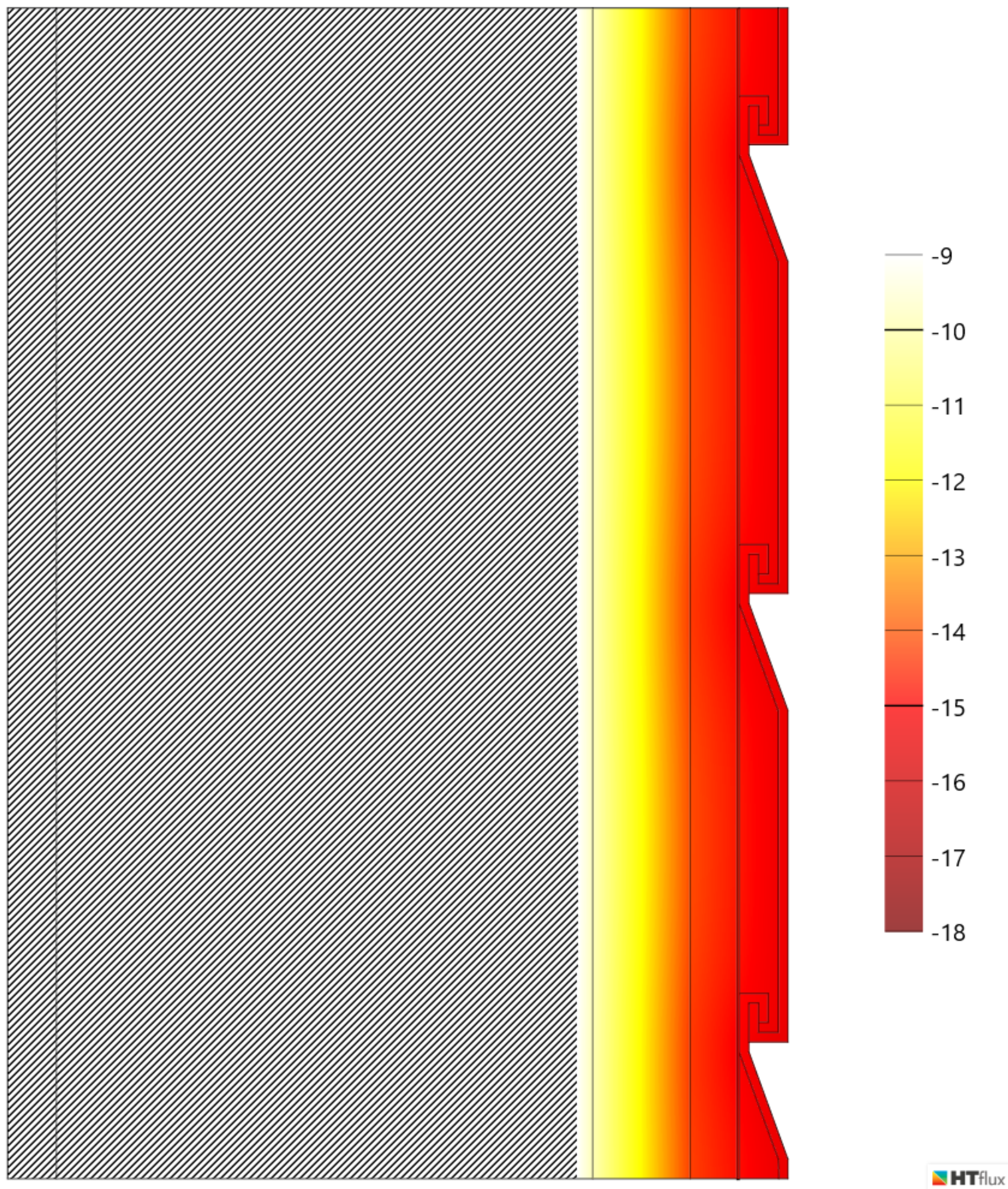

Figure 0.25: Assembly H simulation with coldest expected outside temperature of -15.6 °C