Field Monitoring of the Hygrothermal Performance of Interior Basement Insulation Systems

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ABSTRACT

An uninsulated basement can contribute a significant fraction of a house's total heating load: insulating the basement can provide significant energy and cost savings, as well as the potential for more useable space. However, traditional interior basement insulation systems have resulted in a large number of moisture-related failures of the wall system, including significant mold problems. In this research, eight different interior basement insulation systems were installed in a model house in the Chicago, IL area and monitored, including stud walls with fiberglass and polyethylene, rigid foam insulation, rigid foam plus insulated stud walls, rigid fiberglass with a variable permeability facer, and roll fiberglass blanket with perforated facer. In the first year of monitoring, the insulation systems were tested under normal conditions to determine baseline performance. In the second year, a basement water leak was simulated, in the form of a wetting system injecting water into all insulation assemblies. The hygrothermal responses of these walls were compared under both conditions. Due to low humidity interior conditions, none of the tested systems experienced failures. Data showed that the concrete wall and/or exterior soil environment was a source of moisture, even after two years of drying prior to installation of the insulation. This exterior to interior moisture flow highlights the risk of the stud frame/polyethylene assemblies (walls 1 and 2), which place a vapor impermeable layer between the concrete wall and the interior. Some assemblies had very rapid drying rates due to an air leakage path to the interior, but under less favorable operating conditions, moisture issues might result.

Introduction

As high performance houses progress towards lower energy use, heat loss through the foundation must be minimized. Including the basement within the building enclosure is the recommended practice, resulting in improved airtightness, recovery of mechanical equipment losses, and additional conditioned square footage. However, the increased use of basements as finished space has resulted in more moisture-related failures of their wall insulation systems (Building Science Corporation 2002).

In an effort to increase understanding of the hygrothermal performance of interior basement insulation systems, a test basement with multiple interior insulation options was set up in the Chicago area. The eight assemblies included stud walls with fiberglass and polyethylene, rigid foam insulation, rigid foam plus insulated stud walls, rigid fiberglass with a variable permeability facer, and roll fiberglass blanket with perforated facer. Although exterior insulation of basement walls is a solution that will minimize problems, builder adoption of this technique is rare, resulting in this focus on interior insulation systems.

Physics and Historical Failures

Water Transport Mechanisms

Moisture transport and accumulation are critical to the performance of basement insulation: the mechanisms at work, in roughly decreasing order of transport rate, are: bulk water flow, capillary flow, air-transported moisture, and vapor diffusion. This order also suggests requirements for drying mechanisms: if an assembly is wetted by one mechanism, using a slower mechanism may be insufficient to prevent accumulation unless drying is allowed for long periods between rare wetting events.

Bulk water entry is the most critical problem, due to the high loading that that can result. Typical paths for bulk water entry include inadequate surface drainage, leakage through cracks, or buildup of hydrostatic head below grade. A 1996 study (CMHC 1996) linked the majority of mold problems in basement walls to inadequate surface drainage (e.g., improper grading, disconnected downspouts). Poor drainage also results in greater capillary loading through concrete basement walls and footings, especially when dampproofing and capillary breaks are not present or are inadequate. After capillary transport, air transport is the next most important. Air transported moisture will accumulate in an assembly if moisture-laden air comes in contact with a surface below the dewpoint; typically problems are seen when interior air is allowed to bypass the insulation and comes in contact with cold exterior sheathing or structural materials. Finally, vapor diffusion is the slowest moisture transport mechanism. In common building applications, air transport can move moisture at a rate an order of magnitude faster than vapor diffusion; however, vapor diffusion can still cause failures if inadequate drying is available. All of these mechanisms work interactively to move moisture between the interior space, the insulation system, and the above and below grade environments.

Soil Thermal and Moisture Conditions

The below-grade environment is significantly different than the above grade environment. The below grade portion must contend with soil contact: due to thermal mass, soil surrounding a foundation has a temperature distribution that varies with season and depth. Deep ground temperatures are constant, but temperatures closer to grade show a damped response to daily outdoor air temperature changes as well as a seasonal phase shift. As a result of the phase shift, temperatures at the bottom of a foundation wall are typically at their minimum during early summer. Soils are typically at or near 100% RH throughout the year (Crocker 1974); combined with dampproofing on the outside of the wall, this leaves the interior as the only available drying direction. In addition, the temperature of the lower portion of a basement wall is often below the dew point of outdoor air in early summer. There is a potential for summertime condensation on this surface, if interior dewpoints are not controlled.

Foundation Insulation Failures

Design of interior insulation systems are often based on assemblies used above grade, with a low permeance material, such as polyethylene, on the interior side of the assembly. The purpose of this vapor barrier is to prevent vapor-transported moisture (and if properly detailed, air-transported moisture) from contacting the cold upper portion of the wall in winter. However, it is typically installed full-height, limiting drying in the only available direction (inwards). This is a risk for moisture-sensitive assemblies, given that the concrete wall can be a source of water, either from construction moisture, liquid or capillary flow, or vapor diffusion from the surrounding soil.

As noted above, the concrete surface temperatures at the lower portions of the wall are often below outdoor dewpoint temperatures in early summer: in houses without air conditioning or dehumidification, interior dewpoints will be close to exterior dewpoints. Concrete can safely store moisture due to its porous hygroscopic nature and lack of vulnerable organic components. However, condensation can occur at the lower portions of the wall if vapor or air transported moisture is deposited in an amount that exceeds the storage capacity of the concrete. This would be exacerbated at interior corners, due to colder surface temperatures resulting from the interior-exterior geometry and reduced convective and radiative heat gain from the conditioned space.

Another warm-weather issue is condensation on the exterior side of the polyethylene vapor barrier at the above-grade portion, typically seen in late spring and summer (Karagiozis & Swinton 1995). This is usually seen in newly insulated construction. This problem occurs because moisture stored in the concrete (especially construction moisture) is driven to the interior by the vapor pressure gradient, and is trapped at the vapor barrier layer.

Some code bodies attempted to eliminate the concrete wall as a moisture source by requiring an insulated stud wall with polyethylene on both exterior (between studs and concrete wall) and interior sides. Although this provides a barrier from solar-driven moisture, it results in a very "unforgiving" wall system: given the minimal permeability of both sides, it allows little drying if incidental wetting occurs. If there is an imperfection that allows interior air into the stud bay cavity, condensation and accumulation can occur; this assembly was found to result in a high number of failures (Goldberg 2002) and appears to be losing acceptance. Furthermore, the exterior layer of polyethylene eliminates the moisture storage capacity available in the concrete wall; entry of moisture-laden interior air into the stud bay results in condensation in the insulation assembly as opposed to storage in the concrete. The effect of the storage capacity of the concrete wall has been demonstrated by research on assemblies with high vapor permeability but low air permeability, such as fiberglass covered with spun-bonded polyolefin or low-density spray urethane foam (Goldberg 2002 & 2004). These products gave acceptable performance under some conditions, while the same assemblies with polyethylene at the concrete-insulation interface accumulated condensation at the above-grade portion of interior face in winter.

These failures reflect the challenges of foundation wall insulation; Timusk & Pressnail (1997) proposed a solution to deal with the contradictory demands of the above-grade and below-grade portions by using two different assemblies, one above grade and one below. Although this approach seems promising, it has not been adopted by the industry. Exterior insulation of foundations remedies all of the problems noted above (control of surface condensation, inwards vapor drive) and often explicitly addresses bulk water drainage as well. However, builder adoption of exterior systems has been low, due to cost and construction sequencing issues.

Experimental Setup

Test House Description

A model house in the Chicago, Illinois area was used in this research; the test walls were installed on the south basement wall. The basement wall is nine-foot tall poured concrete with spray-applied dampproofing on the exterior and no visible bulk water leakage; downspouts and grading adequately direct bulk water away from the foundation. The house was unoccupied for the duration of this experiment. The house had been completed and space conditioned for approximately two years before the installation of the test walls; therefore, construction moisture was not a significant loading of the experimental assemblies.

Walls

Four-foot wide, full-height insulation test panels were installed on the interior of the foundation, with 1-½" foil-faced polyisocyanurate buffer panels between test panels. Buffers were also used in the corners to avoid temperature anomalies in the test panels. The three remaining orientations of the basement were left uninsulated. Panel edges were air sealed to reduce lateral air leakage and thermal edge effects. Southern solar exposure of the above-grade portions of the walls is minimally blocked by vegetation, but is reduced at the bay windows, shading certain test panels. Figure 1 shows the test layout.

Figure 1. Test Panel and Soil Sensor Locations

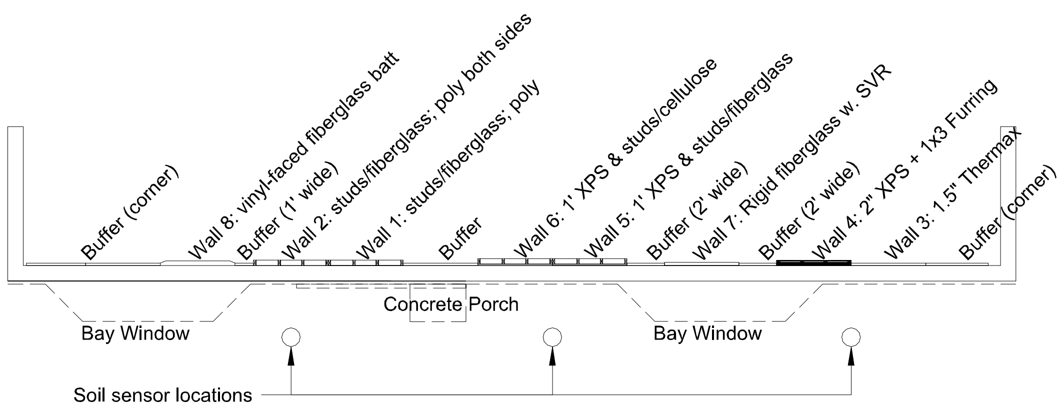


Table 1 describes the tested basement insulation assemblies. These insulation systems are intended for essentially dry basements. Basements with severe moisture problems such as regular bulk water leakage require more extensive measures and are not covered in this research.

Stud frame walls. The two stud frame walls discussed earlier were both tested in this research; they were built with 2x4 framing (16" o.c.) and unfaced fiberglass batts; the assembly has a capillary break (polyethylene foam sill seal) below the bottom plate and is pushed tight to the concrete wall. Although the walls were laterally air sealed, the joint between the top plate and concrete was not sealed. Wall 1 has a 6 mil polyethylene sheet on the interior side of the stud wall; Wall 2 has 6 mil polyethylene sheet on both the interior and exterior sides.

Table 1. List of Wall Assemblies

Wall #	Wall Description	Wall Assembly (Exterior to Interior, from Concrete)
1	2x4 frame with polyethylene interior	2x4 studs 16" o.c. with R-13/RSI 2.3 fiberglass batt insulation, 6 mil polyethylene film
2	2x4 frame w. polyethylene interior & exterior	6 mil polyethylene film; 2x4 studs 16" o.c. with R-13/RSI 2.3 fiberglass batt insulation; 6 mil polyethylene film
3	Foil-faced polyisocyanurate (1.5")	Foil-faced polyisocyanurate (1.5"/38 mm; R-10/RSI 1.8) attached using proprietary PVC plastic channel
4	Extruded polystyrene (2") w. gypsum wall board	Extruded polystyrene (2"/50 mm; R-10/RSI 1.8); 1x2 furring strips 16" o.c. with airspace; ½" gypsum wall board
5	Extruded polystyrene (1") w. 2x4 frame, fiberglass	Extruded polystyrene (1"/25 mm; R-5/RSI 0.9); 2x4 studs 16" o.c. with R-13/RSI 2.3 fiberglass batt insulation; spun-bonded polyolefin housewrap
6	Extruded polystyrene (1") w. 2x4 frame, cellulose	Extruded polystyrene (1"/25 mm; R-5/RSI 0.9); 2x4 studs 16" o.c. with R-13/RSI 2.3 damp-spray cellulose insulation; spun-bonded polyolefin housewrap
7	Rigid fiberglass (2") with polyamide film	Semi-rigid fiberglass board (2-3/8"/60 mm; R-10/RSI 1.8); 2 mil polyamide film and laminated perforated scrim facer
8	Fiberglass roll blanket (3") with perforated facer	Fiberglass roll blanket (3"/76 mm; R-11/RSI 1.9) 4' wide; perforated vinyl facer; 2x2 wood attachment

R-value in $ft^2 \cdot °F \cdot h/Btu$; RSI value in $K \cdot m^2/W$

Foam plastic insulation walls. Wall 3 uses 1-½" thick foil-faced polyisocyanurate insulation, attached to the concrete basement wall using manufacturer-supplied two-piece PVC plastic tee channels. The attachment system creates a small air gap between the insulation and the concrete, between 1/8 and 1/4" (3-6 mm); the effects of this gap will be discussed later.

Wall 4 has 2" thick extruded polystyrene (XPS), attached to the concrete basement wall with fasteners through 1x3 furring strips, 16" o.c. This attachment method resulted in the XPS being held tightly against the concrete wall, with minimal chance of air leakage. To provide code-required fire protection, gypsum wallboard was attached to the furring strips.

Composite walls. Two "best-practice" insulation systems were tested, which combine XPS and a 2x4 frame wall to provide high moisture resistance and high R-value, albeit at a higher first cost. Both walls consist of one inch of XPS directly against the concrete wall, followed by a 2x4 stud wall, cavity insulation, and spun-bonded polyolefin (SBPO) housewrap used as an air barrier. The assembly has a capillary break below the bottom plate. Like wall 4, the foam is fastened tightly against the concrete. A high permeability housewrap is used here instead of a finish material such as gypsum board (as would be required by code for fire protection) to demonstrate the effect of free vapor flow into and out of the cavity. Wall 5 uses fiberglass batt insulation in the stud bays; Wall 6 uses damp-spray cellulose.

Other walls. Two additional insulation systems were included. Wall 7 is a semi-rigid fiberglass board with a polyamide-6 (PA-6) film and a laminated perforated scrim facer. The film is a variable-permeance vapor retarder; it has increased permeability at higher relative humidities (<1 perm dry cup/25% RH; >10 perms wet cup/75% RH). The material is attached tightly to the concrete wall with concrete screws and nylon washers. Although no special effort was made to air seal the system at top and bottom, semi-rigid fiberglass is of a high enough density that airflow through the insulation would be minimal.

Wall 8 is a 4' wide vinyl-faced fiberglass blanket and represents standard practice in many areas of the country. A product with a perforated facer was used here; it is attached to the concrete wall by installing 2x2 nailing strips to the concrete and stapling flaps on the facer to the nailing strips. The air sealing on this wall failed routinely, and air leakage is likely.

Monitoring System

Temperature (T), relative humidity (RH), and electric resistance-based wood moisture content (MC) sensors were installed in the test panels as per Straube et. al (2002); the sensor package varied according to wall construction, with additional sensors added at noteworthy locations. In all walls, the temperature of the interface between the concrete wall and the insulation was recorded at upper (~100"/2.54 m above finish floor), middle (~50"/1.27 m A.F.F.) and lower (~8"/0.2 m A.F.F.) heights. The upper location is roughly at the level of the exterior grade. A temperature sensor was also installed mid-height at the interface between the insulation and the interior finish material (polyethylene, SBPO, or perforated facer). In addition, relative humidity was recorded at the middle height at the concrete-insulation interface. Sensors were installed along the centerline of each test panel, to minimize edge effects.

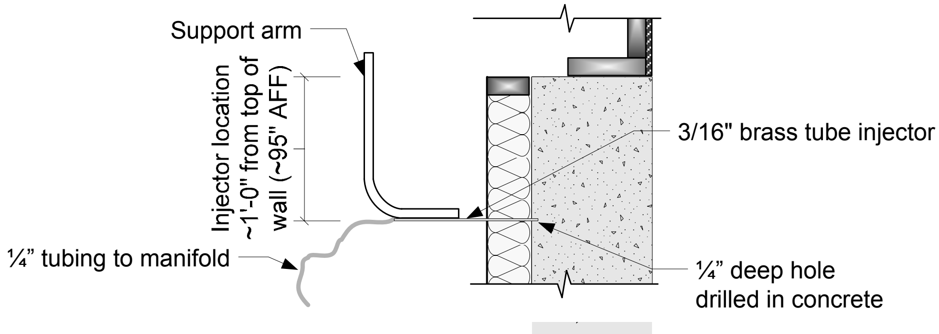
In the test panels with framed cavities (1, 2, 5, and 6), additional sensors were used. Temperature and relative humidity sensors were installed at upper, middle, and lower locations, mid-thickness in the stud bay insulation. In addition, moisture content of a single vertical stud was measured at four locations: at the upper and lower heights, on the exterior and interior sides (3/8"/10mm from the edges of the stud).

Interior and exterior temperature and relative humidity were recorded. In addition, soil temperatures and water potentials (relative wetness) were measured at three lateral locations approximately two feet away from the test wall, as shown in Figure 1. Water potentials were measured using gypsum soil blocks. These sensor packages were installed at three depths (6"/150 mm, 12"/300 mm, and 36"/900 mm), for a total of nine locations. Hourly data was recorded by a Campbell Scientific CR10X system and retrieved with periodic remote downloads; occasional gaps in the data are seen, due to either sensor or logging system failures.

Wetting System

A system that introduces controlled amounts of water into the walls was installed to evaluate the drying behavior of the wall assemblies; it was operated in the second year of the experiment. The wetting system has a water injector at each test panel, fed by a relay-controlled pump. The goal was to equally wet all walls simultaneously; field calibration showed discharge rates within ±10% of the average. The injector assembly is a small-diameter brass tube with a small opening; it was fed through the insulation assembly into a shallow (¼") hole drilled into the concrete wall (Figure 2). The injector was located approximately 95"/2.4 m A.F.F, at the panel centerline. The intent was to simulate a water event originating at the concrete wall, such as a leak or condensation.

Figure 2. Wetting System Injector Detail



Wall 2 was the exception: the injector was fed into the stud bay cavity (between the polyethylene layers) instead of to the concrete-insulation interface. Although the polyethylene ostensibly isolates the frame wall from external moisture sources, failures have occurred by wetting inside the stud cavity; the intent was to provide a similar loading.

The water injection rate was experimentally determined to avoid drainage of excess water to the bottom of the wall and out of the system, and thus was in part a function of the absorption capacity of the concrete. The protocol for each wetting event consisted of running the pump 30 seconds every 30 minutes, over 12 hours, at a flow rate of approximately 18 milliliters/minute test wall, resulting in a wetting volume of 216 ml per test wall per event.

Results

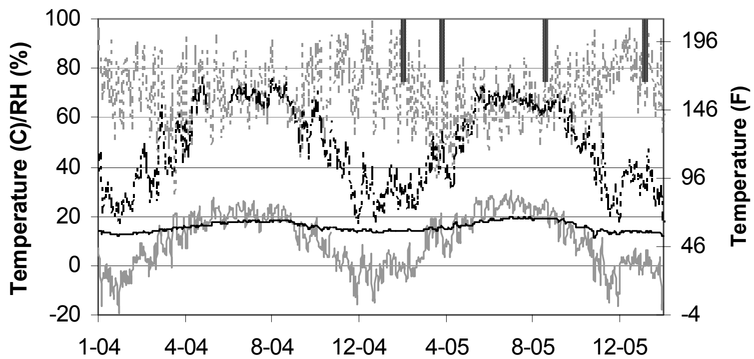
Boundary Conditions and Timeline

Indoor and outdoor temperature and relative humidity conditions are shown in Figure 3 for the two-year monitoring period. Basement interior conditions were not explicitly controlled; setpoint was maintained on the main floor of the house. Winter conditions were in the range of 55-60°F (13-15°C), 20-40% RH; summer conditions were approximately 63-66°F (17-19°C), 60-80% RH. The wetting system was used to cause four distinct wetting events, as shown in the figure.

Soil temperatures showed behavior as predicted by the literature (Hutcheon and Handegord 1983); one interesting illustration of the dramatic difference seen in the below-grade environment was that at the depth of 12"/300 mm, diurnal temperature variations were almost completely damped out. At the shallowest depth of 6"/150 mm, there was very strong damping: the largest daily amplitudes were on the order of 4°F/2°C, while the daily air temperature amplitude was on the order of 40°F/22°C. At the deepest measurement depth of 36"/900 mm, maximum summertime temperature was approximately 72°F/22°C, and minimum wintertime temperature was 41°F/5°C. Measurements at a given depth were quite consistent, with temperatures within approximately ±2°F/±1°C.

Soil water potential sensors showed that the surrounding soil was dryer than the "free drainage" level (i.e., water freely drains out of the soil), but wetter than levels that would typically require irrigation for plants. In addition, correlation between water potential and individual rain events was not seen: this suggests that an immediate wall response to rain wetting in this basement would be due to a bulk water bypass (e.g., a gap at the foundation wall or downspout connected to footing drain), instead of water draining through the surrounding soil. Water potentials at a given depth were essentially identical; effective sensor resolution was lower than differences between measurements.

Figure 3. Interior and Exterior Conditions (Daily Average Values)



Temperature and relative humidity; wetting event timing indicated

Wall Assembly Performance: Non-Wetted Results

Data collected from the year of operation without wetting was examined for consistency. Temperatures at the three concrete wall locations (upper, middle, lower) indicated that all walls had similar thermal behavior (maximum spread of approximately ±2°F/1°C); therefore differences in moisture performance are not likely to result from differences in thermal performance. Minimal difference between the walls would be expected, given the similar insulating values of the assemblies and the small temperature difference across the insulation at middle and lower locations. Dewpoint temperatures at the concrete-insulation interface were calculated from temperature and humidity; they ran parallel to but higher than interior dewpoint; further detail is provided below. This behavior supports the contention that the exterior and/or the concrete wall are sources of moisture, and that drying is to the interior. The relative humidity measurements at this interface were typically in the 60-80% range in the summer and 40-60% range in the winter, which is lower than the 100% humidity expected from literature (Timusk 1984).

Stud frame walls. In wall 2 (double polyethylene), humidity measurements at the concrete-insulation interface showed consistently high relative humidity levels (80-100%), while wall 1 (single polyethylene) has measurements in the 50-70% range. This is expected behavior: wall 2 places an impermeable layer directly against the concrete, allowing moisture accumulation. Stud bay humidity levels were similar in the two walls; they were in the range of 60-75% even at the summer peak—a level that does not foster mold growth. Stud moisture content measurements in both walls remained in the safe range of 8-12% MC, with wall 2 (double polyethylene) showing slightly higher ranges. These measurements were taken at a stud, not at bottom plate, so they would not capture the effect of liquid water pooling at the bottom of the wall. Visual inspections after a year of operation showed some brown staining on the interior face of the fiberglass in both walls, indicating intermittent condensation on the interior polyethylene.

Foam plastic insulation walls. Wall 4 (XPS) had dewpoints at the concrete tracking parallel to but higher than interior, but at lower levels than wall 2 (double polyethylene), showing the greater drying available through the semi-permeable foam (0.5 perms vs. 0.06 perms for polyethylene). Relative humidity was in the 50-80% range. In contrast, the dewpoint behind wall 3 (foil-faced polyisocyanurate) was almost identical to interior dewpoint; this indicates a connection between the air gap behind the insulation and the interior since diffusion is prevented by the foil facings on both sides of the polyisocyanurate.

Composite walls. Humidity levels behind walls 5 (XPS/fiberglass) and 6 (XPS/cellulose) were similar to but drier than wall 4 (XPS). Moisture content measurements of wood framing remained in the safe 8-12% range. Dewpoints in the stud bays were identical to interior dewpoints; this is expected, given the high permeability (57 perms) of the spun-bonded polyolefin interior air barrier.

Other walls. Humidity levels behind wall 7 (polyamide-6/rigid fiberglass) were comparable to those seen at walls 5 and 6 (XPS/frame), indicating similar drying rates to the interior. In contrast, wall 8 (perforated fiberglass blanket) had dewpoints identical to interior dewpoints; this was due to failure of the air sealing.

Wall Assembly Performance: Wetted Results

Four wettings were conducted, in February, April, and September 2005, and January 2006. Only one wetting event will be presented in detail: the September 2005 wetting, which was allowed to dry over the course of five months to January. A total of 0.1 gal/400 ml per wall was applied. The graphs below capture the initial wetting event and resulting rise in humidity, and the drying period. During the drying period, the interior dewpoint fell, following the seasonally declining outdoor dewpoint.

Stud frame walls. Figure 4 shows representative stud bay dewpoints in walls 1 and 2 (frame and polyethylene) at upper and lower locations, with interior dewpoint. The walls are responsive to interior humidity levels, suggesting that a connection exists between the stud bays and interior air, resulting in air leakage drying after wetting. Wall 1 (single polyethylene) dries faster than wall 2 (double polyethylene); wall 1 dried to interior dewpoint by the end of the period.

Foam plastic insulation walls and composite walls. Dewpoints at the concrete-foam insulation interface are plotted for walls 4 (XPS), 5 (XPS/fiberglass), and 6 (XPS/cellulose) in Figure 5. They show similar responses: their drying is much more damped than the frame walls, as would be expected given the direct contact between the foam insulation and the hygrically massive concrete. Wall 4 dries slower than 5 and 6: a predictable result given the lower permeability of the thicker insulation. Wall 3 (polyisocyanurate), however, shows markedly dissimilar behavior: it shows a very brief dewpoint spike, then remains close to interior conditions. This is due to the air space created by the fastening system and resulting liquid drainage behind the insulation system; the other wetting events showed similar responses.

Figure 4. Polyethylene Frame Walls (1 and 2) Dewpoint Data

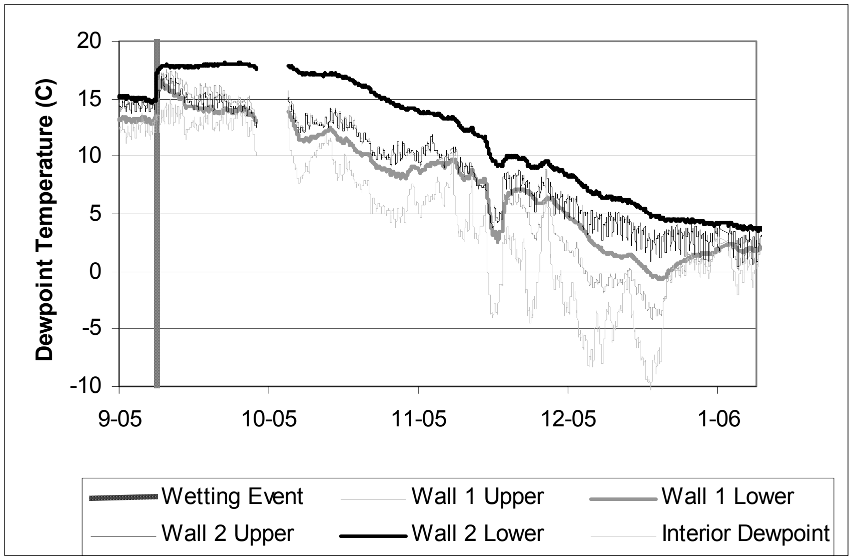
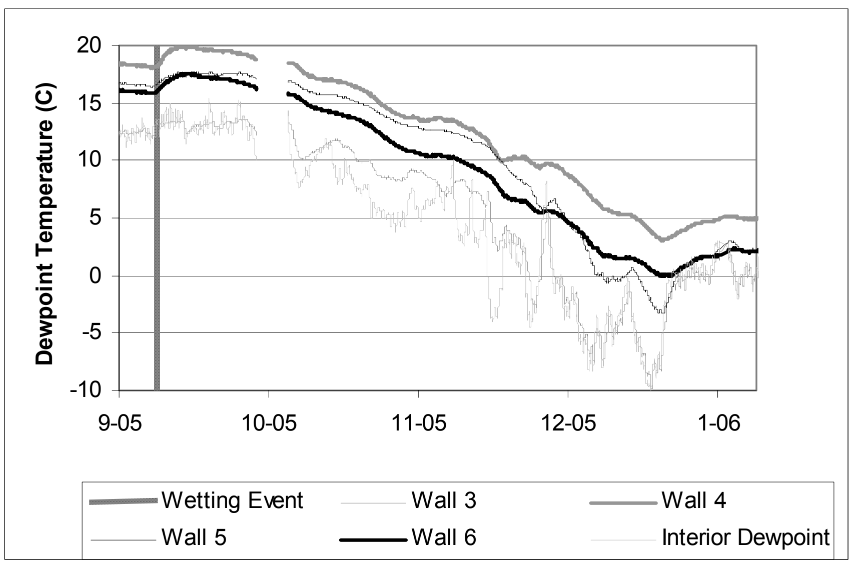
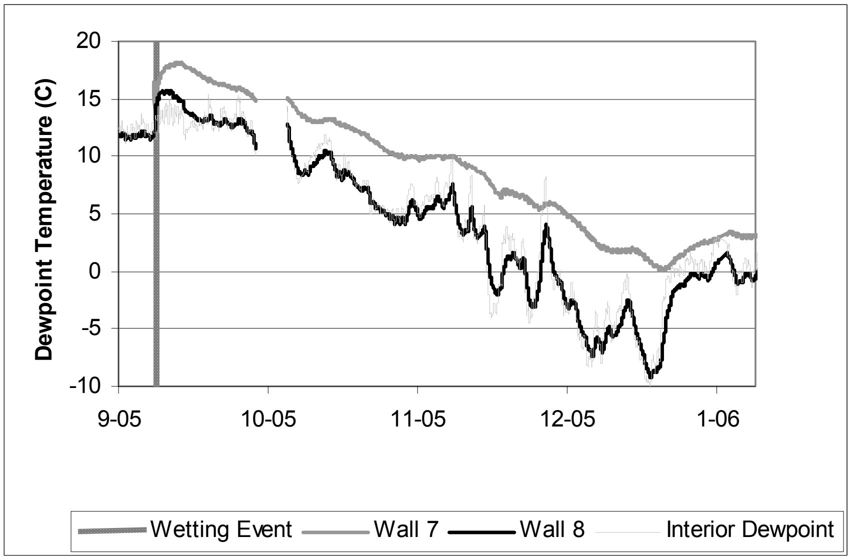


Figure 5. Wall 3, 4, 5, and 6 Dewpoint Data



Other walls. Figure 6 show that wall 7 (rigid fiberglass with polyamide-6 and perforated scrim facer) behaved in a manner similar to walls 5 and 6: a damped response that slowly dried parallel to interior dewpoint. In contrast, wall 8 (fiberglass roll with perforated facer) quickly matched interior dewpoint after an initial rise: this is due to the failure of the air seal.

Figure 6. Wall 7 (PA-6) and 8 (Fiberglass Roll) Dewpoint Data



Analysis

None of these walls were driven to failure conditions, as defined by sustained relative humidity levels over 80% near water-sensitive materials, or wood moisture content levels above 20%. However, the results provide insights into the behavior of interior basement insulation systems in both dry and wet conditions.

Wetting Event Response

The response of the walls to the wetting system combines the effects of the moisture transport mechanisms of drainage, air movement, capillarity, and vapor diffusion. The initial wetting response reveals that construction details can have substantial effects on water accumulation and storage within a system. For instance, humidity levels in wall 3 (polyisocyanurate) dropped quickly due to the gap behind insulation, which provided drainage and air transport of moisture (vapor diffusion through the thickness of the insulation is negligible, given the two impermeable foil facers). In contrast, wall 4 (two inch extruded polystyrene) was installed with the insulation in tight contact with the concrete, creating no easy drainage gap or air cavity. The water flow was directly laterally by the tight contact of the insulation to the concrete wall and only reached the sensor by capillarity.

Differences in initial response were also seen in the frame and polyethylene walls. In wall 2 (two layers of polyethylene), water was introduced at the outer layer of polyethylene instead of the concrete; a good portion of the water drained out of the system due to the lack of storage; staining of the floor at this wall was noted during field visits.

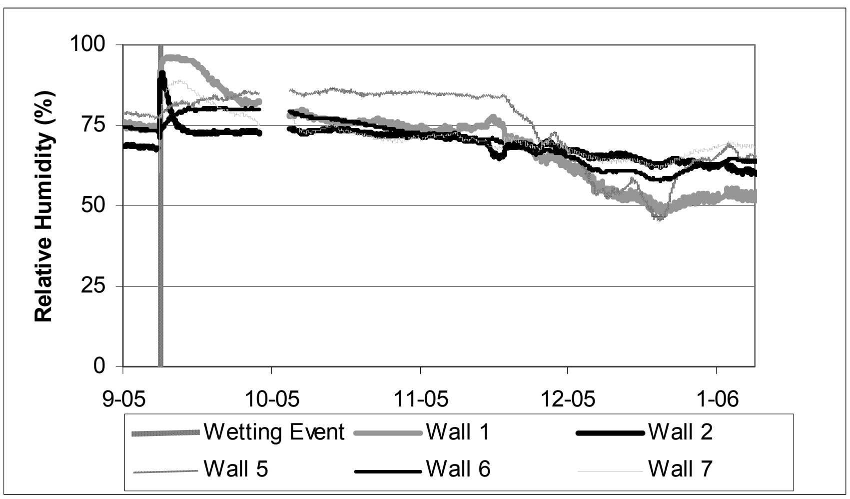
Drying Behavior and Moisture Damage Risks

Understanding the drying behavior of the walls is vital to predicting the likelihood of moisture-related damage in interior insulation systems. For instance, a system that quickly releases its moisture by drainage is unlikely to suffer damage in itself, but in a finished basement with moisture-sensitive materials, it would raise the risk of damage to those materials. A system that retains moisture for long periods would protect interior finishes, but it results in layers of the assembly remaining at a high humidity. This is of great importance if that layer contains moisture-sensitive materials, such as a wood framing. It is of lower importance—but not negligible—if those layers are not moisture sensitive, such as concrete or polystyrene insulation. Although those materials are not mold-sensitive in themselves, microbial growth could occur on surface dust at the interface, given sufficient moisture, temperature, and time.

It should be noted that the observed drying behavior of each wall reflects both the drying ability of the insulation assembly and the retained moisture from the wetting event. As discussed above, differences in construction details can result in significant differences in how much moisture drains out of the assembly and how much is retained.

The overall drying rates of the frame and polyethylene walls (1 and 2), walls 5 (XPS/fiberglass), 6 (XPS/cellulose), and 7 (fiberglass and polyamide-6) were similar (see Figure 7). Relative humidity measurements are plotted, since they are an indicator of mold growth risks. Measurements in these assemblies were in the 60-85% range for the majority of the drying period. Note that none of these assemblies stay at saturation for extended periods.

Figure 7. Relative Humidity in Walls 1, 2, 5, 6, and 7



Stud bay humidity in walls 1 and 2; concrete interface humidity in 5, 6, and 7

It was notable that wall 7 (polyamide-6) dried at a similar rate to walls 5 and 6 (XPS with frame wall and insulation). Fast drying was expected, given the humidity-responsive permeability of the polyamide layer. Calculations based on published data (Gatland 2005) indicated that permeability of the polyamide layer should rise to 80 perms immediately following this wetting event, and remain at 10 perms for most of the drying period. However, diffusion drying is restricted by both the polyamide layer and the perforated scrim. If the perforated scrim has a low permeability, it would be the limiting factor in the drying of the wall.

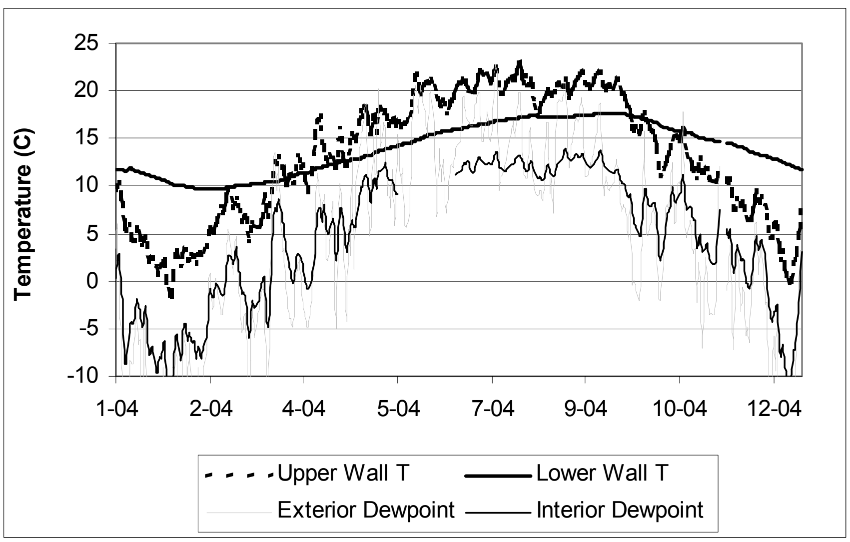
The XPS assembly (wall 4) had a slower drying rate than the above group; the interface between the insulation and concrete dried from 95% to 80% RH over four months. However, as a comparison metric, the humidity at the concrete interface in wall 2 (double polyethylene) remained at 100% for the entire period, even though water was never introduced at that location. This shows that drying does occur through the foam assembly.

The dewpoints in the stud bays of walls 5 and 6 (XPS with cavity insulation) were largely identical to the interior dew point through all wetting events. This demonstrated that although drying was occurring through the XPS layer, the moisture quickly diffused through the high-permeance air barrier. The favorable permeability ratio of the sides of the assembly prevented moisture accumulation and damage to the moisture-sensitive portions of the assembly.

Other Issues

Condensation risks. Figure 8 shows the upper and lower concrete temperatures of a representative wall with interior and exterior dewpoints; measurements for all walls at a given height were close to identical. Due to a lack of interior moisture sources and summer air conditioning, the interior dewpoint is below exterior dewpoint in the summer. As a result, interior dewpoint never rises above the lower basement wall temperature; these conditions eliminate the risk of condensation at this location. However, outdoor dewpoint does rise above the lower basement wall temperature: a non-air conditioned house, or a basement with air communication to the outside, could experience summertime condensation. In addition, greater interior sources could also add sufficient moisture to cause condensation.

Figure 8. Upper and Lower Concrete Temperatures with Dewpoint Data



Similarly, interior winter dewpoint remains below the temperature of the upper portion of the concrete wall due to the lack of interior moisture sources, eliminating wintertime condensation risk. Wintertime relative humidity was equivalent to 15-30% at 70°F/21°C; operating conditions that included occupancy and moisture generation would result in higher interior dewpoints and raise the risk of condensation.

Insulation bottom detail. Some builders using fiberglass blanket insulation (similar to wall 8) have adopted the practice of omitting six inches open at the bottom of the wall, finding that it promotes drying (Zuluaga et. al. 2004). It seems possible that this detail functions by omitting the air barrier at the bottom, which could have positive or negative consequences depending on the indoor conditions. Given the operating conditions of this test, it would dry the insulation. However, at higher humidity conditions, this same detail could increase condensation risks at the top and bottom of the concrete wall surface (in winter and summer, respectively). Furthermore, ingress of radon and soil gasses can be inadvertently limited by interior insulation; this detail would eliminate this effect.

Conclusions and Further Work

No substantial failures of the interior insulation systems occurred during this research, despite four wetting events that introduced a total of 0.6 gal/2200 ml of water per panel. The low humidity conditions of the test dried the wall assemblies and eliminated the risk of condensation damage. Greater volumes of water or higher humidity conditions would greatly increase the risks of failure. It would be difficult to make definitive recommendations on assemblies to implement or avoid; however, drying behavior provides some guidance on the relative risks of these systems.

First, data showed that the concrete wall and/or exterior soil environment is a source of moisture, even after two years of drying before insulation. This exterior-to-interior moisture flow highlights the risk of the stud frame/polyethylene assemblies (walls 1 and 2), which places a vapor impermeable layer between the concrete wall and the interior. The perforated fiberglass blanket (wall 8) and polyisocyanurate system (wall 3) dried at a very rapid rate due to their connection to interior air; however, these results suggest that higher humidity operating conditions could result in condensation problems, depending on seasonal drying and moisture storage capacity of the concrete. As demonstrated in these walls, it is important to understand that air leakage can easily bypass low-permeance vapor control layers if air barrier details are neglected. Finally, the XPS and frame systems (walls 5 and 6) provide exceptional thermal and moisture resistance, but at a higher first cost.

Further work will include an inspection of the assemblies when the experiment is decommissioned and disassembled. This could very well reveal moisture accumulation or damage patterns not evident from the monitoring package. Permeability measurements of assembly components and hygrothermal computer simulation will also be performed.

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