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Comparative Study of Vented vs. Unvented Crawlspaces in Identical Side-by-Side Homes in the Mixed Humid Climate

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Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

CFM	Cubic feet per minute
CMU	Concrete masonry unit
EIFS	Exterior insulation finishing system
HERS	Home Energy Rating System
HFT	Heat flux transducer
OSB	Oriented strand board
PCM	Phase-change material
RH	Relative humidity
TVA	Tennessee Valley Authority
VOC	Volatile organic compounds
WC	Wolf Creek

1. Abstract

There has been a significant amount of research in the area of building energy efficiency and durability. However, well-documented quantitative information on the impact of crawlspaces on the performance of residential structures is lacking. The objective of this study was to evaluate and compare the effects of two crawlspace strategies on the whole-house performance of a pair of houses in a mixed humid climate. These houses were built with advanced envelope systems to provide energy savings of 50% or more compared to traditional 2010 new construction. One crawlspace contains insulated walls and is sealed and semi-conditioned. The other is a traditional vented crawlspace with insulation in the crawlspace ceiling. The vented (traditional) crawlspace contains fiberglass batts installed in the floor chase cavities above the crawl, while the sealed and insulated crawlspace contains foil-faced polyisocyanurate foam insulation on the interior side of the masonry walls. Various sensors to measure temperatures, heat flux through crawlspace walls and ceiling, and relative humidity were installed in the two crawlspaces. Data from these sensors have been analyzed to compare the performance of the two crawlspace designs. The analysis results indicated that the sealed and insulated crawlspace design is better than the traditional vented crawlspace in the mixed humid climate.

2. Introduction

Current building simulation models, performing one- and two-dimensional calculations, are not equipped to fully analyze and compare the hygrothermal performance of an insulated, sealed, and semi-conditioned crawlspace with a traditional vented crawlspace with insulation in the crawlspace ceiling. Insulating and conditioning the crawlspace should result in better overall building performance in the mixed humid climate of East Tennessee [1, 2]. To test this hypothesis, the two different types of crawlspaces have been incorporated into two experimental houses built at Wolf Creek (WC) subdivision in Oak Ridge, TN. This report describes the configuration of the crawlspaces in the two houses and provides an analysis of the temperature, humidity, and heat flux data collected from the crawlspaces.

The two simulated-occupancy test houses are used in this report to compare a more conventional vented crawl space to an insulated and sealed crawl space in houses with exactly the same floor plan. These two houses demonstrate different strategies for saving energy, but are both >50% more efficient than traditional 2010 new construction in mixed humid climate. Based on third-party-certified Home Energy Rating System (HERS) evaluations, the two houses, labeled WC3 and WC4, had ratings of 46 and 51, respectively [3]. The HERS rating of a conventional wood frame house built close to the International Energy Conservation Code (IECC) 2006 is 93 [3].

The two houses have a crawlspace foundation with first- and second-floor square footages of 1802 ft^2 and 919 ft^2, respectively. The houses use different envelope strategies to test their efficiency and durability. WC3's above-grade envelope uses cellulose insulation with an additional ingredient that enables it to store thermal energy: talc-like micro-capsules containing phase-change materials (PCMs) are mixed with recycled newspaper, adhesives, and fire retardants of conventional cellulose. The PCM-enhanced cellulose, which absorbs heat during the day and releases it at night, is installed on the attic floor and in the exterior walls. A hybrid insulating approach of conventional cellulose on the indoor side of the attic and walls and the PCM-enhanced insulation on the exterior side of the walls and on top of the layer of conventional cellulose in the attic was used.

WC4's envelope uses an exterior insulation finishing system (EIFS). Because the insulation is wrapped around the outside of the building frame, thermal short-circuiting through structural members is eliminated. This system is self-drying through a layer integrated into the assembly that provides a path for buoyancy or wind-driven air movement in addition to a condensation and drip plane. The new self-drying design by Dryvit Systems, Inc., exhibits moisture management and includes a flexible, polymer-based membrane applied as a liquid over the plywood sheathing to serve as a weather-resistant membrane and improve air tightness.

A high-efficiency ground-source heat pump with a 320 ft vertical well provides space conditioning and hot water in WC3. WC4 has a high-efficiency air-source heat pump and heat pump water heater. Complete details of the envelope systems of these houses were described by Miller et al. [3]. Jackson et al. [4] provided details and first cost of the construction of the houses as well as appliances, space conditioning and water heating equipment, and other features that are incorporated in WC3 and WC4.

3. WC3 and WC4 Crawlspace Configurations

Figure 1. WC3 (left) with vented crawlspace and WC4 (right) with insulated and sealed crawlspace.

Figure 1 shows the outside front views of WC3, built with a conventional vented crawlspace, and WC4, built with a sealed crawlspace. An oriented strand board (OSB) subflooring was used in the two homes, with a tongue-and-groove joint to improve the airtightness. The subflooring is a pre-engineered panel designed and treated for low water absorption and warp characteristics. The ventilated crawlspace in WC3 has two R-16 fiberglass batts installed in the floor chase cavities above the crawl, while the crawlspace in WC4 is sealed and insulated with 1.5 inch thick foil-faced (Thermax) polyisocyanurate board insulation on the interior side of the block wall. Figure 2 shows the footer construction in WC3 and WC4. The exterior of the masonry block forming the crawlspace on both homes was waterproofed using an emulsion-based asphalt coating (Figure 3). A channel of washed crushed stone backfill was installed on both the inside and the outside of the footer and a drainage pipe was installed that sloped away from the footer and was exposed to daylight.

Figure 2. No. 4 rebar used in construction of footer in WC3 and WC4.

Figure 3. Tremco waterproofing on the exterior of the concrete masonry unit (CMU) crawlspace wall.

On the exterior wall of both houses, stack stones were installed up to the termite barrier of through-the-wall aluminum flashing, which was sandwiched between the 8 inch 2-hollow core concrete masonry block wall and the base plate. A 20 mil (0.02 inch) liner covers the floor of both crawlspaces and is taped to a 10 mil wall liner in WC4 only. WC3 crawlspace walls contain eleven vents, each about 15.5 inch by 7.5 inch, yielding a total vent area of 8.9 ft^2. The wall liner in WC4 was adhered to the masonry block using a low-VOC polyurethane caulk and stopped about 3 inches below the sill plate to allow for termite inspections. DOW's Thermax™ rigid polyisocyanurate foam insulation (R_{US} -9.8) was glued to the wall liner using a polyurethane caulk adhesive. R_{US}-10 was a code requirement for the Tennessee Valley region in October 2010. WC4's crawlspace also incorporates a dehumidifier and is semi-conditioned through an air supply duct from the supply plenum that discharges into the crawlspace. Photographs of the crawlspaces in WC3 and WC4 are shown in Figure 4. The insulation and sealing features were installed by Bennie Marshall of Your Crawlspace Inc. (www.yourcrawlspace.com/).

Figure 4. Vented crawlspace in WC3 (left); walls insulated and sealed in WC4 crawlspace (right). Notice that there are no ducts in either crawlspace.

4. Instrumentation

Temperature, relative humidity (RH), and heat flux measurement probes were installed at various locations within the two crawlspaces to enable direct comparisons between their thermal and moisture conditions. Combination thermistor and relative humidity (T/RH probe) sensors were installed in the crawlspace walls, crawlspace ceiling and the crawlspace air. Heat flux transducers (HFTs) were installed in the north and east walls of the crawlspaces. Individual thermistors were also installed to measure the below-grade outer wall temperatures and the ground temperatures within the crawlspace area. Table 1 shows the list of sensors located in WC3 and WC4 crawlspaces. Also listed is the nomenclature for the different sensors used in the subsequent "Data Analysis and Discussion" section.

Table 1. Description and location of sensors in WC3 and WC4 crawlspaces

Section	Sensor(s)	Location	Nomenclature
WC3			
Crawlspace ceiling	Thermistor/Humidity/Heat Flux Transducer	Underside subflooring; Center of crawlspace below the living/dining area.	Subfloor (Liv/Din)
	Thermistor/Humidity/Heat Flux Transducer	Underside subflooring; below master bedroom.	Subfloor (M Bed)
Crawlspace air	Thermistor/Humidity	Center of crawlspace below the living/dining area.	Crawl Air (Liv/Din)
Floor chase cavity	Thermistor	Bottom surface of each fiberglass insulation batt; Center of crawlspace.	
Floor joist	Thermistor	Bottom surface of floor joist; Center of crawlspace below the living/dining area.	Under Joist
East wall	Heat Flux Transducer	Inside masonry block, below grade.	East_Down
	Thermistor/Humidity	Inside masonry block, below grade.	East_Down_In
	Heat Flux Transducer	Inside masonry block, above grade.	East_Up
	Thermistor/Humidity	Inside masonry block, above grade.	East_Up_In
	Thermistor	Outside masonry block, below grade; 36 inch from crawlspace ceiling.	East_Down_Out
	Thermistor/Humidity	Outside masonry block, above grade; 12 inch from crawlspace ceiling.	East_Up_Out
North wall	Heat Flux Transducer	Inside masonry block, below grade.	North_Down
	Thermistor/Humidity	Inside masonry block, below grade.	North_Down_In
	Heat Flux Transducer	Inside masonry block, above grade.	North_Up
	Thermistor/Humidity	Inside masonry block, above grade.	North_Up_In
	Thermistor	Outside masonry block, below grade; 36 inch from crawlspace ceiling.	North_Down_Out
	Thermistor/Humidity	Outside masonry block, above grade; 12 inch from crawlspace ceiling.	North_Up_Out
Ground	Thermistor	1 foot from east wall; 6 inch depth.	
	Thermistor	12 feet from east wall; 6 inch depth.	
WC4			
Crawlspace ceiling	Thermistor/Humidity	Underside subflooring; North center of crawlspace.	Subfloor (N)
	Thermistor/Humidity/Heat Flux Transducer	Underside subflooring; South center of crawlspace below living/dining area.	Subfloor (Liv/Din)
	Thermistor/Humidity/Heat Flux Transducer	Underside subflooring; below master bedroom.	Subfloor (M Bed)
Crawlspace air	Thermistor/Humidity	North center of crawlspace.	Crawl Air (N)
	Thermistor/Humidity	South center of crawlspace below living/dining area.	Crawl Air (Liv/Din)
East wall	Heat Flux Transducer	Inside masonry block and outside foam insulation, below grade.	East_Down
	Thermistor/Humidity	Inside masonry block and outside foam insulation, below grade.	East_Down_In
	Heat Flux Transducer	Inside masonry block and outside foam	East_Up

		insulation, above grade.	
	Thermistor/Humidity	Inside masonry block and outside foam insulation, above grade.	East_Up_In
	Thermistor	Outside masonry block, below grade; 20 inch from crawlspace ceiling.	East_Down_Out
	Thermistor/Humidity	Outside masonry block, above grade; 6 inch from crawlspace ceiling.	East_Up_Out
	Thermistor/Humidity	Inside foam insulation, vertical midpoint.	East_Cnt_Foam_In
North wall	Heat Flux Transducer	Inside masonry block and outside foam insulation, below grade.	North_Down
	Thermistor/Humidity	Inside masonry block and outside foam insulation, below grade.	North_Down_In
	Heat Flux Transducer	Inside masonry block and outside foam insulation, above grade.	North_Up
	Thermistor/Humidity	Inside masonry block and outside foam insulation, above grade.	North_Up_In
	Thermistor	Outside masonry block, below grade; 32 inch from crawlspace ceiling.	North_Down_Out
	Thermistor/Humidity	Outside masonry block, above grade; 12 inch from crawlspace ceiling.	North_Up_Out
	Thermistor/Humidity	Inside foam insulation, vertical midpoint.	North_Cnt_Foam_In
Ground	Thermistor	1 foot from east wall; 6 inch depth.	
	Thermistor	12 feet from east wall; 6 inch depth.	
Dehumidifier	Watt-hour sensor		
Conditioning Duct	Thermistor/Humidity	Near the duct outlet	Crawlspace Duct Outlet
	Flow Meter	Duct outlet	Crawl Air Supply

Figure 5 and Figure 6 show plan schematics of the sensor layout in WC3 and WC4 crawlspaces. The sensor locations are indicated by distances from the crawlspace walls. Multiple sensors were placed at the under-subfloor and wall locations and are shown as sensor groups. In WC3, the crawlspace air and ceiling sensors were located under the living/dining area. In WC4, there were two sets of sensors in the crawlspace air and ceiling. The sensors designated as “South center of crawlspace” or (S) were installed under the living/dining area, while those in “North center of crawlspace” or (N) were in an area between the living/dining room and the master bedroom. Under-subfloor sensors were also located below the master bedroom in both crawlspaces.

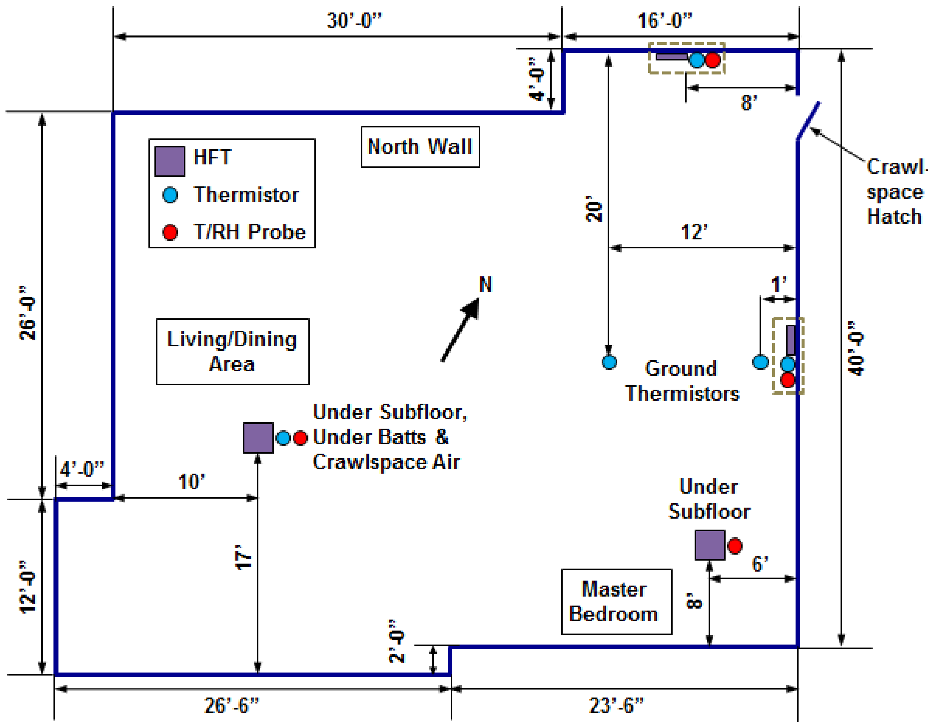

Figure 5. Schematic showing the sensor layout in WC3 crawlspace.

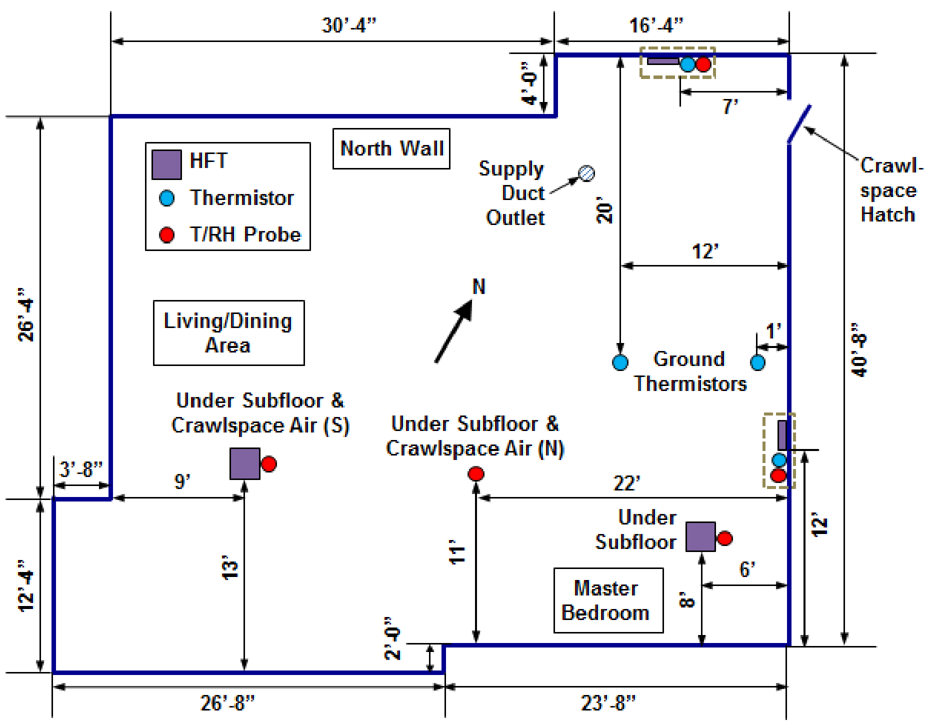

Figure 6. Schematic showing the sensor layout in WC4 crawlspace.

Figure 7 shows schematics of the vertical cross section of the WC3 and WC4 crawlspaces. It shows the sensor layout in the crawlspace ceiling and air and in the floor chase cavities in WC3. The layouts represent the cluster of sensors located in the "center of crawlspace" and under the master bedroom in WC3 and WC4. The HFTs were installed using ½ inch thick and 12 inch by 12 inch OSB attached to the bottom of the subfloor, with square slots in the middle to house the HFTs.

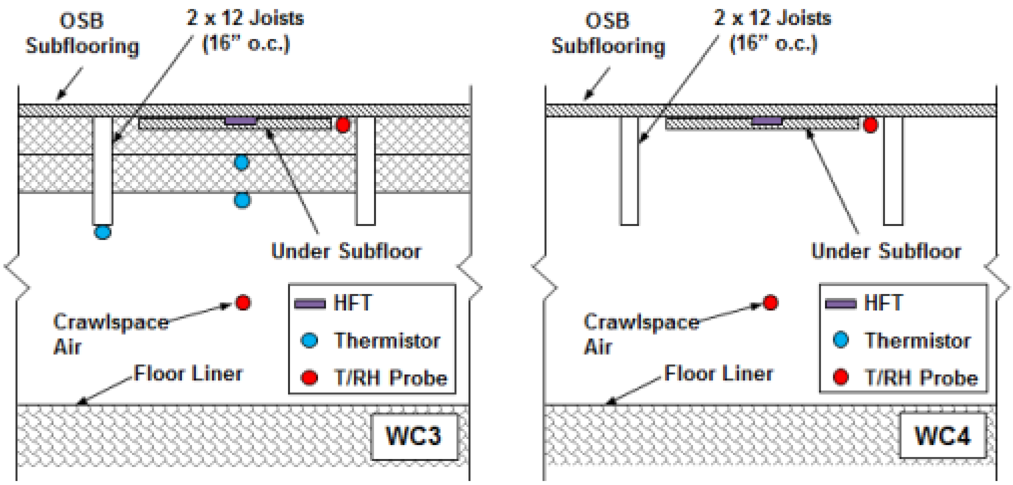

Figure 7. Schematic of the cross-sectional sensor layouts in WC3 and WC4 center of crawlspace.

In WC3, additional thermistors were located under each fiberglass batt surface and at the bottom of a floor joist. Lstiburek [1] identified the floor joists and the ceiling insulation as being susceptible to condensation, especially during humid summer months. Crawlspace air temperature and RH data with temperature data from the floor joist were used to determine the potential for condensation and mold growth in the WC3 crawlspace, and the analysis results are shown in the 'Data Analysis and Discussion' section of this report.

Figure 8 shows cross-sectional details of the temperature, humidity, and heat flux sensors located in the north wall of the two crawlspaces; the east walls were similarly instrumented. The HFTs and T/RH sensors on the inside of masonry blocks were installed directly across from the thermistors and T/RH sensors on the outside.

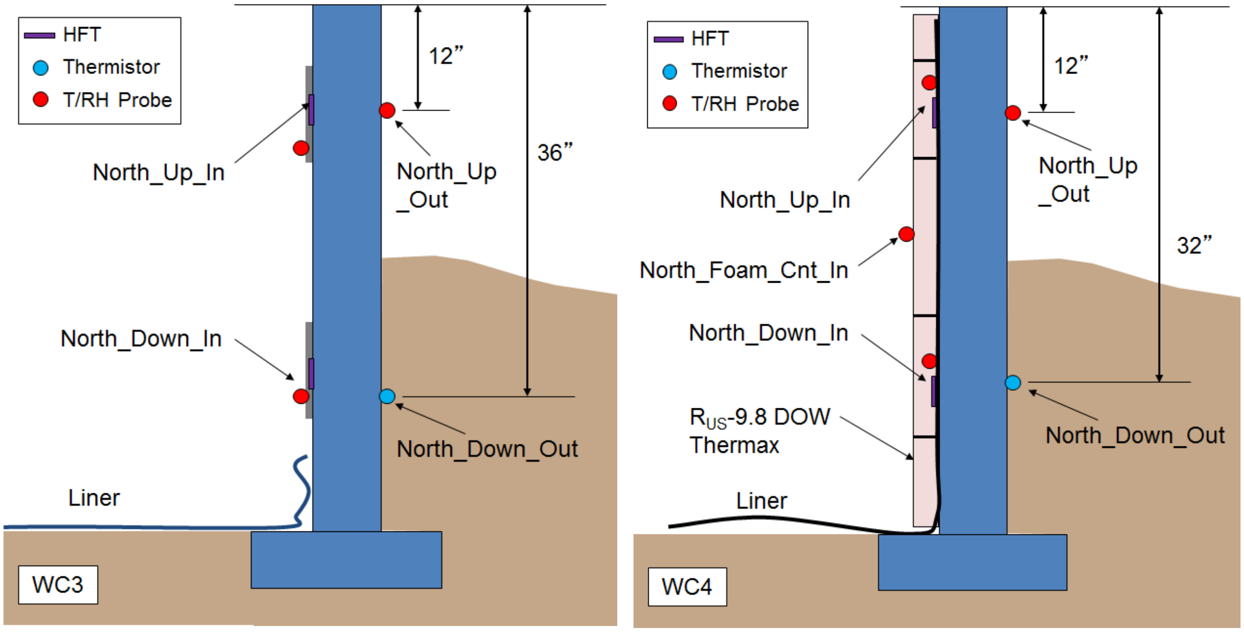

Figure 8. Crawlspace north wall sensor details in WC3 (left) and WC4 (right).

As indicated in Table 1, the east and north walls of the two crawlspaces were instrumented with thermistors and humidity sensors inside and outside the masonry walls, both above- and below-grade. In the WC4 crawlspace, thermistor and humidity probes were also installed on the foam surface facing the crawlspace interior. Heat flux transducers were installed on the interior surfaces of the masonry wall, in WC3 using ½ inch gypsum board and in WC4 between the foam sheet and the masonry wall. The ½ inch gypsum boards and the foam sheets had square slots routed on their surfaces to house the inlaid HFTs to ensure good contact with the masonry walls and prevent the formation of air pockets. Figure 9 shows the installation of HFTs in WC3, with “+” signs marking HFT locations. The T/RH combination probes (in white) can also be seen on top of the gypsum board surface.

Figure 9. Sensor installation on the WC3 crawlspace masonry wall.

5. Data Analysis and Discussion

In this section, data collected from August 2010 through July 2011 from the crawlspace sensors are presented and analyzed to compare the performance of the crawlspaces and determine their potential impact on whole-house energy consumption.

Crawlspace Walls

Figure 10 and Figure 11 show the temperature histories of the WC3 and WC4 north walls, during months representing the heating (December 2010) and cooling (June 2011) seasons. These months were close to the peak winter and summer periods and are appropriate for comparing the two crawlspaces. “Up” refers to above-grade locations and “Down” to below-grade. The above-grade masonry wall exterior (‘North_Up_Out’) showed the highest temperature fluctuations and the most extreme temperatures, lowest in winter and highest in summer. The above-grade interior temperatures (‘North_Up_In’) mirrored the exterior temperatures, but with lower fluctuations. Below-grade interior (‘North_Down_In’) and exterior (‘North_Down_Out’) temperatures were relatively stable and less extreme.

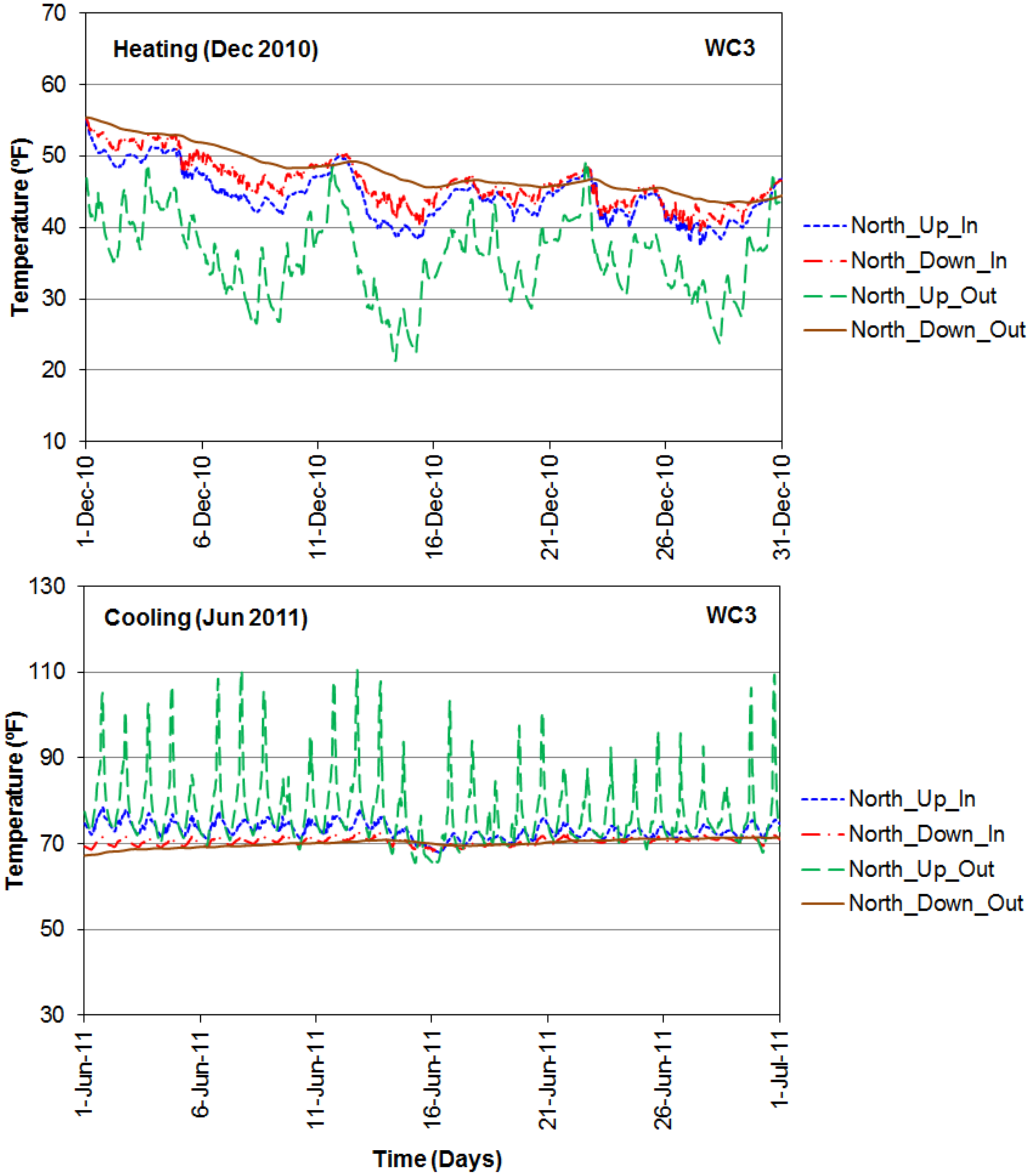

Figure 10. Temperatures on north wall of WC3 crawlspace in December 2010 and June 2011, with vents open.

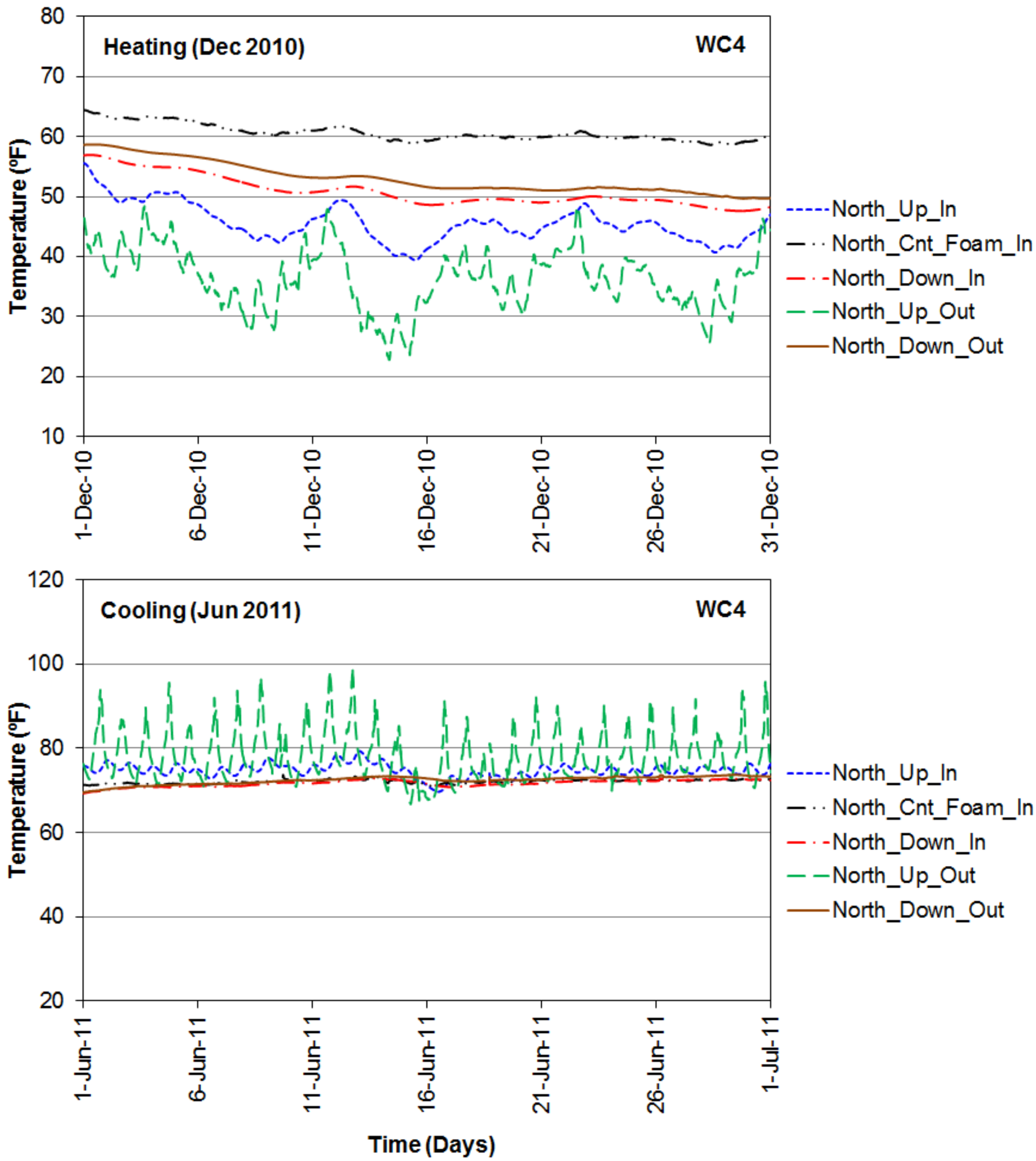

Figure 11. Temperatures on north wall of WC4 crawlspace in December 2010 (supply duct open) and June 2011 (supply duct closed).

During December, the interior north wall above-grade temperatures in WC3 and WC4 showed similar magnitudes and fluctuations. However, differences were seen in the below-grade interior surface temperatures. The WC3 interior below-grade temperature fluctuated above and below the outside ground temperature ('North_Down_Out'), while in WC4 the interior temperature between the masonry wall and the insulation was always lower. Figure 11 also shows the interior foam insulation temperature in WC4, which was 5-10 ºF higher than the outside ground temperature.

During June, the interior temperatures in both WC3 and WC4 and the interior foam temperature in WC4 were relatively constant with minor fluctuations. All interior temperatures were very close to the exterior below-grade ground temperature.

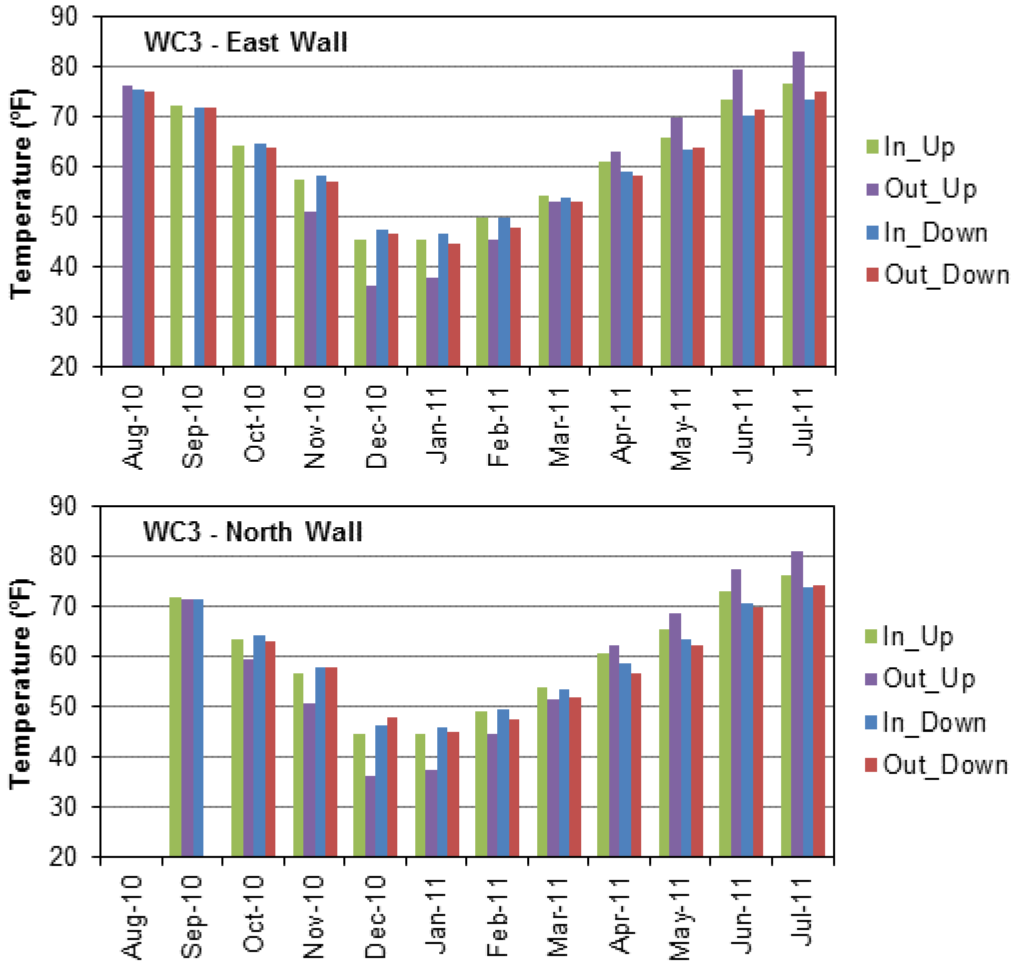

Figure 12. Monthly average masonry wall temperatures in WC3 crawlspace.

Figure 12 shows the monthly averages of the east and north wall temperatures in WC3. During the "shoulder" and heating months, the average above-grade interior temperatures were always higher than the outside temperatures, with larger differences during the coldest weather. The trend reversed starting April 2011, with higher temperature differences during the peak of summer (July 2011). The below-grade average interior and exterior temperatures stayed fairly close to each other and, similar to above-grade temperatures, showed a reversal of the temperature difference trend between heating and cooling seasons.

Considering December 2010-January 2011 as the peak heating season, during this time, the interior above-grade temperature was higher than the above-grade exterior temperature by about 8.1 ºF on average. During June-July 2011 (cooling season), the above-grade interior was cooler than the exterior by about 5.4 ºF. Below-grade, the temperature differences were about 1 ºF or less during both heating and cooling seasons, with the interior temperature being both higher and lower than the exterior.

Figure 13 shows the monthly average wall and interior foam temperatures in WC4. The interior foam surface was warmer than the wall exterior during heating and shoulder months, and cooler during the summer months. During the coldest winter months, the foam interior was warmer than the wall exterior by about 23 ºF above-grade and 10 ºF below-grade. During peak summer months, the foam interior was cooler than the exterior by about 7.2 ºF above-grade and 2.2 ºF below-grade.

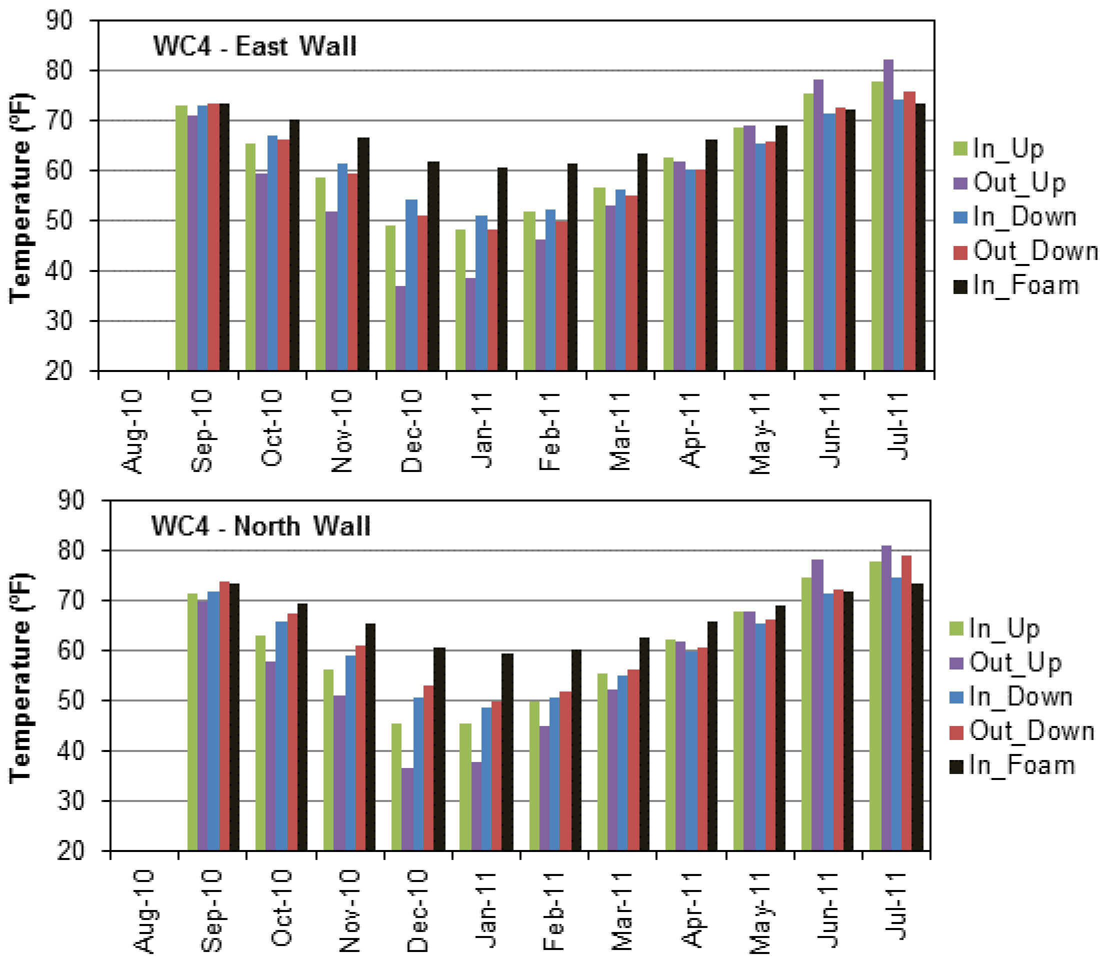

Figure 13. Monthly average masonry wall temperatures in WC4 crawlspace.

Figure 14 and Figure 15 show the heat flux through the north walls of the WC3 and WC4 crawlspaces during December 2010 and June 2011. The heat flow into the crawlspace is considered positive and heat flow out is negative. The heat flux histories follow the temperature histories seen in Figure 10 and Figure 11, with the heat flow direction depending on the temperature gradient.

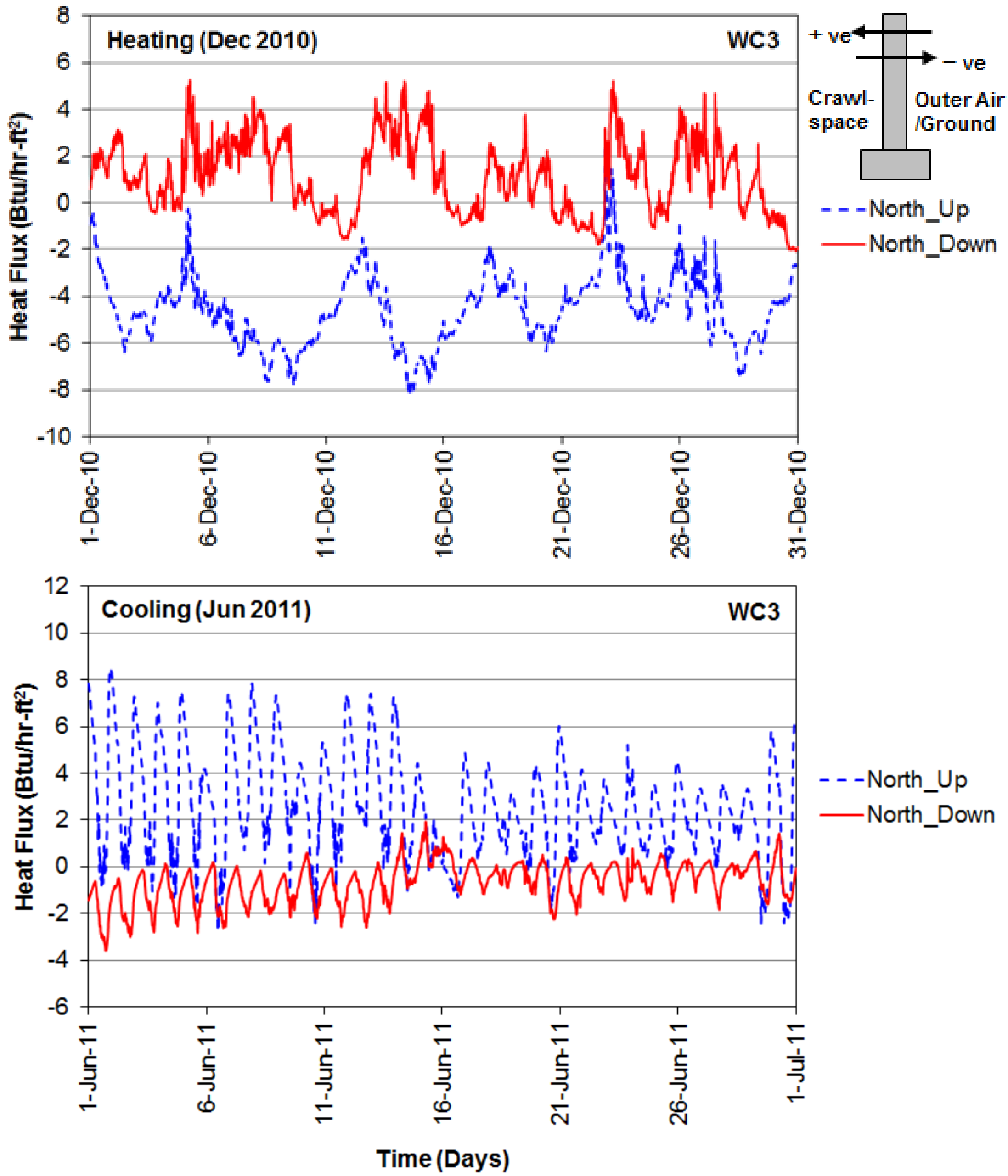

Figure 14. Heat flux through the north wall in WC3 crawlspace during December 2010 and June 2011.

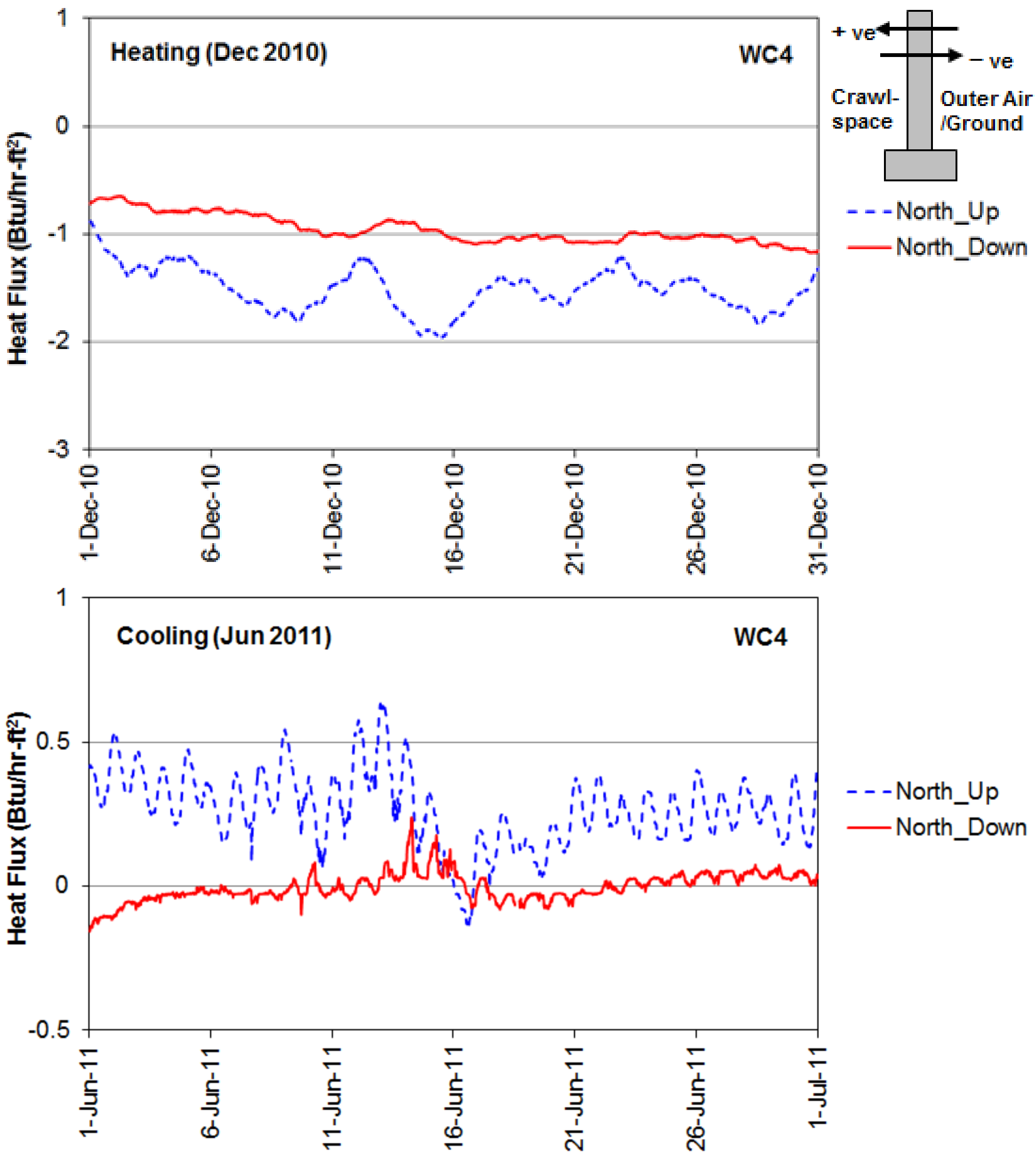

Figure 15. Heat flux through the north wall in WC4 crawlspace during December 2010 and June 2011.

During December, in the north wall of WC3, the below-grade heat flow was predominantly into the crawlspace and the above-grade heat flow was out of the crawlspace; both showed similar magnitudes and fluctuations. During June, below-grade, the heat flux is predominantly out of the crawlspace, while the above-grade heat flux is into the crawlspace. The heat flux magnitude and fluctuations above-grade were much higher than below-grade, as expected from the temperature profiles (Figure 10).

In the WC4 north wall, both above- and below-grade heat flows were out of the crawlspace throughout December. During June, the above-grade heat flow was predominantly into the crawlspace; below grade the heat flow was mainly out of the crawlspace at the beginning of the month and then reversed to be predominantly into the crawlspace. The WC4 heat flows were much lower than those in WC3 because of the interior foam insulation.

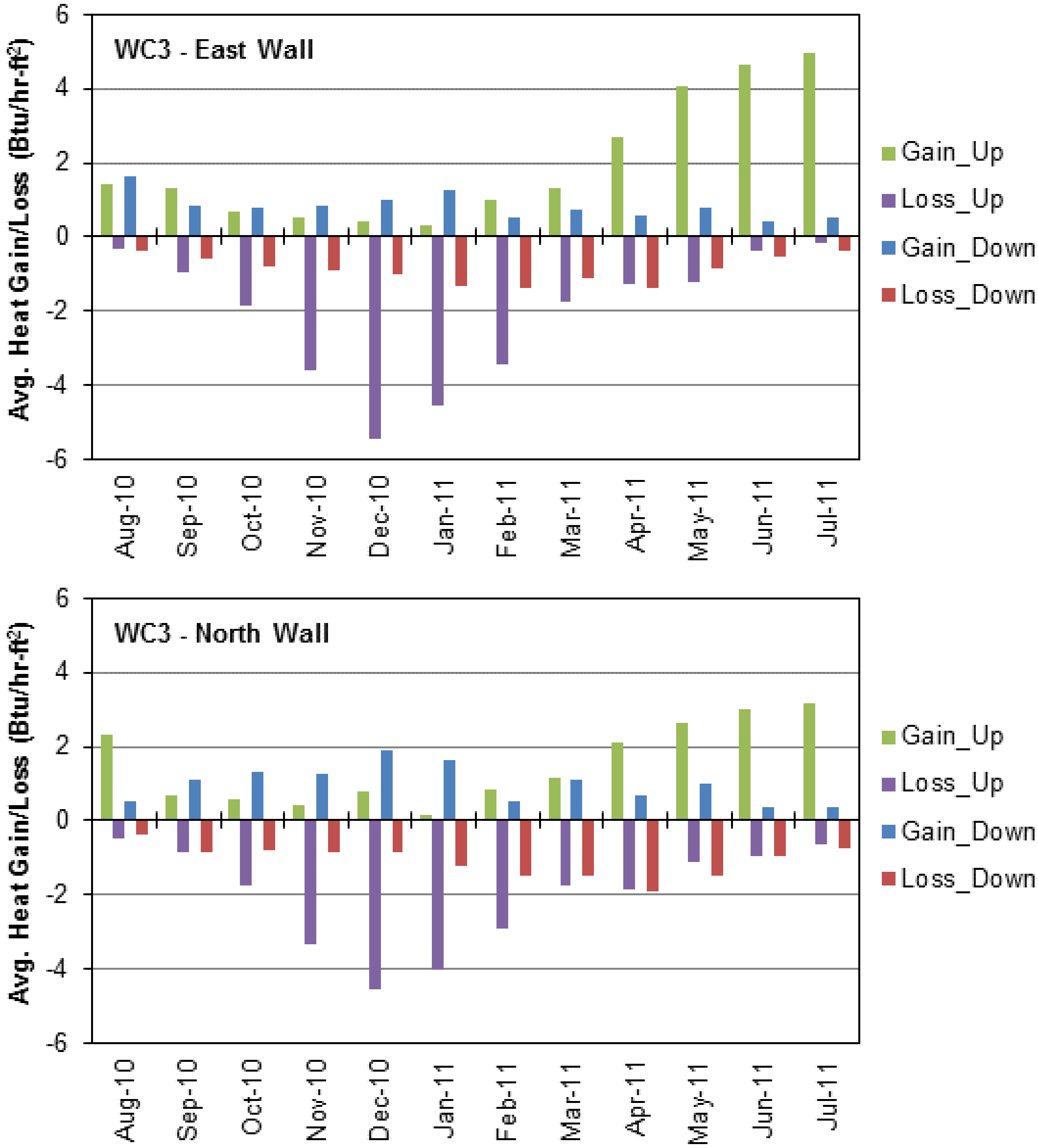

Figure 16. Monthly heat gains and losses through the crawlspace walls in WC3.

Figure 16 shows the average monthly heat gains and losses through the east and north walls of WC3, which were calculated by separately averaging the positive and negative heat fluxes. Similar trends were seen in the east and north walls. During winter, the above-grade heat flows are predominantly out of the crawlspaces, as illustrated by the large heat loss bars ("Loss_Up"), and into the crawlspace during summer months (larger "Gain_Up" bars). The below-grade ("Down") heat gains and losses showed similar trends, but had lower magnitudes than the above-grade average heat gains and losses.

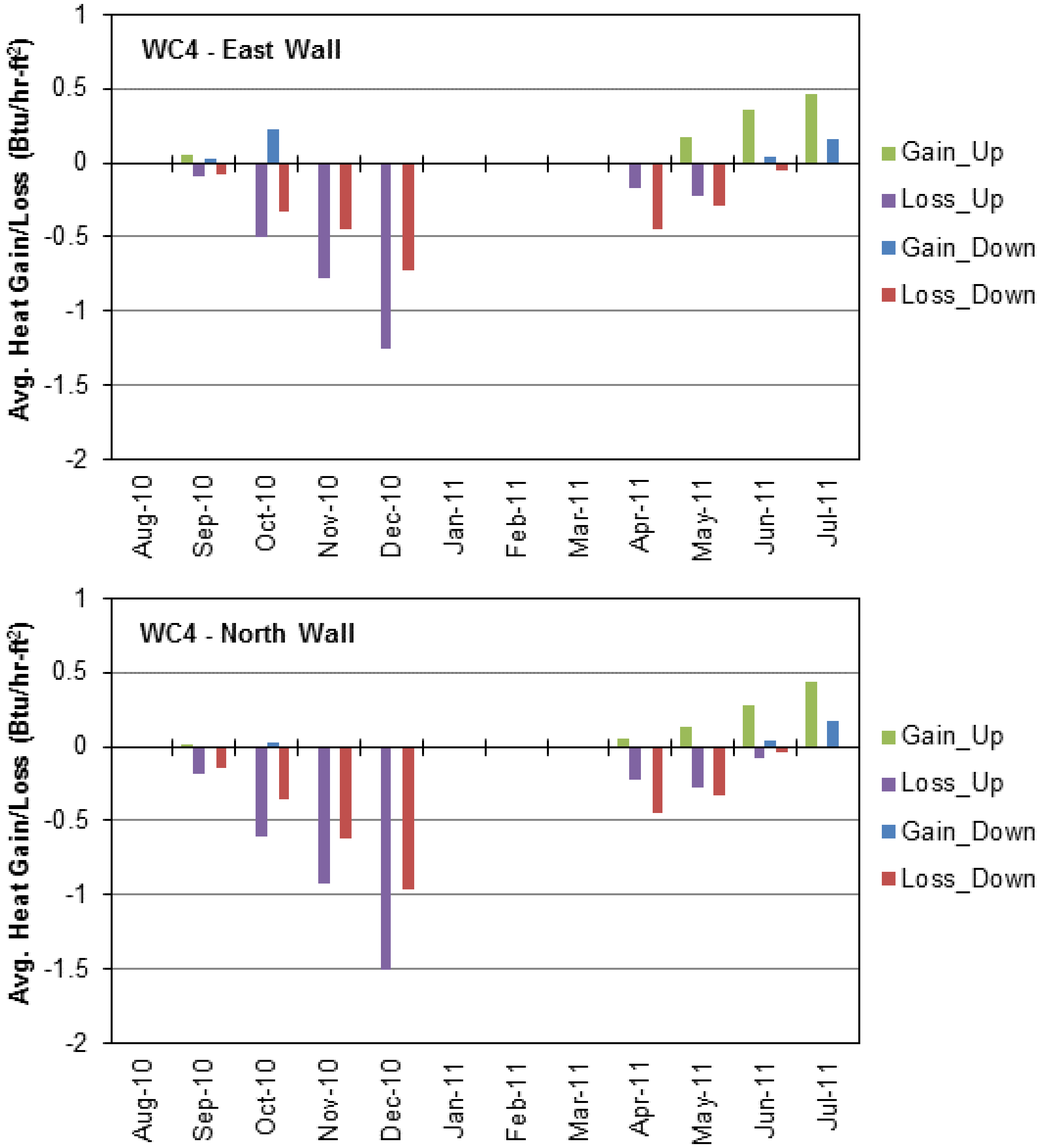

Figure 17. Monthly heat gains and losses through the crawlspace walls in WC4 (missing data: Aug. 2010 and Jan. – Mar. 2011).

Figure 17 shows the heat gains and losses through the WC4 crawlspace walls. WC4 HFT data were not available for August 2010 and were corrupted during January-March 2011 and are not shown here. Some trends can still be identified from the available data. During winter, both above- and below-grade sensors showed relatively high heat losses, with no significant heat gain. During peak summer months, there is some heat gain into the crawlspace, especially above grade. It is noted that the peak winter heat loss was a factor of 3 higher than peak summer heat gain. Compared to WC3, the above-grade peak heat gain/loss was about a factor of 4 – 5 lower; below grade, the WC4 average heat flows were lower, but comparable to those in WC3.

It should be noted that the thermal mass of the earth was expected to benefit the crawlspace in WC3, whereas in WC4 the insulation was expected to block the residual soil thermal mass heat transfer during both early winter and early summer.

Crawlspace Air and Ceiling

Temperature data from the crawlspace air and ceiling are presented here along with the living area temperatures. From the perspective of whole-house energy performance, the conditions in the crawlspace and at the crawlspace ceiling (subfloor) are important. The crawlspace air and ceiling temperatures are the controlling factors in determining the added heating or cooling loads on the house from the crawlspace.

Figure 18 and Figure 19 show temperatures in the living area and crawlspace air and ceiling ('Subfloor') in WC3 and WC4. In December, the average living room and bedroom temperatures in the two houses, measured 5 feet from the floor, were about 71 ºF, with minor fluctuations. During this month, the mean crawlspace air temperature was about 15 ºF lower in WC3 than WC4, but the crawlspace ceiling or subfloor temperatures in WC3 and WC4 were comparable.

In June, the average living room temperatures were about 75 ºF in both houses; average bedroom temperature in WC3 was about 72 ºF. The subfloor temperature under the master bedroom in both houses and the under-joist temperature in WC3 are also shown. These additional thermistors were installed in March 2011. In WC3, the subfloor and room temperatures showed significant overlap in both the living/dining and bedroom areas. The crawlspace air and under-joist temperatures were predominantly lower than the living room temperatures, but rose above the room temperature sporadically. The joist temperature is within about 3 ºF of the crawlspace air temperature at all times, which is expected given the close proximity of the sensors. In WC4, both the crawlspace air and subfloor were consistently cooler than the living room.

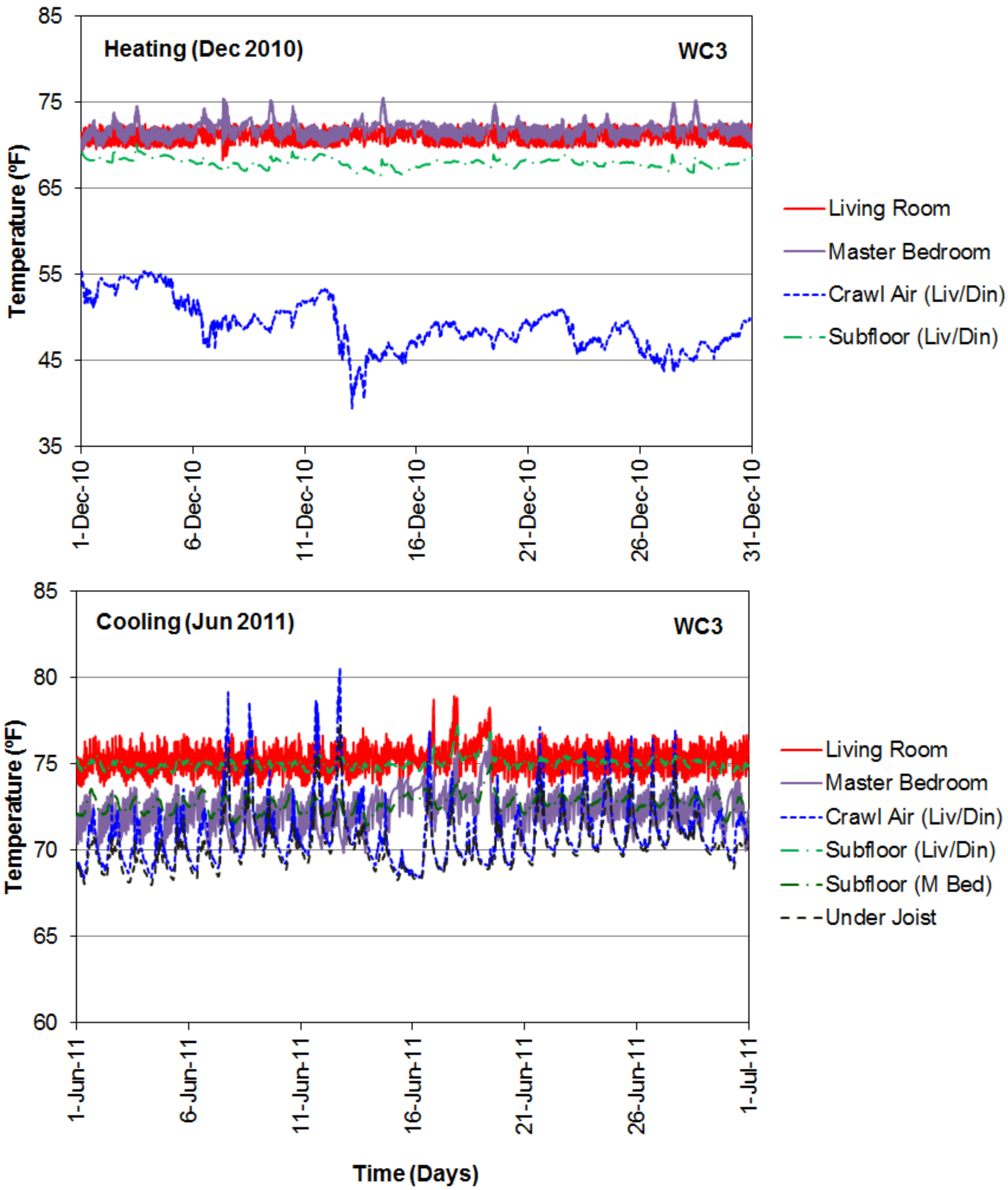

Figure 18. Temperatures in the crawlspace and living area of WC3 during December 2010 and June 2011.

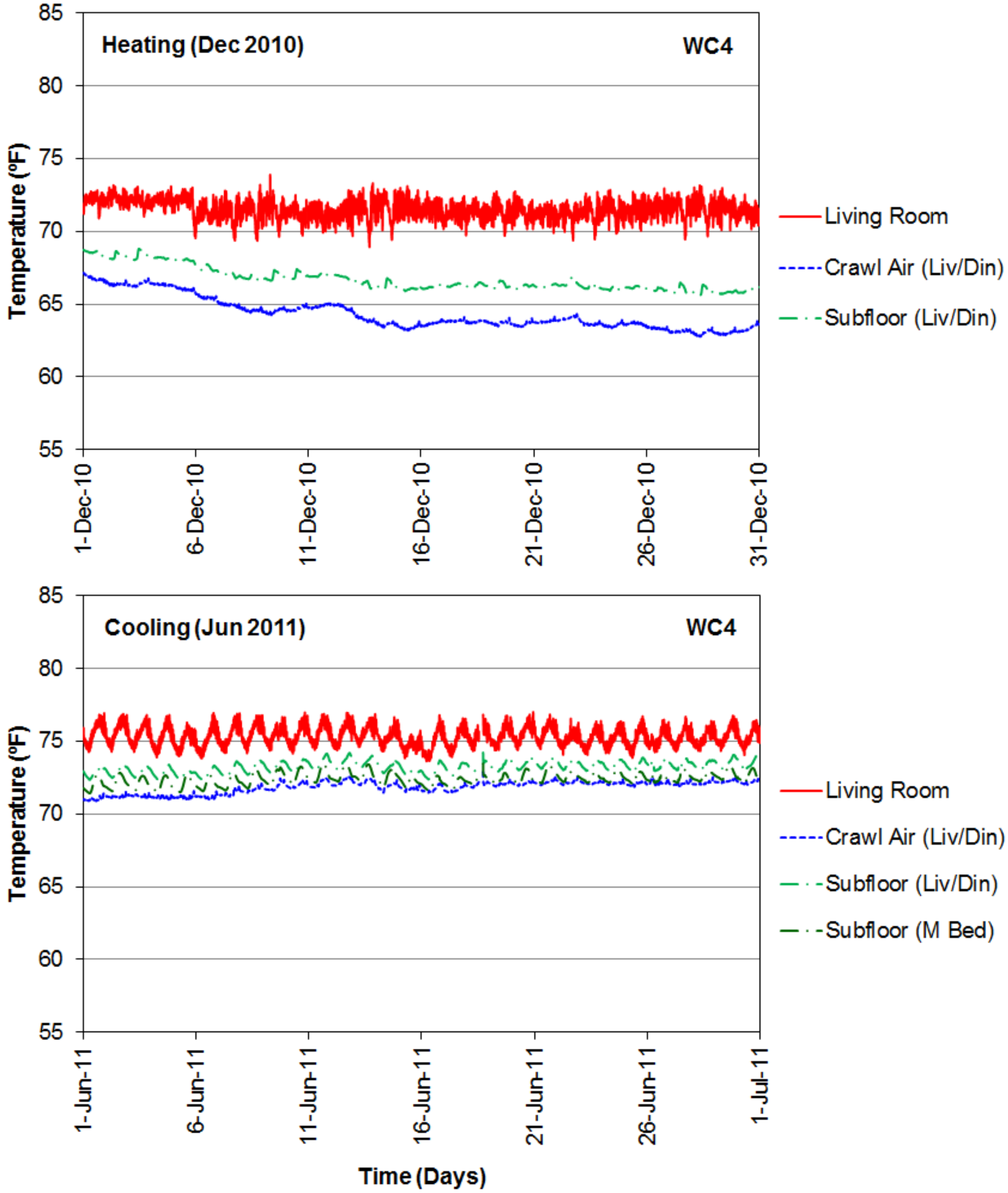

Figure 19. Temperatures in the crawlspace and living area of WC4 during December 2010 and June 2011.

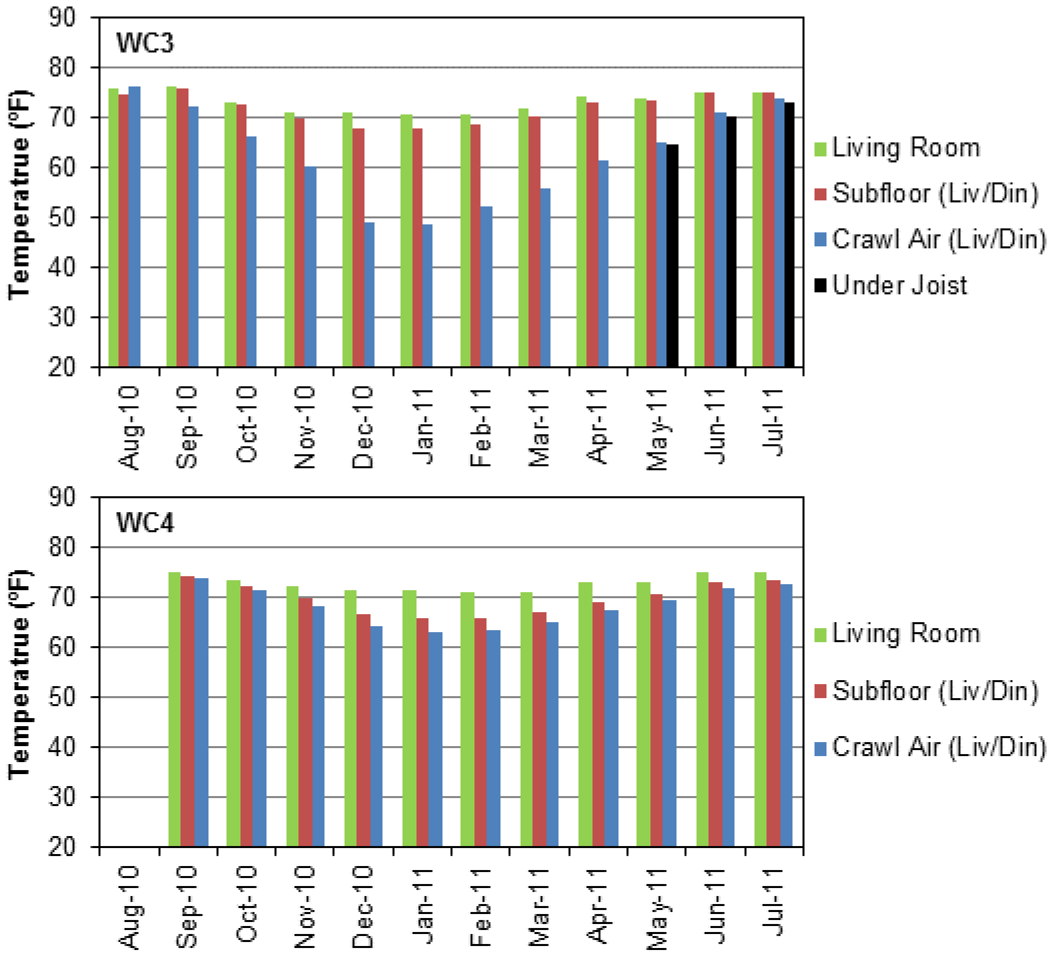

Figure 20. Monthly average subfloor and crawlspace air temperatures.

Figure 20 shows the monthly average temperatures in the two houses. As expected, the average WC3 crawlspace air temperature was much lower than the living room temperature during winter, with a maximum drop of 22 ºF. During summer, the average WC3 crawlspace air temperature was closer to the room temperature, within 5 ºF. The two R-16 batts installed in the WC3 subfloor were very effective in reducing the temperature difference between the subfloor and the living room, which was very small throughout the year. WC4 crawlspace air temperatures were higher than WC3's during winter, with a maximum difference of 15.3 ºF, and comparable during summer (within 1.5 ºF). The WC3 and WC4 subfloor temperatures were not significantly different, but the WC3 subfloor was consistently warmer by 0.5-4 ºF. Also shown are the average joist temperatures in WC3 during May-July 2011, which were within 1 ºF of the WC3 crawlspace air temperatures.

The average temperature differences (ΔT) between living area and subfloor were calculated and are shown in Figure 21. ΔT is positive when the living room temperature is higher than the crawlspace ceiling temperature. The average subfloor temperatures were predominantly lower than the living room temperatures in both houses, except WC3 subfloor in July 2011. Larger temperature differences were observed between the living room and the subfloor in WC4. During peak winter, December-January, the WC3 subfloor was colder than the living room by about 3 ºF and the WC4 subfloor was colder by 5.2 ºF. In summer (June-July), the differences were smaller, about 0.2 ºF in WC3 and 1.7 ºF in WC4.

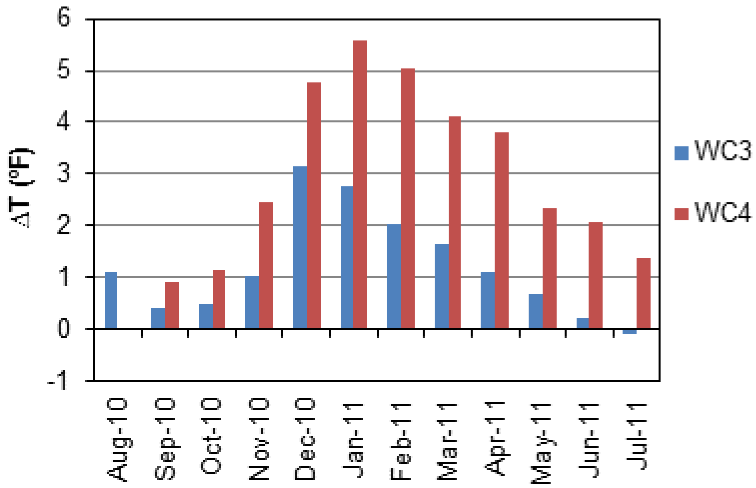

Figure 21. Differences in average crawlspace ceiling (under subfloor) and living room temperatures.

In March 2011, HFTs were installed in the subfloors under the living/dining and bedroom areas to directly measure the heat flow between the crawlspace and the main house. Figure 22 shows the heat flows through the subfloor in WC3 and WC4 during June 2011. Positive heat fluxes indicate heat added to the crawlspace (heat loss or heating load for the main house) and negative values indicate heat flow out of the crawlspace (heat gain or cooling load for the house). In Oak Ridge, TN, peak summer usually occurs during July and August, and data from these months would have allowed a more critical comparison of the crawlspaces. However, data from WC4 were missing for parts of July 2011, so could not be used for comparison. The cooling-season heat flow through the WC4 subfloor was greater than in WC3. Also, the heat flow was always from the house into the crawlspace in WC4, indicating a potential reduction in the cooling load. In WC3, the subfloor heat flows were both into and out of the crawlspace.

Figure 23 shows the monthly average heat gains and losses through the subfloor in the two houses. It is interesting that during summer the WC4 crawlspace shows higher heat gains through the subfloor, which actually means a net heat loss from the living space of the house and a potential reduction in the overall cooling load during summer. During winter, however, a heating penalty can be expected in WC4 due to the higher ΔT which would cause greater heat flow into the crawlspace from the house (Figure 21).

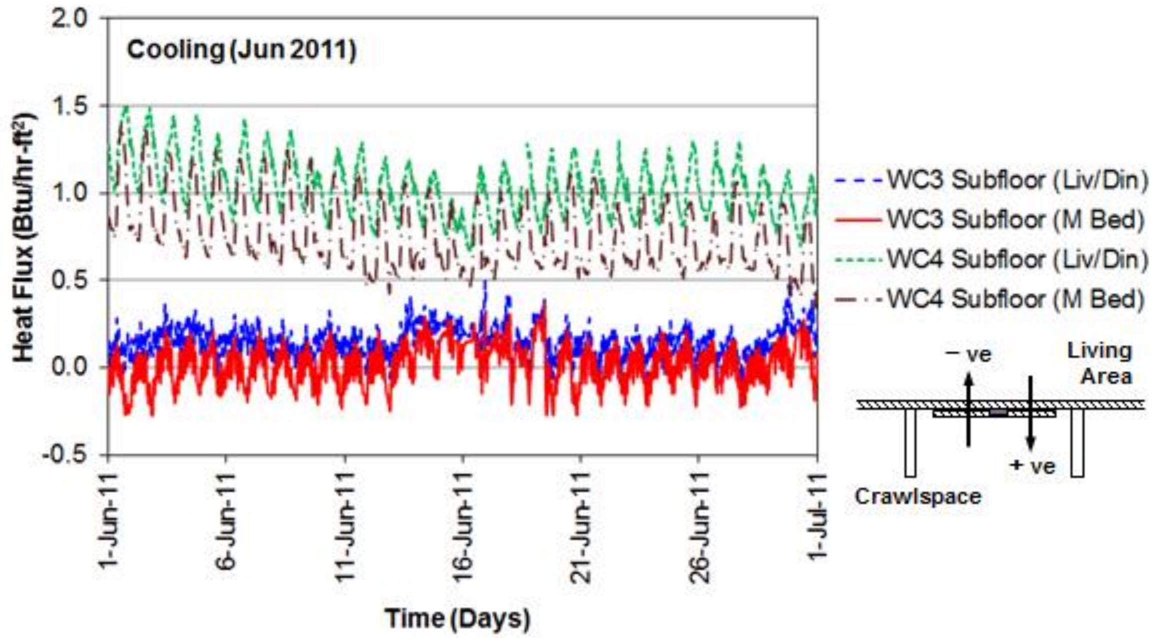

Figure 22. Heat flux through the subfloor (crawlspace ceiling) during June 2011.

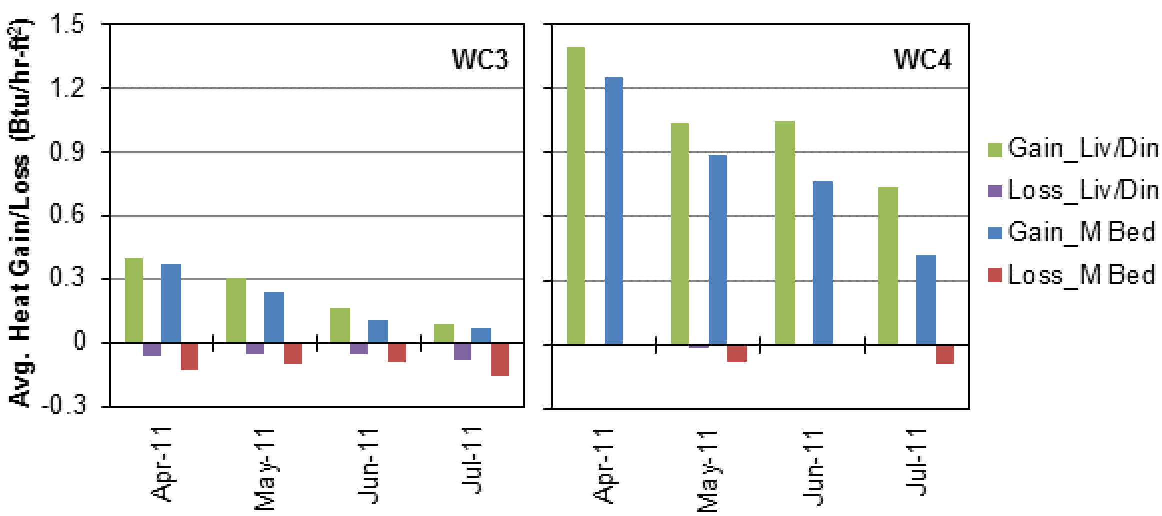

Figure 23. Average monthly heat fluxes through the subfloor (crawlspace ceiling) in WC3 and WC4.

The heat flux and temperature data coupled with a thermal model, Heating [5], were used to estimate the heat loss or addition due to the crawlspaces. Figure 24 shows the thermal models of the subfloor cross sections. The contours represent normalized temperatures, based on the room (T_i) and crawlspace air (T_o) temperatures. The models show the cross section between adjacent subfloor cavity centers. The models include the ¾ inch OSB floor, joist, fiberglass insulation (in WC3 only) and the ½ inch OSB used to install the HFTs. In the model, the two R-16 batts were each assumed to be 3.5 inches thick.

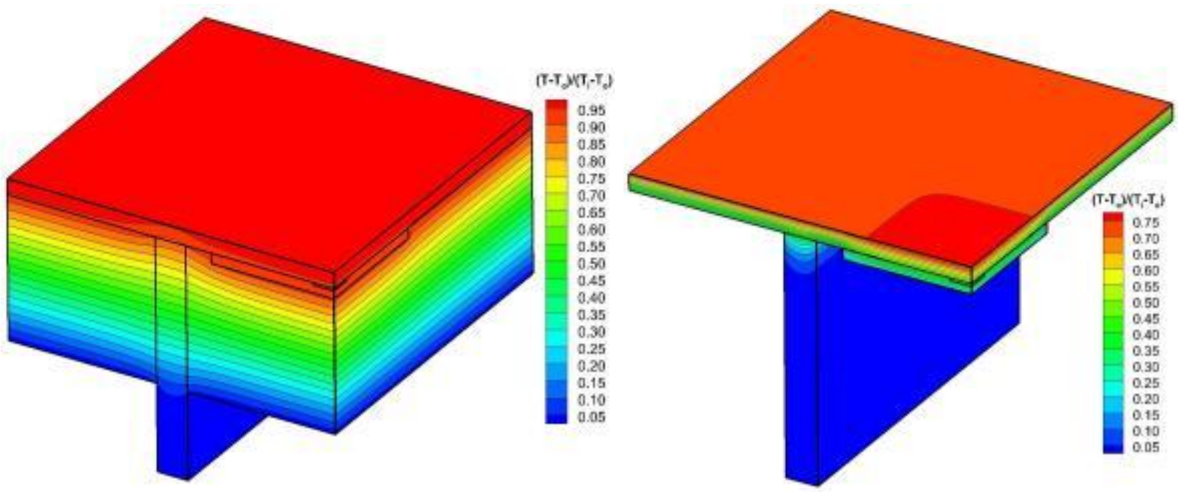

Figure 24. Heating models of WC3 (left) and WC4 (right) subfloor cross sections.

Table 2 lists the material properties that were used in the model. Properties were obtained from measurements or manufacturers' specifications. ASHRAE handbook [6] values were used for the convection heat transfer coefficients at the top and bottom surfaces.

Table 2. Material properties used in the Heating model

Material	Thermal Conductivity (Btu-in/hr-ft^2-°F)	Specific Heat (Btu/lb-ft)	Density (lb/ft^3)
Wood joist	1.0	0.390	36.0
OSB	0.9	0.336	44.6
Fiberglass	0.285	0.196	2.9

Modeling results indicated that addition of the ½ inch OSB to install the HFTs substantially altered the thermal resistance at the heat flux measurement location in WC4; the impact was relatively minor in WC3 due to the large thermal resistance of the fiberglass batts. Correction factors were calculated to account for the added resistance of the ½ inch OSB, which would reduce the true heat flow at the HFT location. Further, the heat flow through the joists is expected to be different from the cavity centers where the HFTs are located, especially in WC3 where the joists are major thermal bridges. Calculations showed that the heat flow at the HFT location is 101% of the average heat flow over the total floor area in the WC4 model (cavity area and joist); in WC3, the heat flow through the HFT location was 84% of the average, which is expected because of the presence of the joists.

Accounting for the location of the HFTs with respect to the joist and cavity, and the effect of the ½ inch OSB, the calculated overall correction factors for WC3 and WC4 were 1.12 and 1.28, respectively. Multiplying the measured heat flux through the subfloor by the respective correction factor would yield a better estimate of the actual heat transfer per unit area between the crawlspace and living area.

May and June 2011 data from the HFTs installed under the subfloor in WC3 and WC4 were used to estimate the heat gain/loss of the living area, through the subfloor. Heat flux data (Btu/hr-ft^2) averaged over 15 minutes were first multiplied by the correction factors, then multiplied by the total floor area and time interval (0.25 hour) to estimate the energy added to or removed from the living area.

Combining the measurements and the modeling results, there were net heat additions of 265.5 and 260.1 Wh to the WC4 crawlspace in May and June 2011, respectively. As discussed earlier, these represent heat removal from the living area of the house and, hence, would potentially reduce the cooling load on WC4. In WC3, there were net heat additions of 60.5 and 19.4 Wh to the crawlspace in May and June. Assuming both houses were in cooling mode throughout May and June, a simple summation of the positive and negative values was used to determine the net heat gain or loss through the subfloor. Thus, during the cooling season, the WC4 crawlspace configuration is marginally more beneficial from an energy perspective to the interaction between the living area and the crawlspace, with an incremental cooling load reduction of about 0.2-0.25 kWh over the WC3 crawlspace design. However, the monetary benefit due to the WC4 crawlspace design during the cooling months will be insignificant given the cost of electricity (~ $0.10/kWh). Monitoring will continue through the next heating season to quantify the heating penalty due to the sealed crawlspace design.

It should be noted that the vents to the WC3 crawlspace were closed for part of the winter months (mid-January to March 2011), potentially affecting conditions in the crawlspace. It is also important to note that both crawlspaces were devoid of ductwork. Their performance can be expected to be very different with the presence of ducts and the associated leakage.

Crawlspace Relative Humidity

According to the Moisture Control Handbook [7], the following conditions are required for surface mold and biological growth, with the conditions needing to last for a week or more:

- Mold spores and nutrient base
- Temperatures between 40 and 100 ºF
- Relative humidity greater than 70% near the surface

To assess the RH in the crawlspaces, sensors were placed inside and outside the masonry walls, in the crawlspace air, under the subfloor and, in WC4, inside the foam wall insulation. The RH variations during December 2010 and June 2011 are shown in Figure 25 and Figure 26.

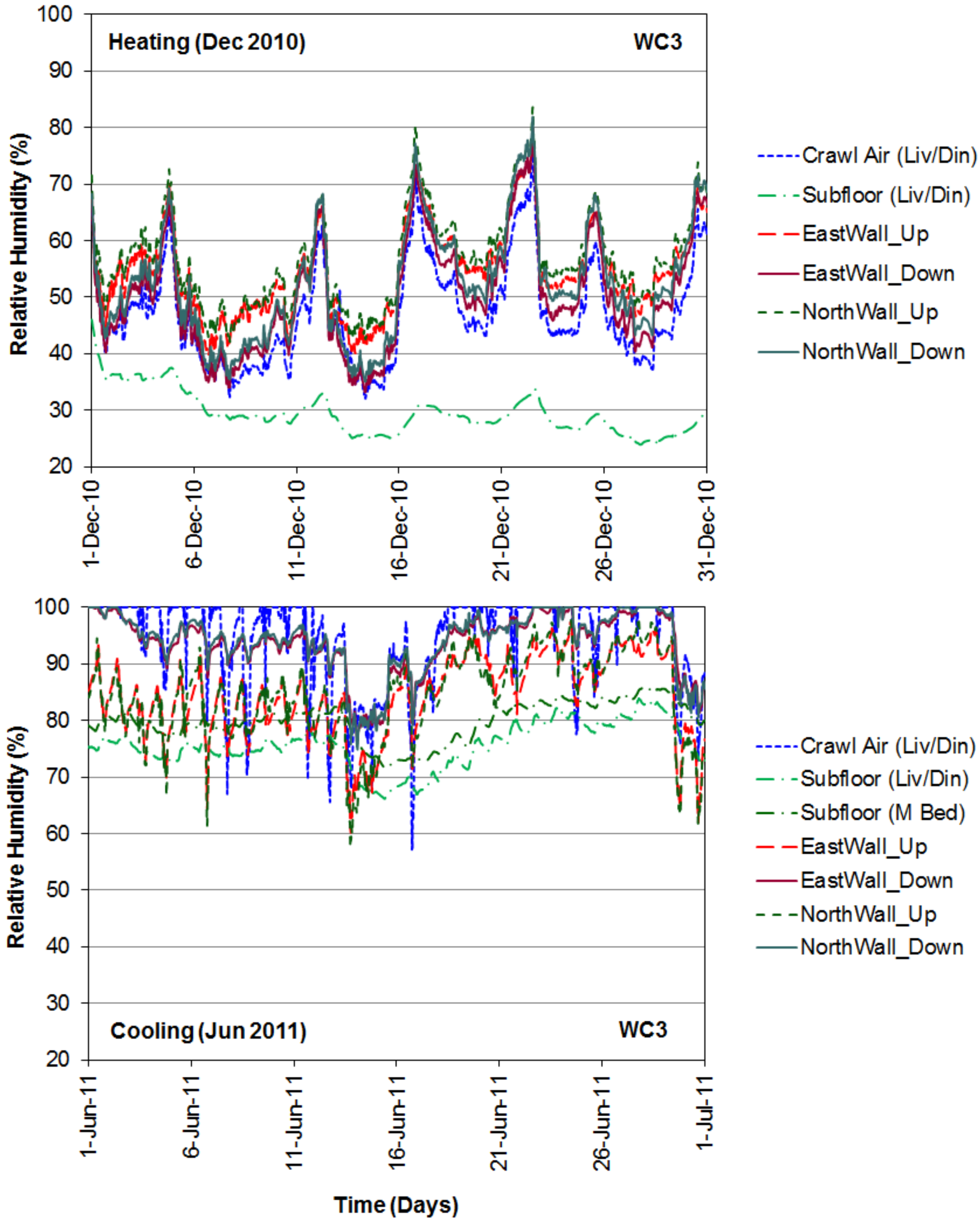

Figure 25. Relative humidity in WC3 crawlspace during December 2010 and June 2011.

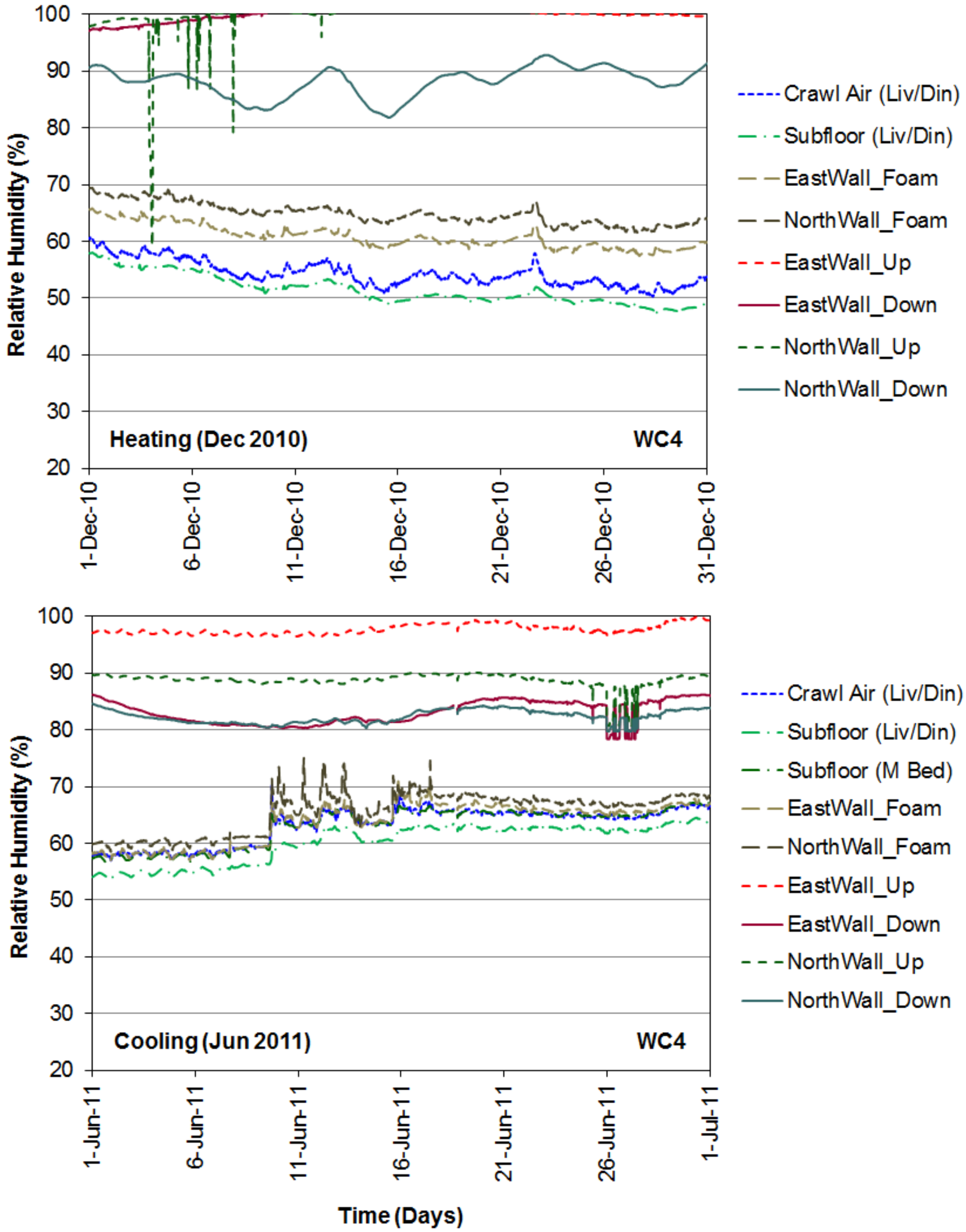

Figure 26. Relative humidity in WC4 crawlspace during December 2010 and June 2011.

During December in WC3, the crawlspace air and wall interiors showed large RH fluctuations, from about 30% to over 80%, but high humidity (RH > 70%) conditions did not persist for a week or longer at any time. The under-subfloor surface never rose to 70% RH. However, during June, RH of the WC3 crawlspace air and on all surfaces was predominantly over 70%, and the crawlspace air was at or close to 100% for significant time periods. The subfloor surfaces varied from 70% to 90%.

In WC4 crawlspace (Figure 26), the wall interiors (between the masonry block wall and the insulation) were close to or at 100% RH for the entire month of December. However, the crawlspace design, with wall and floor liners, prevented any condensates from entering the conditioned crawlspace. The crawlspace air and the interior foam and under-subfloor surfaces did not rise to 70% RH. During June, RH of the interior masonry wall surfaces varied from 80 to 100%. The interior foam surfaces were usually below 70%, with sporadic spikes over 70%. The crawlspace air and subfloor RH remained below 70%.

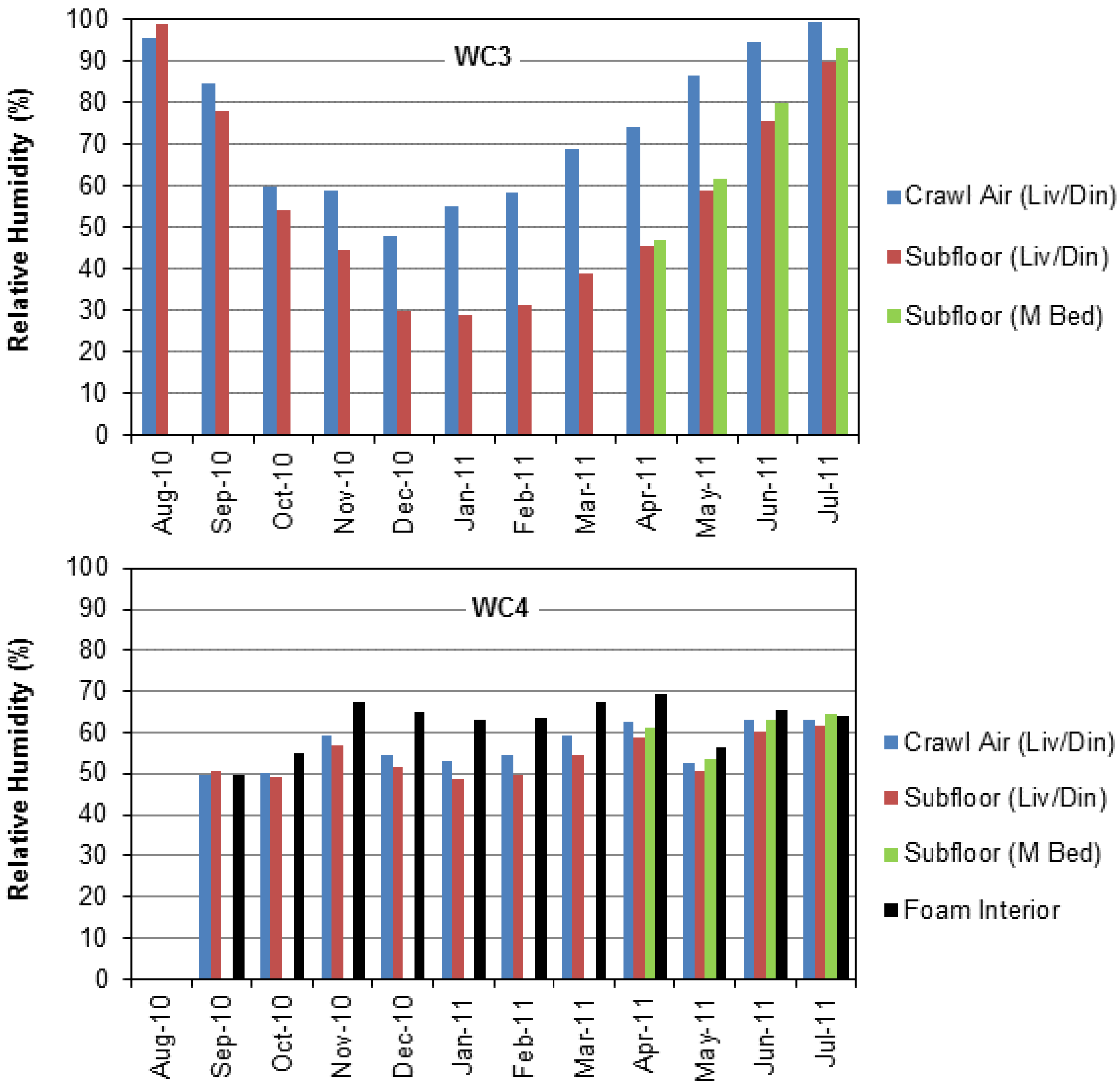

Figure 27. Monthly averages of relative humidity in WC3 and WC4 crawlspaces.

Figure 27 shows the monthly averages of RH in the crawlspace air and subfloor in the two crawlspaces. Monthly average RH values for the WC3 crawlspace and subfloor varied substantially between winter and summer. The crawlspace air and subfloor had minimum of 48 and 29% average RH, respectively, during winter, but both rose to close to 100% RH during summer.

In WC4, the average RH of the crawlspace air, subfloor, and interior foam surfaces varied from 50 to 70% during the evaluation period. Note that the dehumidifier in the WC4 crawlspace was continuously operated during the early part of the evaluation period (August – October 2010), but was turned off at the end of October in anticipation of the drier winter months. An increase in RH levels was seen from October to November 2010, after which they stabilized. The dehumidifier was turned on again at the end of April 2011, but had very high power consumption, as discussed in a later section, and was turned off on May 24, 2011. The dehumidifier in the WC4 crawlspace was turned on briefly again for about 4 days in mid-July, when the crawlspace RH rose to over 70% following a period of persistent rainfall. Even with the dehumidifier turned off for majority of the summer, the RH levels remained below the critical 70% except for the one instance in mid-July.

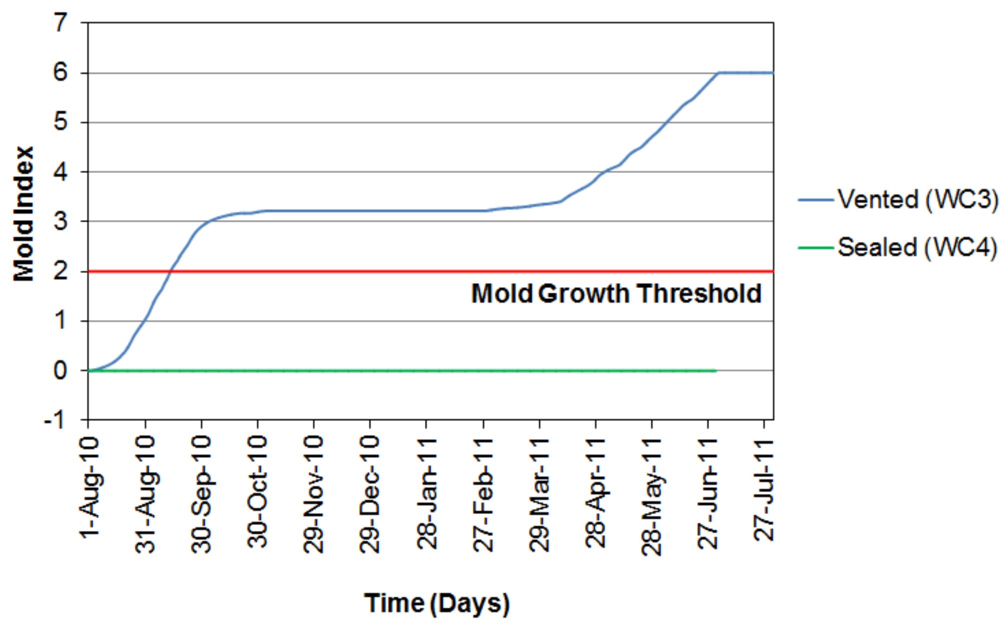

Figure 28. Calculated mold growth indices in WC3 and WC4 crawlspaces.

Based on RH levels, the WC4 crawlspace performed better than the WC3 crawlspace during the humid summer months. However, according to the moisture handbook [7], it is a combination of suitable temperature and RH conditions that leads to moisture related problems. To analyze the combined effect of temperature and RH, mold indices in the crawlspaces were calculated based on the method described by Sedlbauer [8]. Sedlbauer [8] listed a mold index of 2 as the threshold for mold growth that is visible to the naked eye, 3 as noticeable growth, 4 as strong growth, and 5 as total overgrowth. Figure 28 shows the evolution of the calculated mold indices in WC3 and WC4 crawlspaces, and the mold growth threshold. The calculations assumed untreated wood joists and were based on the measured crawlspace air temperature and RH. The use of crawlspace air temperature and RH was deemed appropriate because of the proximity of crawlspace air sensors to the joists. When available, the measured joist and air temperatures in WC3 were very close to each other (Figure 18).

To begin the calculations, the mold indices were assumed to be zero at the beginning of the evaluation period. In WC3, the mold index showed a steady increase during August and September and stabilized over a value of 3. The index stayed stable through winter and spring before increasing again during summer to 6. It is clear from Figure 28 that in WC3 crawlspace, conditions suitable for noticeable mold growth were reached within about two months into the evaluation period. By the end of the 12-month period, severe mold growth potential is predicted. The mold index in the WC4 crawlspace remained at zero throughout the evaluation period, indicating that the strategy of sealing and insulating the crawlspace is better from a moisture perspective.

Figure 29 shows a visual comparison of the joists in the WC3 and WC4 crawlspaces after the end of the evaluation period. Some discoloration was visible on a number of joists in both crawlspaces. Overall, the joists in WC3 crawlspace did not appear to be worse than the WC4 joists. There was some powdery deposit on a few joists in the WC3 crawlspace, seen in the left panel in Figure 29, which could indicate a mold-related problem. It should be noted that, early in the construction period, mold growth was observed and mitigated in WC4 crawlspace. The two crawlspaces will continue to be monitored for another year, with a close focus on the subfloor joists for mold growth.

Figure 29. Visual comparison of WC3 (left) and WC4 (right) crawlspace joists in September 2011.

WC4 crawlspace also incorporates a conditioning duct that was designed to dehumidify the WC4 crawlspace during the cooling season. Temperature, humidity, and flow sensors were installed at the duct outlet during March 2011. Preliminary analysis of the temperature and humidity data at the duct outlet revealed a potential problem with the supply air actually adding moisture to the crawlspace. Figure 30 shows the specific humidity in the WC4 crawlspace and at the duct outlet based on RH and temperature data. The specific humidity was estimated using the calculation method described in Moran and Shapiro [9]. Also shown is the crawlspace duct air supply rate on the right axis.

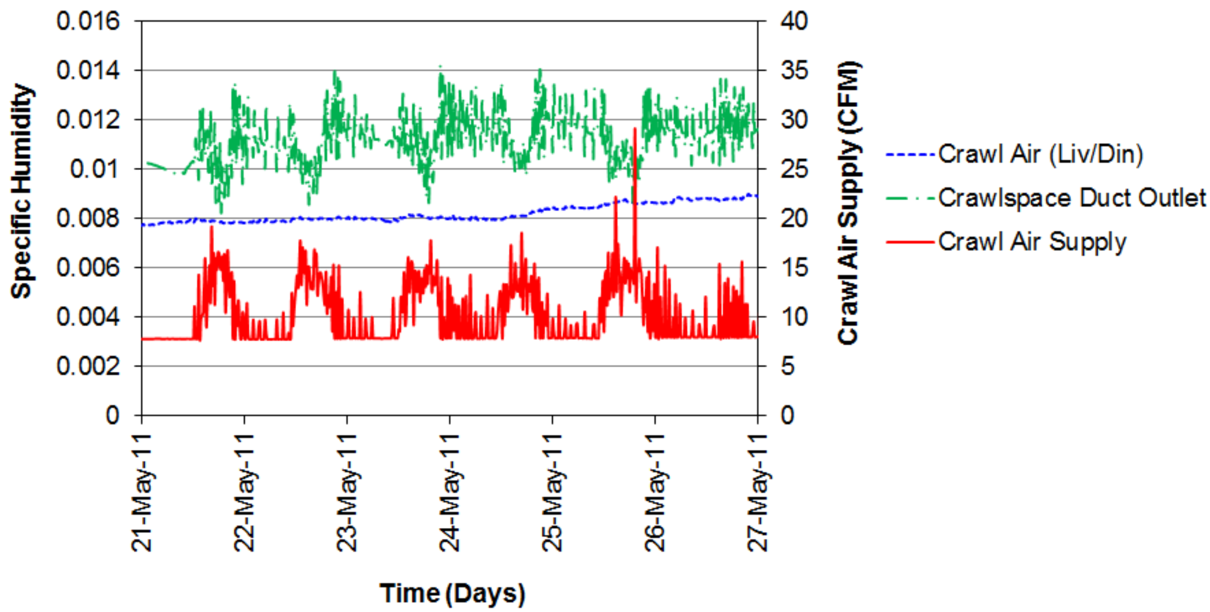

Figure 30. Calculated specific humidity in the WC4 crawlspace and at the supply duct outlet.

The preliminary analysis indicated higher absolute humidity at the crawlspace supply duct outlet compared to WC4 crawlspace. Further investigation revealed that the current duct configuration is such that it allowed unconditioned outside air to be fed into the crawlspace when the air cycler was on, bringing in fresh air to the house and crawlspace, but the heat pump was not operating. This problem could be more prominent in the shoulder months when there is limited cooling requirement, and the indoor coils may not be cold enough to condense some of the moisture in the incoming fresh air. To prevent any outside air from entering the crawlspace, the manual damper regulating the crawlspace air supply was closed and the duct outlet was closed and sealed on June 7, 2011, without adverse effects on the crawlspace RH, as shown by the June – July 2011 data (Figure 27).

WC4 Crawlspace: Additional Energy Considerations

Dehumidifier Operation

The WC4 crawlspace also incorporates a dehumidifier, whose operation was being monitored starting in the end of September 2010. Figure 31 shows the dehumidifier load over 15-minute intervals during October 2010. Also shown are the RH levels of the crawlspace air, ceiling, and foam surface. The interior RH levels were about 50% while the dehumidifier was operating. On Oct. 21, the dehumidifier was turned off for the upcoming winter, as high humidity levels were not expected.

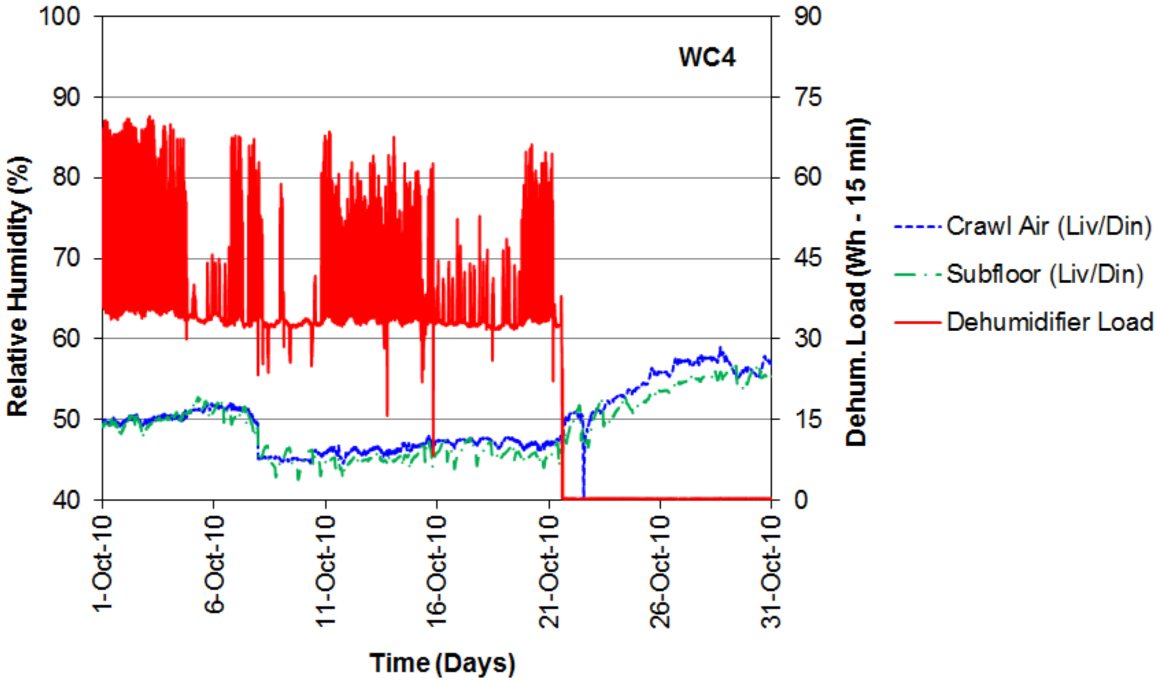

Figure 31. Dehumidifier operation in WC4 crawlspace during October 2010.

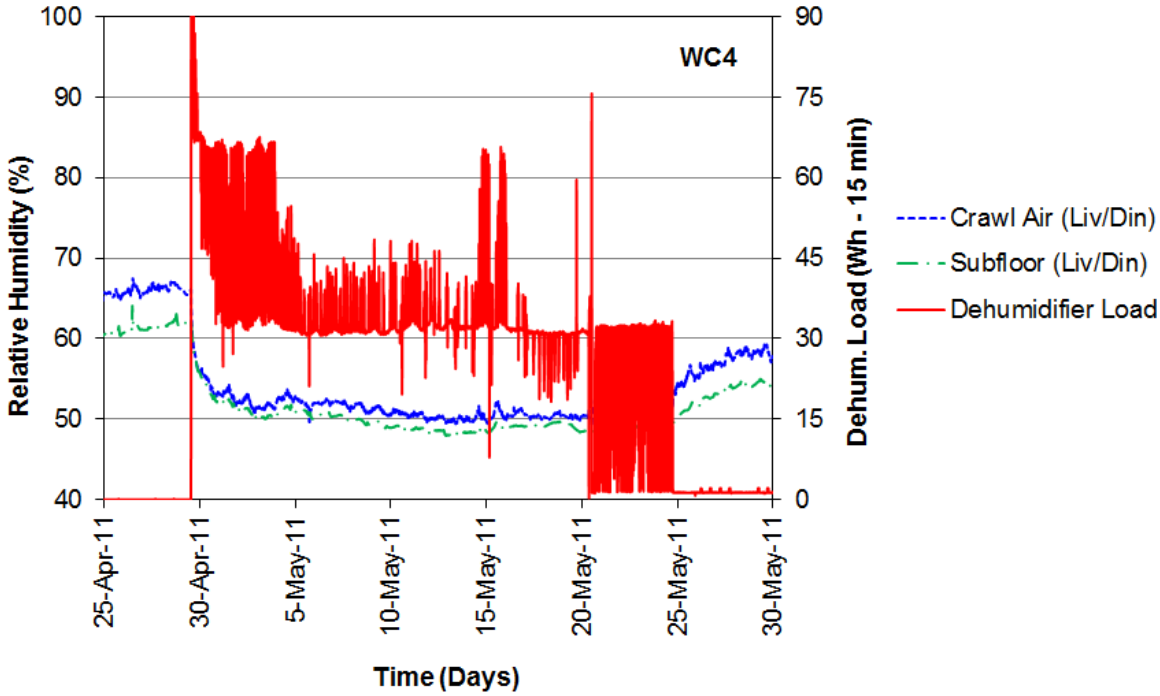

Figure 32. WC4 crawlspace relative humidity and dehumidifier operation during April – May 2011.

Near the end of April, in anticipation of the humid summer months, the dehumidifier was again powered on and set to automatically turn on at 60% RH in the WC4 crawlspace. Figure 32 shows the RH history during April – May 2011; note the reduction in the RH values from about 65% to about 55% once the dehumidifier was turned on near the end of April. With the 60% RH setting, the dehumidifier was consuming nearly 3 kWh per day. To reduce the energy consumption the RH setting was raised to 70% and was monitored for a few days, but there was no substantial reduction in energy consumption. The dehumidifier was subsequently turned off and unplugged on May 24, 2011. The RH levels were observed to rise and stabilize at just below 60%, which was deemed low enough not to cause any moisture-related problems.

Conditioning Duct

WC4 incorporates a conditioning duct in the crawlspace which is fed by the heat pump through the supply plenum. A manual damper is installed between the crawlspace duct and the supply plenum, and it was left open. To calculate the additional energy consumption, the respective flow rates (CFM) to the different zones of the house and the crawlspace were measured using Duct Blaster [10] and TrueFlow plates [11]. The power consumption to condition the crawlspace could then be calculated as

$$P_{crawl} = \left(CFM_{crawl} / CFM_{total} \right) \cdot P_{HeatPump} \quad (1)$$

Table 3. Distribution of air flow volume between WC4 house zones and crawlspace

Zones Open	Crawlspace (CFM)	Total (CFM)
Zone 1	24.9	807
Zone 2	50.6	407
Both zones	23.1	708

Table 3 lists the measured flow rates when air is supplied to different zones of the house along with the crawlspace. The house is divided into zones 1 and 2. Electromechanical dampers control the times during which each zone is supplied air, based on the demand. In Figure 33, the flow rate into the crawlspace is shown as a function of the total flow rate when air is supplied to the different zones. Also shown is a best-fit curve to calculate the crawlspace CFM based on total CFM. The times during which the electro-mechanical dampers were open were recorded, and based on those times the total and the crawlspace CFM was estimated. Finally, using the measured heat pump power and Equation 1, the power consumption to condition the crawlspace is estimated.

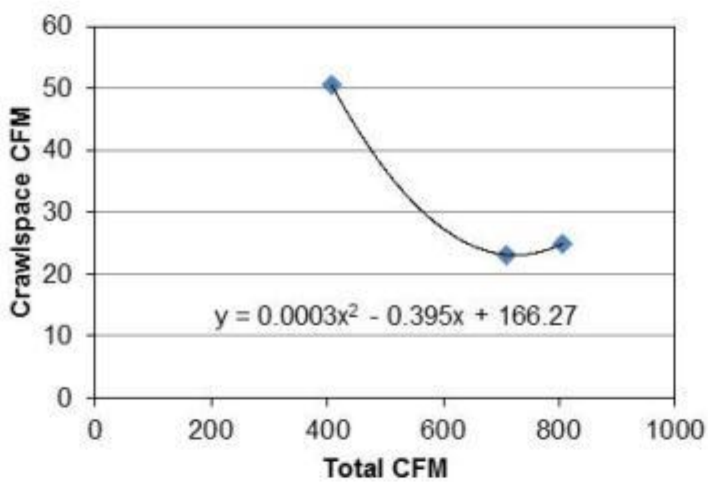

Figure 33. Comparison of conditioned air flow rate to the crawlspace and total flow rate.

Table 4 lists the estimated energy consumption for crawlspace conditioning during months representing the heating (January), shoulder (May), and cooling (July) seasons. As a fraction of the heat pump energy consumption, the crawlspace conditioning energy consumption was 3.2%, 6.9% and 7.3% for the heating, shoulder and cooling months, respectively.

Table 4. Comparison of WC4 crawlspace conditioning to the heat pump energy consumption

Month	Heat Pump Energy Consumption (kWh)	Crawlspace Conditioning Energy Consumption(kWh)
January, 2011	950.0	30.0
May, 2011	120.4	8.3
July, 2011	470.9[a]	34.4

[a] Note: The crawlspace supply duct was closed and sealed in early June 2011. Therefore, the July crawlspace duct energy consumption was estimated after adjusting the actual pump energy consumption to include the effect of an open crawlspace duct. The measured heat pump consumption was increased by an amount representing the additional consumption if the crawlspace duct had been open.

6. Summary and Conclusions

Two different types of crawlspaces were incorporated into two experimental houses built at the Wolf Creek (WC) subdivision in Oak Ridge, TN. One crawlspace was insulated, sealed, and semi-conditioned, while the other was a traditional vented crawlspace with insulation in the crawlspace ceiling. The vented crawlspace contained two R-16 fiberglass batts installed in the floor chase cavities above the crawlspace, while the sealed and insulated crawlspace contained R_{US}-9.8 foil-faced foam insulation on the interior side of the block wall. Sensors to measure temperatures, heat flux through crawlspace walls and ceiling, and relative humidity were installed in the two crawlspaces. Data collected between August 2010 and July 2011 were analyzed to compare the performance of the two crawlspace designs on an annual basis.

Two findings led to changes in the strategy for dehumidifying and conditioning the WC4 crawlspace. First, the dehumidifier, while very effective in maintaining the crawlspace RH at about 50%, had unreasonably high energy consumption. It was turned off in late May 2011 without an increase in the RH to critical levels. Further, data from the air supply duct into the WC4 crawlspace revealed that the supplied air could potentially increase the crawlspace humidity. The strategy of partially ventilating the house with fresh outside air resulted in unconditioned air being forced into the crawlspace when the heat pump compressor was not operating. This problem could be worse during spring and fall months, when there is limited space cooling requirement. Subsequently, the duct outlet was closed and sealed in early June 2011. The humidity levels in WC4 were monitored for the remainder of the evaluation period and were observed not to exceed critical levels.

From an energy perspective, based on the current analysis, the two crawlspace designs do not significantly differ in their impacts on the cooling energy cost. Higher temperature differences between the living room and the crawlspace ceiling in WC4 indicated higher heat transfer through the subfloor in WC4 compared to WC3, with the heat flow being predominantly into the crawlspace throughout the evaluation period. In the cooling season, higher heat transfer through the subfloor actually appeared to reduce the cooling load in WC4 more than WC3. However, the temperature differences across the subfloor were higher in the heating season compared to the cooling season, and a higher heating penalty in winter can be expected in WC4. Due to lack of instrumentation, the heat loss through the subfloor could not be quantified for the previous winter months. Monitoring will continue through another cycle of heating and cooling seasons to measure the subfloor heat flux and estimate the incremental heating penalty due to the sealed WC4 crawlspace versus the vented WC3 crawlspace, with respect to the whole house heating load.

The estimated WC4 crawlspace conditioning energy consumption was 3.2% and 7.3% of the heat pump energy consumption during a heating and a cooling month. The dehumidifier, when operated, consumed up to 3 kWh in a day.

Based on relative humidity data, WC4 crawlspace was significantly better from a moisture perspective, with and without the dehumidifier. Severe mold growth potential was predicted in the vented crawlspace of WC3 based on temperature and humidity data. The calculations showed no mold growth potential in the WC4 crawlspace. A recent inspection revealed no conclusive signs of mold in either crawlspace. These crawlspaces will be closely monitored through the next cooling season for mold growth.

The main conclusion of this study is that sealing and insulating the crawlspace is the recommended strategy in a mixed humid climate like Tennessee. Further, in a sealed crawlspace, it may be advisable to monitor the relative humidity level and operate a dehumidifier periodically, especially during and after a period of heavy rainfall. Constant use of the dehumidifier could result in very high energy consumption. Finally, if conditioning the crawlspace, care must be taken to prevent any unconditioned outside air from entering the crawlspace.

7. References

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