Polyisocyanurate Foam Board vs. **Closed Cell Foam** vs. **Open Cell Foam**

Moisture Performance of Insulated, Raised, Wood-Frame Floors: A Study of Twelve Houses in Southern Louisiana

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ABSTRACT

In flood-prone areas, elevating a building's floor system above the anticipated flood level can significantly limit the extent of property damage associated with flooding. In hot and humid climates, such as the Gulf Coast region, raised floor systems may, however, be at risk for seasonal moisture accumulation, as the majority of residential buildings in such climates are now mechanically cooled. Conditions were monitored over a one-year period in a sample of 12 houses with insulated raised floors, eight in New Orleans and four in Baton Rouge, Louisiana. Eleven of the 12 houses were located in flood hazard areas and were constructed with open pier foundations. Several types of insulation were compared across the sample of houses.

In all houses, crawlspace vapor pressure was essentially the same as outdoor vapor pressure and exceeded indoor vapor pressure from May to October. Moisture conditions within plywood or solid wood subfloors were found to depend on several variables: season, indoor temperature during summer, type of interior floor finish, and type of under-floor insulation. In most cases subfloor moisture levels were higher in summer than in winter. For a given type of insulation and interior floor finish, subfloor moisture content generally increased with decreasing indoor temperature during summer. For a given indoor temperature and type of insulation, subfloor moisture content was generally higher under an impermeable finish, such as vinyl tile, than under a more permeable finish, such as carpet.

Floors with foil-faced polyisocyanurate foam board installed below floor joists displayed no discernible seasonal trend in moisture content and little difference between various interior floor finishes. Subfloor moisture readings were consistently in the 10–14% moisture content (MC) range. Floors with closed cell sprayed polyurethane foam showed only a slight seasonal trend and subtle differences between interior floor finishes. Subfloor moisture contents with closed cell foam in all cases were less than 16% MC in plywood and less than 18% MC in solid wood. Clear seasonal trends were observed in floors with open cell foams and with kraft-faced glass fiber batt insulation. Subfloor moisture content readings above 20%, particularly under impermeable interior floor finishes and with low indoor temperatures during the cooling season, suggest that these insulation types do not reliably protect subfloors from seasonal moisture accumulation. For carpeted floors, where subfloor moisture contents were relatively low, application of vapor retarder paint to open cell foam had no discernible effect. In contrast, for floors finished with vinyl, vapor retarder paint applied over open cell foam appeared to result in lower summertime subfloor moisture content, as compared to that for floors insulated with open cell foam without the paint.

INTRODUCTION

The climate of the Gulf Coast region presents significant challenges to the durability of wood-frame housing. Aside from catastrophic events such as hurricanes and floods, the ordinary environmental conditions include considerable precipitation and atmospheric humidity. In flood-prone areas, building codes and design guidelines typically require that houses be constructed with the floor level at some elevation above the design flood elevation (FEMA 1984, 2000; ICC 2006). Following Hurricane Katrina, flood elevations have been raised in many jurisdictions.

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Figure 1 Houses with pier foundations recently constructed by Habitat for Humanity in New Orleans, Louisiana.

This study focuses on moisture conditions in the subfloors of insulated wood-frame floor systems of 12 houses in southern Louisiana, all of which were built on pier foundations. Adequate elevation for flood protection can be attained with a pier foundation and wood floor system, but little field research has been conducted in the Gulf Coast region to identify best practices for insulating these floor systems. Different thermal insulation systems might be expected to have differing influence on seasonal moisture conditions in these floor systems.

Potential moisture-related problems relevant to floors are wood decay, insect infestation, mold growth, corrosion of metal fasteners, and expansion/contraction damage (e.g., swelling and buckling of wood flooring). Insect infestation is not the focus of this study, although moisture control can limit infestation risk. Some building practices can limit the likelihood of either elevated moisture conditions or pest infestation. For example, concrete piers are usually covered with metal shields to prevent termites from creating hidden pathways directly into the wood framing; these also serve as capillary breaks, preventing moisture transfer from the concrete to the wood framing. In contemporary buildings in the region, preservative-treated wood is commonly used in floor framing to protect against insects as well as decay fungi. Mold growth, fastener corrosion, and dimensional movement of subflooring (each associated with moisture) remain potential concerns in buildings with treated framing.

In untreated wood, it is commonly held that the moisture content (MC) needs to exceed the fiber saturation point (~30% MC, on the basis of the dry mass of wood) for decay fungi to initiate propagation, while at levels below 20% MC their propagation is completely inhibited. The traditional guideline for protection of wood and wood products from decay has been to keep the moisture content below 20% (Carll and Highley 1999). For protection of wood surfaces against mold propagation, it is recommended that the surface relative humidity (RH) be kept below 80% (IEA 1991), and studies have shown that mold growth can occur on wood at moisture contents above 15–18% (Viitanen and Ritschkoff 1991). Corrosion of metal fasteners in treated wood can occur when moisture content exceeds 18–20% (Dennis et al. 1995). For the moisture-related failure modes discussed above, duration at a particular elevated moisture level is also a key factor. Expansion/contraction damage depends on the magnitude of the change in moisture content and the sensitivity of the particular wood product to such changes.

The main sources of moisture exterior to a house include rain, surface water, groundwater, and atmospheric humidity. Indoor sources include occupants (respiration and transpiration), pets, plants, and activities such as showering, bathing, cooking, cleaning, etc. Plumbing leaks can occur inside or outside the house.

Houses with “crawlspaces” or raised floors, for the purpose of discussing moisture management, can be classified into three different types. We refer to houses with open pier foundations (Figure 1) as “open crawlspaces”. Those constructed with continuous perimeter walls that include vents we refer to as “wall-vented crawlspaces.” Finally, those with continuous perimeter walls with no vents we refer to as “closed crawlspaces”.

Previous research on various types of crawlspaces in various climates has shed light on the major causes of moisture accumulation (for an overview, see Rose 2001; Rose and TenWolde 1994; Glass and TenWolde 2007). Site grading and management of roof runoff can largely determine how wet the soil becomes under the structure. The common method of limiting evaporation of moisture from wet soil under a raised floor is covering the soil with a vapor retarder such as polyethylene, typically 0.15 mm (6 mil) or thicker. Ventilation of the crawlspace with outdoor air may raise or lower wood moisture content depending on outdoor vapor pressure, crawlspace vapor pressure, and wood surface temperature. Other factors that affect moisture levels in wood floor members include indoor temperature during the cooling season, floor insulation, and interior floor finish (Verrall 1962; Lstiburek 2008).

A soil cover has been reported as having no discernible effect on moisture levels in wood floors over open pier foundations (Choong and Cassens 1985). Because this type of foundation is very open to airflow, the air temperature and humidity in the crawlspace may differ only slightly from outdoor conditions. In contrast, houses with wall-vented crawlspaces tend to have a significant thermal coupling to the ground and lower rates of air exchange with the exterior. Studies conducted in southern New Jersey (Stiles and Custer 1994), east-central North Carolina (Advanced Energy 2005a; Davis and Dastur 2004), and Baton Rouge, Louisiana (Dastur et al. 2009), have shown that, with the perimeter walls and soil covered with a vapor retarder (thereby eliminating these sources of moisture), during the summer months outdoor air served as a moisture source for the crawlspaces, rather than a moisture sink. Admission of outdoor air during summer months led to high relative humidity in the crawlspaces and, in some cases, in significant moisture accumulation in the wood floor members.

An alternative method of construction is the closed crawlspace, which has perimeter foundation walls without vents. With regard to air and water vapor flow, the crawlspace is treated as part of the interior and is intended to be isolated from the ground and the exterior. The ground and perimeter walls are covered with a vapor retarder, and the crawlspace may be provided with conditioned supply air. A number of studies in various climates have shown that this type of crawlspace can remain safely dry (Advanced Energy 2005b; Dastur et al. 2009; Davis and Dastur 2004; Dutt et al. 1988; Duff 1980; Moody et al. 1985; Quarles 1989; Samuelson 1994; Stiles and Custer 1994).

This method of construction is atypical in flood hazard areas. The high water table and potential for flooding in many parts of southern Louisiana present considerable risks for closed crawlspaces. Building codes require that raised floor foundations in flood hazard areas permit floodwaters to move through the space underneath the building; this can be achieved in closed crawlspaces with breakaway panels or “vents” that normally stay closed but open when floodwaters exert pressure. The long-term ability of these devices to remain sufficiently airtight to provide an essentially closed crawlspace has not been demonstrated. Furthermore, in the event of a flood, the crawlspace will flood, the crawlspace’s perimeter wall will inhibit after-flood drainage and drying, and potential floodwater contaminants and subsequent mold growth will be coupled with indoor air. Because of these hazards, the closed crawlspace is not advisable in flood hazard zones. An open pier foundation is therefore deemed the most robust option on sites prone to flooding.

Open pier foundations are typical of coastal construction and have a long history of use in southern Louisiana. The majority of existing houses with open crawlspaces were however built without floor insulation. Recent building codes have mandated the use of floor insulation in new construction (ICC 2006). For the purposes of managing heat, air, and moisture flows in this type of construction, the crawlspace is considered exterior space, and the floor system functions as the separating layer. A variety of insulation methods are currently in use, both for new construction and for retrofit of existing houses. Conventional practice has been installation of glass fiber batt insulation between floor joists, with the kraft facing up against the subfloor. Alternatives include sprayed polyurethane foam insulation and rigid foam board insulation attached to the underside of floor joists. For air-conditioned buildings in hot-humid climates, outdoor water vapor pressure would be expected to exceed indoor vapor pressure for much of the year. The temperature and humidity conditions in open crawlspaces and the magnitude of the exterior–interior vapor pressure difference (inward vapor drive) have not been documented in the Gulf Coast region to our knowledge. Furthermore, the effects of floor insulation and air-conditioning with regard to moisture management in open and wall-vented crawlspaces have not been studied recently with experimental field monitoring.

The objectives of this study are as follows:

1. Determine how closely the air temperature and humidity conditions in the crawlspaces of raised floor houses are related to the outdoor air temperature and humidity.
2. Determine whether there is a seasonal trend in subfloor moisture content.
3. Determine whether subfloor moisture content increases measurably with increasing vapor permeance of the subfloor insulation, decreasing vapor permeance of the interior floor finish, and decreasing indoor temperature during the air-conditioning season.
4. Determine whether certain types of insulation applied below the floor provide adequate protection against moisture accumulation in the subfloors of a set of raised floor houses.

METHODOLOGY

Selection of Houses

Twelve homes were selected for monitoring. The sample included nine recently-constructed houses and three existing, older houses. Eleven of the twelve houses were located in flood hazard areas and were constructed with open pier foundations. Site conditions were fairly challenging. Only one of the houses had any roof guttering, site grading was generally inadequate to keep the soil under the houses from being wet,

Figure 2 *Pier foundation supporting a raised floor framed with treated lumber.*

Table 1. Characteristics of Houses in New Orleans

House Number	Year of Construction	Exterior Floor Dimensions, m (ft)	Floor Height,[a] m (ft)
1	2006	6.7 × 14.3 (22 × 47)	1.14 (3.8)
2	2007	6.7 × 14.3 (22 × 47)	0.79 (2.6)
3	2006	7.3 × 13.4 (24 × 44)	0.79 (2.6)
4	2006	6.7 × 14.3 (22 × 47)	1.22 (4.0)
5	2007	6.7 × 14.3 (22 × 47)	1.19 (3.9)
6	2006	6.7 × 14.3 (22 × 47)	1.19 (3.9)
7	2006	6.7 × 14.3 (22 × 47)	1.17 (3.8)
8	2007	7.3 × 13.4 (24 × 44)	0.76 (2.5)

[a] Distance from ground to bottom of floor joists.

and a ground vapor barrier was present under only one of the houses. Eight of the homes were in New Orleans; the other four were in Baton Rouge.

The eight houses in New Orleans are located in the Upper 9th Ward, in a neighborhood that flooded during Hurricane Katrina. All were constructed by the New Orleans Area (NOLA) Habitat for Humanity, for post-Katrina recovery of the neighborhood. The two most distant of the houses in the eight-house sample are within 260 m (840 ft) of each other. The homes share a nearly-identical design, with a simple rectangular footprint (see Figure 2). The foundation is constructed with reinforced concrete masonry unit (CMU) piers on a poured concrete grade beam. The front side of each house has a continuous CMU wall; the other three sides are open. Roof gutters and ground covers are not present in any of the eight houses; surface soil type in the neighborhood is sand. Pressure-treated southern yellow pine (SYP) framing is used: 6 by 6 beams rest on the piers and support 2 by 10 floor joists and rim joists. The subfloor is 18-mm-thick (nominally 23/32-in.) SYP plywood, either untreated or treated with alkaline copper quaternary (ACQ), most likely at a retention of 4 kg m^{-3} (0.25 lb ft^{-3}). Houses as constructed had nominal R-19 glass fiber batt insulation supported by metal wires between floor joists with the kraft facing up against the subfloor. Interior finishes were generally vinyl tile in kitchens, bathrooms, and utility rooms, and carpet elsewhere. House 2 had bamboo flooring in place of carpet. House 5 had vinyl tile exclusively. Table 1 lists year of construction, floor dimensions, and floor heights for these eight houses.

The four houses located in Baton Rouge vary in type, floor area, height above ground, and age. Three have open crawlspaces (three sides open but the front of the house with a continuous perimeter wall), and one has a vented brick skirting enclosing the perimeter. Table 2 lists their characteristics. The soil type below houses 9, 10, and 11 was silt loam. The soil

Table 2. Characteristics of Houses in Baton Rouge

House Number	Year of Construction	Type of Crawlspace	Approximate Floor Area, m^2 (ft^2)	Floor Height,[a] m (ft)	Ground Cover	Roof Guttering
9	Before 1930	Open	147 (1580)	0.64–0.91 (2.1–3.0)	No	No
10	Before 1930	Open	163 (1750)	0.79–1.07 (2.6–3.5)	No	No
11[b]	1950	Wall-vented	149 (1600)	0.39–0.43 (1.3–1.4)	Yes	Yes (Partial)
12	2002	Open	158 (1700)	1.07 (3.5)	No	No

[a] Distance from ground to bottom of floor joists.

[b] House 11 floor area given is for the crawlspace; an additional 32 m^2 (350 ft^2) is on a slab-on-grade foundation; roof guttering is only on the back side of the house.

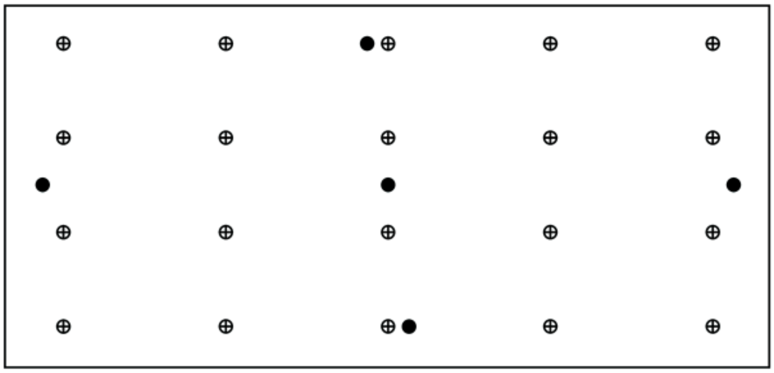

Figure 3 *Locations of moisture pins and thermocouples (crossed circles) and of T/RH data loggers (solid circles) under the floor of a typical house.*

type below house 12 was loam. At all locations in Baton Rouge the primary soil component was silt.

Instrumentation

Air temperature (*T*) and relative humidity (RH) were monitored at 15-minute intervals with battery-powered data loggers. Sensor accuracy is ±0.2°C (±0.4°F) and ±2.5% RH. For each house, three loggers were placed indoors, mounted away from heating/cooling registers and exterior walls to avoid possible thermal fluctuations and gradients. Five loggers were mounted to the bottom of floor joists or beams under each house. Figure 3 is a schematic diagram showing the placement of under-floor loggers for the eight houses in New Orleans. For the four houses in Baton Rouge, the under-floor loggers were also distributed in an essentially spatially uniform manner (similar to, but not identical to, what is shown in Figure 3). In houses with existing glass fiber insulation (all in New Orleans), two additional under-floor loggers were deployed. These additional loggers were fitted with external probe sensors on 2-m (6-ft) cables with the probe inserted into the insulation at a distance of approximately 25 mm (1 in.) below the kraft facing. One logger at each of the 12 building sites was housed in a solar radiation shield and mounted near floor level to monitor outdoor conditions. The 12-month monitoring period began the last week of October 2008 and concluded the last week of October 2009. Data were downloaded from the loggers in May 2009. At the end of the study, the loggers were removed from the houses and data were downloaded.

Wood moisture content was measured approximately twice per month at 20 locations in the subfloor of each house using a digital handheld electrical resistance moisture meter. Because the subfloor would not be easily accessible after insulation was installed, it was necessary to install permanent electrodes or “moisture pins” in the subfloor. We wanted to detect the wettest part of the subfloor, so we selected uninsulated pins, which read the location of highest conductance or greatest moisture content in contact with both electrodes. We also wanted electrodes that could be easily installed in the field, would not suffer corrosion, and would provide reliable contact with the wood over changing moisture conditions for the duration of the study. We selected 16-mm (5/8-in.) #6 stainless steel screws and permanently inserted them in pre-drilled holes in the subfloor at a spacing of 32 mm (1.25 in.). Lead wires soldered to ring terminals were connected to the screws to provide an easy connection to the moisture meter. Moisture content readings determined by the meter for SYP lumber, untreated SYP plywood, and ACQ-treated SYP plywood were calibrated in the laboratory over a range of moisture contents using gravimetric measurements (Glass and Carll 2009). Corrected readings are accurate to ±1.5% MC.

Temperature at the bottom surface of the subfloor was measured at the same frequency and locations at which moisture content was measured. Type-T washer thermocouples were fastened to the subfloor with stainless steel screws. A digital handheld thermocouple reader was used in acquiring temperature measurements.

Ground surface temperature and soil moisture content were measured approximately twice per month at five locations under each house, directly below the T/RH data loggers (Figure 3). A hand-held digital thermometer and soil moisture meter were used for these measurements.

Floor Insulation

Six insulation systems were included over the sample of 12 houses:

A. 51-mm (2-in.) thick rigid foil-faced polyisocyanurate foam insulation installed below the floor joists (nominally R-13). All seams were sealed with foil tape, penetrations were sealed with spray foam, and rim joist areas were insulated with spray foam type D below;

B. 51-mm (2 in.) average thickness of approximately 32 kg m^{-3} (2 lb ft^{-3}) closed-cell sprayed polyurethane foam (SPF) below the subfloor (nominally R-13).

C. 66-mm (2.6 in.) average thickness of medium density [16 kg m^{-3} (1 lb ft^{-3})] open-cell SPF below the subfloor (nominally R-13).

D. 86-mm (3.4 in.) average thickness of low density [8 kg m^{-3} (0.5 lb ft^{-3})] open-cell SPF below the subfloor (nominally R-13).

E. Same as D, except with the addition of a spray-applied vapor retarder paint coating [<30 ng m^{-2} s^{-1} Pa^{-1} (0.5 perm)] after the SPF cure.

F. 160-mm (6.25-in.) kraft-faced glass fiber batts installed between floor joists with the kraft facing up against the subfloor, supported by metal wires (nominally R-19).

Each house was provided with two or more types of insulation, as indicated in Table 3. In Houses 1–8, existing glass fiber insulation (F) was left in place in approximately half the floor area, the other half then being insulated with foam insulation of types A–E. The foam insulations were installed by professional contractors. In the even-numbered houses in the sample of eight, the glass fiber insulation was retained in the front half of the floor area, whereas in the odd-numbered houses the glass fiber insulation was retained in the back half of the floor area. In Houses 9–11, the floors were insulated with two types of foam insulation, each installed under approximately half of the floor area. In House 12, type A was installed below approximately 50% of the floor area, type D below 30%, and type E below 20%.

RESULTS

Environmental Conditions

Exterior Temperature, Humidity, and Precipitation. Figure 4 shows the mean monthly dry-bulb and dew point temperatures from the National Weather Service stations at the New Orleans International Airport (KMSY) and the Baton Rouge Ryan Airport (KBTR) (NCDC 2008a, 2008b, 2009a, 2009b). The 12-month monitoring period (November 2008 – October 2009) was generally warmer and drier than the historic average. For example, the mean dry-bulb temperature in July 2009 in New Orleans was 28.9°C (84.1°F) compared with the 70-year July average value of 28.0°C (82.4°F). For the same location and month, the mean dew point in 2009 was 22.1°C (71.7°F) compared with the 25-year average value of 23.3°C (74.0°F).

Figure 5 depicts monthly precipitation from the same weather stations. In both locations, precipitation was below average for April, May, and June 2009, but above average for August, September, and October 2009. Total precipitation values for the period November 2008 through October 2009

Table 3. Types of Insulation (A–F above) in Floors of Houses (1–12)

	1	2	3	4	5	6	7	8	9	10	11	12
A	✓	✓										✓
B			✓	✓					✓	✓	✓	
C					✓	✓			✓	✓	✓	
D							✓					✓
E							✓	✓				✓
F	✓	✓	✓	✓	✓	✓	✓	✓				

were below average in both locations. Values for this 12-month period and 30-year average values were 1.43 m (56.35 in.) and 1.63 m (64.16 in.), respectively, for New Orleans, and 1.41 m (55.39 in.) and 1.60 m (63.08 in.), respectively, for Baton Rouge.

Interior Temperature and Humidity. Figure 6 depicts mean monthly values of interior dry-bulb temperature and water vapor pressure for the 12 houses together with exterior values for New Orleans and Baton Rouge, recorded with on-site data loggers. Indoor temperatures (mean monthly values) during the cooling season varied across the sample from 20.6°C (69.1°F) to 27.4°C (81.3°F). During the winter, indoor vapor pressures did not differ considerably from outdoor values. However, indoor vapor pressures were significantly lower than outdoor values from May through October and varied substantially between houses (Figure 6b). This interior vapor pressure deficit, or inward vapor drive, is the result of dehumidification associated with air-conditioning during the hot and humid part of the year. The inward vapor drive is strongest during the months of June, July, August, and September. In July, when outdoor vapor pressures peaked at 2970 Pa and 2950 Pa for New Orleans and Baton Rouge, respectively,

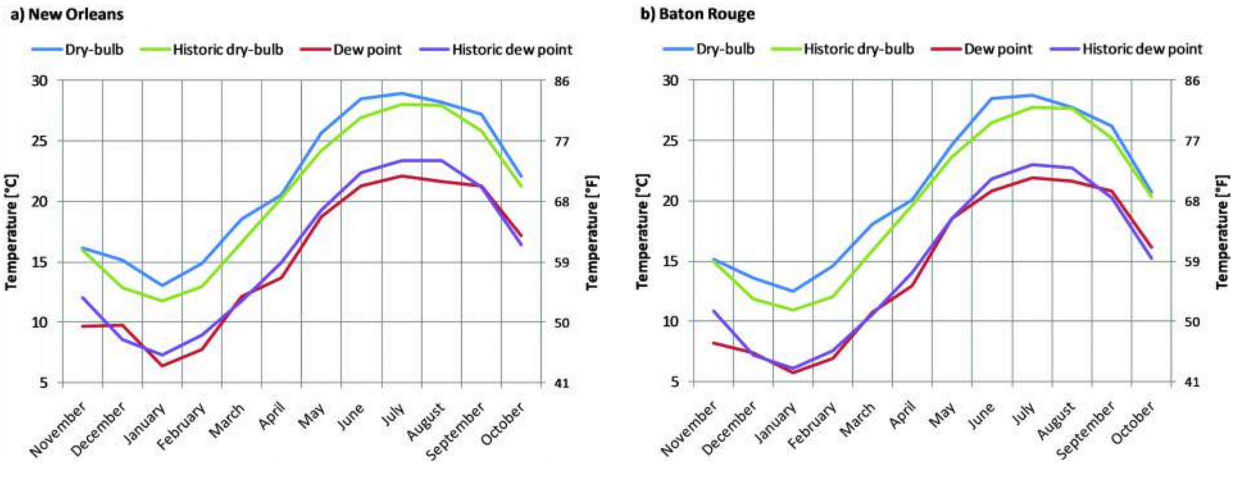

Figure 4 *Mean monthly dry-bulb and dew point temperature in (a) New Orleans and (b) Baton Rouge from November 2008 through October 2009 with historic values.*

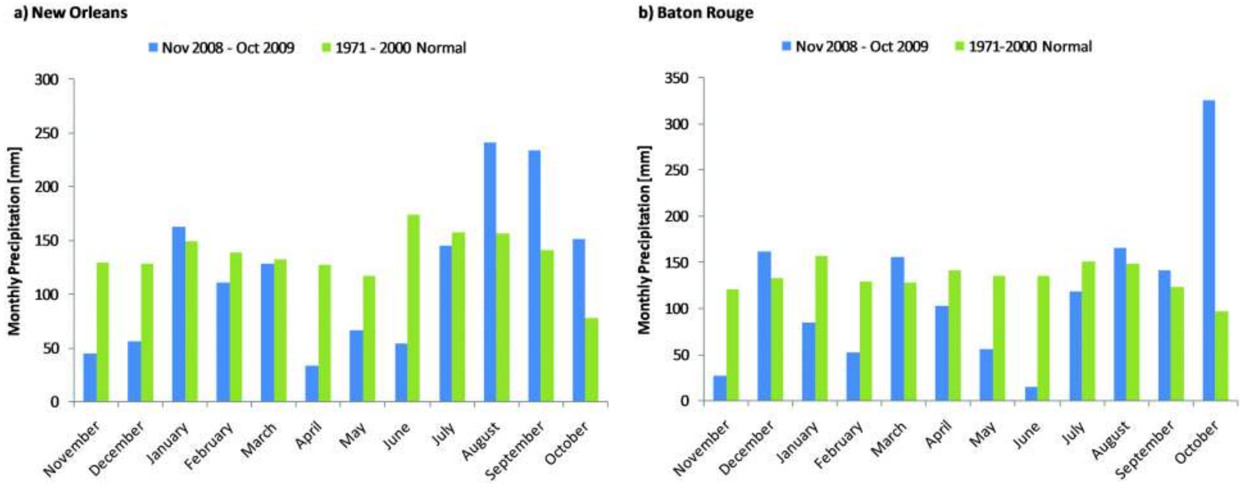

Figure 5 *Monthly precipitation in (a) New Orleans and (b) Baton Rouge from November 2008 through October 2009 with average monthly values from 1971–2000 data.*

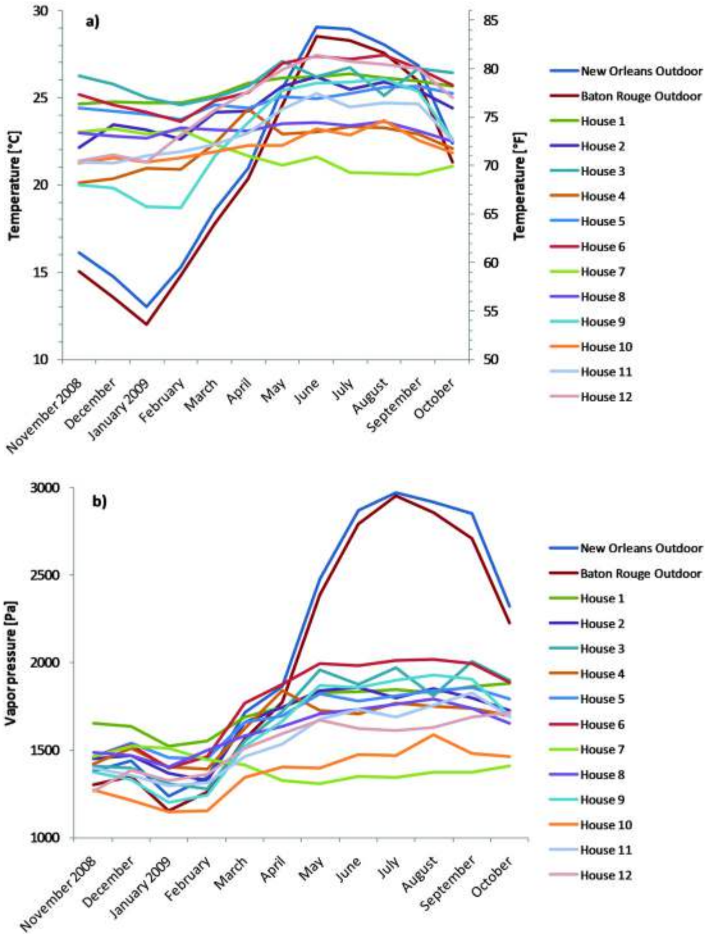

Figure 6 *Mean monthly (a) interior dry-bulb temperatures and (b) water vapor pressures for Houses 1–12 with mean monthly exterior values for New Orleans and Baton Rouge.*

indoor values ranged from 1350 Pa to 2010 Pa. Between-building differences in vapor pressure during the summer were driven, to large extent, by indoor temperature. Figure 7 shows a strong correlation between interior vapor pressure and temperature, a result of air-conditioning. The majority of houses had a summer average indoor relative humidity within a few percentage points of 55% RH.

Crawlspace Temperature and Humidity. Figure 8 shows how temperatures recorded by data loggers varied over the monitoring period for House 1, which has an open crawlspace (as in Figures 1 and 2). Values are plotted as 7-day running averages for three different groups of sensors: outdoor ambient conditions (one sensor), crawlspace conditions (average of five sensors), and conditions within glass fiber batt insulation (average of two sensors). The crawlspace temperature followed the outdoor temperature very closely with slight differences. In cold weather, the crawlspace was slightly warmer than outdoors, and in warm weather, the crawlspace was slightly cooler than outdoors; the temperature differences were barely measurable. In contrast, the temperature within the insulation, about 25 mm (1 in.) below the subfloor, differed considerably from outdoor or crawlspace conditions (as expected). The eight houses in New Orleans, all having open crawlspaces, display the same patterns. The three houses in Baton Rouge with open crawlspaces (like the houses in New Orleans) display only slight differences between outdoor temperature and crawlspace temperature. In contrast, the house with a wall-vented crawlspace (House 11) shows much larger differences between crawlspace temperature and outdoor temperature. The contrast in temperature between an open crawlspace and a wall-vented crawlspace is depicted more clearly in Figures 9a and 9b.

Figure 10 shows mean monthly outdoor and crawlspace water vapor pressures for House 11. Vapor pressures outdoors and in the crawlspace were essentially the same; seasonal differences that can be seen in Figure 10 during the coldest and hottest months are within the measurement error. This was the case for all twelve houses, indicating that the absolute water

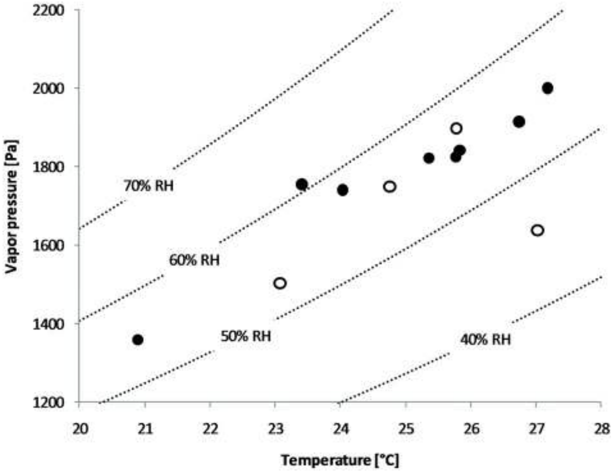

Figure 7 *Interior vapor pressures versus interior dry-bulb temperatures for Houses 1–8 (filled circles) and Houses 9–12 (open circles) averaged from June 1, 2009 through September 30, 2009.*

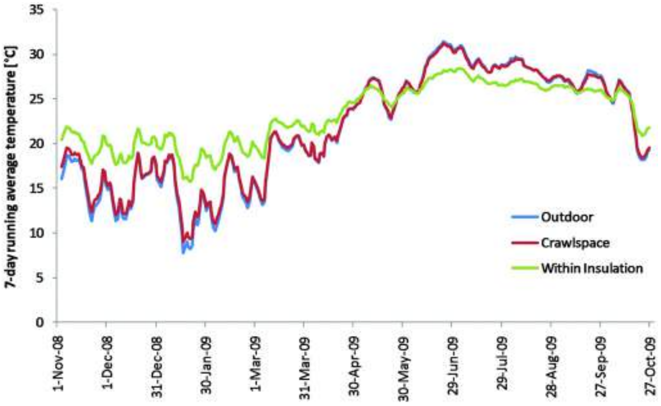

Figure 8 *Seven-day running average temperature from data loggers placed outdoors, in the crawlspace, and within glass fiber batt insulation (House 1).*

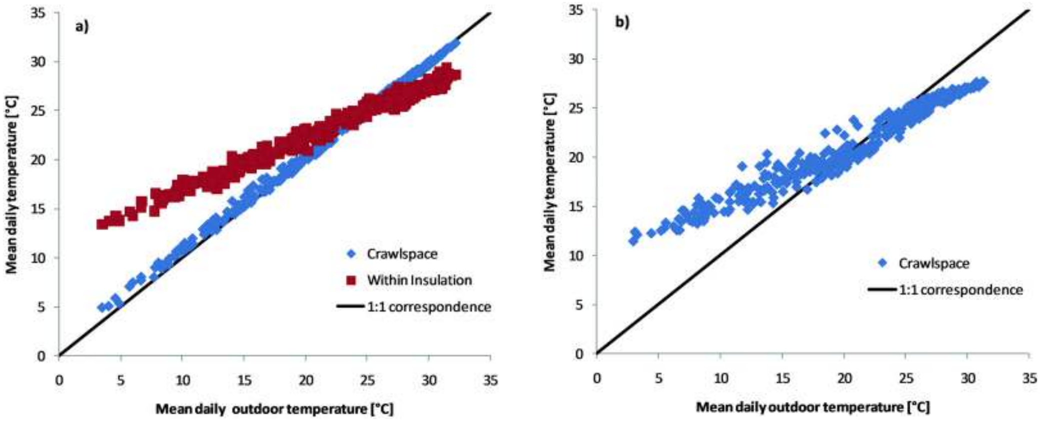

Figure 9 *Daily average temperature of crawlspace air versus daily average outdoor air temperature in (a) an open crawlspace (House 1) and (b) a wall-vented crawlspace (House 11). Average temperature of sensors located within glass fiber insulation is also shown in (a).*

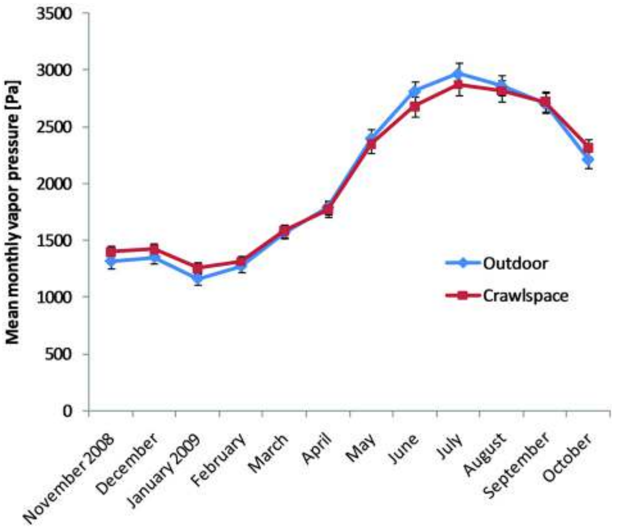

Figure 10 *Mean monthly vapor pressure measured outdoors and in the crawlspace of House 11. Error bars indicate measurement accuracy, based on temperature and relative humidity sensor accuracy.*

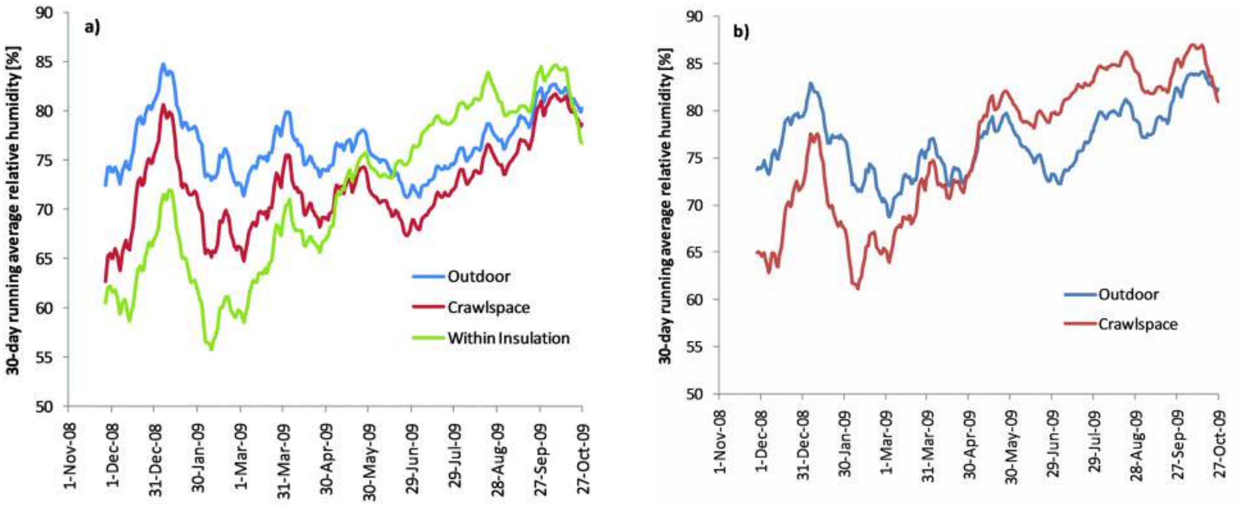

Figure 11 *Figure 11. (a) 30-day running average relative humidity outdoors (recorded on site in New Orleans), in an open crawlspace (House 1), and within glass fiber insulation. (b) 30-day running average relative humidity outdoors (recorded on site in Baton Rouge) and in a wall-vented crawlspace (House 11). Measurement error is ±2.5% RH.*

vapor content did not differ significantly between outdoor air and crawlspace air, regardless of whether the crawlspace was open or wall-vented. For House 11, the combination of the ground vapor retarder and air exchange between the crawlspace and outdoors apparently had the effect of making the vapor pressure the same (the separate effects of the ground vapor retarder and air exchange cannot be discerned). For all the other houses, which lacked ground vapor retarders, the rate of air exchange between the crawlspace and outdoors was apparently high enough that evaporation from the soil did not significantly affect crawlspace vapor pressures. This was the case whether the soil in the crawlspace was wet or dry. Measured soil moisture contents over the monitoring period varied from a few per cent by volume to saturated. Standing water was sometimes observed underneath houses in Baton Rouge, where soils were dominated by silt.

Given that the crawlspace and outdoor vapor pressures were nearly the same and that the temperatures were considerably moderated in the wall-vented crawlspace compared to outdoors, the relative humidity values would be expected to differ. Figure

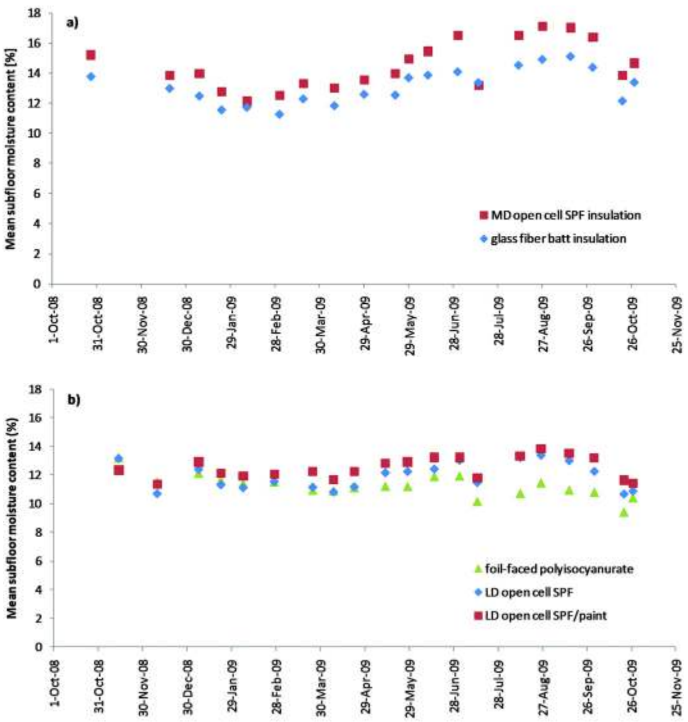

Figure 12 *Mean moisture content in the plywood subfloors of (a) House 5 with two types of insulation and (b) House 12 with three types. The interior floor finishes in House 5 are vinyl tile throughout and in House 12 are carpet, ceramic tile, and hardwood.*

11 shows the 30-day running average RH values for the same two houses discussed above. For the open crawlspace (House 1), RH values in the crawlspace are very close to outdoors for much of the year (considering the measurement error of ±2.5% RH). RH values measured within glass fiber insulation are considerably lower than outdoors from November to April and somewhat higher than outdoors in July and August. For the wall-vented crawlspace (House 11), a similar pattern is observed: RH values in the crawlspace are lower than outdoors from November to March and higher than outdoors in July and August, with 30-day running average values exceeding 80% RH for July and August.

Subfloor Moisture Conditions

Moisture conditions within plywood and solid wood subfloors were found to depend on several variables: season of the year, indoor temperature during summer, type of underfloor insulation, and type of interior floor finish.

Figure 12a shows plywood subfloor moisture content for the two types of insulation in House 5 over the 12-month monitoring period, medium-density open cell SPF and kraft-faced glass fiber batts. The interior floor finish is vinyl tile. There is a general trend of lower moisture content during the winter and higher moisture content during the summer. The months of August and September generally show the highest values and the largest differences between types of insulation. The trend generally is more noticeable in houses with low interior temperature and vapor pressure (large vapor pressure difference between crawlspace and interior), with impermeable floor finishes such as vinyl tile, and with semi-permeable insulations such as open cell SPF. Figure 12b (House 12) serves as an example where there is little change in moisture content over the course of the year. Interior floor finishes in this house (carpet, ceramic tile, and hardwood flooring) are more permeable than vinyl tile. The trend for foil-faced polyisocyanurate foam insulation appears to be a slight gradual decrease in subfloor moisture content. Subfloor moisture levels in floors having open cell SPF with and without vapor retarder paint are similar; the differences are small relative to measurement error. This indicates that the paint had no discernible effect on subfloor moisture levels when interior floor finishes were permeable.

Figure 13 and Table 4 focus on the summer period (when subfloor moisture levels are typically highest) in Houses 1–8. Figure 13a indicates the effects of indoor temperature (air-conditioning) and different interior floor finishes on plywood subfloor moisture content with glass fiber insulation. "Mean subfloor moisture content" is the average moisture content for a particular group of sensors with the same types of insulation and interior floor finish over the peak summer period (August 1– October 1, 2009). "Mean indoor temperature" refers to

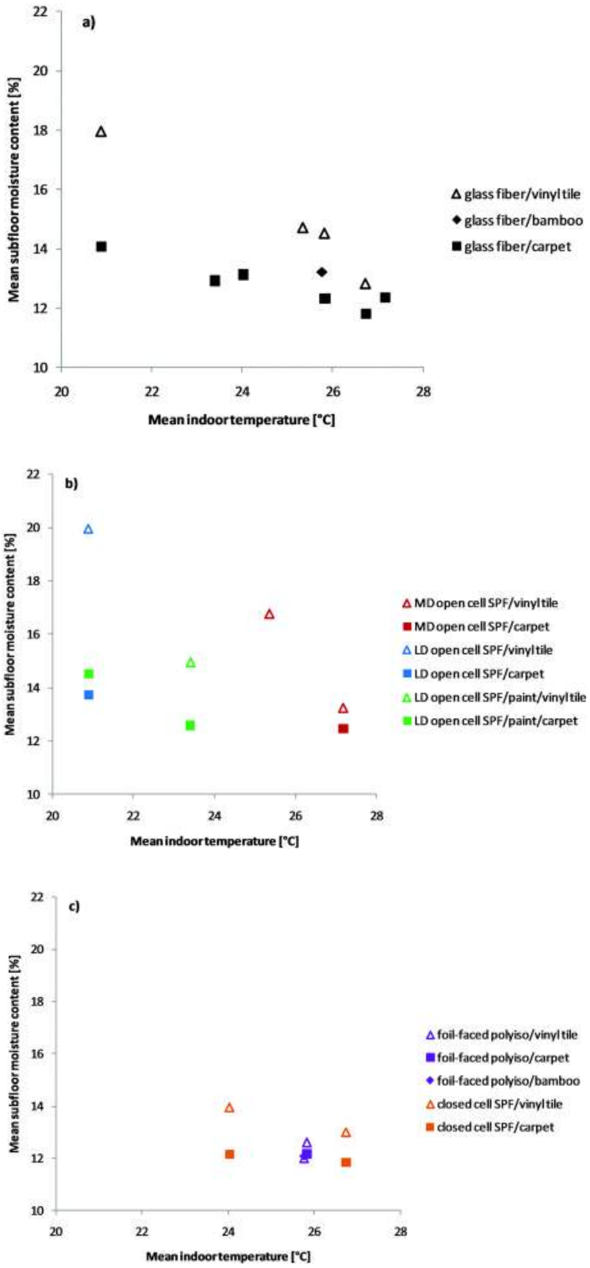

Figure 13 *Figure 13. Mean moisture content readings in the plywood subfloors of Houses 1–8 as a function of mean interior dry-bulb temperature, with various interior floor finishes and types of under-floor insulation: (a) kraft-faced glass fiber batts, (b) open cell SPF with and without vapor retarder paint, and (c) closed cell SPF and foil-faced polyisocyanurate foam board.*

interior dry-bulb temperatures recorded by data loggers averaged from June 1 through September 30, 2009. Although the differences in moisture content are not large, two trends are apparent in Figure 13a: (1) for a given type of interior finish, moisture content generally increases as indoor temperature decreases; and (2) for a given indoor temperature, subfloor moisture content is higher when the floor finish is vinyl tile than when it is carpet. Both of these trends are expected, and the physics are discussed in the discussion section.

The same two trends were also observed in floors insulated with different varieties of open cell (OC) SPF insulation (Figure 13b). For a given type of floor finish, subfloor MC tends to increase with decreasing indoor temperature. This can be seen for floors with medium density OCSPF (vinyl tile, red

Table 4. Moisture Content (%) in Plywood Subfloors of New Orleans Houses Classified by Mean Indoor Temperature (6/1 – 9/30/2009), Type of Interior Floor Finish, and Type of Insulation.[a]

		Mean Indoor Temperature							
Interior Floor Finish	Under-Floor Insulation	20.9°C (69.6°F)	23.4°C (74.1°F)	24.0°C (75.2°F)	25.4°C (77.7°F)	25.8°C (78.4°F)	25.8°C (78.4°F)	26.7°C (80.1°F)	27.2°C (81.0°F)
Vinyl	Foil-Faced Polyiso.					12.6 ± 0.8 (8)	12.0 ± 0.6 (24)		
	Closed-Cell SPF			14.0 ± 1.8 (24)				13.0 ± 1.9 (6)	
	MD Open-Cell SPF				16.8 ± 2.6 (48)				13.2 ± 0.9 (24)
	LD Open-Cell SPF	20.0 ± 6.8 (8)							
	LD Open-Cell SPF/paint		14.9 ± 2.1 (24)						
	Glass Fiber	18.0 ± 5.8 (16)			14.7 ± 1.8 (32)	14.5 ± 2.0 (16)		12.8 ± 1.2 (12)	
Carpet	Foil-Faced Polyiso.					12.2 ± 0.6 (40)			
	Closed-Cell SPF			12.2 ± 0.8 (24)				11.8 ± 0.6 (30)	
	MD Open-Cell SPF								12.5 ± 0.8 (24)
	LD Open-Cell SPF	13.7 ± 1.5 (8)							
	LD Open-Cell SPF/paint	14.5 ± 2.4 (32)	12.6 ± 1.0 (24)						
	Glass Fiber	14.1 ± 2.6 (16)	12.9 ± 0.9 (32)	13.1 ± 1.1 (32)		12.3 ± 0.9 (16)		11.8 ± 0.4 (12)	12.4 ± 0.8 (32)
Bamboo	LD Open-Cell SPF/paint						12.1 ± 0.7 (24)		
	Glass Fiber						13.2 ± 1.5 (32)		

[a] MC values are given as mean (8/1 – 10/1/2009) ± standard deviation, with number of observations in parentheses.

triangles), for floors with OCSPF with vapor retarder paint (carpet, green squares), for the aggregate of floors with vinyl tile finish (triangles of mixed colors), and (to a lesser degree) for the aggregate of floors with carpet (squares of mixed colors). The effect of indoor temperature is evidently more pronounced in subfloors under vinyl tile than in those under carpet. As was the case for floors insulated with glass fiber insulation, in floors insulated with OC foams, subfloor moisture content during summer was, without exception, higher under vinyl tile than under carpet.

Evaluating the effect on subfloor MC of applying vapor retarder paint to open cell SPF requires careful inspection. For carpeted floors (blue and green squares), the differences are small relative to measurement error, indicating that the paint has no discernible effect; this is consistent with the observations above in Figure 12b for permeable interior floor finishes. For corresponding floors finished with vinyl tile, the evidence is incomplete but suggests that vapor retarder paint applied over low density OC foam may be helpful. As indicated in the previous paragraph, the inverse relationship between summertime interior temperature and subfloor moisture content for floors insulated with OC foams and finished with vinyl tile appears notably strong. The sole data point in Figure 13b for low density OC foam with vapor retarder paint under vinyl (green triangle) shows a below-average subfloor moisture content (for floors insulated with OC foam), at an approximately average indoor temperature. If the inverse relationship between indoor temperature and subfloor moisture content is as strong as it appears, the data point suggests that use of vapor

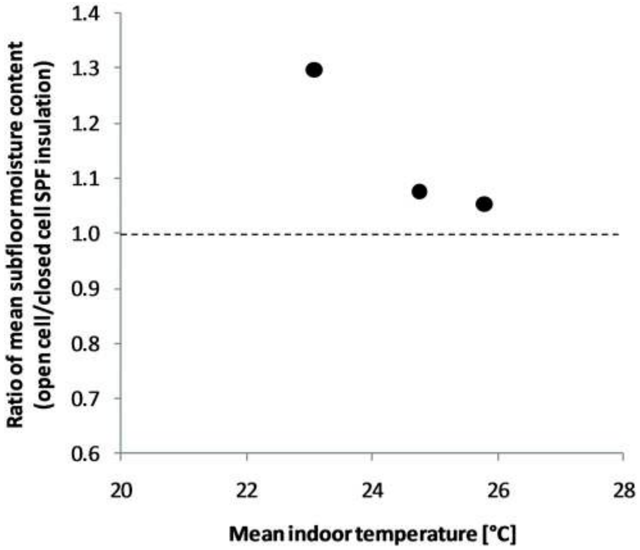

Figure 14 *Ratio of summertime mean subfloor moisture content in floors with medium density open cell SPF to that in floors with closed cell SPF, as a function of summertime mean interior dry-bulb temperature in Houses 9, 10, and 11.*

retarder paint over OC foam is effective when the floor covering is vinyl tile.

Figure 13c shows values for foil-faced polyisocyanurate foam and for closed cell (CC) SPF. The two trends that are evident in Figures 13a and 13b can also be discerned in Figure 13c, although the trends are more subtle and apply only to CCSPF. For CC foam and either vinyl tile (orange triangles) or carpet floor covering (orange squares) there appears to be a (weak) inverse relationship between summertime indoor temperature and subfloor moisture content. As was the case for floors insulated with glass fiber batts and with OC foams, summertime subfloor moisture contents in floors insulated with CC foam are, without exception, higher under vinyl tile than under carpeting. In contrast, for floors insulated with foil-faced foam, the effect of indoor temperature cannot be evaluated because the two houses had nearly identical mean indoor temperatures. Subfloor moisture contents in these floors were all at approximately 12%; interior floor finishes had essentially no discernible effect.

Table 4 presents the subfloor moisture content data in greater detail, providing the standard deviation and number of observations in addition to the mean values. The standard deviations tend to increase as the mean values increase; they are higher when indoor temperature is lower and higher when the interior floor finish is vinyl than when it is carpet.

Houses 9, 10, and 11 in Baton Rouge were each insulated with closed cell SPF and medium density [16 kg m^{-3} (1 lb ft^{-3})] open cell SPF. These three houses had solid southern pine tongue-and-groove floor boards and predominantly hardwood flooring. In all three cases, the mean summertime subfloor moisture contents were higher with open cell SPF than with closed cell SPF. The moisture content calibration for Houses 9 and 10 is somewhat uncertain, as discussed below. However, the relative comparison between CC and OC foam is valid. Figure 14 depicts the ratio of mean subfloor MC in floors insulated with OCSPF to mean subfloor MC in floors insulated with CCSPF, plotted with respect to mean indoor temperature. This ratio increases as temperature decreases. The most likely explanation is that moisture content in floors insulated with open cell SPF increases to a more substantial degree as temperature decreases. Floors insulated with open cell SPF appear to be more sensitive to indoor temperature than floors insulated with closed cell SPF; this observation (made in the sample of houses in Baton Rouge) concurs with observations made in the houses in New Orleans (shown in Figures 13b and 13c).

Moisture meter readings in the solid SYP floor sheathing in Houses 9 and 10 appeared dubiously high in comparison to readings in other houses. Houses 9 and 10 were of pre-1930 vintage and were renovated in 2006–2007. The renovation included adding plywood sheathing over the existing (diagonally installed) board floor sheathing. However, at two locations in House 9 and one location in House 10, the SYP board floor sheathing was absent, and moisture pins had thus been installed on the bottom side of the new plywood. Calibrated moisture readings in the plywood were considerably lower than in the solid boards. The plywood moisture levels were generally consistent with levels observed in other houses; we thus suspected that some surface contamination or aging (or both) was affecting the meter readings taken for the boards. The board surfaces were noticeably discolored (darkened) with age (as can commonly be observed in attics of old houses and on the unfinished interiors of old out buildings such as barns and garages). In addition, professional painters have for decades recognized that the underside of soffit areas of houses, over time, accumulate surface contaminants that interfere with paint adhesion and performance unless washed away during surface preparation for painting. The manner in which moisture readings were taken for this study (with un-insulated "pins" through ring terminals that contacted the wood surfaces) was perhaps particularly sensitive to the effects of age-related surface phenomena. It was not possible to remove any parts of the boards after the fact for testing. We therefore used the plywood MC values as a basis for correcting the solid board MC values. We determined the mean ratio of material-corrected plywood MC readings to board MC readings, taken where the type of insulation and interior floor finish were the same, to be 0.76. We also accounted for the fact that plywood is less hygroscopic than solid wood; at a given relative humidity, plywood has a lower equilibrium moisture content (EMC) than solid wood. The mean ratio of solid SYP EMC to SYP plywood EMC is 1.10, from the data of Lee and Biblis (1976), Glass and Carll (2009), and Zelinka and Glass (2010) for RH values between 60% and 97%. The product of these two ratios, 0.84, was then used to adjust the solid board moisture meter readings. The adjusted values are given in Table 5.

DISCUSSION

Environmental Conditions

The weather over the course of the 12-month monitoring period was somewhat less humid than the past average. For example, the July 2009 mean vapor pressure (calculated from dew point temperature shown in Figure 4) was about 200 Pa less than the 25-year average. The interior conditions, however, displayed considerably more variation across the sample of houses, with values differing by over 650 Pa (Figure 6). During the cooling season, these differences in indoor vapor pressure are primarily attributable to different thermostat set points for air-conditioning. Figure 7 shows a strong correlation between interior vapor pressure and temperature values averaged from June through September. The correlation is not perfect because interior vapor pressure depends on additional factors such as interior moisture generation, interior heat gain (largely associated with roof color, shading, and solar orientation of the building), air-tightness of the building envelope, air-tightness of the duct system, and sizing of the air-conditioning system. No attempt was made in this study to characterize occupant activities, duct leakage, or envelope leakage. In all 12 houses, ductwork was located in unconditioned attic spaces. None of the houses was known to have a stand-alone dehumidifier.

Water vapor pressure within an open crawlspace can be considered a balance involving moisture storage, sources, and

Table 5. Moisture Content (%) in Subfloors of Baton Rouge Houses Classified by Mean Indoor Temperature (6/1 – 9/30/2009), Type of Interior Floor Finish, and Type of Insulation.[a]

		Mean Indoor Temperature			
Interior Floor Finish	Under-Floor Insulation	23.1°C (73.6°F)	24.8°C (76.6°F)	25.8°C (78.4°F)	27.0°C (80.6°F)
Hardwood	Foil-faced polyiso.				10.8 ± 0.5 (16)
	Closed-cell SPF	13.8 ± 1.0 (40)	14.9 ± 0.7 (44)	16.1 ± 0.9 (24)	
	MD open-cell SPF	17.9 ± 3.2 (32)	16.0 ± 1.1 (32)	16.9 ± 1.4 (40)	
	LD open-cell SPF				12.9 ± 0.8 (16)
	LD open-cell SPF/paint				12.9 ± 0.3 (4)
Ceramic Tile	Foil-faced polyiso.				11.4 ± 0.7 (12)
	Closed-cell SPF			15.1 ± 1.5 (16)	
	MD open-cell SPF	21.0 ± 2.2 (8)			
	LD open-cell SPF				13.6 ± 1.7 (8)
	LD open-cell SPF/paint				14.5 ± 0.3 (4)
Carpet	Foil-faced polyiso.				10.4 ± 0.4 (4)
	Closed-cell SPF				
	MD open-cell SPF				
	LD open-cell SPF				12.0 ± 0.5 (4)
	LD open-cell SPF/paint				13.0 ± 0.4 (4)

[a] MC values are given as mean (8/1 – 10/1/2009) ± standard deviation, with number of observations in parentheses.

sinks. Storage refers to moisture uptake and release by hygroscopic materials such as wood. This has a buffering effect on humidity but is less important when sources and sinks are large and when the time scale is longer than about a week (Glass and TenWolde 2009). The major moisture source is evaporation from damp soil. The major sink is air exchange between the crawlspace and the exterior. The observation that water vapor pressure in crawlspaces was nearly the same as in outdoor air is most likely the result of the rate of evaporation from wet soil being small in comparison to the rate of air exchange. This can be shown with a simple calculation. Assuming that the rate of evaporation from the soil is between 0.05 and 0.4 kg m^{-2} day^{-1} (between 0.01 and 0.08 lb ft^{-2} day^{-1}) (TenWolde and Pilon 2007) and that the crawlspace area is on the order of 100 m^2 (1080 ft^2), the air exchange rate would have to exceed 80–640 L s^{-1} (170-1,400 ft^3 min^{-1}) in order for the crawlspace vapor pressure and outdoor vapor pressure to differ by less than 100 Pa, the approximate error in sensor readings. For a crawlspace height of 1 m (3.3 ft), these values correspond to 3–20 air changes per hour (ACH). In comparison, measured airflows in eight wall-vented crawlspaces in the Pacific Northwest ranged from about 1 to 10 ACH with an average of about 5 ACH (Francisco and Palmiter 1996). Actual airflow is expected to be much higher in open crawlspaces. This may explain why a previous study (Choong and Cassens 1985) of three open crawlspaces in Baton Rouge found that a ground vapor retarder had no discernible effect on subfloor moisture conditions. Thus in an open crawlspace, the rate of air exchange overwhelms the rate of evaporation from the soil, and hygroscopic buffering is negligible when air exchange rates are so high.

Subfloor Moisture Conditions

As noted previously, subfloor moisture conditions depended on season, indoor temperature during the cooling season, type of under-floor insulation, and type of interior floor finish. In the hot-humid climate monitored in this study, the predominant direction of water vapor migration in floor assemblies is from exterior to interior during the summer months, as shown clearly in Figure 6. The role of indoor temperature can be considered from two perspectives. First, when insulation is present below the subfloor, the temperature of the subfloor is expected to be fairly close to indoor temperature. The subfloor moisture content is affected by the local relative humidity. For a given vapor pressure at the subfloor, a colder subfloor experiences a higher RH and therefore higher moisture content. Second, indoor temperature and indoor vapor pressure are correlated (Figure 7). Lower indoor temperature corresponds to lower interior vapor pressure and therefore a larger difference in vapor pressure between exterior and interior, or larger inward vapor drive. Moisture accumulates in the subfloor when the rate at which water vapor enters (into the subfloor from the crawlspace) exceeds the rate at which water vapor leaves (to the interior). Impermeable floor finishes such as vinyl tile essentially prevent moisture in the subfloor from migrating to the interior. In summary, the moisture content of the subfloor depends on its temperature, the magnitude of the inward vapor drive, the vapor permeance of the interior floor finish, and the permeance of the under-floor insulation.

Rigid foil-faced polyisocyanurate foam insulation is essentially impermeable. Measured subfloor moisture contents with this insulation type showed no discernible seasonal trend, showed little difference between various interior floor finishes, and were consistently in the 10–14% MC range. It should be noted that in the three houses with this type of floor insulation, relatively high indoor temperatures were maintained during the summer [mean values > 25°C (77°F)]. Nevertheless, foil-faced foam is essentially impermeable, and if installed in an air-tight manner, would be expected to prevent objectionable seasonal moisture accumulation in floors of buildings maintained at lower indoor temperatures during summer.

Closed cell sprayed polyurethane foam insulation is considered semi-impermeable. Published measurements (Kumaran et al. 2002) indicate a slight effect of relative humidity on vapor permeability of closed cell SPF, with values of 2.3 and 3.2 ng m^{-1} s^{-1} Pa^{-1} (1.6 and 2.2 perm-in.) at 10% and 90% RH, respectively. Manufacturers' data (probably derived from dry cup measurements) list values in the range of 0.6–3.7 ng m^{-1} s^{-1} Pa^{-1} (0.4–2.6 perm-in.). Measured subfloor moisture contents showed only a slight seasonal trend and subtle differences between interior floor finishes. Moisture contents in all cases were in safe ranges, being less than 16% MC in plywood and less than 18% MC in solid wood.

Open cell SPF can vary considerably in vapor permeability. According to manufacturer's data (for which test method is not specified), the value for medium density [16 kg m^{-3} (1 lb ft^{-3})] foam is 5.2 ng m^{-1} s^{-1} Pa^{-1} (3.6 perm-in.). For low density [8 kg m^{-3} (0.5 lb ft^{-3})] foam, Kumaran et al. (2002) list a value of 88 ng m^{-1} s^{-1} Pa^{-1} (60 perm-in.) over the entire RH range. Manufacturers of low density foam list permeability values in the range of 8–80 ng m^{-1} s^{-1} Pa^{-1} (5.5–55 perm-in.). The type of foam selected for this study, according to the manufacturer's stated value, had a permeability at the low end of this range. In floors with either medium density or low density open cell foams, subfloor moisture levels were on average higher than in those with closed cell SPF. More pointedly, individual subfloor readings above 20% MC were sometimes observed over periods of two months or longer in floors insulated with the open cell foams included in this study.

The effect of vapor retarder paint applied over open cell SPF was not entirely clear. In floors with permeable interior finishes, where subfloor moisture contents were relatively low, application of vapor retarder paint to OC foam had no discernible effect. In contrast, in floors finished with vinyl tile, OC foam with vapor retarder paint appeared to result in lower subfloor moisture content than OC foam without the paint. We consider this finding (regarding the influence of vapor retarder paint in floors with vinyl tile) to be tentative. The number of data points is not sufficient to state this finding as a conclusion.

In addition, the in-service vapor permeance of the vapor retarder paint is not known with certainty. The paint was listed by the manufacturer as having a permeance of 25 ng m^{-2} s^{-1} Pa^{-1} (0.43 perm) at a recommended dry thickness of 0.025 mm (1 mil). This listed value is most likely based on the dry-cup method (ASTM 2008). A dry-cup value is determined at an average RH of 25% (much lower than ambient RH during summer months in Louisiana), and it is not known whether permeance of the paint film is RH-dependent. For a variety of reasons, further research is needed to determine whether vapor retarder paint, used in conjunction with open cell SPF, provides a reliable moisture control strategy.

Glass fiber insulation itself offers little resistance to vapor diffusion. The kraft facing, however, is rated by the manufacturer at less than 57 ng m^{-2} s^{-1} Pa^{-1} (1 perm), which is most likely based on a dry-cup measurement. Published data (ASHRAE 2009; Burch et al. 1992) indicate that permeance increases with increasing RH. A recent investigation (NAHB Research Center 2010) found values greater than 170 ng m^{-2} s^{-1} Pa^{-1} (3 perm) for both dry-cup and wet-cup methods. In most instances, sheathing moisture levels in floors insulated with glass fiber batt insulation were lower than in floors insulated with open cell SPF. The majority of readings in subfloors of houses insulated with glass fiber batts were below 18% MC. However, with low indoor temperature and vinyl tile, individual moisture contents above 20% were observed for periods of two months or longer. It should be noted that the locations in Houses 1–8 with vinyl tile—kitchen, bathroom, and utility room—were also locations where water might incidentally find its way onto the floor. It is possible that interior water spills may have contributed to the higher moisture readings below these locations. Additionally, when glass fiber insulation was being removed for sensor installation, visible mould growth was occasionally observed on the kraft facing and plywood subfloor. It was not always possible to determine whether these instances resulted from interior water spills, initially wet subfloors from construction, or seasonal moisture accumulation.

CONCLUSIONS

In all 12 houses the predominant vapor drive was from exterior to interior during May to October. Air temperature in open crawlspaces was very close to outdoor air temperature, with slight moderation. In contrast, the wall-vented crawlspace showed considerable thermal coupling with the earth. In all crawlspaces, water vapor pressure was essentially the same as outdoor vapor pressure. Relative humidity values in the wall-vented crawlspace were lower than outdoors from November to March and higher than outdoors in July and August.

Moisture conditions within plywood or solid wood subfloors were found to depend on several variables: season of the year, indoor temperature during summer, type of interior floor finish, and type of under-floor insulation. In most cases a seasonal trend was observed of higher moisture levels during summer and lower levels during winter. For a given indoor temperature and type of insulation, summertime subfloor moisture content was generally higher under an impermeable floor finish such as vinyl tile than under carpet. For a given type of insulation and interior floor finish, subfloor moisture content generally increased with decreasing indoor temperature during summer. The latter trend was more pronounced in floors finished with vinyl tile.

The subfloor layer in floors insulated with rigid foil-faced polyisocyanurate foam board installed below floor joists showed no discernible seasonal trend in moisture content, and subfloor MC was essentially unaffected by the type of interior floor finish. Moisture readings were consistently in the 10–14% MC range. Floors insulated with closed cell sprayed polyurethane foam showed only a slight seasonal trend in subfloor moisture content, with a subtle effect of interior floor finish. Subfloor moisture contents in all cases were in safe ranges, with values below 16% MC in plywood subflooring and below 18% MC in solid wood subflooring.

Clear seasonal trends in subfloor moisture levels were observed when the insulation was either open cell foam or glass fiber batt. Moisture content readings above 20%, particularly for impermeable interior floor finishes and low indoor temperatures during the cooling season, suggest that these insulation types do not reliably protect subfloors from seasonal moisture accumulation. The effect of vapor retarder paint applied over open cell SPF on subfloor moisture levels was not clear. In carpeted floors, where subfloor moisture contents were relatively low, application of vapor retarder paint to OC foam had no discernible effect. In contrast, in floors finished with vinyl, OC foam with vapor retarder paint appeared to result in lower summertime subfloor moisture content than OC foam without the paint.

ACKNOWLEDGMENTS

The authors acknowledge the support of the U.S. Forest Products Laboratory (FPL), APA—The Engineered Wood Association, and the Southern Pine Council. We thank the staff of New Orleans Area Habitat for Humanity for their cooperation; Audrey Evans and Sydney Chaisson for assistance with selecting houses; Robert Munson and C.R. Boardman of FPL for assistance with preparing instrumentation and processing data; Kevin Ragon, Stuart Adams, and Brett Borne of Louisiana State University (LSU) for assistance with field data collection; Cathy Kaake of the Southern Forest Products Association, Tom Kositzky of APA, Paul LaGrange of LaGrange Consulting, and Claudette Reichel, Todd Shupe, and Qinglin Wu of LSU AgCenter for helpful discussions on research needs, study design, and facilitation. This manuscript was improved by critical comments from Claudette Reichel of LSU AgCenter, Paul Francisco of the University of Illinois, and an anonymous reviewer.

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Samuel V. Glass, Charles G. Carll Jay P. Curole Matthew D. Voitier: Moisture Performance of Insulated, Raised, Wood-Frame Floors: A Study of Twelve Houses in Southern Louisiana Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference,
December 5-9, 2010, Clearwater Beach, Florida