
Thermal and Moisture Performance of Two Unvented Crawlspace Wall Systems

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ABSTRACT

The thermal and moisture performance of the wall systems in two unvented residential crawlspace foundations built in Pennsylvania is characterized in this paper. Both wall systems include drainable exterior insulation and concrete block walls with interior insulation in some areas. The results indicate that nonconductive heat loss resulting from air leakage or internal air circulation can affect thermal performance and may greatly increase heat loss. Normalized seasonal heat loss estimated at measurement locations ranged from 1,634 to 5,736 Btu/ft² (18.56 to 65.16 MJ/m²). Absolute humidity was generally higher in the crawlspaces than in outdoor air, and in one of the two homes, the block wall acted as a humidifier throughout the year. Temperature and humidity conditions that could support mold growth were present on crawlspace wall surfaces in both homes for significant time periods, although no mold was observed in either home.

INTRODUCTION

Building scientists generally agree that unvented crawlspace designs offer better moisture control and better energy efficiency than vented designs (BSC 2003), and some field studies have produced data characterizing the temperatures and typical moisture levels in unvented crawlspaces (Stiles and Custer 1992). However, many questions remain about the thermal and moisture performance of crawlspace foundations (Davis et al. 2002).

The U.S. Department of Energy's Building America program seeks to test, validate, and enhance the adoption of practical energy efficiency improvements in production housing built in the U.S. The project covered in this report made use of two Building America homes to explore and characterize heat loss and moisture migration patterns in unvented crawlspaces, with the objective of validating their performance and identifying areas for further research and design improvement.

METHODOLOGY

Foundation Construction and Monitoring

Two homes in western Pennsylvania were used in this study. Both homes have unvented crawlspaces, including concrete block walls with exterior dampproofing and drainable high-density fiberglass insulation, poured concrete floor slabs, and conventional wood-frame floors above. The two foundation systems are shown schematically in Figure 1 and Figure 2. House 1 includes two different crawlspace wall cross sections, one with and one without interior insulation. Both homes were occupied during the study period and were heated and cooled under the control of the occupants. See Table 1 for more information.

The exposed portion of the foundation wall in House 2 was constructed using unpainted split-face concrete block, less common than smooth-face block, but expected to exhibit similar thermal and moisture performance.

The estimated water vapor permeance of the vinyl insulation facing used on the inner surface of the interior insulation in both homes is 1.0 perm (57.4 ng/s m² Pa). Both homes have

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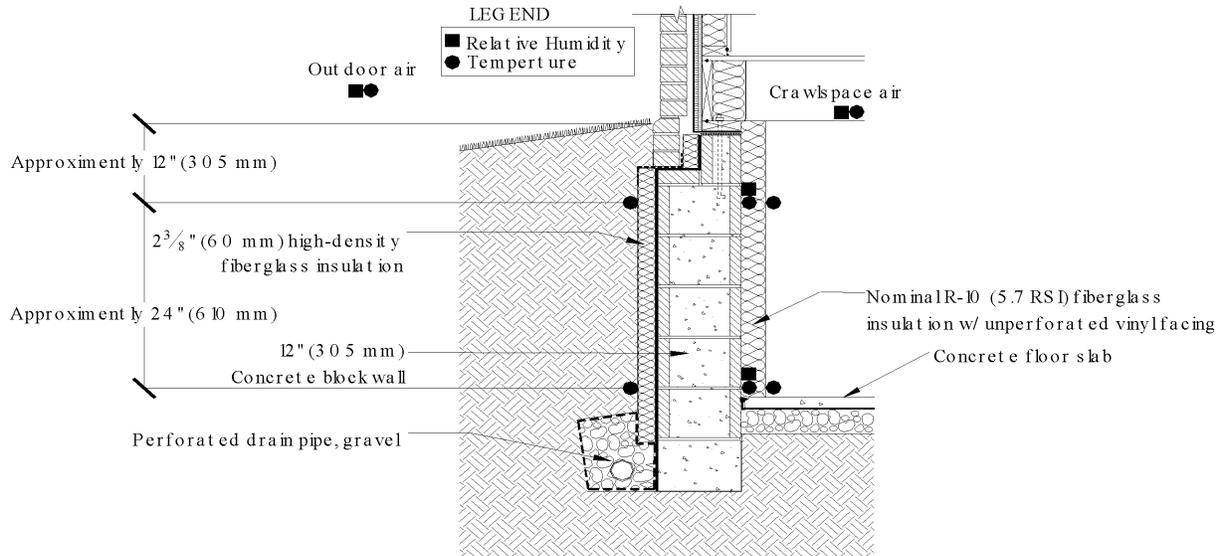


Figure 1 House 1 crawlspace wall section. Note: Poly film (not shown) is installed beneath slab.

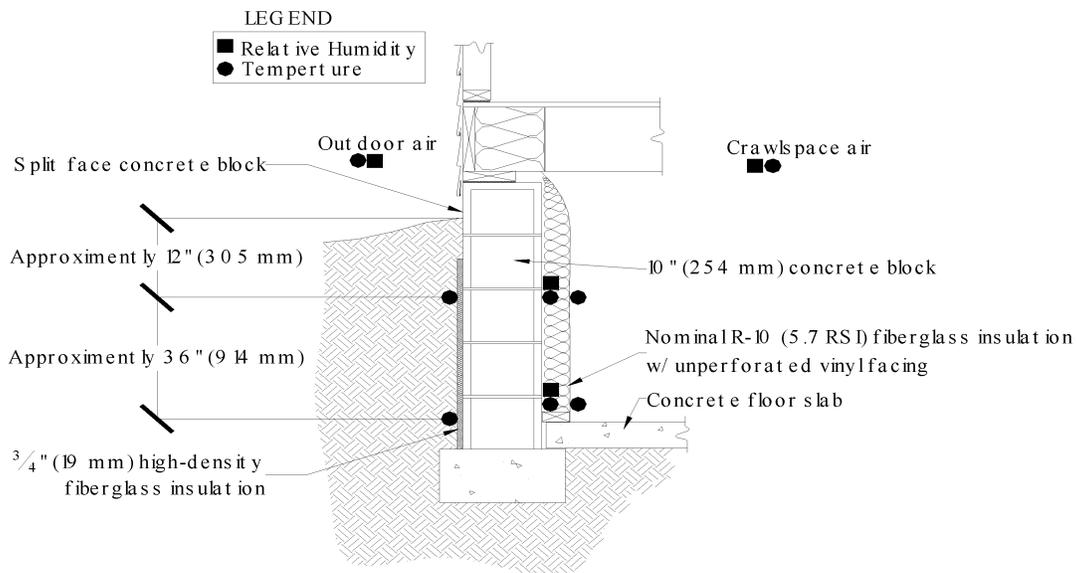


Figure 2 House 2 crawlspace wall section. Note: Poly film (not shown) is installed beneath slab. Top row block is closed at sill.

poured concrete slabs over polyethylene film covering the crawlspace floor and include nominal sealing of the floor-wall joint with caulking. However, the caulk joint in House 1 was found to be incomplete during inspection at the end of the data collection period. (House 2 was not inspected.) The HVAC system in each home includes supply ducting installed in the crawlspace. Each system is designed to deliver supply air at the rate of roughly 1 air change per hour to the crawlspace when the system blower operates, providing partial but uncontrolled conditioning of crawlspace air. In both homes, the wood-frame floor over the crawlspace is uninsulated.

The monitoring system in each home included thermocouple temperature sensors at the surfaces of the foundation wall and insulation, in crawlspace air, and in outdoor air, as well as capacitive-type relative humidity sensors at the inside of the foundation wall, in the crawlspace air, and outdoor air. All sensors were connected to an on-site data acquisition system, which typically took individual sensor readings every minute and stored average values for each parameter once per hour. Data were retrieved remotely via a modem connection to each data acquisition system. Figure 1 and Figure 2 show typical sensor positions. In House 1, soil temperature sensors were

Table 1. Summary of Crawlspace Wall Construction in Study Homes

House and Wall	Below-Grade Foundation Wall Construction
House 1 Internally Uninsulated	2.375 in. (60 mm) exterior high-density fiberglass insulation, dampproofing, concrete-filled-core concrete block, no interior insulation.
House 1 Internally Insulated	2.375 in. (60 mm) exterior high-density fiberglass insulation, dampproofing, concrete-filled-core concrete block, 3 in. (76 mm) vinyl-faced fiberglass interior insulation.
House 2	0.75 in. (19 mm) exterior high-density fiberglass insulation, dampproofing, open-core concrete block, 3 in. (76 mm) vinyl-faced fiberglass interior insulation.

placed adjacent to the internally uninsulated wall section only. The crawlspace air temperature and humidity measurements were made at the level of the wood-frame floor at the top of the crawlspace in each home.

House 1 was equipped with a sub-slab depressurization system for radon control. The system was inactive for the first portion of the monitoring period and then was activated to depressurize the area under the crawlspace slab on January 8, 2003. On March 1, 2003, the fan flow direction was reversed in an effort to reduce radon levels in the home so that the system positively pressurized the area under the slab. The system remained in this mode of operation through the end of the study.

DATA ANALYSIS

Thermal Conduction Analysis

In purely conductive steady-state heat transfer, with constant material properties, heat flux and temperature drop are related in a purely linear fashion. Thus, the temperature drop across each element (e.g., insulation or concrete block) along a series heat flow path should be a fixed proportion of the total temperature drop across the system. This principle allows us to test the assumption of conductive heat transfer by evaluating the correlation of measured temperature difference across individual elements of the crawlspace wall system with the total temperature difference between interior air and the soil immediately adjacent to the wall system. Note that the “system” defined here extends from the interior crawlspace air to the exterior surface of the crawlspace wall, excluding the temperature drop across the soil around the home. This definition is used because the thermal mass effects of soil are so large as to violate the assumption of steady-state heat transfer unless an averaging period on the order of a year is used. The use of a 24-hour averaging period, on the other hand, should be sufficient to reduce thermal mass effects of wall and insulating materials to unimportant levels, consistent with an assumption of steady-state behavior.

Constant proportionality in the temperature drop across each element will result in correlations that are linear and can be taken as confirmation of purely conductive heat transfer across the system, while a lack of proportionality, resulting in poor linearity, can be interpreted to mean nonconductive heat transfer mechanisms are at work.

Estimation of Heat Loss

The heat loss across a wall system can be estimated by summing over time the temperature drop across an element multiplied by the conductance of the element. This has been done for a period roughly corresponding to the heating season in the two homes. These calculations must be considered approximate due to the use of nominal values of thermal resistance for insulation and wall materials.

Estimation of Apparent Thermal Resistances

The heat loss through a wall section as calculated above may be used to estimate apparent thermal resistance values for other elements in the system, including in particular the soil and the air temperature stratification effects. Air temperature stratification is used here to mean the temperature difference from a central measurement location in the crawlspace to a wall surface and includes the effects of poor mixing and temperature stratification as well as surface convective coefficients.

Comparative Absolute Humidity

Absolute humidity is calculated for locations where both temperature and relative humidity data are available. Since moisture transfer via diffusion proceeds in the direction of declining absolute humidity, comparison of the absolute humidity across locations in each system provides information as to which locations are moisture sources.

Prevalence of High-Humidity Conditions

The potential for mold growth at any location depends in part on temperature and humidity, with higher humidity and moderate temperatures (warm-humid conditions) most likely to support growth. In this study, warm-humid conditions are defined as temperature exceeding 55°F coincident with relative humidity above 90%.

RESULTS AND DISCUSSION

Data used in this study were collected in House 1 from June 4, 2002, through October 21, 2003, and in House 2 from May 16, 2002, through July 16, 2003, with some missing periods in each case.

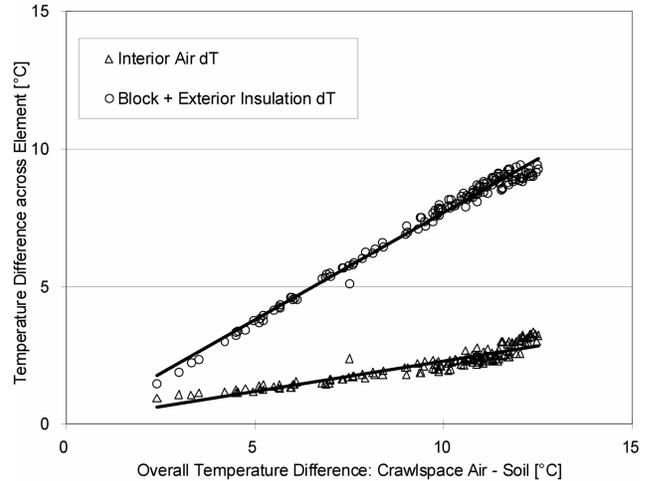
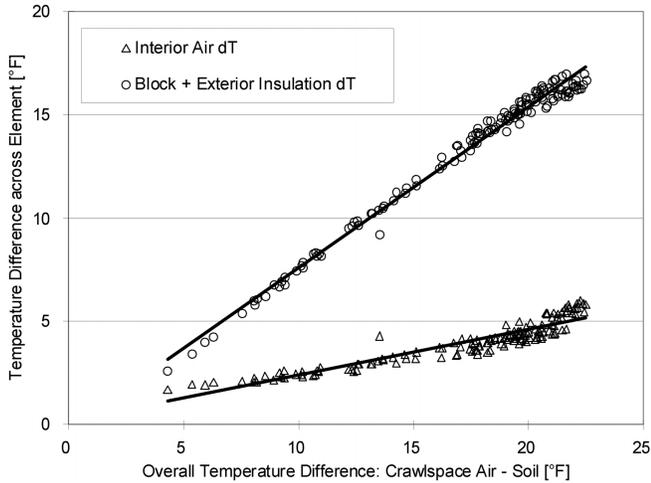


Figure 3 Correlation of temperature difference across elements of crawspace wall to overall temperature difference, House 1, uninsulated wall section, 10 in. (254 mm) below grade, October 1, 2002, to April 22, 2003.

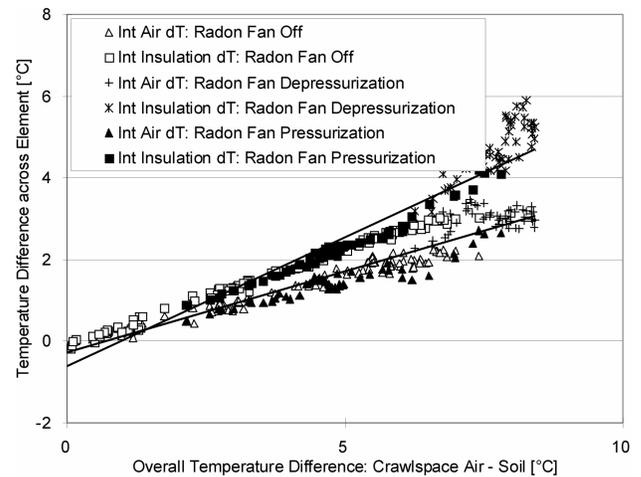
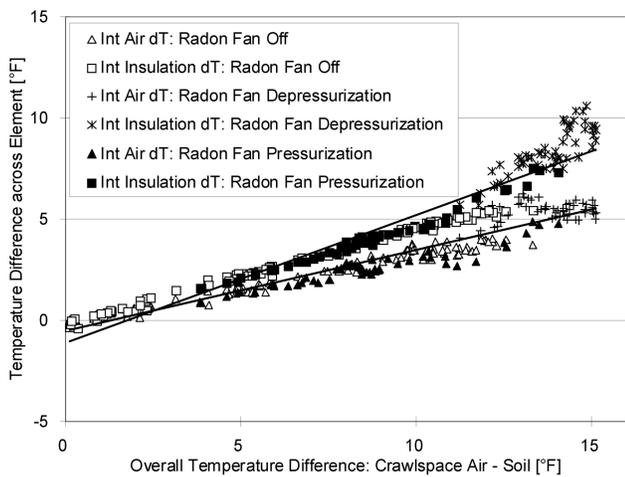


Figure 4 Correlation of temperature difference across elements of crawspace wall to overall temperature difference, House 1, insulated wall section, 10 in. (254 mm) below grade, October 1, 2002, to April 22, 2003.

Thermal Conduction Analysis

The correlation of temperature difference across the wall elements against the temperature difference between crawspace air and soil adjacent to the exterior wall surface is presented for the internally uninsulated wall section in House 1 in Figure 3. There appears to be good proportionality in temperature drop across each element, an indication that this wall section is behaving generally as a thermally conductive system.

Similar correlations for the internally insulated wall section in House 1 are presented in Figure 4. The regression lines represent the overall trend of temperature drop across interior insulation (upper line) and interior air (lower line).

The temperature drop values appear to be generally proportional but with somewhat greater scatter than appeared in Figure 3. Noting the grouping of data according to the status of radon fan operation, it seems likely that fan operation induces air leakage through a path behind the wall insulation. The effect of fan depressurization is to cool the wall-insulation interface, while the effect of positive pressurization appears to be small. Thus, fan depressurization produces nonconductive thermal behavior. Based on this observation, we have excluded the period of fan depressurization from further analysis of heat loss below.

Similar correlations for House 2 show poor proportionality. Figure 5, for example, shows both negative values and

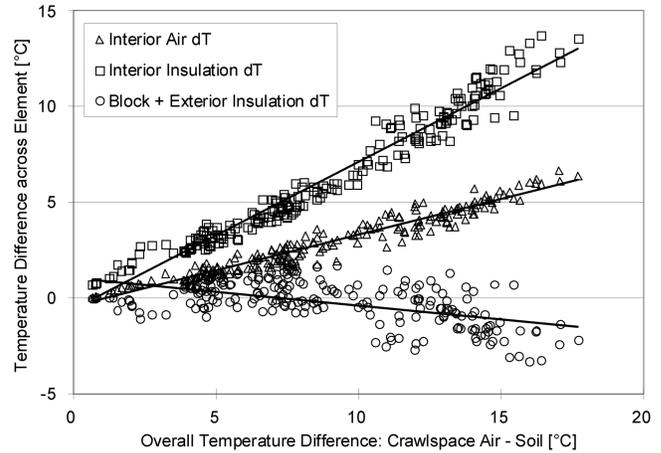
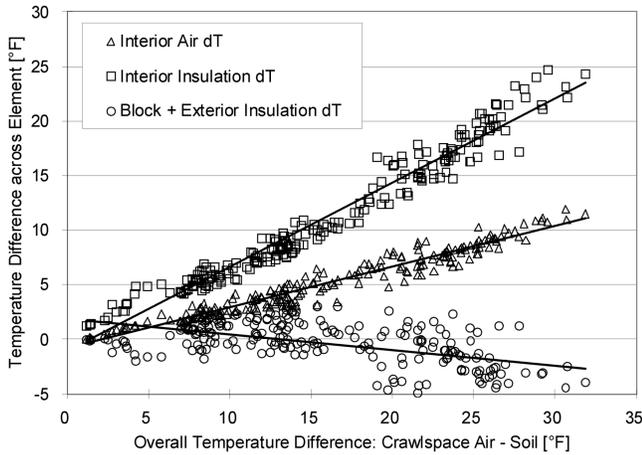


Figure 5 Correlation of temperature difference across elements of crawlspace wall to overall temperature difference, House 2, insulated wall section, 48 in. (1219 mm) below grade, November 1, 2002, through December 11, 2002, and January 7, 2003, through March 31, 2003.

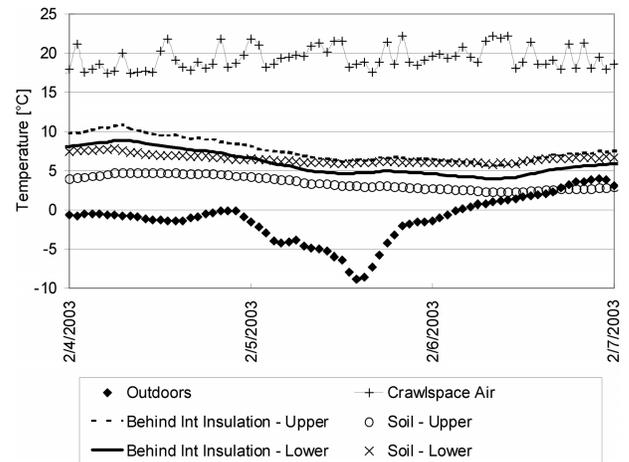
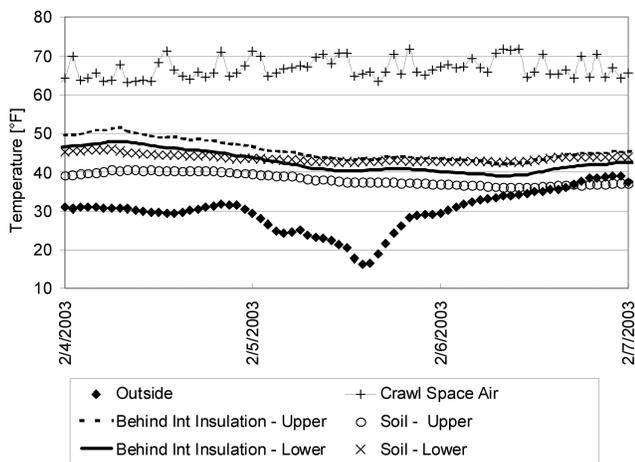


Figure 6 Observed hourly average temperatures, House 2 wall section, February 4-6, 2003.

negative slope in the correlation of temperature difference across the block wall and exterior insulation against total temperature difference. Clearly, this wall is influenced by nonconductive effects. Air leakage across the wall or air circulation within the wall are likely factors.

Inspection of detailed time-series data for the House 2 wall system helps provide an explanation of this non-conductive behavior. Figure 6 displays hourly temperature data during a midwinter period for the wall in House 2. Throughout this period, the soil temperature at 48 in. (1219 mm) below grade remains warmer than that at 12 in. (305 mm) below grade, as expected given the moderating effect of soil depth. However, the inner face of the concrete block (behind insulation) is colder at the lower level than at the upper level, contrary to expectations.

Air leakage into the wall alone seems unlikely to produce this pattern. The cold block face temperatures low on the wall cannot be the result of air leakage directly through the wall, since the soil at that level is warmer than observed wall temperatures. Alternatively, if air were leaking down the wall cavities from grade level, it seems likely, though not certain, that the cold airstream would yield block face temperatures at the 12 in. (305 mm) below-grade level as cold or colder than those at 48 in. (1219 mm) below grade.

Thermosiphoning, or the circulation of air within the block cavities driven by temperature-induced density differences, provides a better explanation for this pattern. In this scenario, air that is cooled by heat loss through the above-grade exposed part of the wall moves down the outer face of the block cores, cooling the bottom of the wall, and moves up

the inner face of the cores as it gains heat from the crawlspace, thus systematically producing lower temperatures lower on the wall. The observation of colder temperatures at the block face than at the soil is the result of the insulation on the outside of the block, which retards cooling of the soil by the cold air in the cavity. Air leakage and thermosiphoning may, of course, both be acting on the wall. The temperature relationships identified in Figure 6 are typical of the behavior of the House 2 wall system during the period when outdoor temperatures remain colder than the wall system.

Calculated Heat Loss

Total seasonal heat loss across each wall section, as calculated from measured temperatures and nominal thermal conductance, is presented in Table 2. For ease of comparison, the results are extrapolated from the observed outdoor conditions at each site to 5000°F heating degree-days (°FHDD), (2778°CHDD). The heat loss for these wall sections is shown to be small compared to the heat loss predicted for the same wall section exposed above grade. This result is expected, given the effects of soil in mitigating heat loss.

The estimated heat loss for the lower wall location in House 2 is strikingly large. Both the magnitude and the fact that the value for this location is larger than that for the upper measurement location on the same wall are results of the very cold temperatures observed on the face of the wall and are attributed to the thermosiphoning and/or air leakage affecting this location.

The heat loss estimate for the lower measurement position on the internally insulated wall in House 1 is, unexpectedly, larger than the comparable value for the internally uninsulated wall, perhaps due to the effects of air leakage.

While this analysis does not extend to cost analysis, it appears likely that only modest levels of below-grade wall insulation, possibly less than used on these walls, would be required to achieve economically optimized performance.

Apparent Thermal Resistance of Soil and Air

The analysis is taken a step further by calculating an “apparent thermal resistance” value for the soil and for the interior air temperature difference (from the crawlspace air temperature measurement location to the surface of the wall insulation) as shown in Table 3. While based on observed performance of systems, these values cannot be considered estimates of physical properties of the materials involved. In the case of the interior air, the apparent thermal resistance is an indicator of the combined effects of limited air distribution, stratification, and air films. In the case of the soil, the apparent thermal resistance includes some seasonal thermal storage effects. The values of apparent thermal resistance of the air are much larger than air film resistance values. ASHRAE, for example, lists an air film resistance for horizontal heat transfer of 0.68 h ft² °F/Btu (0.12 m² °C/W) (ASHRAE 2001). This appears to be largely the result of stratification and poor mixing of air in the crawlspaces. The implication of these large values is that an assumption of uniform, mixed air temperature in crawlspaces may lead to errors in predicting heat loss through crawlspace wall systems.

The low values for soil in House 2 result from the nonconductive heat transfer effects discussed above.

Absolute Humidity Across Measurement Locations

Data for House 1 show that the monthly average absolute humidity, expressed as humidity ratio, at locations against the masonry wall is almost always higher than that of the outdoor air or crawlspace air, as shown in Figure 7. Since moisture moves in the direction of decreasing absolute humidity, this indicates that the walls are moisture sources at most times. Only the upper location on the internally uninsulated wall shows values comparable to those of the interior crawlspace air.

Table 2. Calculated Heat Loss in Crawlspace Walls

Home & Wall Type	Nominal Thermal Resistance of Wall, R (RSI) <i>Note 1</i>	Thermal Resistance Used for Heat Loss Calculation, R (RSI)	Depth Below Grade, in. (mm)	Heat Loss @ 5000 °FHDD (2778°CHDD), Btu/ft ² (MJ/m ²)	Fraction of Heat Loss Compared to Same Wall Above Grade
House 1 Internally Uninsulated	8.8 (1.55)	Block + Exterior Fiberglass 10 (1.77)	10 (254)	4,651 (52.84)	0.34
			30 (762)	1,634 (18.56)	0.12
House 1 Internally Insulated	18.8 (3.31)	Interior Fiberglass 10 (1.77)	10 (254)	3,920 (44.53)	0.62
			30 (762)	1,965 (22.32)	0.31
House 2 Crawlspace	14.5 (2.55)	Interior Fiberglass 10 (1.77)	12 (305)	4,858 (55.19)	0.59
			48 (1219)	5,736 (65.16)	0.69

Note 1: Nominal wall R-values do not include soil or air films.
R-value units are h ft² °F/Btu
RSI units are m² °C/W

Table 3. Apparent Thermal Resistance Values for Interior Air and Soil

Home & Wall Type	Nominal Thermal Resistance of Wall, R (RSI)	Depth BG, in. (mm)	Apparent Thermal Resistance of Interior Air, R (RSI)	Apparent Thermal Resistance of Soil, R (RSI)
House 1 Internally Uninsulated	8.8 (1.55)	10 (254)	2.9 (0.51)	12.0 (2.11)
		30 (762)	10.8 (1.90)	50.0 (8.81)
House 1 Internally Insulated	18.8 (3.31)	10 (254)	2.1 (0.37)	13.4 (2.36)
		30 (762)	6.9 (1.22)	41.0 (7.22)
House 2	14.5 (2.55)	12 (305)	5.5 (0.97)	6.7 (1.18)
		48 (1219)	4.6 (0.81)	9.5 (1.67)

R-value units are $\text{h ft}^2 \text{ }^\circ\text{F/Btu}$
RSI units are $\text{m}^2 \text{ }^\circ\text{C/W}$

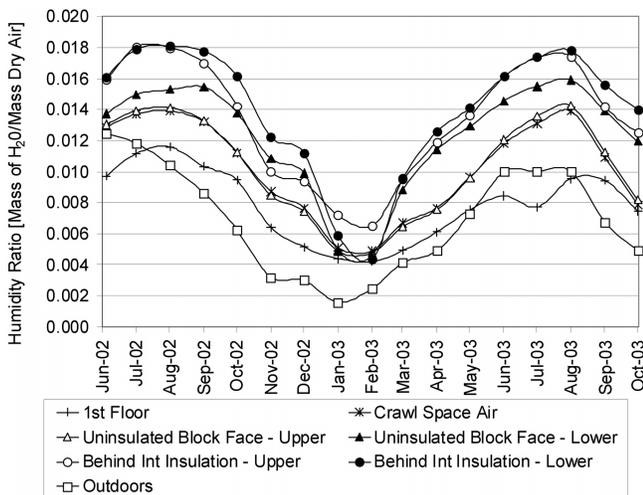


Figure 7 Monthly average humidity ratio, House 1. Note: Upper location is 10 in. (254 mm) below grade, lower location is 30 in. (762 mm) below grade.

During radon fan depressurization in January and February 2003, the humidity levels behind the interior wall insulation drop sharply to about the level of crawlspace air. This is an indication that air from the crawl space and/or outdoor air is passing behind the insulation.

The pattern prevalent before and after the radon fan depressurization period indicates the moisture source is strongest at the bottom of the wall. The probable mechanisms for moisture entry include capillarity and diffusion from the footer into the bottom of the wall system. The lack of an elastomeric coating or a capillary break around the footer or between the footer and wall may be a significant design factor.

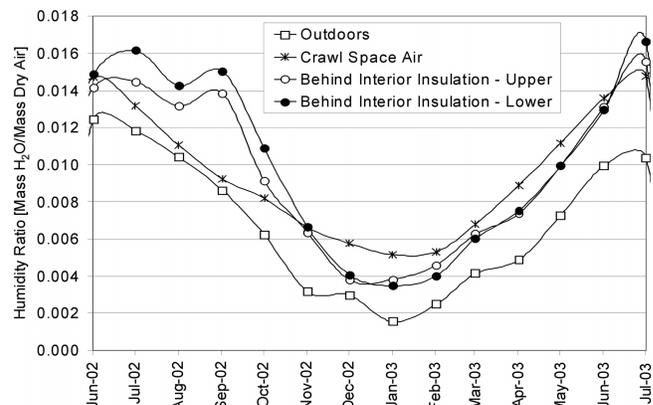


Figure 8 Monthly average humidity ratio, House 2. Note: Upper location is 12 in. (305 mm) below grade, lower location is 48 in. (1219 mm) below grade.

Air leakage upward through the imperfect caulk seal observed at the crawlspace floor perimeter is also a likely contributing factor. The presence of a vinyl vapor-retarder facing on the interior insulation accentuates humidity ratio differences between the wall and interior air.

The pattern for House 2 is different (see Figure 8). Early in the observation period, the humidity ratio is highest behind the wall insulation, demonstrating once again that the wall is a moisture source, probably strongest at the bottom of the wall. After November 2002, crawlspace air humidity surpasses that at the wall locations. This wall is more closely coupled to the outdoor environment than the wall in House 1, since it has

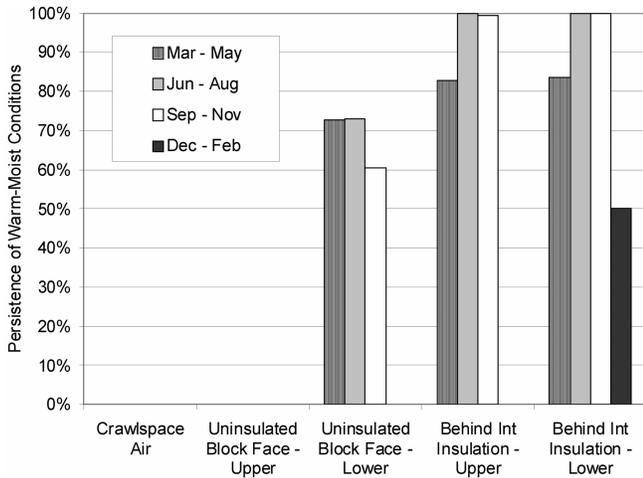


Figure 9 Incidence of warm-moist conditions (>90% RH, >55°F [13°C]), House 1, June 4, 2002, through October 21, 2003.

directly exposed concrete block above grade and experiences air leakage and/or thermosiphoning, as discussed above. We suspect this coupling holds the wall closer to the absolute humidity of the outdoor air, even if the bottom of the wall experiences moisture uptake similar to that of House 1. The crawlspace interior air is more humid than the wall surfaces for many months and therefore must be humidified by sources other than the wall system. Again, the presence of a vapor-retarder facing on the interior insulation means the wall and air are slower to come into equilibrium with one another.

Prevalence of Warm-Moist Conditions

We have characterized the walls studied using conditions of 90% relative humidity combined with temperatures of 55°F (13°C) or greater as an indicator of warm-moist conditions that may support mold growth. Several species of molds found in the built environment appear significantly more likely to appear at temperatures and humidity levels above these minimums (Clarke et al. 1999). Note that this indicator is based only on psychrometric conditions, while other factors, such as the nature of nutritive substrates, also affect the development of mold. No actual mold growth was observed in the crawlspaces in this study.

Figure 9 and Figure 10 show the results of this characterization. The highest incidence of warm-moist conditions occurs during warm seasons, when surface temperatures are typically warm. This indicates that the partial conditioning of crawlspace air is insufficient to limit moisture levels in the wall systems, and suggests that warm-moist conditions are driven more by moisture sources within the walls than by cold-weather condensation. This analysis shows that the elevated moisture present in these wall systems could have a negative impact on the homes by supporting mold growth and empha-

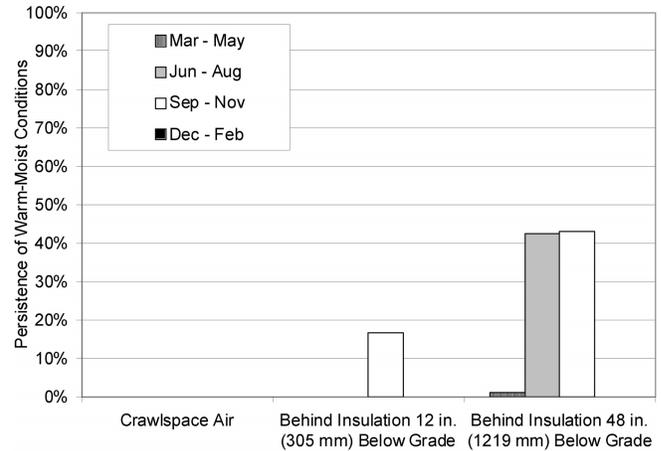


Figure 10 Incidence of warm-moist conditions (>90% RH, >55°F [13°C]), House 2, May 16, 2002, through July 16, 2003.

sizes the need to find improved methods for controlling moisture in unvented crawlspaces, including the entry of soil moisture through crawlspace wall systems.

Such moisture control may include isolation of the footer from moist soil and/or isolation of the footer from the wall system using waterproofing and capillary break materials. Additionally, the edges of vapor retarders on crawlspace floors should be sealed to the walls to prevent entry of moist air.

CONCLUSIONS

Below-grade heat loss from crawlspace walls is much less than from similar above-grade walls, as expected. The thermal mass of exterior soil and temperature stratification of interior air both have a large apparent effect on foundation wall heat loss, and both should be considered in performing thermal performance predictions. Nonconductive thermal behavior, including in particular internal air circulation (thermosiphoning) in concrete block cores, can significantly degrade the performance of foundation walls. Design and construction methods to minimize air leakage and thermosiphoning should be used as possible.

Concrete block crawlspace walls, even when high-quality elastomeric coatings and drainage are used on the exterior wall surface, can behave as moisture sources for most of an annual cycle. Moisture sources in walls of the type studied are stronger near the bottom of the wall, and the mechanisms for moisture entry into wall systems probably include capillary movement and diffusion of moisture through the footers.

Crawlspace walls, as studied, may experience psychrometric conditions conducive to mold growth for significant periods, especially during the spring, summer, and fall. No actual mold growth was observed in the crawlspaces in this study.

Crawlspace walls should be designed to resist moisture entry from soil. In particular, inclusion of capillary breaks between footer and wall and thorough air sealing against air leakage at the floor-wall joint and all other below-grade construction joints is advised.

ACKNOWLEDGMENTS

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