Case Study: Performance of a House Built on a Treated Wood Foundation System in a Cold Climate

Charles G. Carll

Charles R. Boardman
Associate Member ASHRAE

Collin L. Olson, PhD
Member ASHRAE

ABSTRACT

Performance attributes of a home, constructed in 2001 in Madison, WI, on a treated-woodfoundation system were investigated over a multiyear period. Temperature conditions in the basement of the building were, without exception, comfortable, even though the basement was not provided with supply registers for heating or cooling Basement humidity conditions were acceptable (although not ideal), even though dedicated dehumidification equipment was not used in the building. The basement zone did not develop any perceptible smell of mold. No visible moldgrowth occurred on surfaces in the basement. After 98 months of building operation, with design humidity levels being maintained during most heating seasons, the foundationsystem (including cellulose insulation that was below grade) was virtually devoid of visible mold growth. Despite this, moisture contents in the bottomplates of the foundation walls were, at most locations monitored, chronically at or near fiber saturation. Otherparts of the foundation remained substantially drier, but apparently at levels roughly in equilibrium with 80% RH. Energy consumption for space heating of the building, normalized to floor area and heating degree days, was roughly equivalent to that for "average" American dwellings constructed between 1990 and 2001. In summary, the moisture performance and thermal performance of the wood foundation system of this building were acceptable.

INTRODUCTION

The house discussed in this manuscript was constructed on a permanent wood foundation in 2001. It is located on the campus of the US Forest Products Laboratory in Madison, WI, and was constructed for the dual purposes of demonstration and research. This manuscript reports on moisture performance of the foundation system, on ambient conditions in the basement zone of the building and how they compare with conditions in the building's main living space, and on building energy consumption (normalized to house size and climate). In order to characterize the building, and to benchmark the energy consumption values, the building's airtightness and air exchange rates are identified (by blower door and tracer-gas testing, respectively). In addition, leakage of the building's duct system is reported. These values (building airtightness, air exchange rates, and duct leakage characteristics) are presented as background information that characterizes the building, and thus provides insight into the building's energy consumption.

Description of Building and Site

The house is a two-story, four-bedroom, 2200 ft^2 wood-frame building, with attached garage. The building was constructed in 2001; its construction history has been described in a previous publication (Carll et al. 2007). The permanent wood foundation on which the house was erected was constructed with chromated copper arsenate (CCA) pressure-treated southern pine 2 × 8 lumber and CCA pressure-treated pine plywood. The treated lumber and plywood, which are of foundation grade, were kiln-dried after treatment. Exterior walls, including the basement walls, were insulated with spray cellulose. In accord with the recommendations of the trade association representing cellulose insulation manufacturers, an interior vapor retarder was omitted

***Charles G. Carll** is a forest products technologist and **Charles R. Boardman** is a general engineer at the US Forest Products Laboratory, Madison, WI. Collin L. Olson is a physicist at the Energy Conservatory, Minneapolis, MN.*

Table 1. House Size Characteristics and Fenestration Areas and Characteristics

Floor area, Interior volume, and exterior wall, ceiling and floor area (normally conditioned living space)[a]	2200 ft^2 floor area. 18,200 ft^3 volume. 2050 ft^2 exterior wall area (includes window and door area; does not include wall between house and garage). 1250 ft^2 ceiling area to attic. 100 ft^2 cantilevered floor area (exterior conditions below cantilevered floor area)[b]. 3400 ft^2 of thermal envelope.
Floor area, interior volume, and foundation wall area (basement)[a]	1100 ft^2 floor area. 9900 ft^3 (includes volume occupied by floor joists). 1350 ft^2 exterior wall area (of which 1200 ft^2 is foundation wall area and 150 ft^2 is rimn-joist area). 2450 ft^2 of thermal envelope.
Floor area, Interior volume, and insulated exterior wall and ceiling area (attached garage)[a]	500 ft^2 floor area. 4600 ft^3 volume. 500 ft^2 exterior wall area (includes overhead door area; does not include wall between house and garage). 150 ft^2 ceiling area to unconditioned (attic) space (ceiling area not in common with floor area of upstairs bedrooms). 1,150 ft^2 of thermal envelope.
Fenestration (window and door) area,[c] and U-factor (normally conditioned living space)	350 ft^2, of which 60 ft^2 is door (and door side-lite) area. Windows have a U-factor of 0.34. Doors are woodpanel weather-stripped entry doors. Doors and door side-lites are not U-factor rated.
Window area and U-factor (basement)	<10 ft^2 (facing NNE). U-factor not identified (dual-pane but not sealed insulating glass).
Overhead door area and U-factor (garage)	110 ft^2. 0.25 U-factor (very roughly estimated). Hollow hardboard-faced overhead door. During heating seasons when garage was heated and humidified, the overhead door was covered over roughly 2/3 of its area with removable EPS[d] foam in cold weather, and hand screws were also clamped on the tracks to hold the door against its sweep seals.

[a] Floor, wall, and ceillng areas to nearest 50 ft^2, volumes to nearest 100 ft^3.
[b] Second-story floor area above garage (approximately 350 ft^2) not counted in this total.
[c] Fenestration areas to nearest 10 ft^2.
[d] Expanded polystyrene (beadboard).

from all except three stud spaces.[1] The foundation walls are covered with painted gypsum drywall, making the basement semi-finished. The house is cooled in hot weather with central air conditioning. Although the basement is semi-finished, it has neither supply nor return registers for heating/cooling.

Building size characteristics and fenestration areas and characteristics are listed in Table 1. Of the roughly 300 ft^2 of window area (all house levels including basement), only 14 ft^2 faces in a more or less southerly direction (within 30° of south). The house was not designed or oriented to use solar gain through windows during the heating season, or to limit solar gain through windows during the cooling season. Insulation levels are listed in Table 2, and characteristics of the building's mechanical equipment are listed in Table 3. The building plans did not permit location of ducts for second-storyroomsinany locationotherthanthe attic; any other location would have interfered with drain plumbing. The building was constructed from off-shelf plans, and with the exception of the treated wood foundation, the omission of an interior vapor retarder (corresponding with use of spray cellulose insulation), and the inclusion of an energy recovery ventilator, was intended to be representative of a contemporary residential building in Wisconsin.

The building site is on a gently sloping hillside, near, but not at, the crest of a knoll. The site receives no runoff from pavement; all nearby pavement is at lower elevation than the building site, or is curbed and drained to functioning storm sewers. A sump pit is present in the basement, and except for theperiodbetweenlate August 2007 and mid-July of 2008, the pump in the pit was connected to a power source. The sump has a sealed top, with a removable plug fitting that allows inspection. During the period that the pump was disconnected from power, presence of water in the pit was monitored manu-

1. The three stud spaces, all located in the garage, incorporated a polyethylene interior vapor retarder.

Table 2. Nominal Insulation Levels

First- and second-story exterior walls	5.5 in. of spray cellulose[a] in 2 × 6 stud cavities 24 in. stud spacing in house exterior walls. 16 in. stud spacing in garage exterior walls. No interior vapor retarder. Strand-board exterior sheathing covered with spun-bonded polyolefin wrap.
Basement walls	7.25 in. of spray cellulose in 2 × 8 stud cavities. 12 in. stud spacing. No interior vapor retarder. Black polyethylene capillary break on exterior of treated plywood (extends above made to level of floor joists).
Ceilings (normally-conditioned living space and garage)	Dry blown cellulose of approx. 12 in. depthabove attic-accessible ceilings. Dry dense-pack cellulose in sloped (and non-attic-accessible) portions of ceilings. Clear polyethylene vapor retarder in ceilings. Attics ventilated.
Cantilevered floors	Dry dense-pack cellulose to fill I-joist spaces.
Garage and basement floors	No insulation below floors. Concrete slab in garage, finished with clear sealer. Treated wood floor system over gravel bed in basement, with black polyethylene vapor retarder between gravel bed and treated wood floor system.

Table 3. Building Mechanical Equipment

Furnace characteristics	80,000/52,000 Btu/h input rate. 75,000/49,000 Btu/h output rate. Sealed combustion (outdoor combustion air). 93.7 AFUE. Electronically commutated blower motor.
Air conditioner characteristics	30,000 Btu/h rating. 12 SEER.
Duct location and characteristics	Basement location for first-floor ducts (these ducts not insulated but sealed some withmastic, some withmetal tape) Some ‘’panned over” joist spaces used for return collectors. Main return trunk rigid metal and sealed. Attic location for second-floor ducts. Supply trunk in attic not insulated but sealed with mastic, and partially buried inceiling insulation. Flex insulated supply runners to ceiling register boots mostly above ceiling insulation. Supply register boots sealed to drywall cut-outs with latex foam. Stud spaces used as return register collectors. Drywall faces on collector cavities bedded in acoustic sealant.
Energy recovery ventilator	Single speed with nominal flow rate of 130 cfm. Enthalpic core.

ally (with a dip stick) at approximately weekly intervals, with more frequent monitoring during periods of appreciable rain. At all inspection times between June 8 and July 14, 2008, in excess of 6 in. (150 mm) of water was present inthesumppit. The period of June 7 through July 14, 2008, was a period of distinctly above-normal rainfall (16 days with measurable rain, with a total accumulation of 14.4 in. [367 mm]). On July 14, the water level in the sump pit was 6 3/8 in. (160 mm); this subsided to 3/8 in. (10 mm) by July 16. The sump pit observations suggest that a perched water table, within a coupleoffeet (0.6 m) of basement floorlevel, canoccuratthe site during periods of substantial rain, but that groundwater percolation prevents a waterlogged condition from being maintained for an extended time once rainy periods end.

Table 4. Operating Parameters during Heating Seasons

Heating Season	House/Garage Configuration	House Humidification	Garage Humidification	House Temp.	Garage Temp.	ERV Use/ Configuration
2001–2002	one zone	none	none	60°F	60°F	off; ports open
2002–2003	one zone	none	none	60°F then 70°F	60°F then 70°F	off; ports open
2003–2004	one zone	monthly set points	monthly set points	70°F	70°F	off; ports blocked
2004–2005	one zone	monthly set points	monthly set points	70°F	70°F	off; ports blocked
2005–2006	separate zones	10 L/day release	monthly set points	70°F	70°F	ports open; 20 min/h run[a]
2006–2007	separate zones	10 L/day release	none	70°F	tempered (≈ 55°F)	ports open; 20 min/h run[a]
2007–2008	separate zones	10 L/day release	none	70°F	tempered (≈ 60°F)	ports open; 20 min/h run[a]
2008–2009	separate zones	10 L/day release	none	70°F	tempered (≈ 60°F)	ports open; 20 min/h run[a]
2009–2010	separate zones	none	none	70°F	tempered (≈ 60°F)	ports open; 20 min/h run[a]

[a]ERV set on timer control. This setting would provide the normally conditioned space (18,200 ft^3 of volume) with 0.14 air changes per hour, assuming that airflow through the unit, when running, is at its nominal rate. The timer control was actually set to run continuously for 40 minutes over each of a series of 120 minute (2 h) periods

BUILDING OPERATION AND CHARACTERISTICS

Building Operation

Aside from a short (roughly 15 minute) daily public tour that occurs from May through early October, the house is unoccupied. For all except the first two heating seasons after construction, the house was heated to a constant 70°F for the months of October through May; there was no setback of heating set point (for nighttime or other period). The house was cooled in warm weather to a constant 75°F set point. House operating parameters for heating seasons are shown in Table 4. To simplify conduction of seasonal public tours, the door between the first story and the basement was usually removed from its hinges.

The monthly humidity set points (maintained as indicated in Table 4 in the house for the 2003–2004 and 2004–2005 heating seasons, and in the garage for the 2003–2004, 2004–2005, and 2005–2006 heating seasons) were calculated by the methodology outlined in a draft ASHRAE standard (ASHRAE 2006), which would become *ANSI/ASHRAE Standard 160-2009, Criteria for Moisture-Control Design Analysis in Buildings.* The set-point values were described in Carll et al. (2007). The 10 L/day humidifier release rate that occurred in the house during each of the heating seasons beginning in 2005, 2006, 2007, and 2008 (Table 4) yielded indoor humidity values close to design set points.[2]

As indicated in Table 4, the semi-finished garage, which was provided with neither supply nor return ducts or registers, was treated as conditioned space (heated and humidified) during the 2003–2004, 2004–2005, and 2005–2006 heating seasons. Maintaining temperature set-point conditions in the garage required use of electric resistance heat. As indicated in Table 4, during the 2003–2004 and 2004–2005 heating seasons, the door between the house and the garage was left open; some transfer of heat and humidity through the open door no doubt occurred. As indicated in Table 1, the outside of the garage door was partially covered with EPS foam of 1.5 in. (38 mm) thickness during the heating seasons when the garage was heated and humidified. This was necessary to prevent condensation on the inside surfaces of the door. For the summers of 2007, 2008, and 2009, the garage was treated as unconditioned space.

In contrast to humidity levels during the heating season, (which were at design levels, and thus appreciably higher than would be considered desirable), indoor humidity levels on the first story of the building during the cooling season were usually below 60% relative humidity (RH). There was no dedicated dehumidification equipment in the building, so the moderate indoor RH conditions during the summer evidently resulted from the house being air-conditioned while also being unoccupied. Until the summer of 2007, the garage was treated as semi-conditioned space during warm weather. There was no dedicated cooling equipment in the garage (window or portable air-conditioning unit), but the door between the house (which was cooled with central air-conditioning) and garage was, until the summer of 2007, left open.

Envelope Airtightness

Blower door tests were performed in September of 2002, in June of 2007, and in November 2008. Tests were in confor-

[2] This release rate is within the 10–12L/day range cited by Christian (1994) as representative of moisture load, from respiration and activities, for a family of four

Table 5. Results of Blower Door Testing

Month	Door at Basement Stairs	cfm_{50}	ELA[a] at 4 Pa	Flow Equation[b]	Basement Zone w.r.t.[c] House at 50 Pa House Depressurization
9/02	Open	1350	57.3 in.^{2}	$71.3.0(\Delta p)^{0.752}$	0 Pa
9/02	Closed	1298	50.6 in.^{2}	$60.0(\Delta p)^{0.786}$	+8.2 Pa
6/07	Open	1449	69.5 in.^{2}	$92.5(\Delta p)^{0.703}$	+ 0.13 Pa
6/07	Closed	1356	n/a	n/a (one data point 50 Pa.)	+13.1 Pa
11/08	Not noted	1435	67.6 in.^{2}	$89.0(\Delta p)^{0.711}$	Not noted
11/08	Not noted	1405	68.2 in.^{2}	$91.3(\Delta p)^{0.699}$	Not noted

[a] Effective leakage area (ASHAE 2005).
[b] cfm as a function of Pa. This equation mixes measurements systems (as it contains both SI and inch-pound terms), but is the most commonly used equation form in the United States, and is recognized in section 9.5.1 of *ASTM Standard E779-03, Standard Test Methodfor Determining Air Leakage Rate by Fan Pressurization.*
[c] w.r.t. = with reference to.

mance with *CAN/CGSB-149. 10-M86 Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method.* The tests were performed with the weather-stripped door between the house and the attached garage closed, and the hoods for the ERV intake and exhaust blocked. Test results are shown in Table 5. The tests performed in June 2007 and November 2008 indicated higher envelope leakage than those performed in September 2002. A modification had been made to the building during the summer of 2005 that in all likelihood increased its envelope leakage? In June 2007, the pressure differential between the basement and the house with the door closed was noticeably greater than it was in September2002 (13.1 versus 8.2 Pa). This indicates that leakage paths between the basement andthe exteriorbecame larger or more numerous between September 2002 and June 2007. This concurs with observed presence of air leakage paths between the basement and the exterior that had been introduced during the summer of 2005.

Although position of the basement door was not noted in the tests performed in November 2008, one ofthe tests yielded results similar to that of the test in June 2007 with the door open, while the other test yielded results similar to that of the test in June 2007 with the door closed.

The house-to-basement door had a 11/16 inch (17 mm) undercut, amounting to approximately 21 in^2 of nominal leakage area.[4] The basement zonal pressures observed during blower-door tests performed with the basement door closed (8.2 and 13.1 Pa withreference to [w.r.t.] the house) indicate that the air leakage passageways betweenthe basement andthe first story (including the door undercut) were more significant than those between the basement and the exterior.

In June 2007, air leakage between the basement and the exterior wasmeasureddirectly using a "guarded" blower-door test. In this test, the house was depressurized to 50 Pa as would normally be done with a blower door in the house's entry doorway, and a second calibrated blower with the fan reversed, thus moving air from the basement into the house, wasplacedinthe basement doorway (with basement door removed) to maintain zeropressure differentialbetweenthe house andthe basement. Airflow through the second calibrated blower was measured, giving a direct indication of air leakage between the basement and the outside. Results of this test are presented in Table 6. For comparison, two variations of the zonal pressure diagnostic procedure known as the open-a-door method (or flow method) were also conducted on the basement zone. The method is described by the Center for Energy and Environment (2001). Results ofthe two variations are presented on the two lower data rows in Table 6. The guarded blower-door test as well as the two zonal pressure diagnostic tests indicated substantial, although not excessive, air leakage between the basement and the exterior. As expected, the guarded blower door tests estimated zonal leakage with greater confidence (i.e., narrower confidence limits) than either of the open-a-door methods. Also as expected, the variation on the open-a-door method that resulted in greater change in zonal pressure (the one that involved opening a window to the outside) yielded a more confident estimate ofzonalleakage thandidthe variation that resulted in a lesser change in zonal pressure.

The cfm,, value for the basement obtained from the guarded test, when normalized to the area of basement walls and floor, yielded a value of 0.25 cfm_{50} ft^{-2}. By comparison, the cfm,, value for the house and basement in aggregate, normalized to the aggregate area of above- and below-grade walls, basement floor, and ceiling-to-attic areas amounts to roughly 0.24 cfm_{50} ft^{-2} (based on a cfm_{50} value of 1400, the average of the values in Table 5 rounded to the nearest 100 cfm). The basement thus shows envelope leakage roughly on par with that of the rest of the building.

3. The modification was the installation of a covered collection tank forroofwater, in the garage. The tank had an inlet pipe that penetrated the side wall of the garage. It also had an overflow pipe that penetrated the rim joist between the garage and the basement, traversed the basement just below the level of the floor joists, and then exited the basement through the foundation wall. The holes for installation of inlet and overflow pipes were slightly oversized; they had been cut neatly, but no attempt had been made to provide air seals around the pipes.

4. The door thickness and the floor plane would result in greater airflow through this opening than would occur through a sharp-edged orifice of equivalent cross-sectional area.

Table 6. Results of Basement Zone Tests[a]

Test Method	Exterior-to-Basement ELA[b]	Basement-to-House ELA	Flow Equation for Basement-to-Exterior Boundary	Exterior to Basement cfm_{50}	Through-Zone cfm_{50} (Basement Pressure w.r.t. House)
Guarded blower door[c]	30.8 in.^{2} ± 1.0 in.^{2}	n/a	$42.0(\Delta p)^{0.684}$	611 cfm ± 20 cfm	n/a
Open a door (open house-to-basement door)[d]	48–77 i.n^2	92–152 in^2	$47.0(\Delta p)^{0.650}$	597 cfm ± 140 cfm	375–602 cfm (+13.1 Pa) (door closed)
Open a door (open window to exterior)[e]	47–66 in.^{2}	100–120 in^2	$42.3(\Delta p)^{0.650}$	538 cfm ± 90 cfm	374–506 cfm (+13.1 Pa) (door and window closed)

[a] Ranges and ± values in this table represent 63% confidence intervals.
[b] ELA for guarded test based on flow equation determined by measured flows at multiple pressure stations. All other EL As based on assumed pressure exponent of 0.65 and calculated flow coefficient.
[c] Duct Blaster used in lieu of a blower door in the basement doorway.
[d] Basement zone shifted by 13.1 Pausing this variation on the method.
[e] Basement zone shifted by 36.3 Pa using this variation on the method.

The rim-joist area ofbasements is commonly a location of substantial air leakage. In this building, (except where there was a cantilevered floor), the outer surface of the sheathing on the first story walls was in a common plane with the outer surface of the sheathing on the foundation wall. The spun-bonded polyolefin wrap on first-story walls was lapped with the black polyethylene on the outside of the foundation wall.[5] In places where the foundation wall extended substantially above grade, the exterior cladding system on first-story walls extended down past the (platform) structural floor system, and covered part of the foundation wall. The lapping of membranes, and continuity of cladding systems across rim joist areas, might be expected to restrict air leakage potential at the rim joists.

Duct Leakage

Duct leakage was evaluated in October 2003 and December 2009. The evaluations conducted in December 2009 were more extensive, reflecting (in part) the availability of more advanced automated data collection and analysis software at the later date. In October 2003, duct leakage to the exterior was measured by pressurization testing, with separate determination made of supply and return leakage. These measurements were essentially those outlined as Method B of *ASTM Standard E1554, Standard Test Methods for Determining Air Leakage of Air Distribution Systems by Fan Pressurization.* In December 2009, three duct leakage test protocols were undertaken. The first protocol was a repeat of Method B of *ASTM Standard E1554.* The second protocol was determination of total supply leakage and total return leakage by fan pressurization. All pressurization tests (either to exterior or total) were performed in the direction that would occur in operation of the furnace fan (supply ducts pressurized and return ducts depressurized). The third protocol was supply leakage to the exterior and return leakage to the exterior under operating conditions (with registers open and the furnace fan running), by the method known as Delta Q[6] (Walker et al. 2001). This procedure is based on a series of blower-door subtraction (Delta Q) measurements (envelope leakage with furnace fan running versus not running) over a series of both positive and negative envelope pressure differentials. The method is calculation-intensive, and thus relies on the use of software (usually proprietary) to solve Equation 4 of *ASTM Standard E1554-07* for four different variables from a matrix of paired envelope pressure and Delta Q values. The various measures of duct leakage are presented in Table 7.

The tests indicate that duct leakage to the exterior (on either supply or return sides) was low: without exception, less than 50 cfm. For each of the tests for supply leakage to the exterior by fan pressurization, the measured fan orifice pressure at 25 Pa duct pressure with the most restrictive flow ring installed was below thereliable measurement range. The Delta Q tests all provided lower estimates of duct leakage to the outside than the estimates for leakage to exterior by duct pressurization. This was expected, and concurredwiththe findings of Pigg and Francisco (2008). In duct pressurization tests, a largely uniform level of pressurization is assumed to occur throughout the register-masked system. In contrast, the Delta Q protocol was designed to reflect that, under normal operating conditions, the pressure across duct leaks varies with their location within the system. The calculation procedures for Delta Q permit negative values for supply or return leakage to be obtained. As pointed out by Pigg and Francisco, negative leakage values are physically nonsensical, but nonetheless are typically reported, because arbitrarily setting them to zero wouldresult in bias. The low levels of duct leakage to the exterior were not expected, inasmuch as the ducts for second-story

5. The initial lapping of these membranes was reversed. Until the reverse-lapping was corrected, wetting of the rim-joist area occurred during rainstorms.

6. Method A of *ASTM Standard E1554-07* is a variation of the Delta Q method.

Table 7. Results of Duct Leakage Tests

Month	Test Method	Side	Test Pressure, Pa	Leakage Rate, cfm
10/03	Pressurize: Leak to exterior	Supply	**25**	low
			50	**30**
		Return	**25**	**27**
			50	**45**
12/09	Pressurize: Leak to exterior	Supply	25	low
			50	25
		Return	25	27
			50	46
12/09	Pressurize: Total leakage	Supply	25	343
			43.7[a]	493
		Return	25	317
			50	478
12/09	Delta *Q*[c]	Supply (rep 1)	NSOP[b]	−6 (zero)
		(rep 2)	NSOP	12
		(rep 3)	NSOP	17
		(rep 4)	NSOP	12
		Return (rep 1)	NSOP	−23 (zero)
		(rep 2)	NSOP	−7 (zero)
		(rep 3)	NSOP	17
		(rep 4)	NSOP	11

[a]Could not reach 50 Pa with the installed (Largest) flow ring. In contrast, with an open fan (no flow ring installed), the fan orifice pressure reading was too low to obtain a reliable reading.
[b]Normal system operating pressure. Fan set to continuous-run mode with thermostats set to not activate the furnace burners (temperature set point satisfied). This resulted in a return plenum pressure of -50 Pa and a supply plenum pressure of +21 Pa w.r.t. the house and basement.
[c]Wind speed, measured on site, at slightly above the building's roof peak, was less than 5 mph (2.2 m/s) during Delta *Q* testing. For third and fourth test replications, wind speed was below 3 mph (1.3 m/s).

registers are located in the attic. The low level of supply-to-outside leakage is likely the result, in part, of careful sealing of supply register boots in second-story rooms to cut-outs in the ceiling drywall. Low levels of duct-to-outside leakage at operating conditions (by Delta Q or by nulling test protocols) for recently constructed two-story residential buildings in Wisconsin with distribution ducts for second-story rooms in the attic were likewise observed by Pigg and Francisco (2008).

In contrast with low levels of supply or return leakage to the exterior, there were substantial levels of total supply and of total return leakage. This was despite extensive use of metal foil tape and mastic to seal ducts located in the basement, and despite neither mastic nor tape showing evidence of failure. Substantial air passage can be qualitatively detected (by feel) though a humidifier installed at the supply plenum.[7] One supply register on the first story, roughly at floor level, has an oversized floor cut for the register boot, and a notably poor fit between the register and boot. A stud space is used as the main returntrunk for the second story. The drywall sheets that form this return trunk from the second story were installed by a professional drywall crew, and may or may not be bedded in acoustic sealant. In contrast, drywall on second-story stud spaces for return pickup were bedded in acoustic sealant.[8]

Air Exchange Rates

A series of air exchange rate measurements were performed in the building during 2009 by tracer gas testing,

7. The central humidifier has never been used. Free-standing humidifiers with clear refillable tanks provide, in the opinion of the lead author, more readily documented control of humidity release rates.

8. Bedding in acoustic sealant was performed by an FPL scientist who intervened during installation of drywall in these locations The professional drywall hanging crew claimed ignorance regarding the existence or use of acoustic sealant. Effectiveness of acoustic sealant may be assumed to depend on drywall sheets being fastened (screwed down) into sealant beds soon after the sheets are hung. The drywall tradesmen on this project were largely segregated into separate hanging and screw-down crews, who generally were not both present at the site on the same workday.

conducted in accord with *ASTM Standard E741, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.* During each test, which typically lasted for roughly a work day, the furnace fan was set to run in continuous mode (i.e., both zone thermostats set for continuous fan run). This contrasted with the furnace fan setting at other times. During some of the earliest tests, tracer gas was only released on the first and second stories of the building, with the basement door closed. When this was done, tracer gas concentration in the basement would reach levels equivalent to those on first and second floors within a couple hours, indicating substantial air exchange between the house and the basement with the door closed. By conducting multiple tests, it was determined that in this house, which had high house-to-basement ELA values and substantial within-building duct leakage, position of the basement door had no discernible effect on the results of tracer gas tests.

For all tests, the furnace fan was set to run continuously, as indicated previously, and freestanding box fans were operated on each floor level of the building to promote even distribution of tracer gas. Each test was conducted by monitoring decay of tracer gas concentration over the course of a work day. Samples for concentration of tracer gas were taken on each floor level of the house. Air exchange rates during any one of the tests varied to some degree over the period of test, and with sampling location. Measurements taken at the first- and second-story levels were often slightly lower (by roughly 10%) than those taken in the basement. In cool or cold weather, higher rates of observed decay in tracer gas concentration in the basement than on first or second stories may be expected, as they would be consistent with building air exchange being driven, at least in part, by stack effect.

Twelve tests (from April to November) were performed with the ERV run under timer control, the mode under which the house was operated since October 2005. Values taken at the first-story levelranged from 0.16 to 0.22. Outdoortemperature during the 12 tests was never cold the lowest average outdoor temperature during any of the tests was roughly 47°F (8° C). An inverse relationship between outdoor temperature and air exchange rate was apparent in the data? Air exchange rates during cold weather with the ERV running under timer control thus probably exceeded 0.20.

A more extensive series of tests was performed with the ERV disabled and its ports blocked. In these tests, when outdoor conditions were similar to those that prevailed during the tests conducted with the ERV under timer control, the air exchange rates were often less than 0.1 ACH. In contrast, tests performed on days with below-freezing outdoor temperatures, (all with the ERV disabled) yielded ACH values ranging from 0.19 to 0.31.

9. This relationship was expected. Outdoor temperature is an important input parameter for simulation models used to predict building ventilation by wind and stack effects.

Effect of Furnace Fan Operation on Basement Zone Pressure

In order to identify if differential pressure between the basement and the exterior was influenced by operation of the furnace fan, the pressure differential between the basement and the outside was monitored over successive 15-second intervals for slightly less than a one-week period. The period began December 30, 2009 (a time during which there was reasonably frequent cycling of the furnace), Pressure differential between the basement and the furnace return plenum was measured concurrently with a separate pressure transducer. The furnace fan was set via the zone thermostats to run continuously, but it was evident (by ear) that the fan speed varied over time, probably influenced by thermostat calls for heat. There also were roughly minute-long periods when the fan did not run. The door at the head of the basement stairs was in place and closed during the monitoring period.

Pressure in the fumace return plenum with reference to the basement varied substantially over the monitoring period, from - 83 to +1 Pa, with many sustained readings at roughly -20 Pa, -40 Pa, and -50 Pa (indicating a variety of different fan speeds and the fan-off condition).[10] When return plenum pressure changed significantly between sequential readings or over the span of a few sequential readings, basement zonal pressure with reference to the exterior did not measurably change. Average measured basement pressure with reference to the exterior over the roughly week-long measurement period (slightly over 38,100 serial measurements) was -1 Pa. The pressure differential fluctuated over the period from -9 to +2 Pa, with the fluctuations evidently being wind-driven. Although within-building duct leakage had been identified as appreciable, the supply leaks appear to largely be balanced by return leaks during fumace fan operation, with the result that fan operation did not show evidence of influencing pressure conditions in the basement.

MEASUREMENT OF MOISTURE AND TEMPERATURE CONDITIONS AND OF ENERGY USE

Moisture Content of Foundation Wall Materials

Pins with insulated shanks for moisture content measurement by DC resistance were placed in framing members in 13 stud spaces of the foundation during construction, prior to insulation and to hanging of drywall.[11] In all 13 spaces, a pin pair was installed in the foundation bottom plate. In three of

10. The average return plenum pressure w.r.t. the basement was-38 Pa over the measurement period. This pressure differential was of moderately lesser magnitude than that prevailing during Delta Q testing for duct leakage (–50 Pa, with all zone dampers open, and thermostats set such that the furnace fan would run continuously and the burners would not activate).

11. Moisture conditions in above-grade walls were also monitored, with substantial seasonal (cold-weather) moisture accumulation being detected (Carll et al. 2007).

Table 8. Calculated Resistances of Specified Southern Pine Materials at Approximately Room Temperature and Specified Moisture Contents

Material (Calculation by)	Calculated Resistance in MΩ at		
	22% MC	17% MC	12% MC
Shortleaf pine (inverse of Equation 3)	1.6	15	300
CCA-treated southern pine (inverse of Equation 1)	32	45	110
CCA-treated plywood (inverse of Equation 2)	0 37	42	1600

the 13 spaces, pin pairs were also placed at various heights in the foundationplywood sheathing. All three of these wall stud spaces were on the "uphill" side of the building, where foundation walls extended roughly 1 ft (0.3 m) above final grade. The locations where pin readings were made were not uniformly distributed around the foundation. They were all within 20 ft (6 m) of the instrument used for recording moisture content measurements, and were toward the end of the building opposite that where the garage was attached. Due to the removal of wetted cellulose insulation at foundation wall bases in September 2001 (described in Carll et al. [2007]), the top surfaces of foundation bottom plates were in contact with an air space, rather than with insulation. Moisture readings were performed using an instrument marketed for monitoring moisture in industrial dry kiln operations. Temperature was measured via thermocouple at all pin pair locations. Moisture readings were adjusted for material (i.e., treated lumber or treated plywood) using the relationships as follows.

The treatment used in the foundation wall materials was CCA Type C. The relationship betweenmoisture content and DC resistance of the treated southern pine lumber[12] (determined gravimetrically on laboratory specimens at ≈70°F (21°C) and with pins a 1 in. (25 mm) separation) was

$$\ln(\mathrm{MC}) = 4.56 - 0.098 \ln(R) \quad (1)$$

where

MC = moisture content, %

R = resistance, ohms (Ω)

The corresponding relationship for CCA-treated southern pine plywood (also determined gravimetrically on laboratory specimens) was

$$\ln(mc) = 4.45 - 0.106 \ln(R) \quad (2)$$

The relationship for untreated shortleaf pine (a southern pine), derived from data from James[13] (1975), is

$$\ln(\mathrm{mc}) = 4.75 - 0.116 \ln(R) \quad (3)$$

The MC/resistance relationships of the treated pine and treated pine plywood can be compared with that of untreated southern pine by the relative resistance values of the materials at a series of three moisture contents (Table 8). The table indicates that CCA-treated lumber did not show an appreciably different MC/resistance relationship than that reported by James (1975) for untreated shortleafpine. This concurs with the findings of Richards (2000), who reported that treatment with CCA type C (oxide formulation of CCA) did not noticeably raise the electrical conductance of southern pine. The treated plywood was evidently less conductive at 12% moisture content thaneither untreated or treated southern pine, but more conductive than either untreated or treated southern pine at higher moisture contents. The finding of a different conductance/moisture content relationship for southern pine plywood than for southern pine lumber concurred with results of another investigation (Glass and Carll 2009).

Moisture and temperature readings were taken hourly by an automated data collection system. Moisture contents were calculated by a three-step process, as described by Carll et al. (2007). The third step of the process involved converting temperature-adjusted resistance value[14] to moisture content values using Equations 1 or 2 as appropriate.

An extensive survey of treated wood foundations in cold climates was performed by van Rijn et al. (1993). In that investigation, extensive moisture measurements were taken in 28 treated wood foundations in Canada, but the measurements taken in any one foundation were all obtained on the same day, and all measurement dates were evidently during seasons when the ground surrounding the foundation was not frozen. The Canadian survey essentially verified the intuitive assumption that bottom plates and plywood sheathing are locations within the foundation that are relatively likely to show elevated moisture contents. The investigation performed on this foundation system, in contrast with the survey performed by van Rijn et al. (1993), involved monitoring moisture and temperature conditions over time.

Intrusive Investigation of Foundation Walls

In January 2010, sections of gypsum drywall were removed from five stud spaces in the foundation walls to look for presence of mold on back surfaces of the drywall.[15] Over three of the five stud spaces, drywall was removed for the full

12. The specimens for resistance calibration were obtained from lumber andplywood scraps from the CCA-treated basement floor (which unlike the wall sections, was site-fabricated). Pins had insulated shanks, so only pin tips served as electrodes. Pins were driven to half of substrate depth.

13. Pin at 1.25 ln. spacing driven to 5/16 inch depth, at a temperature at 80°F (27°C). Pin shanks not apparently insulated (this detail not provided by James).

14. The temperature correction was outlined in Carll et al. (2007), and was based on data for untreated solid wood from James (1968). We have come to suspect that this temperature correction is not appropriate for plywood (treated or otherwise) at high moisture contents and freezing temperatures.

15. It should be noted that the building was not humidified over the 2009–2010heating season.

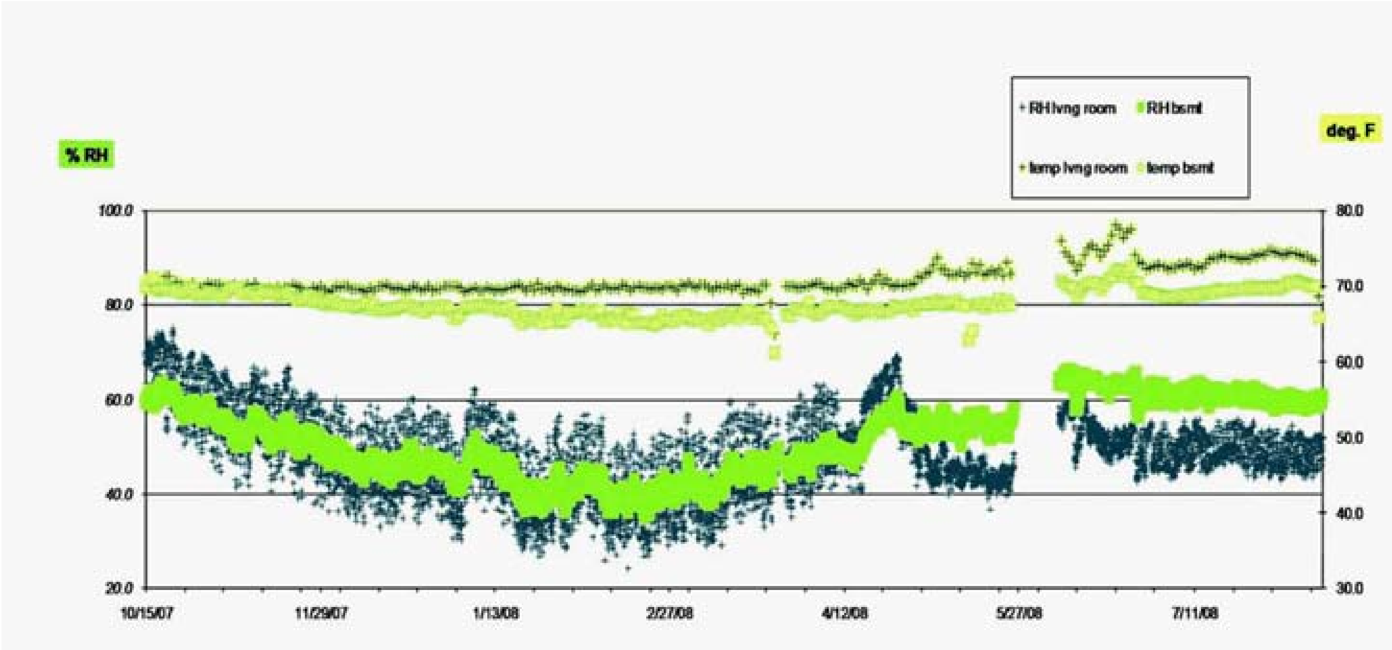

Figure 1 *Living room and basement hourly temperature and RH values from mid-October 2007 to mid-August 2008.*

wall height. Over the other two stud spaces, drywall was removed over only a part (about 20 in. [0.5 m]) of the wall height. A sixth section of drywall, roughly 4 in. (100 mm) wide and 11 ft (3.4 m) long, was removed from the lower edge of the drywall on a 12 ft long section offoundation wall. In this section of foundation wall, moisture readings in the bottom plate taken by the automated data collection system had, over the years, consistently shown high readings (generally at or close to fiber saturation). In five of the six places where drywall was removed, handheld moisture meterreadings were taken in the framing members or plywood (or both).[16] In two of the three stud spaces where drywall was removed over the full wall height, the cellulose insulation was removed and its moisture content determined gravimetrically.

Monitoring Exterior and Interior Conditions and Energy Use

Outdoor temperature and relative humidity were monitored as were temperature and relative humidity in the living room and basement. Monthly energy consumption (natural gas and electricity) was obtained from utility billing records for the building. As stated previously, the building was not occupied, and there was no dedicated dehumidification equipment. The water heater, which was a natural gas power-vented unit, was disabled by disconnection ofitselectrical supply and by closing its gas supply valve. Essentially all energy consumption was assumed attributable to space heating or cooling.

16. Over one of the six stud bays, the drywall was removed solely to look for mold on its back surface. The insulation in this stud bay was left undisturbed, and meter readings were not taken.

RESULTS

Interior Conditions

Conditions on the first story (living or "great" room) and in the basement over much of the 2007–2008 heating season and part ofthe 2008 cooling season are shown in Figure 1. The figure includes a short period in April 2008 when there was a malfunction of the heating system, and a period in June 2008 when there was a malfunction ofthe cooling system. Temperature and humidity plots for other years showed generally similar trends. Figure 1 indicates that basement and living roomtemperatures converged in mid autumn. During winter, spring, and summer, basement temperatures were consistently cooler than living room temperatures, although the temperature differences were never great. Unless there was a malfunction ofthe mechanical system, daily average temperature in the basement, without exception, remained within 6°F of 70°F. The basement may thus be characterized as having been a very well-tempered space, despite the fact that it is not provided with supply or return registers. The combination of conductive and radiant heat transfer from uninsulated ductwork, duct leakage, and air exchange between the house and the basement was sufficient to keep the basement at temperatures reasonably close to indoor set-point temperature conditions.

Figure 1 indicates that, during the heating season (when humidifiers were operated on first and second stories), hourly humidity conditions in the basement were relatively stable compared with those in the living room. This reflects the manner in which the humidifiers were operated: manually charged each day with an aggregate total of 10 L, and run continuously, with the charge completely evaporated before

Table 9. Water Vapor Pressures on Selected Dates

Date	Daily Average Vapor Pressure, Pa		
	Outdoors	First Story	Basement
12/6/08[a]	301	1163	1 OM
2/21/09[a]	340	948	896
4/22/09[a]	528	1318	1124
7/9/09	1735	1545	1594
8/24/09	1721	1465	1606
9/2 7/0 9	1460	1592	1632
12/21/09	393	83 0	932

[a] First and second stories were humidified on these dates.

the next day. On May 1, when humidification ceased, humidity levels in the living room decreased, but humidity levels in the basement did not. Humidity levels in both the living room and the basement were higher during the summer than during May. During the summer, lower-humidity conditions occurred when the air conditioner was functional. During summer months, humidity levels in the basement were consistently higher than in the living room, but did not exceed 70%. The highest hourly humidity levels occurred in the great room in October and in late April, when outdoor temperatures were mild and the house was humidified.

A comparison of vapor pressures[17] on selected days from December 2008 through December 2009 is presented in Table 9. With the exception of 12/21/2009 (which was selected arbitrarily on the basis of it being the date of the winter solstice), all dates in Table 9 were selected on the basis of daily outside dew-point temperature (i.e., the dates in the respective months that most closely approximated monthly average dew-point temperature). During the 2008–2009 heating season, during which humidifiers were operated on the first and second stories of the building, vapor pressure in the basement, while substantially higher than outdoor vapor pressure, was slightly lower than that on the first story. During months when air conditioning was operational (July and August), vapor pressure in the basement moderately exceeded that on the first story, but was lower than outdoor vapor pressure. In the early autumn of 2009, vapor pressure in both the house and basement moderately exceeded outdoorvaporpressure, with basement vapor pressure exceeding that on the first story. On the winter solstice in December 2009, house and basement vapor pressures were, as expected in cold weather, markedly higher than outdoorvapor pressure. In contrast with heating seasons during which the house was humidified, vaporpressure in the basement in December 2009 exceeded that on the first story. When there was not active release of humidity into the house, the vaporpressure in the basement exceeded that in the house.

17. Vapor pressures were derived from measured temperature and relative humidity values using simplified calculation methodology for saturation vapor pressure presented by Buck (1981)

Figure 2 Section of foundation wall bottom plate, showing the interface between bottom plate and plywood sheathing. Foundation wall studs are to left and right of picture. Plywood and bottom plate are visibly wet at their interface. Gray material containing red and white flecks (adhered to plywood and to left stud) is cellulose insulation. White rime above wet area is composed primarily of mycelia of a mold fungus. Bottom plate and plywood, although at moisture contents near fiber saturation, show no obvious mold growth.

Moisture Conditions in Foundation

Moisture content readings from the 13 locations where moisture pins were inserted into wall bottom plates mostly indicated that elevated conditions prevailed throughout the years of monitoring. In more than half of the 13 bottom-plate locations where moisture content was monitored, moisture content never fell appreciably below 30% (the approximate value for fiber saturation). Intrusive investigation verified that there were sections of foundation wall in which the bottom plate was wet (Figure 2). There were two locations, however, where substantially drier conditions (not exceeding 22% MC) prevailed. These locations were on the downhill side of the building, where the foundation wall extended roughly 3 ft (1 m) above grade and there was a significant area of pavement near the building that sloped away from it. These locations were also well removed from the discharges of roof gutter downspouts. Bottom plate locations showed essentially no seasonal variation in moisture content.

As indicated previously, the instrumented foundation wall sections that included moisture pins in the plywood sheathing were all on the uphill side of the building. On this side, although the ground immediately adjacent to the building was graded away from the building, further away from the building, the ground slope was in the building's direction. The site grading resulted in a swale of modest slope that was intended to intercept water running downslope toward the building and direct it away from the building in a direction more or less parallel to the building's long dimension. The final grading adjacent to the uphill side ofthe building resulted in limited above-grade exposure ofthe foundation wall (from roughly 7 to 13 in. [180 to 330 mm]). Moisture content readings in the plywood at mid-wall height (roughly 3 ft [1 m] below grade level) or near the foundation wall top plates (somewhat above grade level) were almost always lower (i.e., drier) thanmoisture readings in the lower portions ofthe wall. At mid-wall height, readings ranged from as low as 13% to appreciably in excess of fiber saturation, depending on location and time of year (rain conditions and seasonal temperature). Above grade level, seasonal variation in plywood moisture content was observed (moisture accumulation in cold weather). The amount of cold weather moisture accumulation in the above grade portion of the wall varied; in one of the three instrumented walls there was a barely perceptible seasonal moisture fluctuation with peak winter values not exceeding 17%, whereas in another wall there was distinct seasonal variation, with peak winter values exceeding 21%. Differences in peak seasonal moisture content values could be explained, in part, by winter temperature conditions in the plywood.[18] Intrusive investigation indicated that the moisture differences observed over long-term monitoring were real.

As indicated previously, intrusive investigation (involving full-wall-height removal of drywall and cellulose insulation) was performed over two foundationwall studspaces, one on the uphill side of the building and one on the downhill side. The one on the downhill side provided the opportunity to observe winter moisture accumulation in a foundation wall section with appreciable (roughly 3 ft [1 m]) above-grade exposure. Moisture meterreadings in the framing materials of this stud space (bottom plates, studs, or top plates) were all well below fiber saturation, even in close proximity to the plywood sheathing. The adjusted moisture meter readings averaged 21% MC in the bottom plate, 17% MC in the studs, and 16% MC in the lower of the two top plates. In contrast, the treated plywood foundation wall sheathing at heights above grade was, at the time the wall was opened (noon on January 7), cold and visibly wet. Meter readings indicated that the plywood was roughly at fiber saturation.[19] A very substantial moisture gradient between the plywood and the framing members was thus evident. The drywall removed from this stud space showed limited patches of unpigmented or lightly pigmented mold on the back surface ofthe drywall; all patches were restrictedto an area within 6 in. (150 mm) ofthe top edge of the panel. Molds isolated from these areas of growth were of Penicillium and Fusarium genera. Drywall removed from the adjacent stud space showed essentially the same limited mold growth, distributed in the same spatial manner (near the top edge). Of the six sections of drywall removed during intrusive investigation, only these two adjacent sections showed visible mold growth.

The stud space on the uphill side of the building where drywall and insulation were removed from the full height of the foundation wall was directly below a first-story wall that was shielded from rain exposure by the building's front porch (a cantilevered second story provided shielding). This stud space had not been instrumented with pins. Adjusted moisture meter readings in this stud space averaged 19% MC in the bottom plate and 17% MC in the studs. Readings in the plywood within roughly 1 ft (0.3 m) of either side of grade level exceeded 20%. The wall studs of this stud space showed similar moisture contents as the studs in the stud space on the other side (the downhill side) of the building. No mold growth was observed on any surfaces within this stud space.

The average moisture content ofthe insulationremoved from the two stud spaces (a total of roughly 12,400 in^3 [0.20 m^3]) was approximately 17%. This wasvirtually identical to the average moisture content of the studs. The moisture content of the insulation was not spatially uniform; it was obviously wet near the plywood in the above-grade portions of the walls and felt dry elsewhere in the wall cavities. We did not however attempt to quantify the spatial variation in insulation moisture content. The average moisture content value for studs and insulation of 17% corresponds with a relative humidity value for wood of slightly in excess of 80% (USDA 1999).

Energy Consumption

Annual building energy consumption for six successive years is presented in Table 10. Each year in Table 10 starts in mid-September, roughly corresponding with the end of a cooling season and the start of a heating season.

Based on the data in Table 10, estimates of space heating and space cooling energy consumptionwere derived; these are presented in Table 11. For space heating energy consumption, low and high estimates are given for each heating season. The low estimates are based solely on natural gas consumption; they are low estimates inasmuch as energy consumed for electric heating (or tempering) of the attached garage is not included in the estimate. The high estimates for space heating energy consumption are based on total energy consumption (gas and electricity) during all months except those during whichthere was no gas consumption. We believe that the high estimates barely overestimate heating load consumption. Waste heat from electricity consumption, which would include that from lighting (operated rarely), humidification

18. Plywood temperatures near the top of the foundation wall were slightly higher in a wall section that had an exterior brick veneer, supported by an unsheathed treated 2 × 4 stem wall outside of the foundation wall, than in a wall section where the exterior cladding was lap siding, not installed on furring. The airspace associated with the brick veneer cladding evidently moderated temperatures in the foundation wall sheathing.

19. Meter readings were temperature-adjusted using surface temperatures readings taken with an infrared (IR) emittance thermometer, and were also adjusted for material (Equation 2). Temperature at driven-pin depth was probably lower than the surface temperature, and as indicated in footnote 14, we are not convinced that we have an appropriate temperature correction factor for treated plywood at high moisture contents and temperatures near freezing. The adjusted values were thus considered approximate.

Table 10. Annual Building Energy Consumption for Each of Six Successive Years

Period[a] (HDD[b] and CDD[c] during Period)	Total Energy Consumption over Period	Consumption, Mid-June to Mid-Sept.
9/16/2003–9/22/2004 (6975 HDD, 367 CDD)	101 × 10^9 J equiv.: 621 thems gas, 9921 kWh electricity	No gas consumption, 2008 kWh electricity
9/22/2004-9/16/2005 (6521 HDD, 663 CDD)	107 × 10^9 J equiv.: 654 them gas, 10,687 kWh electricity	No gas consumption; 2862 kWh electricity
9/16/2005–9/18/2006 (6550 HDD, 546 CDD)	122 × 10^9 J equiv.: 717 therms gas, 12,836 kWh electricity	No gas consumption; 3349 kWh electricity
9/18/2006–9/17/2007 (6861 HDD, 588 CDD)	109 × 10^9 J equiv.: 740 therm gas, 8745 kwh electricity	No gas consumption; 2960 kWh electricity
9/17/2007–9/18/2008 (7354 HDD, 443 CDD)	116 × 10^9 J equiv.: 755 therms gas, 9998 kwh electricity	No gas consumption; 1752 kWh electricity
9/18/2008–9/16/2009 (7438 HDD, 348 CDD)	129 × 10^9 J equiv.: 748 therms gas. 13,980 kWh electricity	No gas consumption: 2309 kWh electricity

[a] Periods correspond with gass meter readings. Electric meter reading dates were usually two days later.
[b] Heating degree days (Fahrenheit, 65°F basis), from utility company gas billing record. Heating degree days that occurred during periods when there was no gas consumption are not counted.
[c] Cooling degree days (Fahrenheit, 65°F basis), from mid-June to mid-September from Weather Service data for MSN airport. Seasonal CDD totals were higher. Occurrence of cooling degree days from mid-May to mid-June and mid-September to mid-October did not necessarily coincide with operation of the air conditioner. Electricity consumption during these month-long “shoulder” seasons furthermore could not be apportioned between the air conditioner and other loads.

equipment, the data collection system, or the furnace fan, would heat the building interior and thus reduce heating load for the furnace. The only waste heat from electricity consumption that would not act to heat the building would be that portion of waste heat from the ERV fan motor that exited the building in the (temperature-moderated) ERV stale air exhaust, and that portion of waste heat from the furnace’s combustion air fan that exited the building in the furnace exhaust. Although small, waste heat from plug loads that occurred during early fall and late spring, when there was no demand for heat, would theoretically result in the high estimates of space heating consumption indeed being overestimated. The space cooling energy consumption values in Table 11 are based on total electricity consumption during those months when there was no gas consumption. Table 11 contains values normalized to floor area and to cumulative outdoor conditions (HDD or CDD). The low estimates for space heating consumption and the estimates for space cooling consumption are area-normalized to 2200 ft^2 (the floor area provided with heat/cool registers). The high estimates for space heating consumption are area-normalized to 2700 ft^2 (the sum of floor areas provided with heat registers or resistance electric heat).

DISCUSSION

Moisture Conditions

Moisture conditions in the foundation system were dependent on foundation wall location, and elevation within the wall. Bottom plates were usually the dampest part of the foundation wall. Bottom-plate moisture conditions at or near fiber saturation were common, although there also were sections of foundation wall where bottom-plate moisture content was essentially steady at roughly 20% moisture content or less. Intrusive investigation indicated that studs and top plates remained drier than bottom plates. These observations (a range of bottom-plate moisture contents with many readings at or exceeding fiber saturation, and bottom-plate moisture contents consistently exceeding stud moisture contents) concurred with those of van Rijn et al. (1993). In this building, bottom plates showed essentially no seasonal variation in moisture content. Gaby (1985) reported elevated moisture conditions in the bottom plate of a foundation wall that was monitored over a four-year period. That foundation wall was in northern Georgia, and was neither finished nor insulated. Gaby reported that the studs and plywood in the foundation showed seasonal variation in moisture content, but made no mention of seasonal variation in bottom-plate moisture content, despite discussing spatial variation in bottom-plate moisture content in some detail. Gaby reported that moisture content in the bottom plate was clearly related to proximity to a roof gutter downspout. The observations made during the current investigation and those made by Gaby (1985)—which, respectively, indicate or imply essentially no seasonal variation in bottom plate moisture content—suggest that the single-day readings reported by van Rijn et al. (1993) for bottom plates may well have been representative of year-round values.

In contrast to conditions in foundation bottom plates, treated plywood sheathing on portions of foundation walls that were above grade showed evidence of winter moisture accumulation. The moisture accumulation during winter appears to be restricted to the plywood. Moisture content in portions of studs in close proximity to the plywood (measured in January) was appreciably below fiber saturation, in a stud space where the plywood was noticeably cold and wet. In a treated-wood

Table 11. Estimated Energy Consumption for Space Heating and Cooling[a]

Period	Space Heating Energy Consumption: Low Estimate	Space Heating Energy Consumption: High Estimate	Estimated Space Cooling Energy Consumption
Sept. 16, 2003–Sept. 22, 2004	65×10^9 J equiv. 62×10^6 Btu equiv. 28,000 Btu/ft^2 89 kWh/m^2 4.1 Btu/ft^2·HDD	94×10^9 J equiv. 89×10^6 Btu equiv. 33,000 Btu/ft^2 104 kWh/m^2 4.7 Btu/ft^2·HDD	7.2×10^9 J equiv. 7×10^6 Btu equiv. 3,100 Btu/ft^2 8.5 Btu/ft^2·CDD
Sept. 22, 2004–Sept. 16, 2005	69×10^9 J equiv. 65×10^6 Btu equiv. 30,000 Btu/ft^2 94 kWh/m^2 4.3 Btu/ft^2·HDD	97×10^9 J equiv. 92×10^6 Btu equiv. 34,000 Btu/ft^2 108 kWh/m^2 5.2 Btu/ft^2·HDD	10×10^9 J equiv. 10×10^6 Btu equiv. 4400 Btu/ft^2 6.7 Btu/ft^2·CDD
Sept. 16, 2005–Sept. 18, 2006	76×10^9 J equiv. 72×10^6 Btu equiv. 32,000 Btu/ft^2 103 kWh/m^2 4.7 Btu/ft^2·HDD	110×10^9 J equiv. 104×10^6 Btu equiv. 39,000 Btu/ft^2 122 kWh/m^2 5.9 Btu/ft^2·HDD	12×10^9 J equiv. 11×10^6 Btu equiv. 5,200 Btu/ft^2 9.5 Btu/ft^2·CDD
Sept. 18, 2006–Sept. 11, 2001	78×10^9 J equiv. 74×10^6 Btu equiv. 34,000 Btu/ft^2 106 kWh/m^2 4.9 Btu/ft^2·HDD	99×10^9 J equiv. 94×10^6 Btu equiv. 35,000 Btu/ft^2 109 kWh/m^2 5.1 Btu/ft^2·HDD	11×10^9 J equiv. 10×10^6 Btu equiv. 4,600 Btu/ft^2 7.8 Btu/ft^2·CDD
Sept. 11, 2007–Sept. 16, 2008	80×10^9 J equiv. 75×10^6 Btu equiv. 34,000 Btu/ft^2 108 kWh/m^2 5.0 Btu/ft^2·HDD	109×10^9 J equiv. 104×10^6 Btu equiv. 38,000 Btu/ft^2 121 kWh/m^2 5.2 Btu/ft^2·HDD	6.3×10^9 J equiv. 6×10^6 Btu equiv. 2,700 Btu/ft^2 6.1 Btu/ft^2·CDD
Sept. 11, 2007–Sept. 16, 2008	79×10^9 J equiv. 75×10^6 Btu equiv. 34,000 Btu/ft^2 107 kWh/m^2 5.0 Btu/ft^2·HDD	121×10^9 J equiv. 115×10^6 Btu equiv, 42,000 Btu/ft^2. 134 kWh/m^2 5.1 Btu/ft^2·HDD	8.3×10^9 J equiv. 8×10^6 Btu equiv. 3,600 Btu/ft^2 10 Btu/ft^2·CDD

[a] Joules are SI units, and imply no preference for fuel type. Btu equivalent units are the units most commonly found in survey data for per-dwelling-space conditioning energy consumption, as reported by the Energy Information Administration (EIA). The EIA also reports space heating consumption units normalized to floor area and heating degree days, most commonly in units that can easily be converted to Btu/ft^2·HDD. Btu/ft^2 (floor area normalized) units are used fairly commonly in the United States. Canadian building scientists commonly report floor area normalized consumption in terns of kWh/m^2.

foundation, the plywood's outer surface is covered with a polyethylene sheet; below grade, this serves as a capillary break between the plywood and the gravel backfill, and above grade, serves as an exterior vapor retarder. In a cold climate like that of Madison, the exterior vapor retarder would be expected to exacerbate cold-weather moisture accumulation, and inhibit its dissipation during spring. The counter-productive effect of an exterior vapor retarder will be relatively larger in foundation walls with greater above-grade exposure. Elimination of the exterior polyethylene sheet on sections of foundation wall that extend appreciably above grade appears justified in cold climates. The role of the polyethylene sheet below grade is important; a design decision to partially eliminate the sheet poses the risk that it will be eliminated at places where it is important.

During intrusive investigation, we only observed limited patches of mold growth in foundation walls. These were located at the base ofthe wall on the uphill side ofthe building (see Figure 2) and on the back surface of interior gypsum boardnear the top ofthe foundation wall (on the opposite side of the building). These patches of mold growth quite likely occurred during construction. As indicated in Carll et al. (2007), wall bases underwent substantial and obvious wetting before roof gutters were installed and the site was graded. In addition, the spatial distribution of mold on the back of gypsum drywall (near the top edge, where the drywall contacted double top plates that were dry in service) was consistent with the occurrence during construction of rainwater penetration at the rim joist. As indicated in footnote 5, the spun-bonded polyolefin house wrap that covered first-story walls and the rim joist was initially reverse-lapped with the polyethylene sheet on the exterior of the foundation, and during the period that the membranes were reverse-lapped, water penetration into the rim joist area occurred during rainstorms.

Summertime relative humidity in the basement has not exceeded roughly 70%; this has evidently been sufficient to inhibit discernible mold growth. It has also been sufficient to prevent development of any discernible smell of mold in basement air. By use of a moisture balance model, Boardman et al. (2010) estimated the contribution of this building's foundation system to indoor humidity within the building. According to the modeling calculations, in warm weather the wood foundation system contributed only modest amounts of water vapor to the indoor air, and even served as a vapor sink during hot weather.

In summary, no discernible mold smell has been detected in the basement, no discernible mold growth has occurred on basement interior surfaces, and intrusive investigation uncovered only small isolated patches of discernible mold within the foundation system. Air sampling indicated higher concentrations of airborne mold spores in basement air than in the air on the first or second stories of the building (Clausen et al. 2009). This is perhaps an inherent characteristic of basements, including those that perform adequately, or even well.

Moisture balance modeling that showed only modest contribution of the building's foundation system to its indoor humidity during warm weather (Boardman et al. 2010) showed significant moisture release from the foundation system into the building's indoor air during cold weather. The apparent mechanism by which this occurred was water vapor evaporated from the gravel bed surrounding the foundation being entrained into air infiltrating the building through the foundation; cold-weather air infiltration was driven by stack effect. The seasonal trend in moisture release from this treated wood foundation (calculated by moisture balance modeling) was apparently different from the (lack of) seasonal trend observed for moisture release into "basement" air from concrete foundations (FTF 1999).[20] For either type of foundation system, however, the potential for moisture release from the foundation into indoor air over the course of a year is apparently substantial.

Energy Consumption

The low and high estimates of heating energy consumption bracket the available survey data for per-household heat energy consumption in roughly similar climates in the United States (EIA 1997). When heat energy consumption figures were normalized to floor area and HDD, the resulting intensity values were lower than for the aggregate stock of existing buildings (having a variety of construction dates) in all climatic regions in the US, and were roughly in line with intensity values for American dwellings constructed between 1990 and 1997, or between 1990 and 2001 (EIA 1997, 2001).

As indicated previously, the building was constructed from off-shelf plans, and with a few notable exceptions was intended to be representative of a contemporary residential building in Wisconsin. The operation of the building was not particularly conducive to lowering energy expenditure for space heating. Heating set point was above 68°F, and there were no temperature setback periods. In addition, the garage was either heated to the same set point as the house or was tempered to a lower temperature set point. The additional heated space in the garage undoubtedly influenced total energy consumption for space heating, but is accounted for in the area-normalized high-estimate values for space heating energy consumption. These estimates are inflated by energy losses associated with the leakiness of the garage zone[21] and the expected low R-values for the garage door and floor (more air leakage and lower thermal resistance than would be expected for the envelopes of normally conditioned parts of contemporary buildings). Conversely, the estimate values for the 2006–2007 heating season and subsequent heating seasons are deflated by the 55°F to 60°F temperature set point in the garage during these seasons. We thus suggest that the area-normalized consumption values are likely comparable with values published by the Energy Information Administration.

CONCLUSIONS

Moisture conditions in the foundation system varied with location, and in some locations varied seasonally. A substantial number of bottom-plate locations chronically remained at or near fiber saturation. Moisture conditions in upper portions of foundation walls were typically drier, but cold-weather accumulation in the plywood sheathing of foundation walls was evident where the walls extended above grade. The extent of cold-weather moisture accumulation was apparently related to the extent to which the foundation wall extended above grade. Extension of the exterior polyethylene sheet above grade probably exacerbates cold-weather accumulation in the plywood. Foundation wall studs evidently remained appreciably below fiber saturation, as did the bulk of the cellulose insulation in the foundation walls, but at levels in equilibrium with rather high levels of relative humidity. Intrusive investigation indicated that discernible mold was not present in the insulation, although there were small, isolated patches

20. Substantial caution must be exercised in comparing results of Boardman et al. (2010) with those from the Foundation Test Facility (FTF 1999). The FTF foundation modules were designed explicitly for energy use monitoring, rather than for moisture research. The FTF modules have "guard" sections of limited height constructed atop them, as opposed to buildings of single- or two-story height. The guard sections are also intentionally well separated from the foundation test sections with structural insulating panels. Foundation moisture release data from the FTF are furthermore limited to the heating season.

21. By the most basic of zonal pressure diagnostic methods, used in conjunction with blower door testing, the garage zone was identified as having high air leakage characteristics. This was most likely associated with the garage door.

of mold on the plywood and on the back surface of the drywall of foundation walls. This mold may have propagated before completion ofconstruction, and may have occurred because of construction errors, which were later remedied. The insulated wood foundation system thus showed acceptable moisture performance. Summertime humidity levels in the basement, although not ideal, were sufficiently low that obvious problems were avoided, even though no dedicated dehumidification equipment was operated in the building. A foundation system is, however, inherently in contact with, or at least in close proximity with ground that is damp or even wet. A foundation system that performs acceptably, or even well, thus cannot be expected to remain dry; portions of it are likely to remain damp or wet, and the foundation may serve as a substantial moisture source for the building.

When heat energy consumption figures were normalized to floor area and heating degree days, the resulting intensity values were roughly equivalent to the norms for American dwellings constructed between 1990 and 2001. Temperature in the basement during the heating season was always within 6°F ofthe heating temperature set point of 70°F, although the basement was not provided with supply or return registers. Much of the supply duct system for the building's conditioned space was, however, located in the basement. In addition, the duct system in the basement was not insulated, and it evidently leaked. Thus, the comfortable basement temperatures that were experienced in this building are not necessarily indicative ofsuperior thermal performance ofthe foundation system. In summary, from a thermal perspective, the house appears to have performed similar to the norm for American houses with similar dates of construction.

ACKNOWLEDGMENTS

The authors acknowledge the support of Windsor Building Systems of Madison Wisconsin, APA—The Engineered Wood Association, the Southern Forest Products Association, and the Cellulose Insulation Manufacturers Association.

We thank Robert Munson, Vina Yang, and Jessie Glaeser for data maintenance and compilation, mold sampling, and identification of mold genera, respectively. We thank Alex Wiedenhoeft for performing microscopic examinations of wood and plywood surfaces, and for providing a variety helpful insights. Finally, we recognize Samuel Glass for alerting us of an efficient method (Buck 1981) for calculation of vapor pressure.

REFERENCES

ASHRAE. 2005. 2005 *ASHRAE Handbook—Fundamentals,* Ch. 27: Ventilation and infiltration. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2006. *Proposed New Standard 160, Design Criteria for Moisture Control in Buildings.* Released as a Public Review Draft, Sept. 2006. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE 2009. *ANSI/ASHRAE Standard 160-2009, Criteria for Moisture-Control Design Analysis in Buildings.* Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

ASTM. 2000. *ASTM Standard E741-00, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.* West Conshohocken, PA: ASTM International.

ASTM. 2003. *ASTM Standard E779-03, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization.* West Conshohocken, PA: ASTM International.

ASTM. 2007. *ASTM Standard E1554-07, Standard Test Methods for Determining Air Leakage of Air Distribution Systems by Fan Pressurization.* West Conshohocken, PA: ASTM International.

Boardman, C.R., S.V. Glass, and C.G. Carll. 2010. Estimating foundation water vapor release using a simple moisture balance and AIM-2: Case study of a contemporary wood-frame house. Accepted for publication/presentation at the *ASHRAE/DOE Buildings XI Conference* scheduled for Dec. 5–9,2010 (accepted June, 15, 2010).

Buck, A.L. 1981. New equations for computing vapor pressure and enhancement factor. *Journal of Applied Meteorology* 20(December): 1527–532.

CAN/CGSB. 1986. *CAN/CGSB Standard 149.10-M86, Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method.* Canadian General Standards Board, Gatineau.

Carll, C., A. TenWolde, and R. Munson. 2007. Moisture performance of a contemporary wood-frame house operated at design indoor humidity levels. *Proceedings Buildings X Conference.* Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

Center for Energy and Environment. 2001. *Investigation into zone pressure diagnostic protocols for low income weatherization crews: Energy Center Report 208-1.* Prepared by Center for Energy and Environment for the Energy Center of Wisconsin, Madison. http://www.ecw.org.

Christian, J.E. 1994. *Moisture control in buildings,* Ch. 8: Moisture sources. MNL 18, H.R. Trechsel, ed. West Conshohocken, PA: ASTM International.

Clausen, C.A., J.A. Glaeser, S.V. Glass, and C. Carll. 2009. *Occurrence of mold in a two-story wood-frame house operated at design indoor humidity levels.* General Technical Report FPL-GTR-186. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory.

Energy Information Administration. 1997, 2001. *Residential energy consumption survey(s), 1997 and 2001.* Available from http://www.eia.doe.gov/emeu/recs/.

FTF. 1999. *The Foundation Test Facility (FTF).* http://www.buildingfoundation.umn.edu/ftf.htm#@FTF_1.

Gaby, L.I. 1985. Moisture content in a wood foundation wall. *Forest Products Journal* 35(6):41-44.

Glass, S.V. and C.G. Carll. 2009. *Moisture meter calibration of untreated and ACQ-treated southern yellow pine plywood.* Research Note FPL-RN-0312. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory.

James, W.L. 1968. Effect of temperature onreadings of electric moisture meters. *Forest Products Journal* 18(10): 23–31.

James, W.L. 1975. *Electric moisture meters for wood.* General Technical Report FPL-6. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory.

Pigg, S. and P. Francisco. 2008. *A field study of exterior duct leakage in new Wisconsin homes.* Energy Center Report #243-1. Madison, WI: Energy Center of Wisconsin. http://www.ecw.org.

Richards, M.J. 2000. Effect of CCA-C wood preservative on moisture content readings by the electronic resistance-type moisture meter. *Forest Products Journal* 40(20): 29–33.

USDA. 1999. *Wood handbook—Woodas an engineering material,* Chapter 3, Table 3-4. General Technical Report FPL-GTR-113. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory.

van Rijn, G.J., P.I. Morris, and D.M. Onysko. 1993. *Afield inspection survey of preserved wood foundations.* Report on Project #31-100-041. Forintek Canada Corp.

Walker, I.S., M.H. Sherman, J. Wempen, D. Wang, J.A. McWilliams, and D.J. Dickerhoff. 2001. *Development of a new duct leakage test: Delta Q.* LBNL 47308. Berkley, CA: Lawrence Berkley National Laboratory. http://epb.lbl.gov/publications/lbnl-47308.pdf.

Charles G. Carll Charles R. Boardman Collin L. Olson, PhD: *Case Study: Performance of a House Built on a Treated Wood Foundation System in a Cold Climate* Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference,
December 5-9, 2010, Clearwater Beach, Florida