Engineering Science and Technology Division

Final Report
for Building Technology Center User Agreement

A Field Study Comparison of the Energy and Moisture Performance Characteristics of Ventilated Versus Sealed Crawl Spaces in the South:
Instrument #: DE-FC26-00NT40995

Hygrothermal Performance Study

(Experimental & Modeling)

PHASE 2

Achilles N. Karagiozis
Oak Ridge National Laboratory

Date Published - June 2005

Prepared for

Advanced Energy Corporation

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
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Executive Summary

In this report submission, the Phase II of the AE/DOE Hygrothermal Pilot Study is presented. The monitored data and the subsequent hygrothermal modeling have provided a definitive differentiation in performance of these two crawlspace systems for the mixed to hot and humid climates found in the south east climate zone.

The sealed crawlspaces for the particular buildings investigated clearly showed superior performance in comparison to the ventilated crawlspace system for both hygric and thermal performance. The benefits of the sealed crawlspace applications in the South East were found in Charlotte, Wilmington and Raleigh. Conditions were found to be drier than in the corresponding ventilated system. With the conditions examined (especially modeling), with adequate drainage and low water table level, the ventilated crawlspace did not enter the catastrophic failure region. However, the surface moisture contents at certain locations in the crawlspace floor did exceed the values of 16 % for wood. The modeling results have shown the importance of the presence of an effective vapor retarder on all ground surfaces and wall surfaces. Without an effective vapor barrier, the sealed crawlspace may lead to moisture accumulation especially when the ground water table level is high.

The experimental investigation has demonstrated the mold growth potential for the ventilated crawlspace, while none was observed for the sealed crawlspace configuration. As fibers, pollutants, radon gas, dust particles may accumulate with time in the crawlspace attention should be taken to have pressures in the crawlspace lower than in the house.

Using the modeling analysis it was concluded that the crawlspace energy performance is benefited more when the joist floor is insulated rather than the perimeter wall for the sealed cases. Insulated perimeter though provides a slightly higher temperature and enhances the moisture performance. Attention should be given to the type of insulation used in the perimeter. During the winter periods a net outward vapor pressure is occurring and condensation may occur at the interface of the insulation and polyethylene vapor retarder.

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ACKNOWLEDGEMENTS

The author of this report would like to acknowledge several important contributors such as Mr. Salonvaara for the scientific input to this project, and Dr. Holm for discussions on the indoor air movement. The full support of Andre Desjarlais, ORNL group leader must also be acknowledged, he has provided input at all stages of the project and assisted in the support of Phase II of this project. The specific support of the U.S. Department of Energy (DOE), Program Manager, Marc LaFrance, to the moisture control research at the Oak Ridge National Laboratory is gratefully recognized, without his recognition of this research area, this project would not have been possible. The demonstrated administrative and technical input provided during the project by Advanced Energy project manager Cyrus Dastur must be also recognized. Without the repeated support, assistance and above all patience provided by Advanced Energy this made the project doable.

INTRODUCTION

The work reported in this document is part of a larger research project administered by Advanced Energy Corporation, and funded by the U.S. Department of Energy (DOE) through a National Technology Laboratory (NTEL) research solicitation. The results reported are for phase II of the project. The overall objective of the project is to investigate the thermal, moisture, and indoor air quality performance characteristics of sealed versus ventilated crawl spaces for residential buildings in the South East of the USA. The Oak Ridge National Laboratory research participation has concentrated on the development of scientific hygrothermal performance data of crawl spaces by means of experimental monitoring and advanced hygrothermal modeling of a defined set of crawl space designs in the south east region of USA. The approach proposed is still an innovative moisture engineering one, accomplished by blending a set of experimentally determined crawl space performance data with accurate hygrothermal loading data, coupled to an advanced moisture engineering model.

Two phases of work are required to achieve the overall objective of the project. These form the two decision points at the end of year 1 and year 3 of the larger project. For detailed information on Phase I, the reader is referred to the Report I Pilot Study by Karagiozis [2002]. Throughout this project, a system engineering approach has been adopted. This required an integrated and flexible approach by all team members, managers (AEC), and the executive scientific advisory board.

Three distinct activities were identified as responsibilities by ORNL for both Phase I and II of the pilot project:

a) Manage the hygrothermal performance field study to obtain comparative information on the performance differences between sealed versus ventilated crawl spaces.
b) Conduct a hygrothermal performance analysis to develop data on crawl space system performance and to calibrate the hygrothermal model. This moisture engineering tool

was used to provide insight and assistance in analyzing issues related to building code provisions for improved crawl space construction.

c) Summarize and report these findings for both the pilot and main study.

The planned effort for all three activities initially had a duration of 34 months, but was interrupted for a period of 1 year, and reinitiated again in late 2003. All aspects of the research project proceeded according to the planned schedule with the exception of last 3 months of delay due to the simulation extension and activities relating to the input reworking.

In Phase 2 specific deliverables encompassed the following sub-activities:

- Continue to collect hygrothermal experimental data in both the sealed and ventilated crawlspace, analyze the data, and develop system information
- Perform a series of simulations using advanced hygrothermal modeling of the phase 2 pilot study.
- Prepare a final report : Pilot Hygrothermal Performance Study

It is important to understand that the intention of the pilot study is to provide realistic continuous crawl space system and sub-system information, data verification that did not exist at present. The data have critical value to the research community, research partners, and DOE, as they are expected to provide classical benchmark data not only for modeling crawl spaces, but also for developing experimental monitoring protocol.

GOALS OF PHASE II

The goals of Phase II of the hygrothermal pilot study is to characterize the multi-year crawlspace-building-environment performance, develop the needed understanding and recommended improved crawlspace performance. A list of these goals are:

- To monitor the retrofitted, “proposed configuration”, in terms of the hygrothermal response in a crawlspace environment to develop a set of experimental data, that will demonstrate the differentiable performance of two different crawlspace designs, the ventilated and the seal systems.
- To develop input parameters from the greater AEC field study project, and other sources (material properties, etc). Integrate knowledge from air flow measurements, RH, moisture content and develop system performance characterization.
- To develop a number of parametric analysis of the performance of crawlspaces in the south-east of USA.

STATE OF UNDERSTANDING

Currently, 2005, the most adopted method for constructing crawlspaces in the South-East of the US, are ventilated crawlspace systems. Poorly constructed crawlspaces contribute to presence of mold problems, indoor air problems, and increase the cost of operation of the home’s mechanical equipment. Many problematic crawlspaces have an excavated crawl space floor without providing an effective drainage, have poorly installed ground cover, and are naturally ventilated with exterior air. Today’s moisture induced problems can be caused by very different reasons than those in the 40’s, 50’ s and 80’s. One example is the presence of mechanical equipment in the crawlspaces, during the cooling period, condensation is formed on or around the region of the leaky ducts. This was not an issue in the 40’s, 50’s and even 70’s, but is probably a main problem for 1990’s and 2000.

Indeed, local exterior climate plays one of the determining influence decisions factors, along with the air tightness of the floor, and the leakiness of the mechanical systems especially the duct work. Many have advocated that if the decision is to include the mechanical equipment in the crawlspace, the unvented option should be recommended. However, the fact is that both systems can perform satisfactory. However, as we will demonstrate later in this report are there have been some very important advantages to insulating the crawlspace walls and sealing the crawlspace [DOE Fact Sheet] such as reducing problems associated with ventilating the crawlspace , employing less insulation, eliminating or reducing the requirement for insulation piping and ductwork, less impact of air sealing of floor. In the DOE Fact Sheet put assembled before the start of this crawlspace project, 2000, three energy efficiency approaches were demonstrated.

PROJECT BACKGROUND INFORMATION

In May, 2001, a contract between the Advanced Energy Corporation and the Oak Ridge National Laboratory was signed and the collaborative research agreement was initiated for phase I. Phase II was renegotiated after a 1.5 year interruption (although AEC was able to maintain the data collection system running without any interruption during this period) and was focused in continued understanding of the ventilated versus sealed crawlspace systems coupled with a limited number of parametric using hygrothermal modeling to develop better understanding of the physics involved in these two very different moisture management strategies.

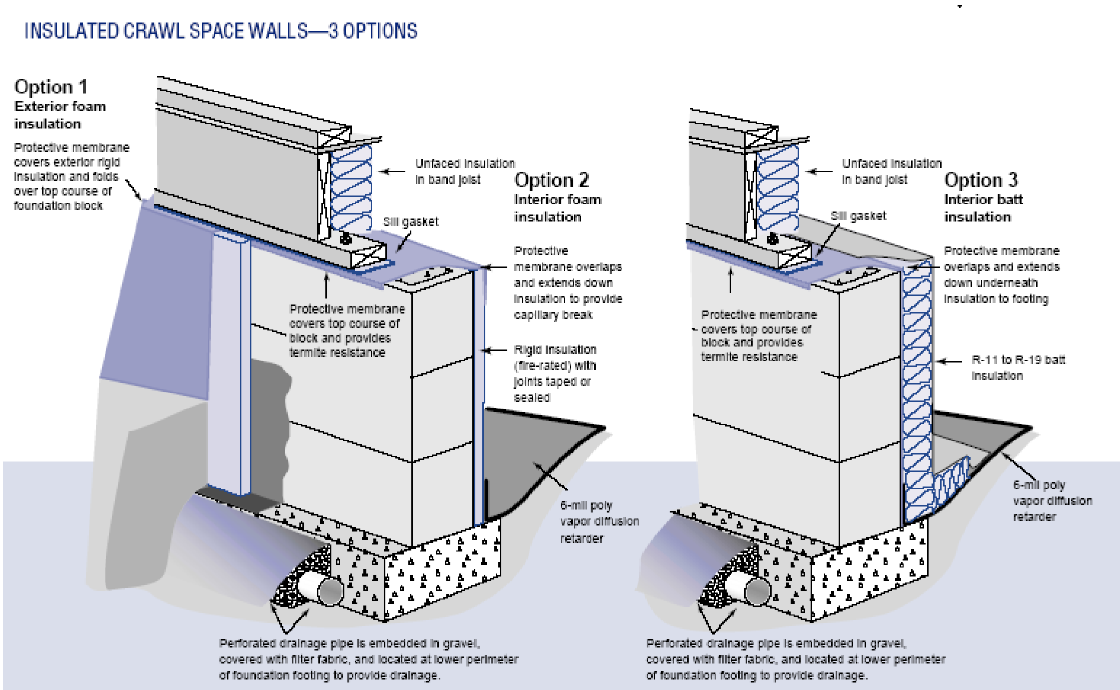


Figure 1: Three insulated crawlspace designs; 2000 Crawlspace Insulation Technology Fact Sheet "Improve comfort and increase durability in the home", Energy Efficiency and Renewable Energy Clearinghouse (EREC)

Particular information on the set-up and monitoring equipment, sensor calibration and crawlspace locations can be found in first report by Karagiozis [2002]. The details will not be repeated in this report. In previous report, a series of preliminary simulations were performed to determine the possible thermal and moisture distributions in both sealed and ventilated crawl space basements. Selection of the monitoring locations for the relative humidity, temperature, and moisture conditions were based on a series of preliminary hygrothermal simulations. These simulations were performed for a period of three years and only data from the third year were used for defining the monitoring location. This approach of using advanced hygrothermal modeling for defining the placement of sensors is still considered the most valuable approach. The integration of modeling and field monitoring not only provides valuable data after experimental data is gathered, but also allows identification of locations where significant hygric thermal and moisture gradients are present. This is of particular importance when monitoring moisture accumulations, as just a few millimeters depth or distances between monitoring locations may show very significant differences. Essentially those simulations provide the scientific justification for the number and selection of the sensor placement.

ORNL has been collecting data recorded on a 15 minute basis averaged every half and hour and stored into an array file once an hour. An automatic data acquisition system was developed to monitor the crawl space performance for a variety of criteria, including: conditions that indicate mold growth (T and RH dependent), conditions that could support moisture accumulation in building materials (moisture content dependent), relative moisture content inside and outside the crawl space, thermal temperature differences. Crawlspace collected data include pressure conditions, and exterior conditions such as solar irradiation, temperature, relative humidity, wind speed and orientation, see Table 1. The field monitoring work provided measured hygrothermal performance data for crawl spaces that are ventilated or sealed. A total of 111 sensors with the exception of a few sensors that failed during the course of the experimental investigation.

Data from the two systems were retrieved on a weekly basis (with the exception of the interrupted 1 year period). A few problems in Phase II occurred interfacing with the sealed crawl space, but the Advanced Energy staff resolved the faulty conditions/connections in a timely fashion.

Table 1: Original List of Instrumented Sensors

	Sealed	Vented	Total
Soil MC / T	3/2	3/2	6/4
Air RH / T	2/2	2/2	4/4
Block Inside Face MC/T	1/1	1/1	1/1
Block RH / T	1/1	1/1	2/2
Wood Joist MC / T House Air RH / T Air Velocity	15 / 15 1/1	17 / 17 1/1 4	32/32 2/2 4
Pressures	4	4	8
Wind speed / Direction			1/1
Solar Radiation- horiz.			1
Exterior Air RH / T			1/1
Total Sensors	49	57	111

In the AEC report Pilot Hygrothermal study [2002] by Karagiozis, the complete instrumentation configuration was presented in graphical manner both the sealed and vented crawl spaces. Additional measured data on the air leakage of the two pilot houses, crawlspace, ducts, and leakage between crawl space and other building components were conducted by Advanced Energy, Davis et al [2002]. This parallel activity building characterization (air leakage characterization) and the corresponding data derived provided the necessary sub-system evaluation that allowed load-based data measured by the pilot study to be applicable to other conditions. In others words, it allowed the modeling of crawl spaces by evaluating the system and sub-system independently from environmental loads. This is exactly what this report Phase II, employed to extend the performance analysis to an array of crawl space designs.

In each of the pilot crawl spaces, three joist were monitored--Joists A, B, and C. Joists A and C were chosen because the simulations showed that these locations have dynamic hygrothermal performances that were influenced by geometric parameters, such as whether they are placed next to the ground surfaces (JOIST C) and whether they are shielded by the surrounding exterior environmental loads (JOIST B).JOIST A was chosen because the simulations indicated that air flow through the vents affect the moisture distribution in the vented crawl space. The moisture content and temperature was monitored in the rim joist and the sill plate for each of the joists. In the middle of the joist, three moisture contents and temperatures were also monitored, one at the outer most surface of the sub-floor, one 4.5 inches from the sub-floor, and one 10 mm from the surface of the joists. Two sets of relative humidity sensors at the NE and SW regions of the crawl space were positioned to evaluate the sensitivity of the differences between the two crawl space regions, one having the bulk of the HVAC ducting (blocking effects) and the other having relatively open crawl space areas.

Four crawl space pressure differences were measured:

a) Pressure difference between crawl space and interior
b) Pressure difference between South Face at vent
c) Pressure difference of crawl space (average of 4 walls)
d) Pressure difference between North Face at vent

The moisture content and ground temperature was also monitored at three locations for each crawl space at 8 inches under the ground. Three hotwire anemometers were installed to measure the velocity at three of the vents, and another one at the relative humidity and temperature stations. This was done to allow a better understanding of the flow dynamics of the crawl spaces at openings and in the interior of the crawl space.

In the sealed crawl space, a wooded block was recommended by the scientific advisory committee to be installed with temperature, relative humidity, and moisture content sensors placed behind the polyethylene sheet in contact with the concrete block crawl space wall. This was installed in the NE corner, as it was assumed from the environmental load analysis to have the highest hygric loads.

Experimental Analysis of the Sealed and Ventilated Princeville Crawlspaces

Measured conditions in the houses with vented or sealed crawlspaces

The conditions in the monitored crawlspace homes were either vented or sealed crawlspaces and have been monitored during the period 2001-2004 (including the interrupt period). The temperatures, relative humidities, moisture contents and air velocities were measured for indoor air and crawlspace air, and the applicable elements for the wood joists and concrete blocks in the sealed and vented crawlspaces.

In this part of the report, the results from the last year of the measurements are presented. This experimental interval extends from October 2003 till October 2004. These results are expected to be representative of the performance of sealed and vented crawlspaces.

Details and measurement locations of crawlspace measurements

In the following paragraphs we use notations SC house and VC house when referring to the Sealed Crawlspace House and to the Vented Crawlspace house, respectively.

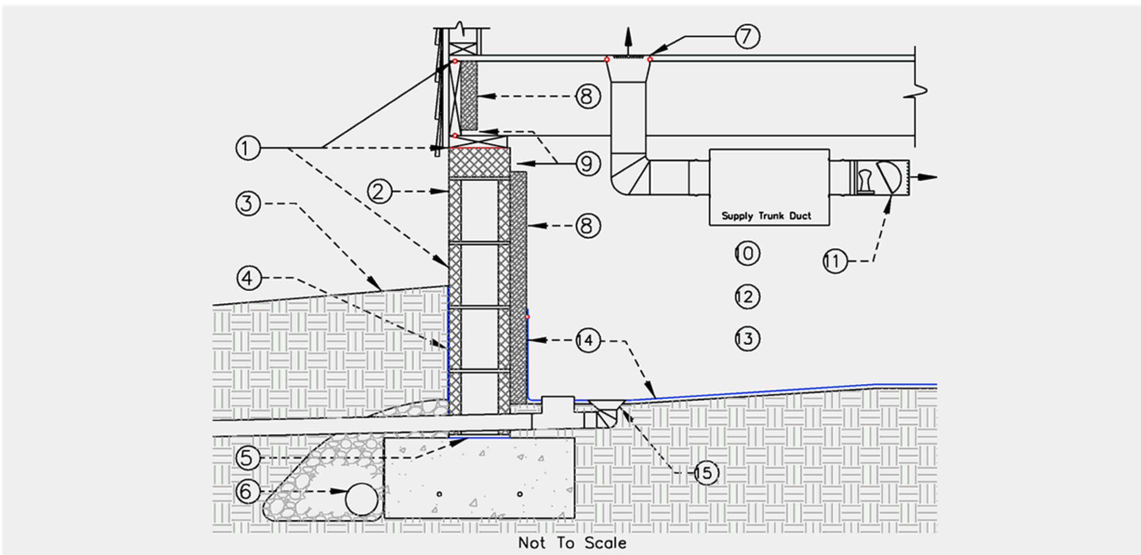


Figure 2: Sealed crawlspace with insulation at the exterior perimeter and without floor insulation.

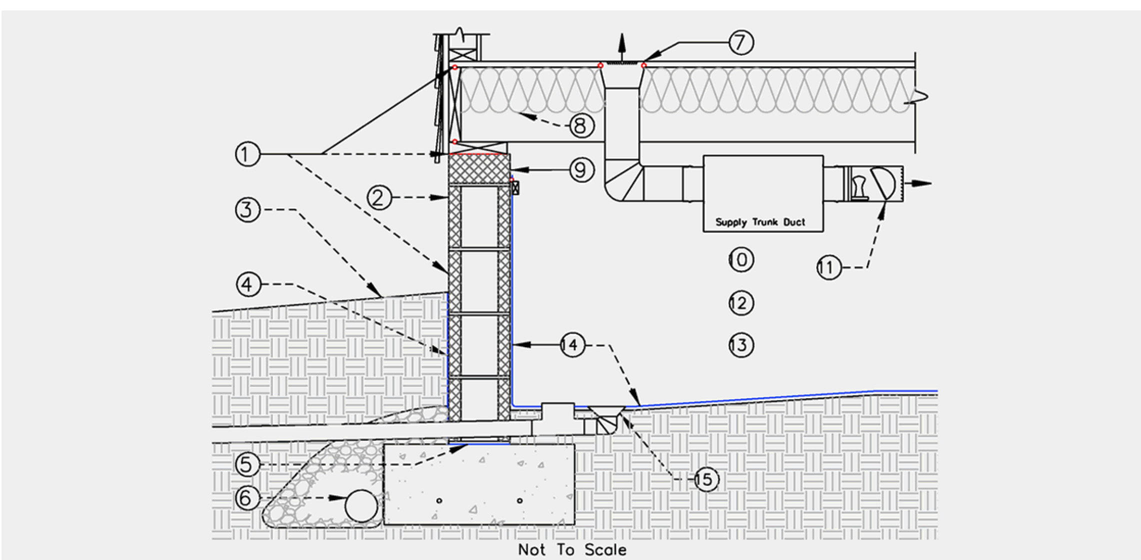


Figure 3: Vented crawlspace with insulated floor. Vented crawl space does not have supply duct coming out of duct trunk line as shown in the figure.

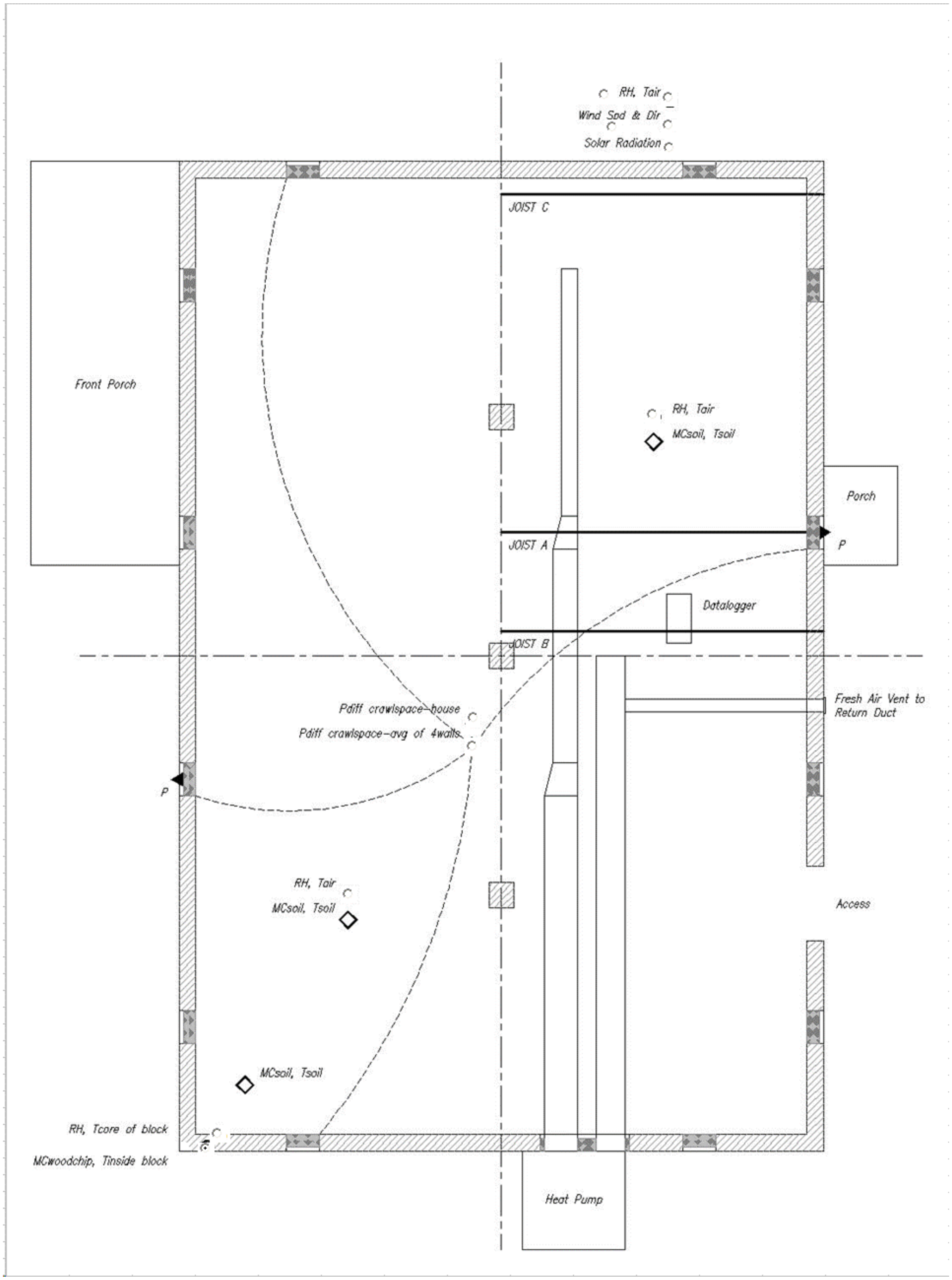


Figure 4: Measurement locations in the floor plan of the sealed crawlspace house.

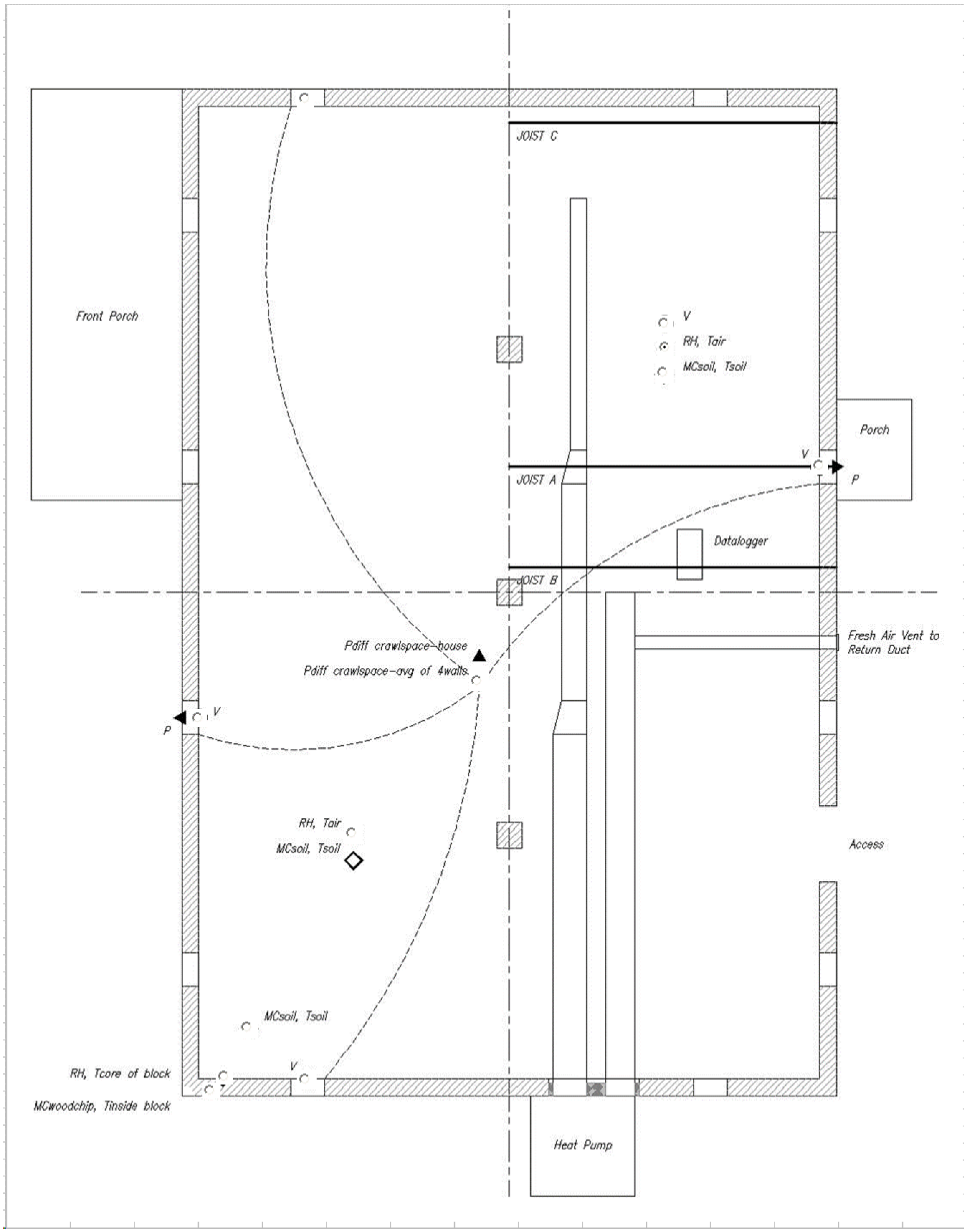


Figure 5: Measurement locations in the floor plan of the vented crawlspace house.

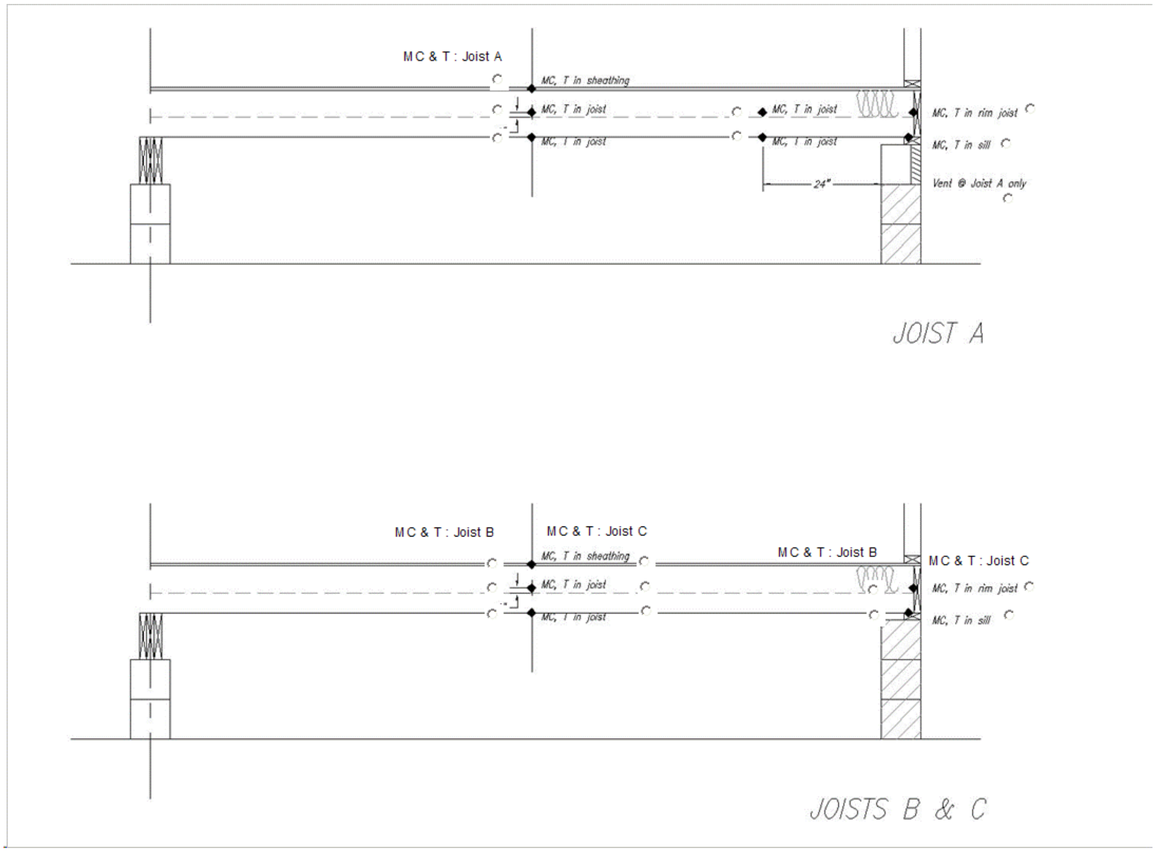


Figure 6: Measurements in the Floor Joist.

Air velocities through the vents

The main differences between the sealed and vented crawlspaces are: the location of the insulation and the air exchange rate (with fresh outdoor air) in the crawlspace.

The air velocities were measured at the air vents in the vented crawlspace. Figure 7 shows the measured velocities at the West and East vents when compared against each other. The sensors to measure the air velocities had the measurement range up to 0.5 m/s and it can be clearly seen that the upper range have been reached several times which means that there have likely been multiple occasions when the air velocity has been higher than 0.5 m/s. Correlation could be found for the air velocity at the west vent as a function of the air velocity at the east vent indicating flow through the crawlspace due to wind pressures. The measured air velocities indicate that the vented crawlspace has a high air exchange rate. The vented crawlspace had 11 vents as shown in Figure 5 (the 12th vent was used for the outside air duct intake).

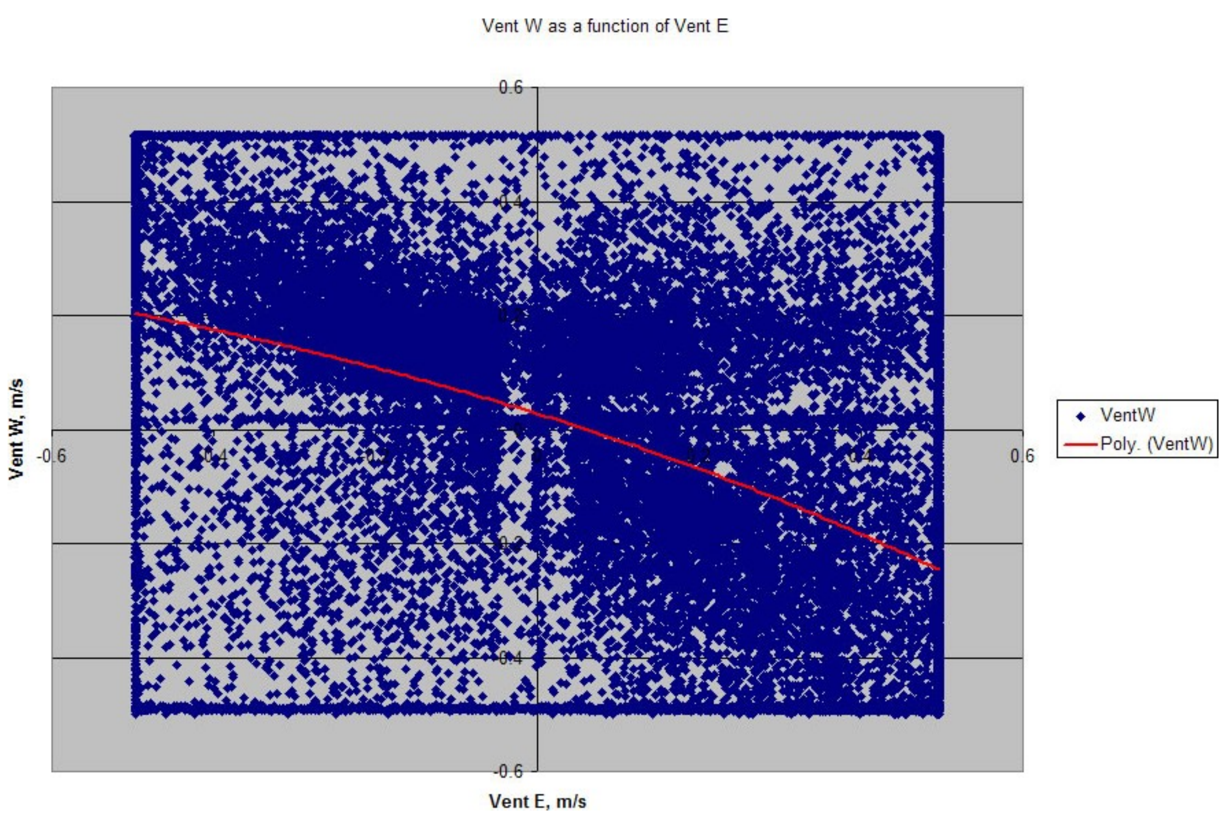


Figure 7: Correlation between air velocities at the inlet/outlet vents facing East and West.

Figure 8 shows the instantaneous wind speed and the four day moving average. On average the wind speed is mostly between 1-2 m/s.

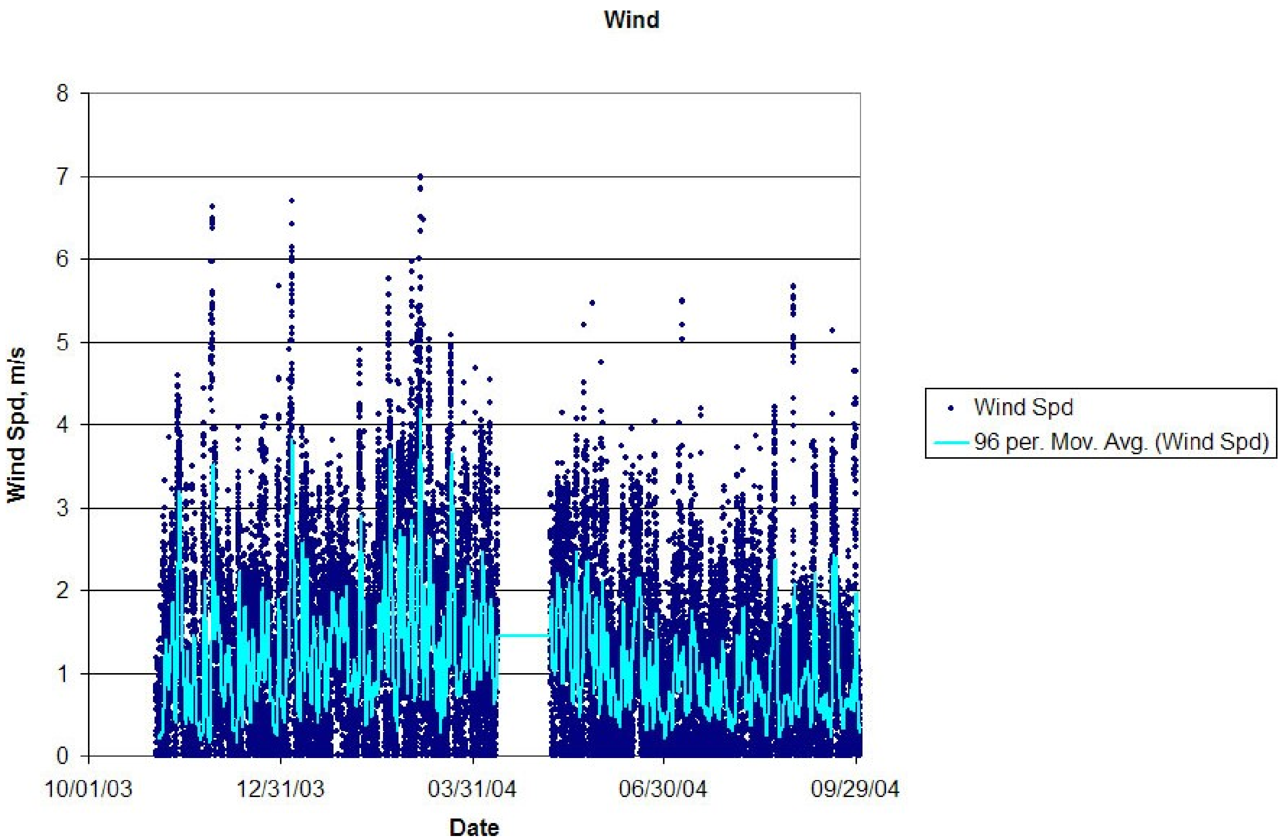


Figure 8: Measured wind speed at the weather station adjacent to the houses.

Pressure differences between the house, crawlspace and outdoor air

The crawlspace with open vents to the outside follows the air pressures of the outside air more closely than the sealed crawlspace. The pressure measurements show that the pressure difference between the vented house and its crawlspace is between 2 and 4 Pa whereas for the sealed crawlspace the pressure difference is about -2 Pa throughout the year with more fluctuations than for the vented crawlspace (Figure 9). These differences may be at least partly due to the individual differences in the controls of heating and ventilation systems.

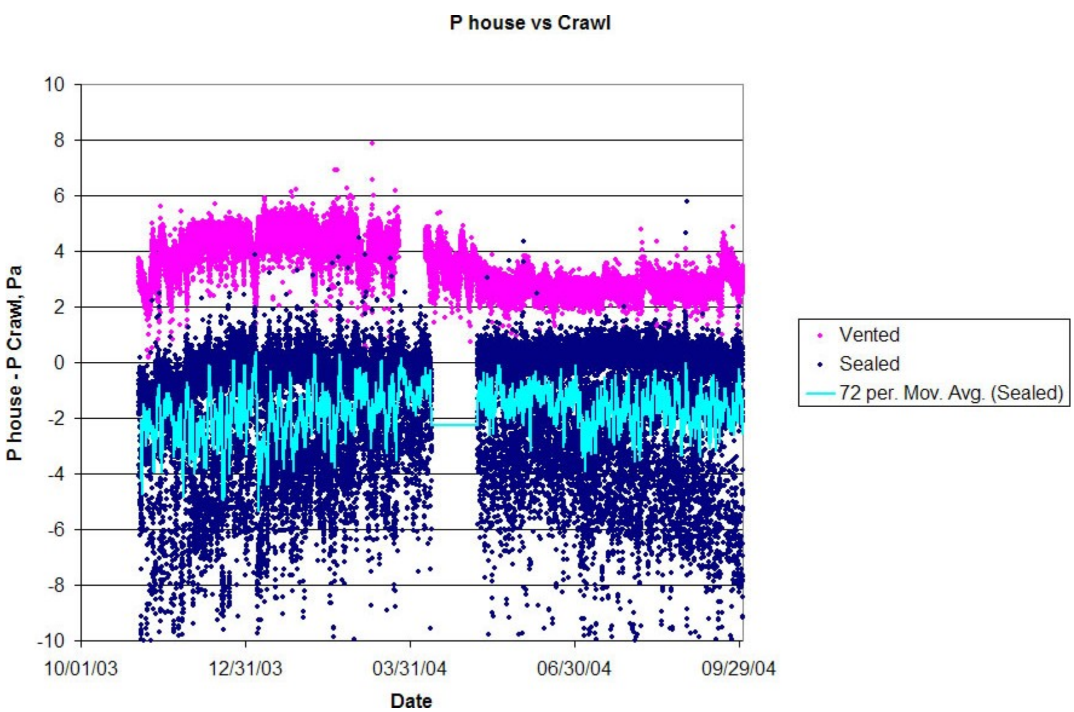


Figure 9: Pressure difference between the interior of the house and the crawlspace for houses with vented and sealed crawlspaces.

The measurements of the pressure differences between the outdoor and the West and East locations in the crawlspace show some inconsistent results. The pressure difference between the outside and the crawlspace near the East vent is almost constant at about 1-2 Pa for the sealed crawlspace (Figure 10). The pressure difference between the outside and the vented crawlspace varies seasonally being about 5 Pa in the winter and fluctuates around 0 Pa in the summer. Near the West vent the pressure difference between the outside and the crawlspace (Figure 11) however fluctuates seasonally and both the sealed and the vented crawlspaces follow the same pressure difference pattern and magnitude. The pressure difference (average of all directions) between the outside air and the crawlspace for houses with vented and sealed crawlspaces is shown in Figure 12. The measured data for the vented house is however incorrect showing constant 0 Pa pressure difference.

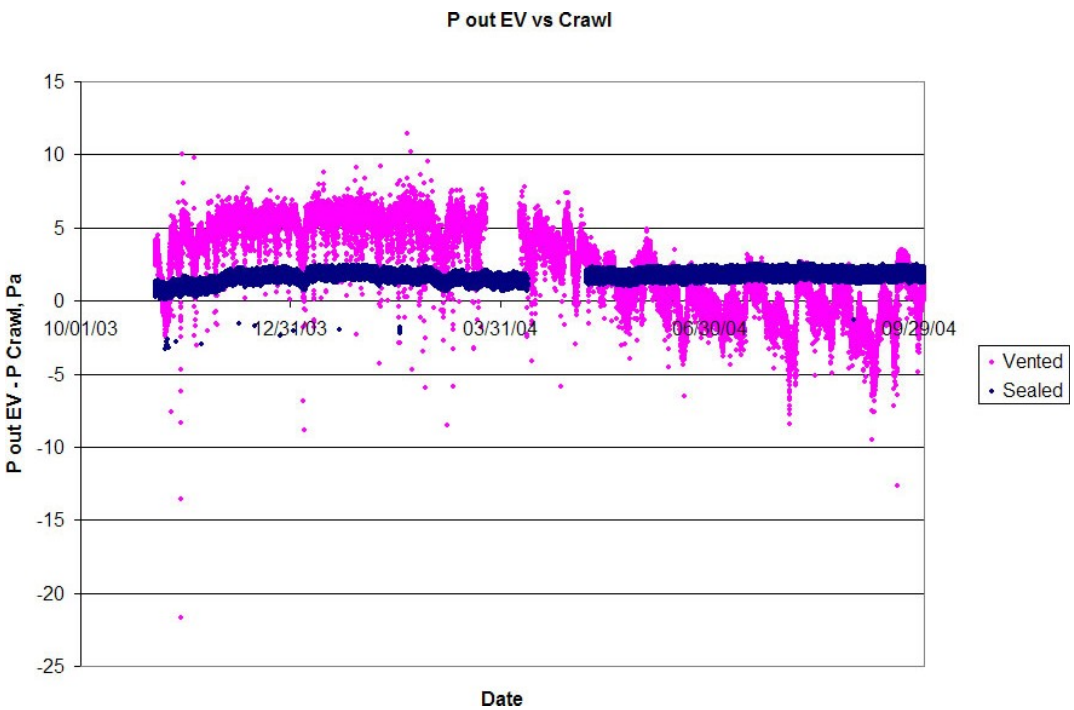


Figure 10: Pressure differences between the pressure outside of the East Vent and the crawlspace.

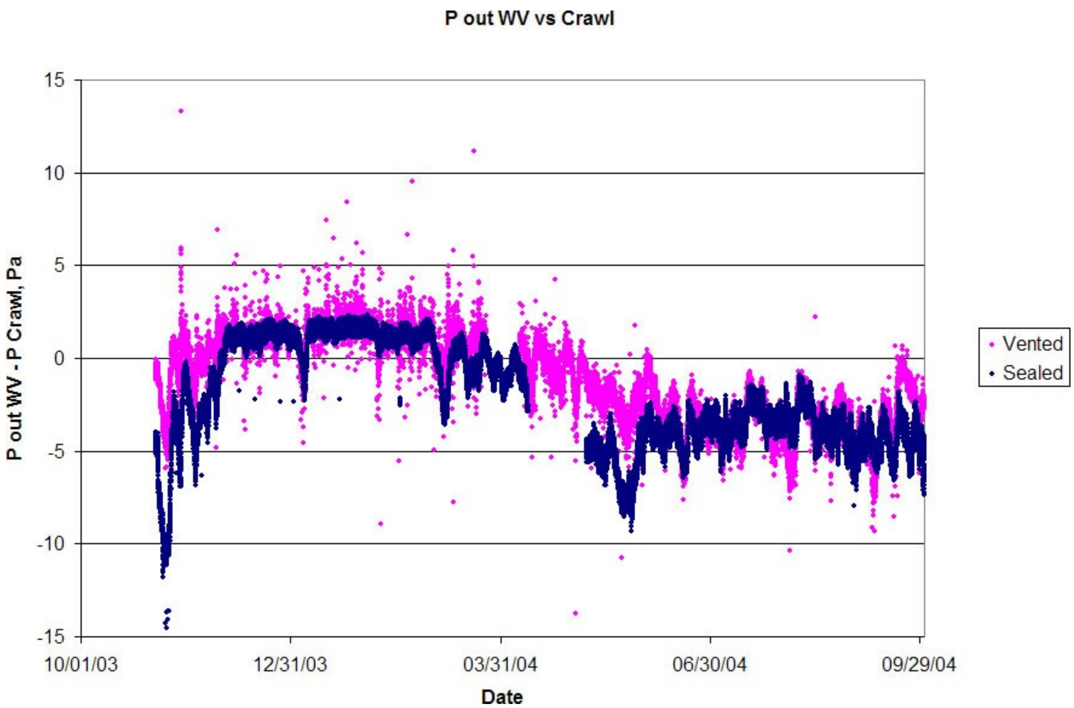


Figure 11: Pressure differences between the pressure outside of the West Vent and the crawlspace.

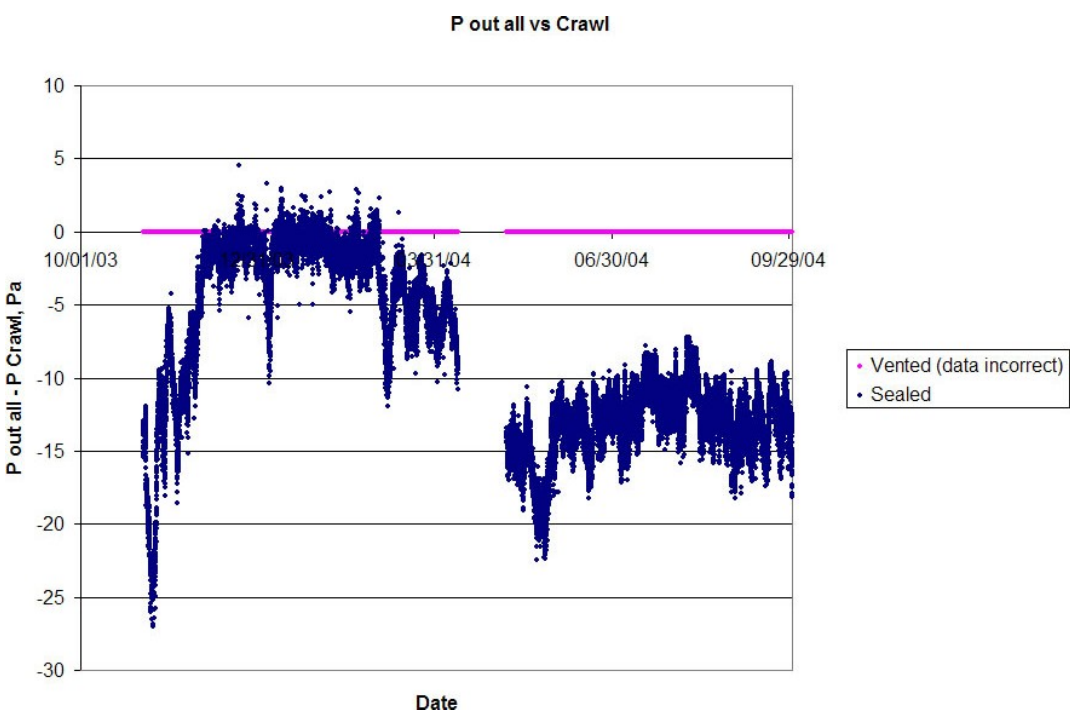


Figure 12: Pressure difference (average of all directions) between the outside air and the crawlspace for houses with vented and sealed crawlspaces.

Indoor and crawlspace air performance

Temperature

The temperatures in the house were a couple of degree higher in the sealed crawlspace house than in the ventilated crawlspace house. The temperature fluctuations were higher in the ventilated crawlspace house which may be due to the interactions between the indoor air and the crawlspace air through the floor. Figure 13 shows the indoor and outdoor temperatures for the sealed and vented crawlspace houses with four day moving averages to allow for better viewing of long term performance.

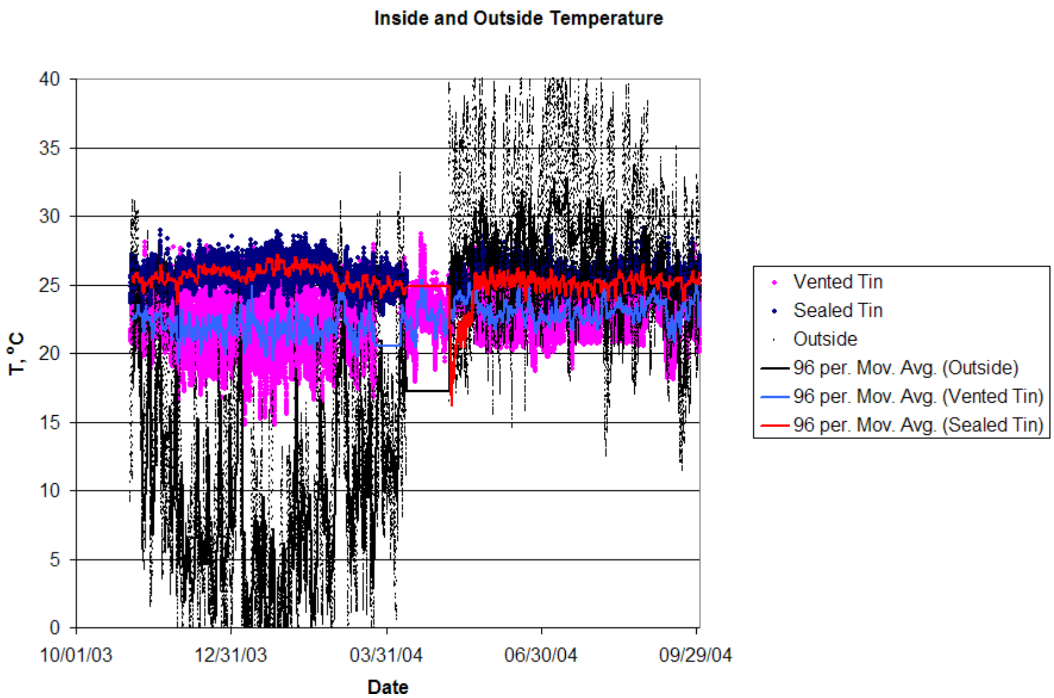


Figure 13: Measured indoor air temperature in the houses with vented or sealed crawlspaces.

The air temperature in the vented and sealed crawlspace is shown in Figure 14. The sealed crawlspace has rather stable temperature throughout the year whereas the vented crawlspace experiences large variations in temperature due to the ventilation with outdoor air. The temperatures also fluctuate more in the vented crawlspace than in the sealed crawlspace.

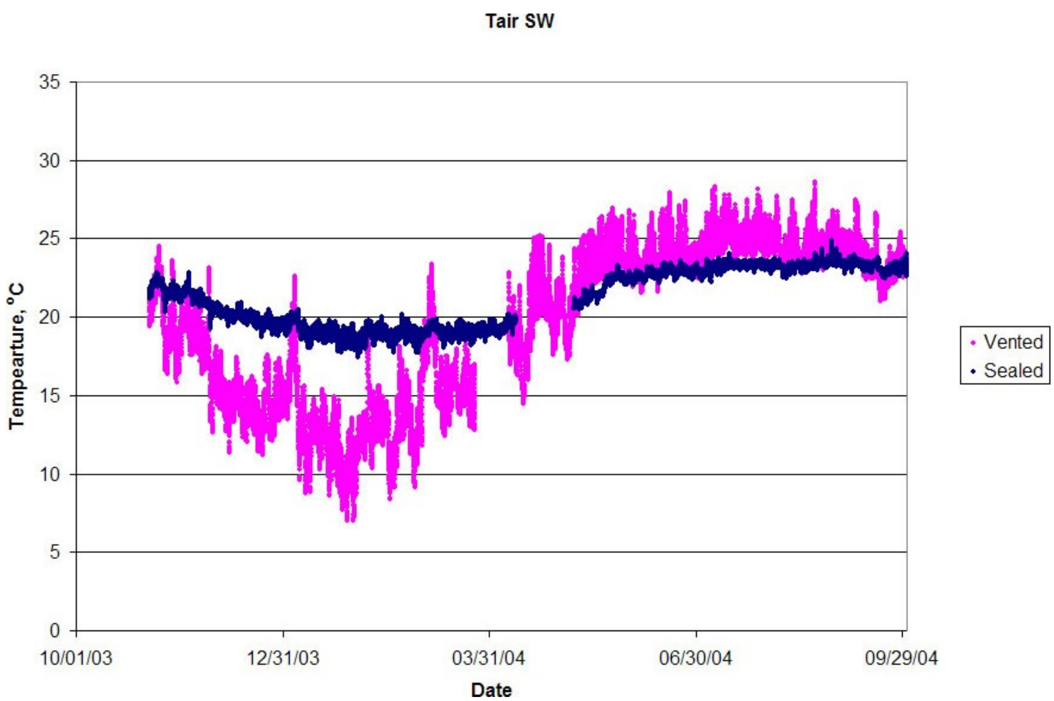


Figure 14: Air temperature at the South West corner of the vented and sealed crawlspaces.

Relative humidity

The relative humidity in the crawlspace air at the North East location in the crawlspace is presented in Figure 15 for the vented and sealed crawlspaces. The relative humidity in the vented crawlspace fluctuates heavily from 30% to saturation whereas the conditions in the sealed crawlspace are very stable and fluctuate only within 5%-RH in daily cycles. The relative humidity never reached 80%. The relative humidity in the South West locations of the crawlspaces (Figure 16) behaved in a very similar way which indeed shows that the conditions are well mixed in the crawlspace air.

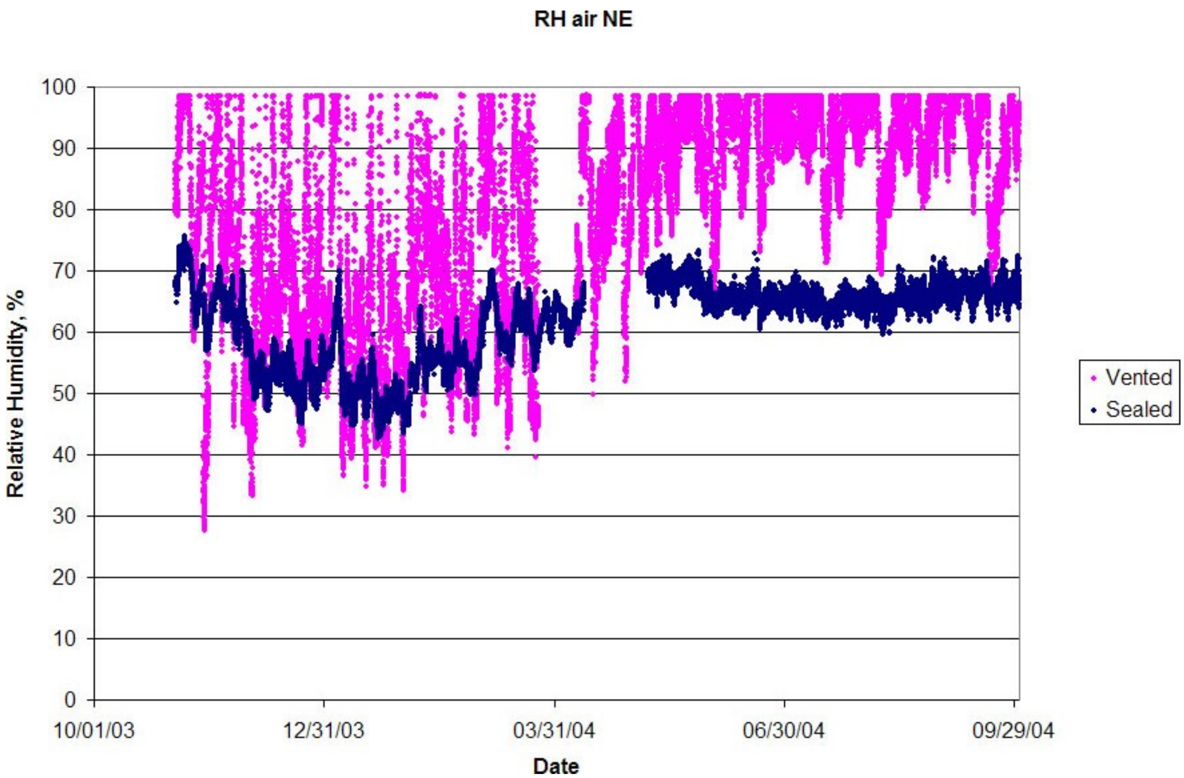


Figure 15: Relative humidity in air at the South-East corner of vented and sealed crawlspaces.

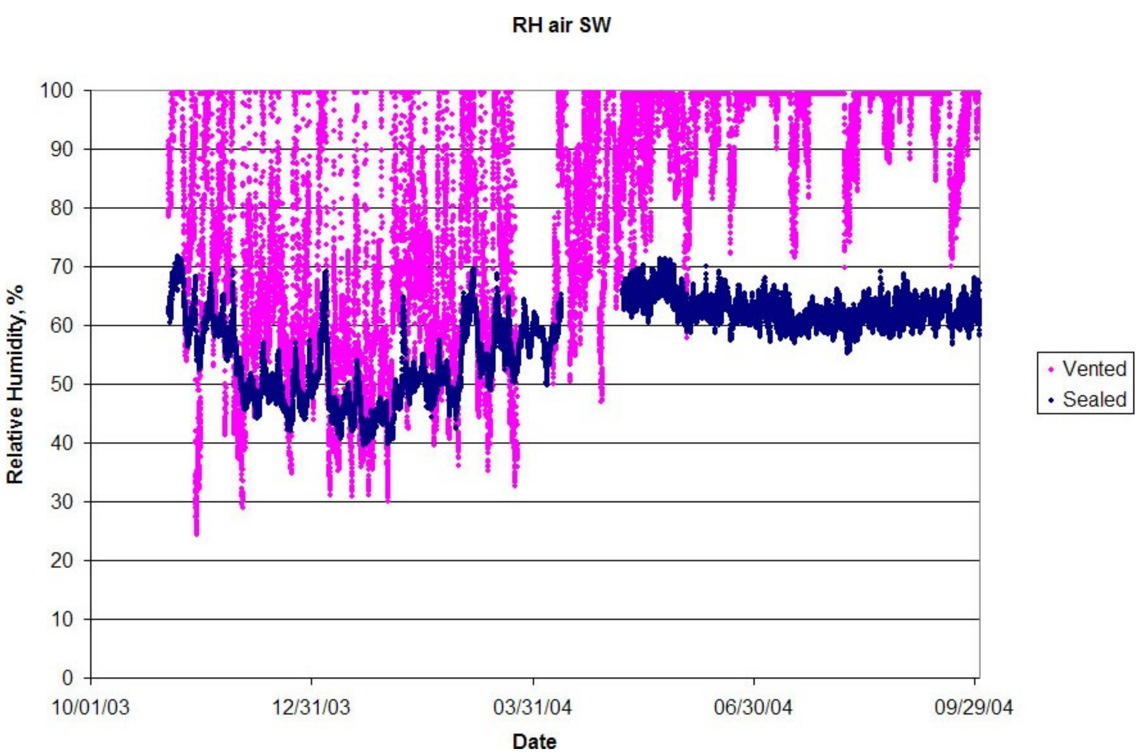


Figure 16: Relative humidity in air at the South-West corner of vented and sealed crawlspaces.

Differences in absolute humidities of the crawlspaces and outdoor air

Difference in moisture contents (g/m3) in the crawlspace air and in the outdoor air are presented in Figure 17. The long term average (polynomial curve fit) shows that the air in the vented crawlspace has the same moisture content as the outdoor air (on average) which again is a good indicator of reasonably high air exchange rate between the crawlspace and outdoor air. Large short term variations exist in both the vented and sealed crawlspaces and these are mainly due to the rapid changes in the outdoor climatic conditions. The air in the sealed crawlspace has the same moisture content as the outside air during the winter season. Between April and September the crawlspace air is much drier than the outside air.

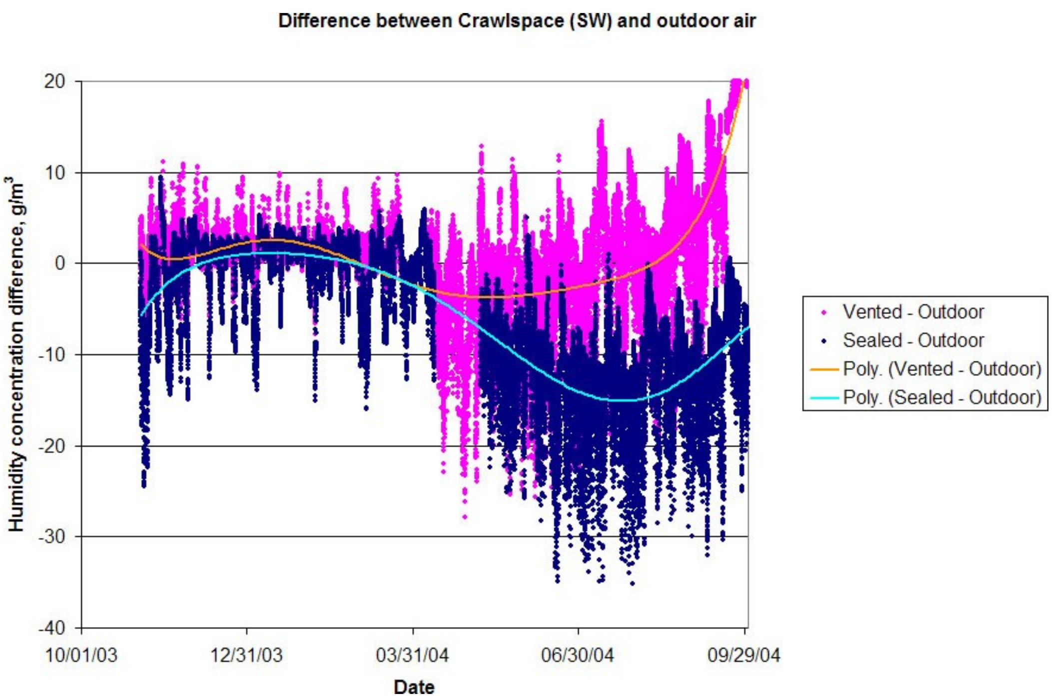


Figure 17: Difference in humidity concentrations of crawlspace air and outdoor air in vented and sealed crawlspaces.

Risk of mold growth in the crawlspaces

The relative humidity and the temperature in the vented and sealed crawlspaces are plotted in the same chart (Figure 18) with a curve showing the critical conditions that would allow mold growth to occur (based on Viitanen et al.). It can be clearly seen that the conditions in the vented crawlspace are favorable to mold growth whereas the conditions in the sealed crawlspace never reached high enough humidity to allow mold growth. The conditions were favorable for mold growth 60% of the time in the vented crawlspace and 0% of the time for the sealed crawlspace. The critical relative humidity as a function of temperature is calculated using the equation RHcritical = -0.00267*T3+0.16*T2-3.13*T+100, where the unit of T is ºC.

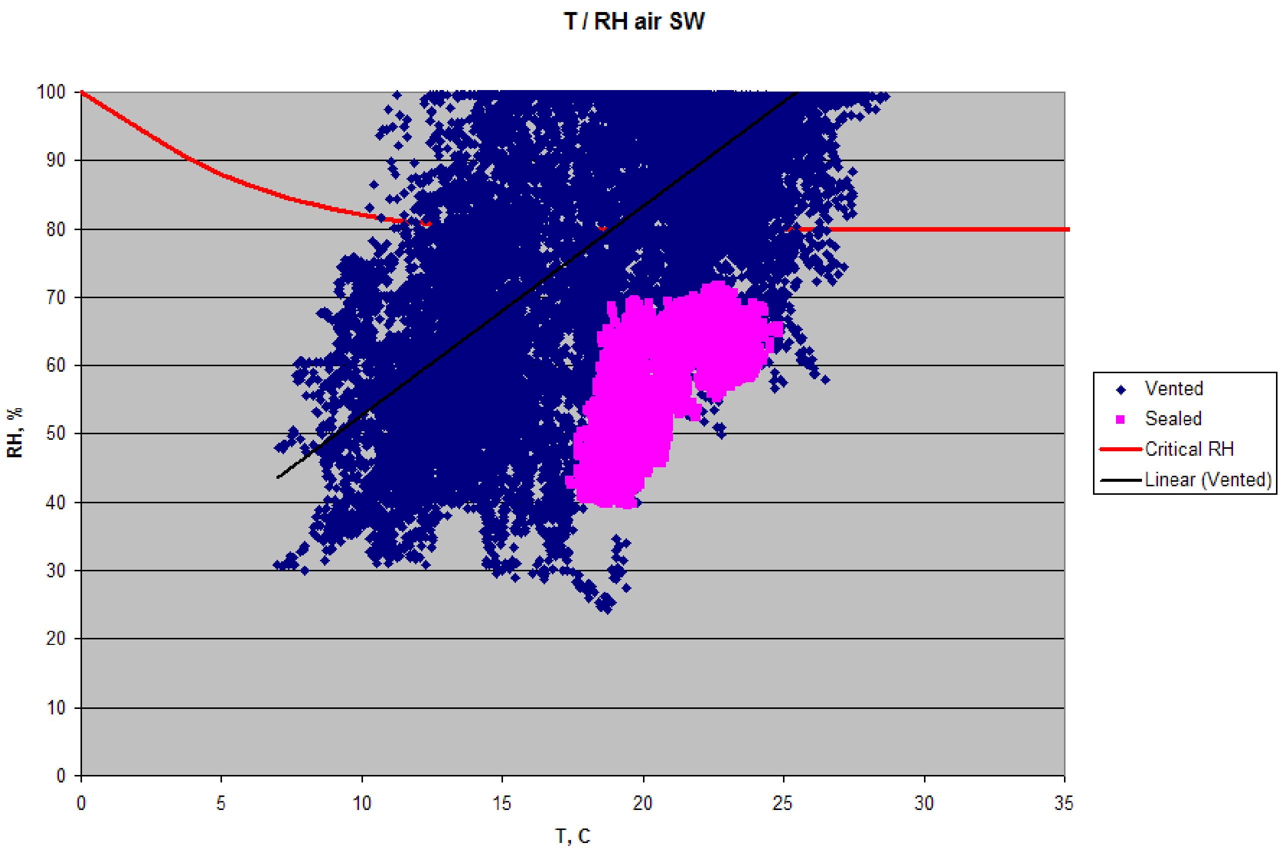


Figure 18: The relative humidity and temperature of the crawlspace air in vented and sealed crawlspaces and the critical relative humidity as a function of temperature according to Viitanen et al.

Building envelope performance

Temperature

The temperature of the concrete block in the South West corner of the crawlspaces is shown in Figure 19. The temperatures follow the same path in both configurations except that the block temperatures are a couple of degrees higher in the sealed crawlspace.

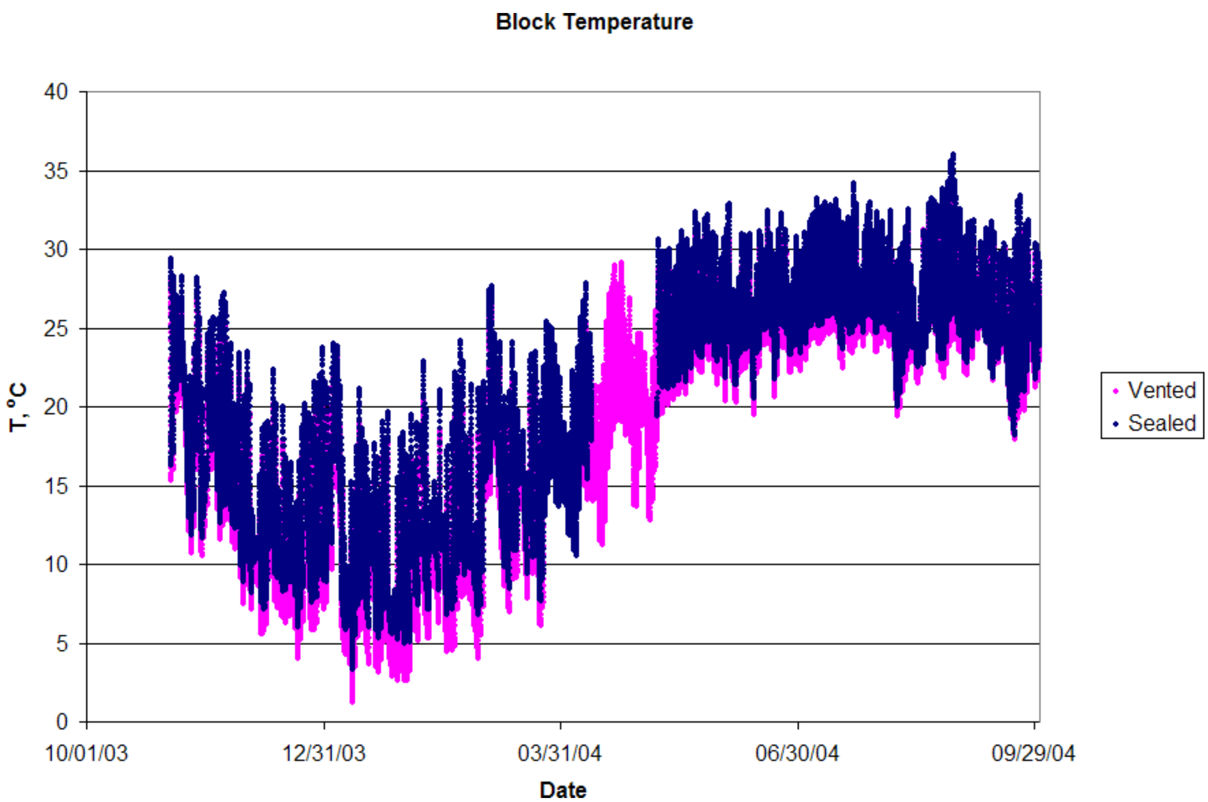


Figure 19: Concrete block temperatures in the crawlspace walls of vented and sealed crawlspaces.

The inside surface temperature of the concrete block (Figure 20) experiences high temperatures up to 37 ºC (98F)in the sealed crawlspace and the temperature does not go below 15 ºC (59F) even during the winter. The block temperature in the vented crawlspace goes up to 30 ºC (86F) in the summer and goes down to about 3 ºC (37F) in the winter.

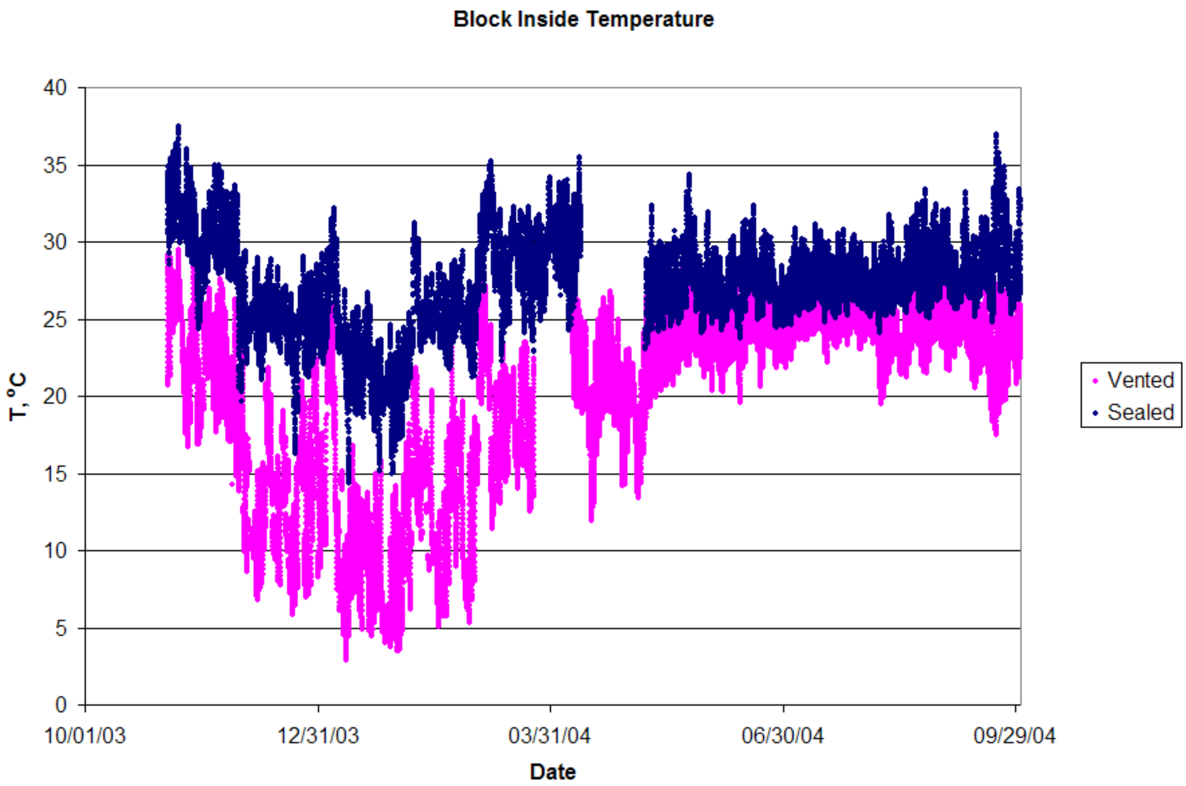


Figure 20: Inside surface temperatures of concrete blocks in the walls of vented and sealed crawlspaces.

The joist temperatures in the middle of the crawlspaces (Joist A, Figure 21 and Joist B, Figure 22) follow the crawlspace air temperatures both in the vented and the sealed crawlspaces. Differences of about 5ºC (9 F) can be found both in the summer and winter between the air temperature and the joist temperature in the vented crawlspace the joist being warmer in the winter and cooler in the summer than the crawlspace air. This is likely due to the thermal mass of the ground and the radiation heat exchange between the floor and the ground in the crawlspace.

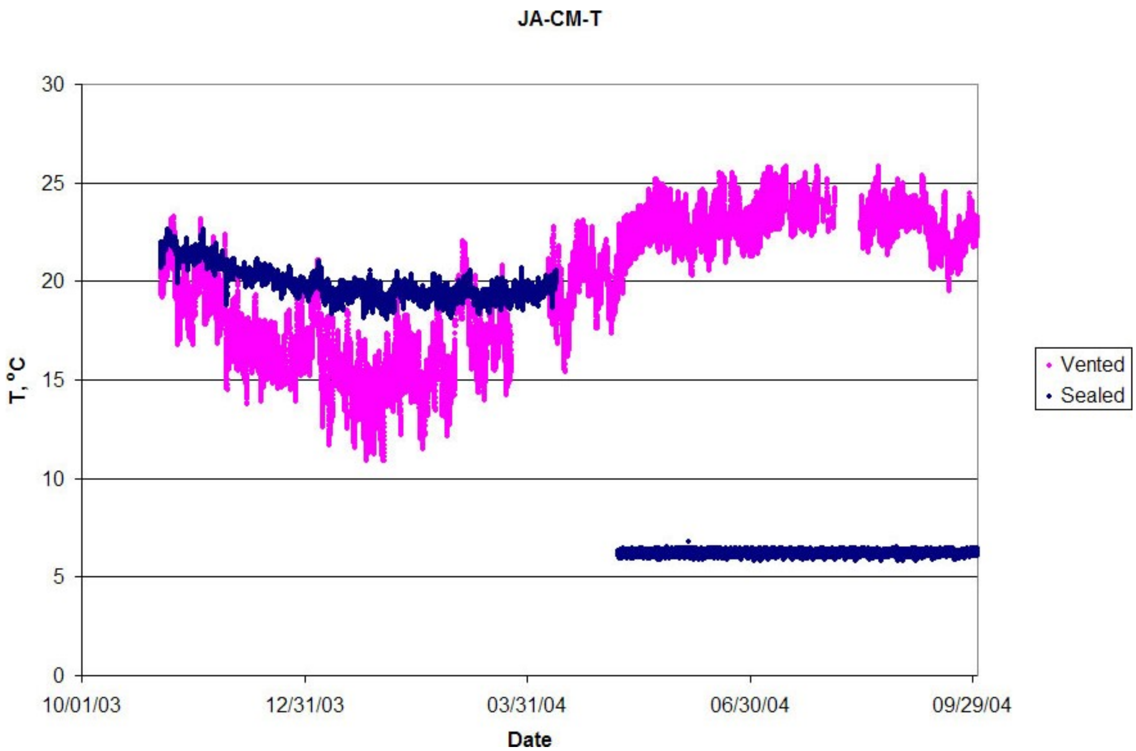


Figure 21: Temperatures in the middle (vertically) of Joist A in the Center of the crawlspace in vented and sealed crawlspaces.

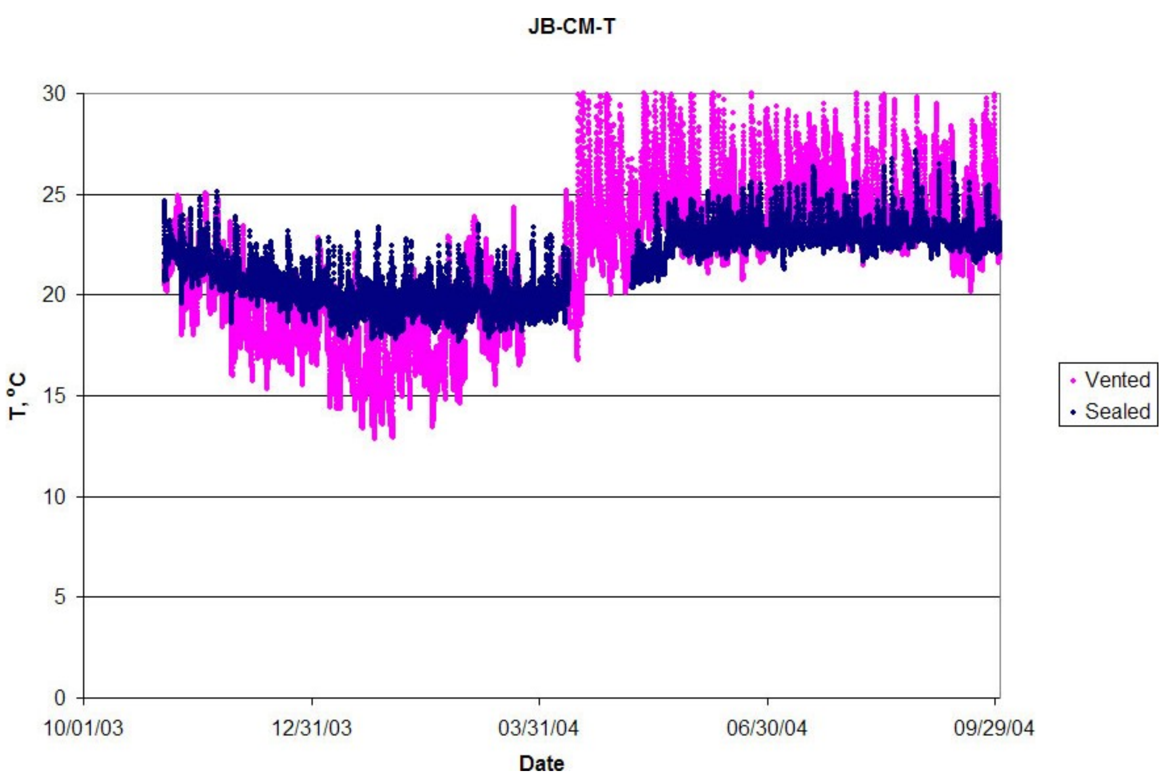


Figure 22: Temperatures in the Middle (vertically) of Joist B in the Center of the crawlspace in vented and sealed crawlspaces.

The joist temperatures at the perimeter of the crawlspace follow the outdoor temperature better than the indoor temperature. The temperatures are almost on top of each other for the vented and sealed crawlspaces for Joist A (Figure 23).

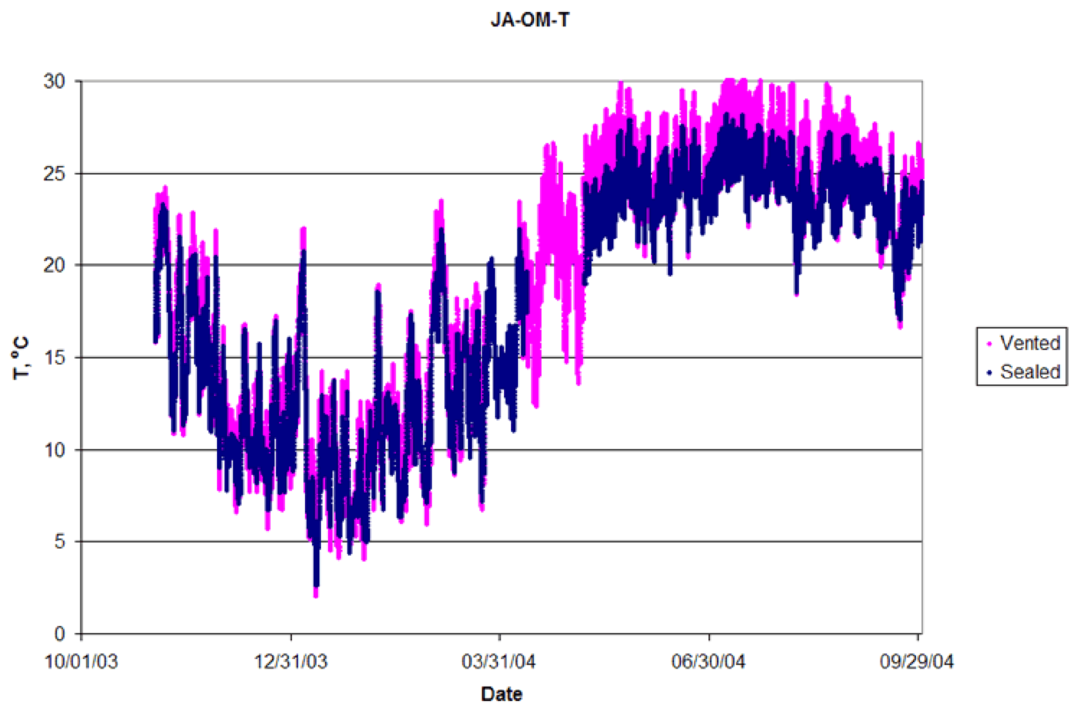


Figure 23: Temperatures in the Middle (vertically) of Joist A at the perimeter of the crawlspace in vented and sealed crawlspaces.

Moisture content

The moisture contents in the joists follow the crawlspace air conditions. The moisture pin measurements are not reliable below approximately 7%-weight for wood and therefore the results can not be presented for many of the wood joists of the sealed crawlspace because the moisture contents are too low. Figure 24 presents the moisture contents of Joist C in the center of the crawlspace and at the bottom of the joist (JC-CB-M) for the vented and the sealed crawlspaces.

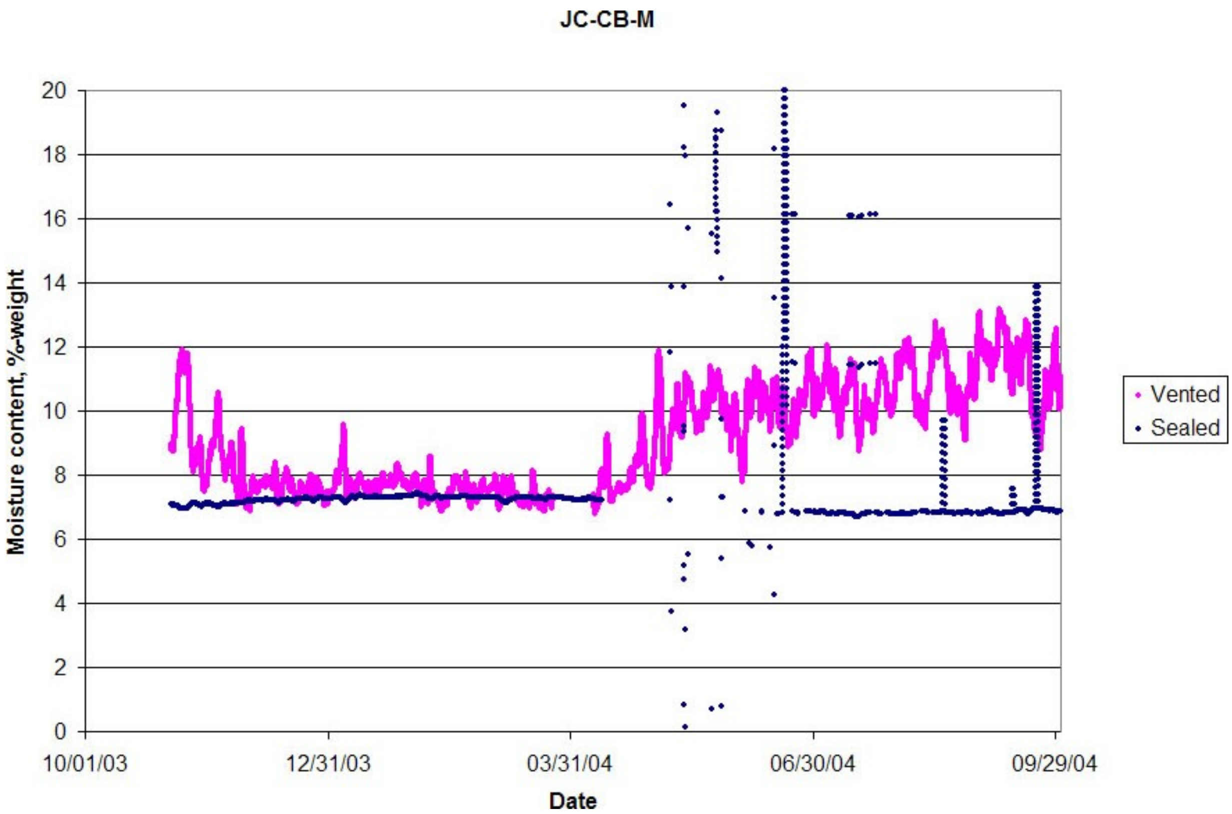


Figure 24: Moisture contents at the Bottom (vertically) of Joist C in the Center of the crawlspace in vented and sealed crawlspaces.

The moisture contents of the joist are low in both of the crawlspaces until April when the moisture contents in the vented crawlspace start increasing whereas the moisture contents are very stable and do not indicate any change in the sealed crawlspace. Moisture contents in Joist A in the middle of the crawlspace and in the middle height of the joist (Figure 25) increase much more rapidly and to higher level (up to 18%-weight) than in Joist C. The fluctuations are quite large and fast which may be an indication of surface condensation at times.

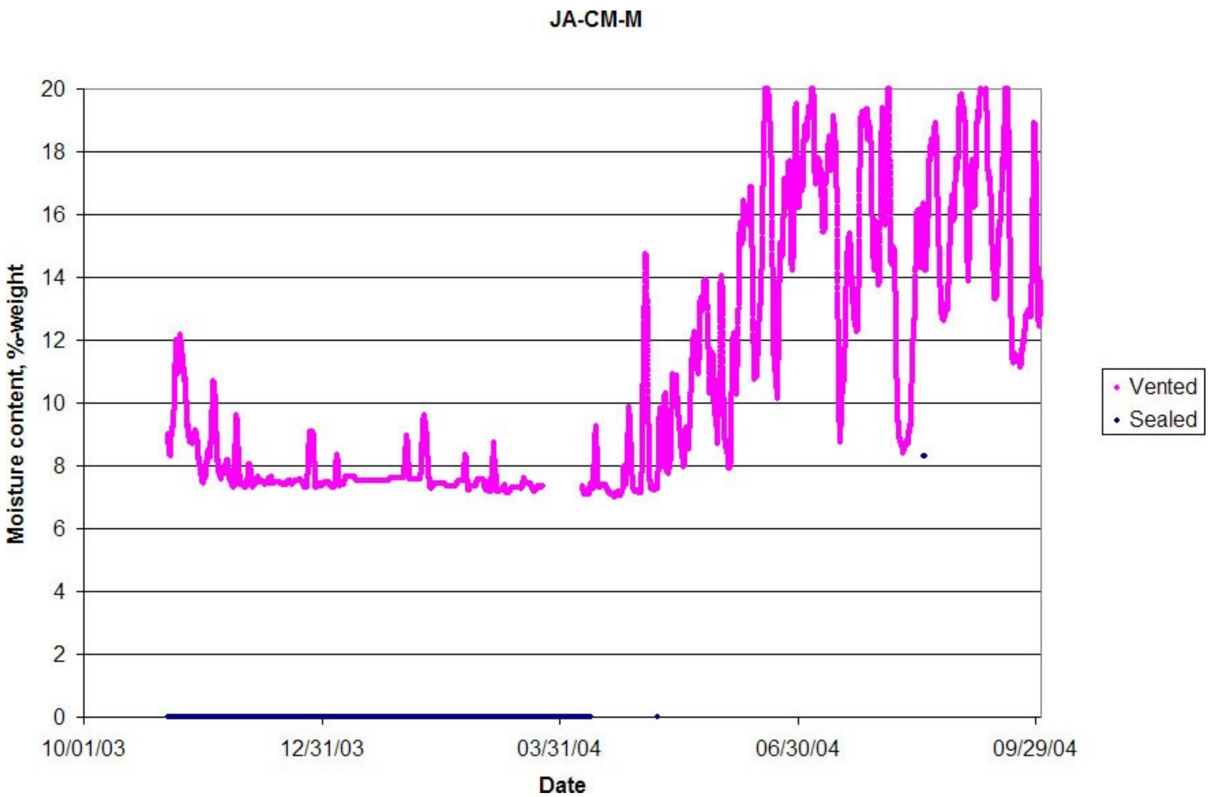


Figure 25: Moisture contents in the Middle (vertically) of Joist A in the Center of the crawlspace in vented and sealed crawlspaces.

Moisture contents at the perimeter in Joist A (Figure 26) follow the same path as the other joists showing the same pattern in behavior. Moisture contents in sealed crawlspace joists are stable and do not indicate change in conditions in the summer whereas the joists in the vented crawlspace have increasing moisture contents starting in the spring.

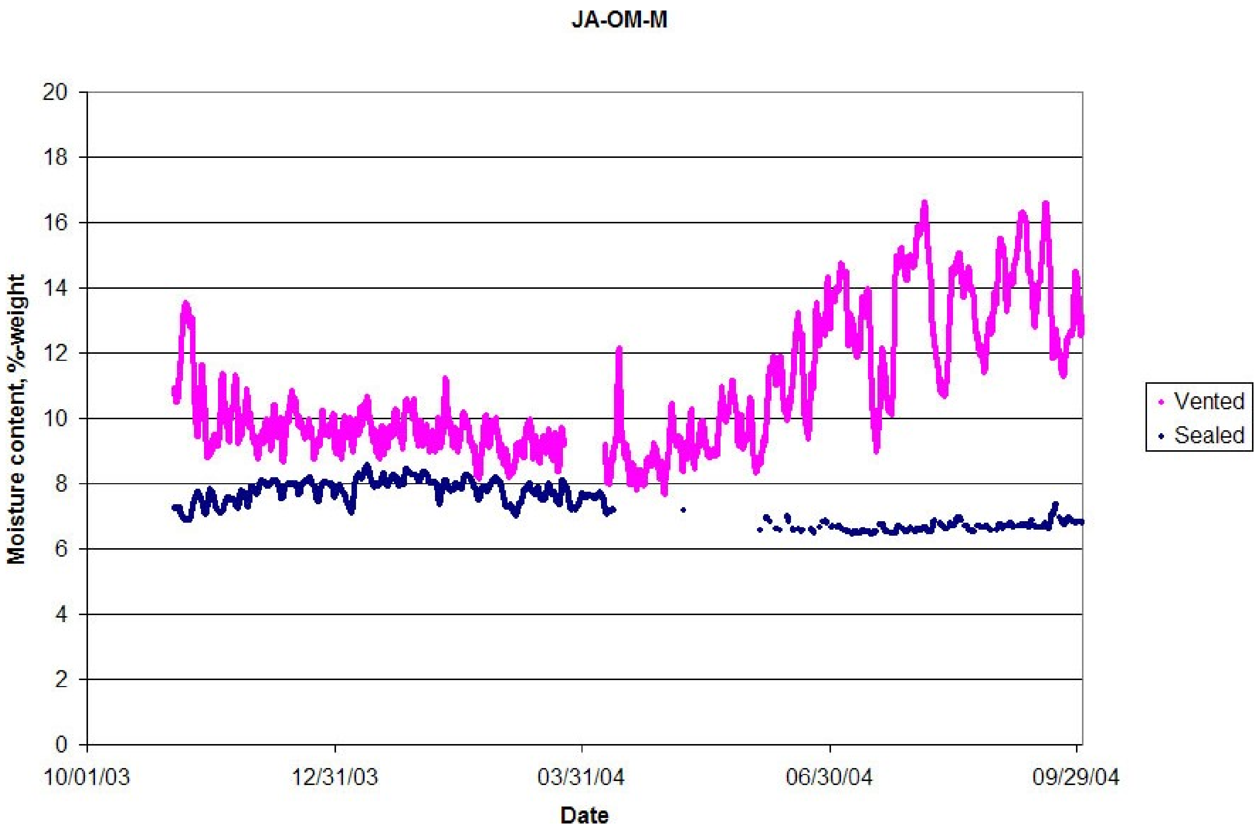


Figure 26: Moisture contents in the Middle (vertically) of Joist A at the perimeter of the crawlspace in vented and sealed crawlspaces.

Concrete block relative humidity

The relative humidity of the concrete block at the perimeter of the crawlspace (Figure 27) behaves in a similar fashion in both the sealed and the vented crawlspaces. The relative humidity of the concrete block is relatively high throughout the year on average around 90%-RH. The concrete block in the vented crawlspace is a bit more humid in the winter than the concrete block in the sealed crawlspace reaching saturation a couple of times. The relative humidity measurements at the range from 95-100%-RH are not very reliable and therefore this difference may be considered insignificant.

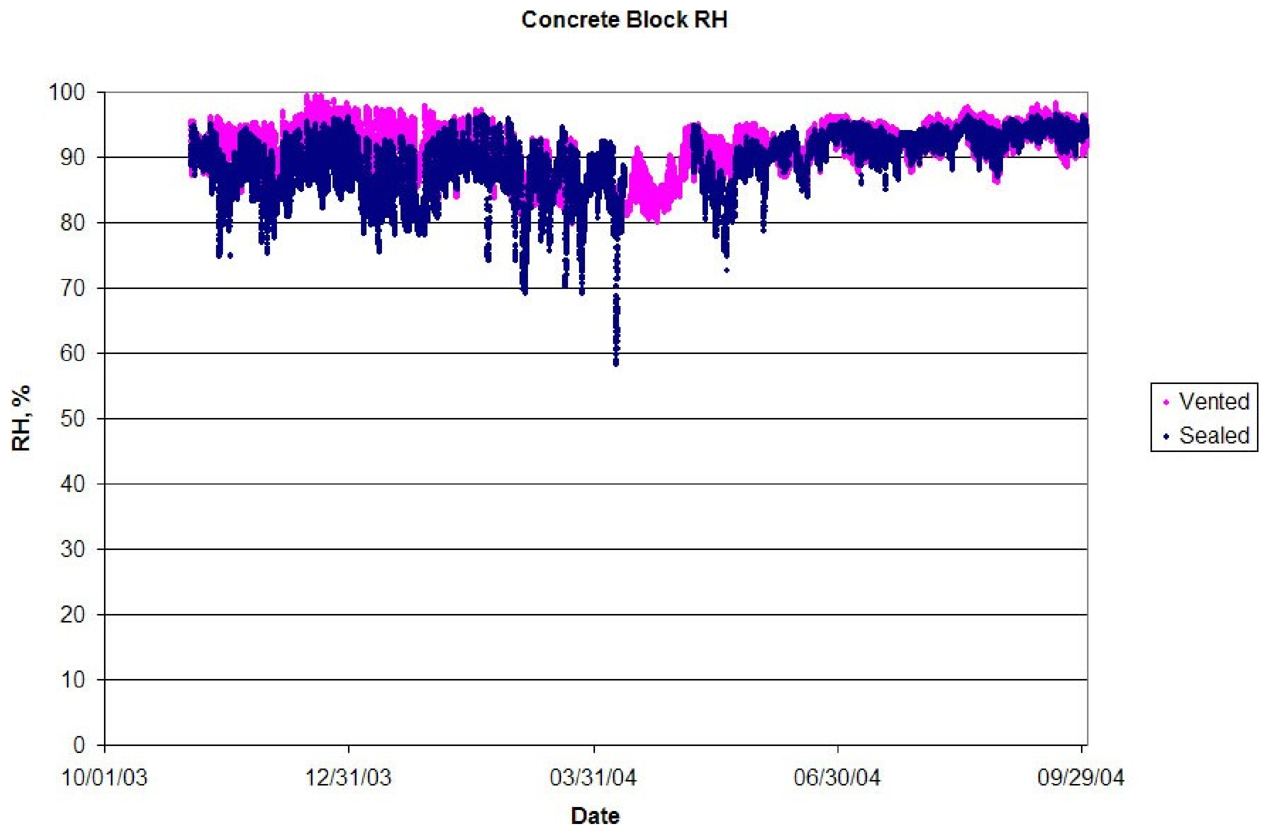


Figure 27: The relative humidity of the concrete block in the vented and sealed crawlspaces.

ADVANCED MOISTURE ENGINEERING MODELING

In Phase I of the Advanced Energy project, ORNL was expected to develop a working model of the crawl space by developing the necessary inputs. In this phase, ORNL developed a simulation parametric for a number of different crawl space systems. The pilot study experimental data was expected to provide not only benchmark data for model simulation, but also system and sub-system characterization such that the model can be calibrated for a higher quality of prediction. In the following pages, an overview of the required inputs are given.

The ORNL MOISTURE-EXPERT v. 2.0 model [Karagiozis, 2001] is deploy in this part of the research in developing a parametric analysis of the performance of crawl space systems in Southern US climates. Five crawl space walls were developed by Advanced Energy and ORNL for analysis. Three different environmental conditions were considered for the project. All systems were identified as critical systems, and agreement between all research project staff was secured.

The climates chosen were weather stations located were Charlotte, Wilmington and Raleigh. Two climatic years representing the 10% percentile cold and 10 % percentile warm year were determined from the 30-year hourly data, as is currently proposed by ASHRAE SPC160P (Anton, TenWolde ASHRAE SPC 160P Chair [2004]). From the series of parametric simulations, the hygrothermal performance was tracked and assessed. A mold growth model was also used to assess the risk for possible durability problems. This moisture engineering approach has been used in a number of moisture research projects. This approach allows a fair assessment of the hygrothermal influences that affect design decisions such as those proposed in this AEC crawlspace research work. In many regards the work reported using advanced hygrothermal modeling is unique and has not been reported in the open literature. As with any research activity especially one not performed in the past, this research will be improved with further advancements in models.

In all simulations, the transport phenomena considered are:

1. Vapor transport
2. Liquid Transport

3. Convective Air Transport (Natural Convection Induced (temperature and density difference driven) and Forced (Wind Dependent))
4. Water table movement
5. Wind Driven Rain
6. Solar Driven Moisture
7. Night-time sky radiation effects

Within these transport phenomena, the latent heat and evaporation effects from phase changes are also included in the modeling.

The combined effects of both vapor flow within the air crawl space systems can be effectively compared against those with imbedded moisture control elements. The ASHRAE SPC 160P proposed methodology to compute the interior environment load (moisture conditions) was employed in the project simulation analysis. The indoor air quality requirements set by ASHRAE were also considered and addressed in the simulations. The SPC160P methodology, recently presented at Thermal VIII conference in Clearwater, 2001 by TenWolde, A.and Walker I. was adopted for determining the indoor moisture conditions.

The house air leakage performance as characterized by the Advanced Energy staff employing a series of blower door and duct tests was used to determine the natural ventilation of the all the Habitat for Humanity houses and, in particular, the two homes that were used for the hygrothermal pilot study. The overall leakage data was used to calculate the interior environmental loads and the corresponding interior vapor pressure and relative humidity conditions as proposed by ASHRAE SPC 160P.

PARAMETRIC ANALYSIS

A parametric analysis was performed to understand better the dynamic performance of a particular size of crawlspace (similar to the experimental study)

The following hygrothermal issues were examined with emphasis on the moisture issues:

a) Influence of climatic location using three climatic locations in North Carolina;Wilmington, Raleigh and Charlotte
b) Influence of water table level
c) Impact of ventilation on crawlspace (venting or unvented)
d) Impact of duct leakage
e) Impact of water penetration
f) Impact of vapor retarders in crawlspace system

In addition, the thermal performance of the crawlspace was also performed using the information on the heat flow characteristics.

In the analysis of the crawlspace systems several, additional supplementary analysis was performed to include the impact of the pressurization. Additionally, as only a 2-D analysis was performed, the 3-D effects of the presence of the total amount of wood and other construction elements were included in terms of a series of sinks and sources, all calibrated using the field monitored Princeville crawlspaces. The 3-D corner dynamic thermal effects and corresponding moisture effects in the crawlspace were not accounted for. Currently this is a limitation of our modeling capability, however those contributions are estimated to not be critical to the quantification of the total hygrothermal performance of the crawlspace.

In the following sections information provided information on the boundary conditions and initial conditions used in the parametric modeling investigation.

The general inputs required to the model are:

- Material Properties(#1)
- Exterior Environmental Loads (#2)
- Interior Environmental Loads (#3)
- Envelope System and Sub-System Characteristics(#4)

The pilot hygrothermal study of Phase I and II has providing valuable data to item # 4 on the envelope system and sub-system characteristics. In total, the number of inputs required by the model for a two-dimensional crawl space simulation is approximately 6,000 (Material Properties, Exterior and Interior environmental loads and system characteristics).

Boundary conditions & initial conditions

The simulation analysis requires exposing the crawl space exterior boundary of the walls to real weather data (including temperature, vapor pressure, wind speed and orientation, solar radiation, wind-driven rain, sky radiation, and cloud indexes) for three locations in NC (Wilmington, Charlotte and Raleigh). Thirty years of hourly data is analyzed to determine moisture design years. Wind-driven rain water has been included in the analysis, and the exterior surface was exposed to the amount of rain water that hits a vertical wall under wind conditions. The ground also received water, depending on the horizontal precipitation. The hourly solar radiation and long-wave radiation exchange from the outer surfaces of the wall will also be included in the analysis. This approach is currently being proposed by TenWolde (ASHRAE SPC 160P) and Treschel (ASTM Manual 40, 2001), and has been examined in detail by IEA Annex 24.

Interior conditions (occupant floor) were allowed to vary, depending on the time of day and exterior conditions, and by adding hourly moisture sources. Results were developed for the internal conditions that were dynamic, and hourly moisture production generation schedule was implemented.

The heat and mass transfer coefficients for external surfaces were dynamic and assigned values that varied from hour-to-hour, depending on the exterior weather wind speed and orientation conditions.

In the two-dimensional simulations, the combined effects of infiltration/exfiltration were examined, as well as the effects of mechanical pressure, and the two-dimensional spatial effects. The two-dimensional simulations allowed a better understanding of the attributes of mechanical ventilation, the effect of insulation, interior vapor control strategies, and other variations on the total drying performance of building envelopes parts.

Material property

In this section, some additional information is given on the particular moisture properties that are needed in advanced hygrothermal models:

1) Sorption Isotherms:

- Most building materials are hygroscopic, which means that they absorb water vapor from the environment until equilibrium conditions are achieved. This behavior can be described by sorption curves over a humidity range between 0 and 95% R.H. For some materials, where the equilibrium water content is not very sensitive to changes in temperature, the sorption curves are called sorption isotherms. Sorption curves and sorption isotherms for these materials from 95% R.H. up to the capillary saturation at 100 % R.H. are difficult to measure.

The units for moisture content employed in the sorption isotherms in the modeling analysis is:

- moisture content by mass (kg/kg)

2) Vapor Permeability

The vapor permeability (kg/m Pa s) is defined as the transport coefficient for vapor diffusion in a porous material subjected to a vapor pressure gradient. In most technical publications, vapor permeance is used to characterize the vapor transmission coefficient.

Vapor permeance ((kg/m^2 Pa s) is defined as the ratio between the vapor flow rate and the magnitude of vapor pressure difference across a slab in steady state conditions.

3) Liquid Transport Properties

The coefficient that describes the liquid flow is defined as the liquid transport coefficient. The liquid flux in the moisture transport equation is only slightly influenced by the temperature effect on the liquid viscosity and consequently on liquid transport coefficients. Most of the time moisture diffusivity is used, which is the total diffusivity measured.

- Moisture diffusivity, Dw (m^2/s)

The transport coefficient for liquid flow can change dramatically from one time step to the other. Several orders of magnitude changes occur in the transport coefficients when rain first strikes the building’s exterior façade due to the steep increase of the diffusivity with water content. These large changes may cause numerical stability or convergence problems, and special numerical solution methods are required.

To summarize, the following material properties were gathered and included:

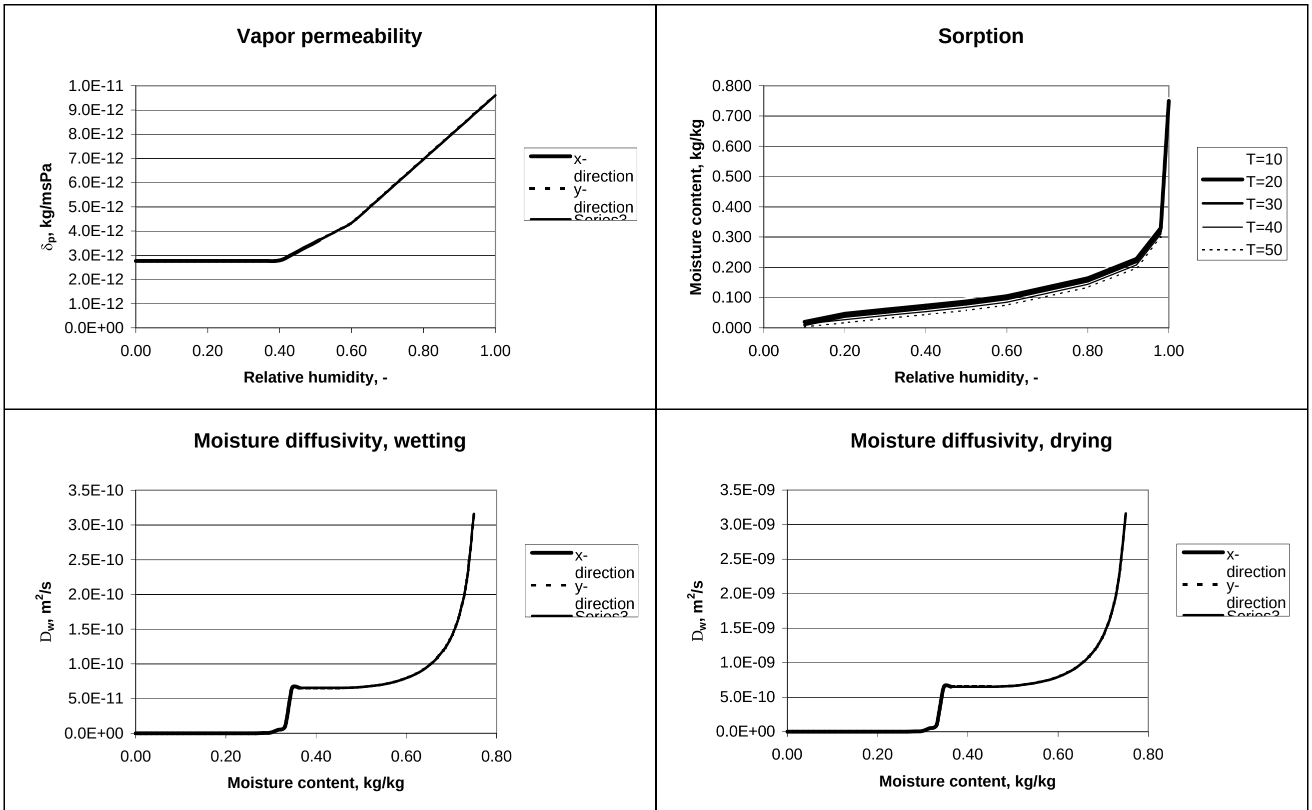
- Water vapor permeance as a function of relative humidity
- Liquid diffusivity as a function of moisture content
- Sorption + suction isotherm as a function of temperature
- Thermal conductivity, density and heat capacity

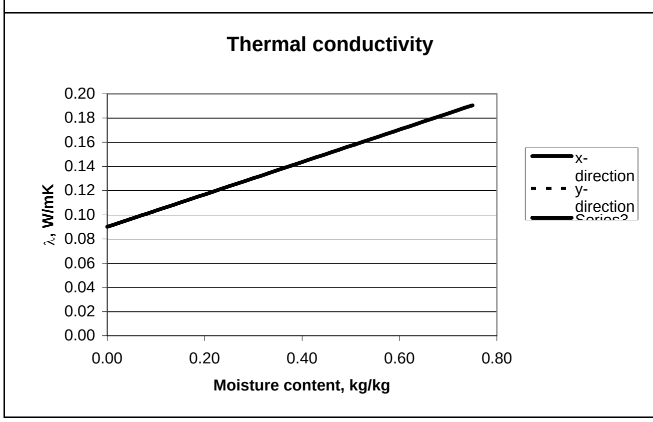
These properties are not single valued, but may also depend on time, history, or other dependent variables. Directionally-dependent material properties were employed for the wood-based and insulation materials. Because the existence and reporting of basic material properties varied widely from manufacturer to manufacturer, the material properties employed in these simulations were taken from (Kuenzel, 1994), (Kuenzel et al,2001), IEA Annex 24 (Kumaran, 1996), and from the recent 2001 ASTM Manual 40 (Treschel, 2001).\

The MOISTURE-EXPERT model includes the capability of handling internal heat and moisture sources, gravity-driven liquid moisture, and surface drainage capabilities. The model also captures experimentally determined system and sub-system performances and anomalies of the building envelope. One of the model's unique features is its capability to handle temperature-dependent sorption isotherms, and directional and process-dependent liquid diffusivity.

In Figure 28 to 32, material properties were solicited from a range of manufacturers, including the ASHRAE Handbook of Fundamentals, ASTM Manual 40 on Moisture Analysis and Condensation Control in Building Envelopes, IEA Annex 24 Data, and other literature data. The data was analyzed and processed in a file format required by MOISTURE-EXPERT. These files have been prepared specifically for the simulation as inputs. In most cases, there is limited data not only on the important hygrothermal properties, but also the spatial variation, x-y-z directions.

Wood

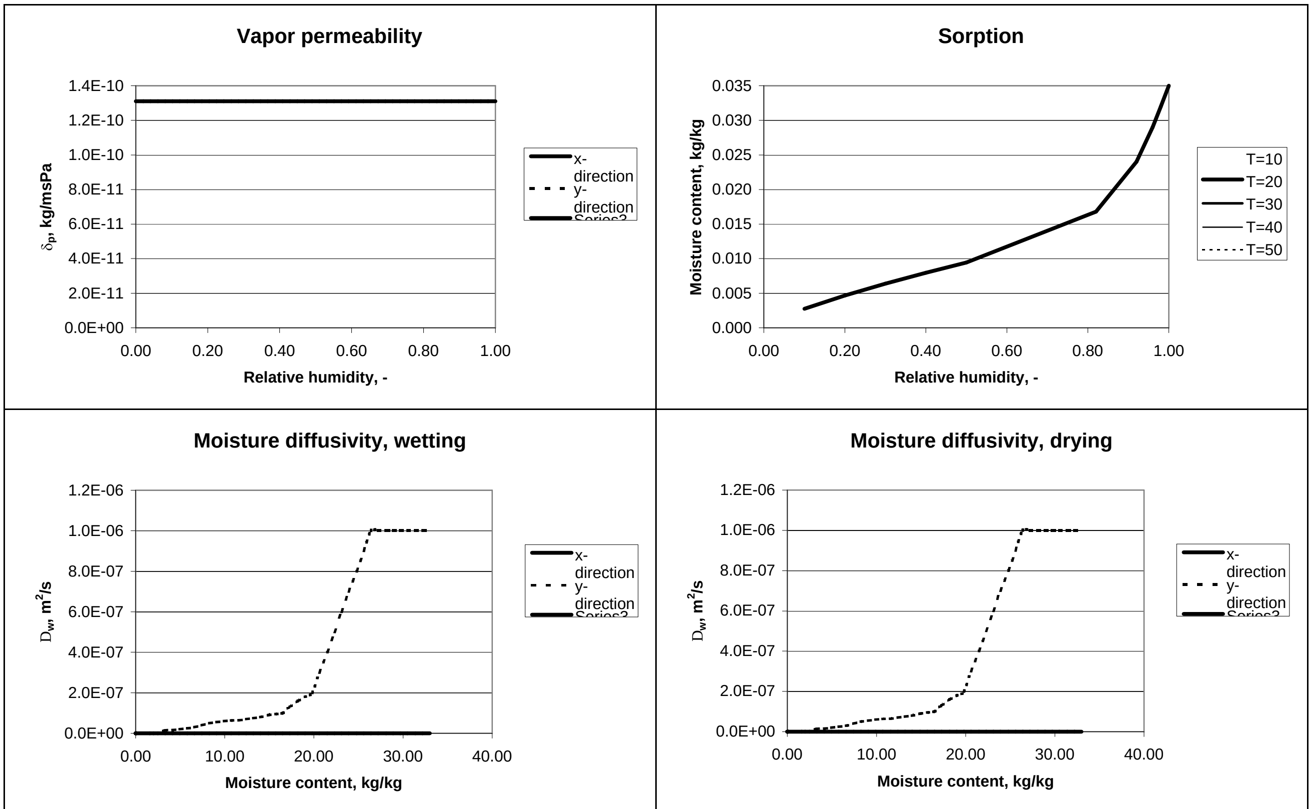


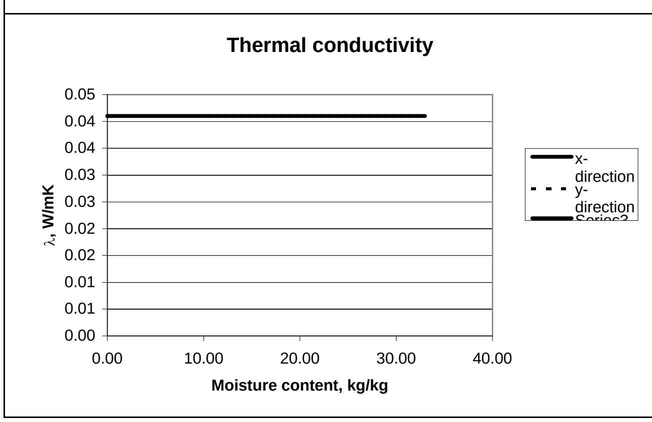


Density425 kg/m^3
Specific heat capacity2390 J/kgK

Figure 28: Hygrothermal Material Properties for Wood Joists

Mineral wool





Density20 kg/m^3
Specific heat capacity670 J/kgK

Figure 29: Hygrothermal Material Properties for Mineral Wool

Concrete

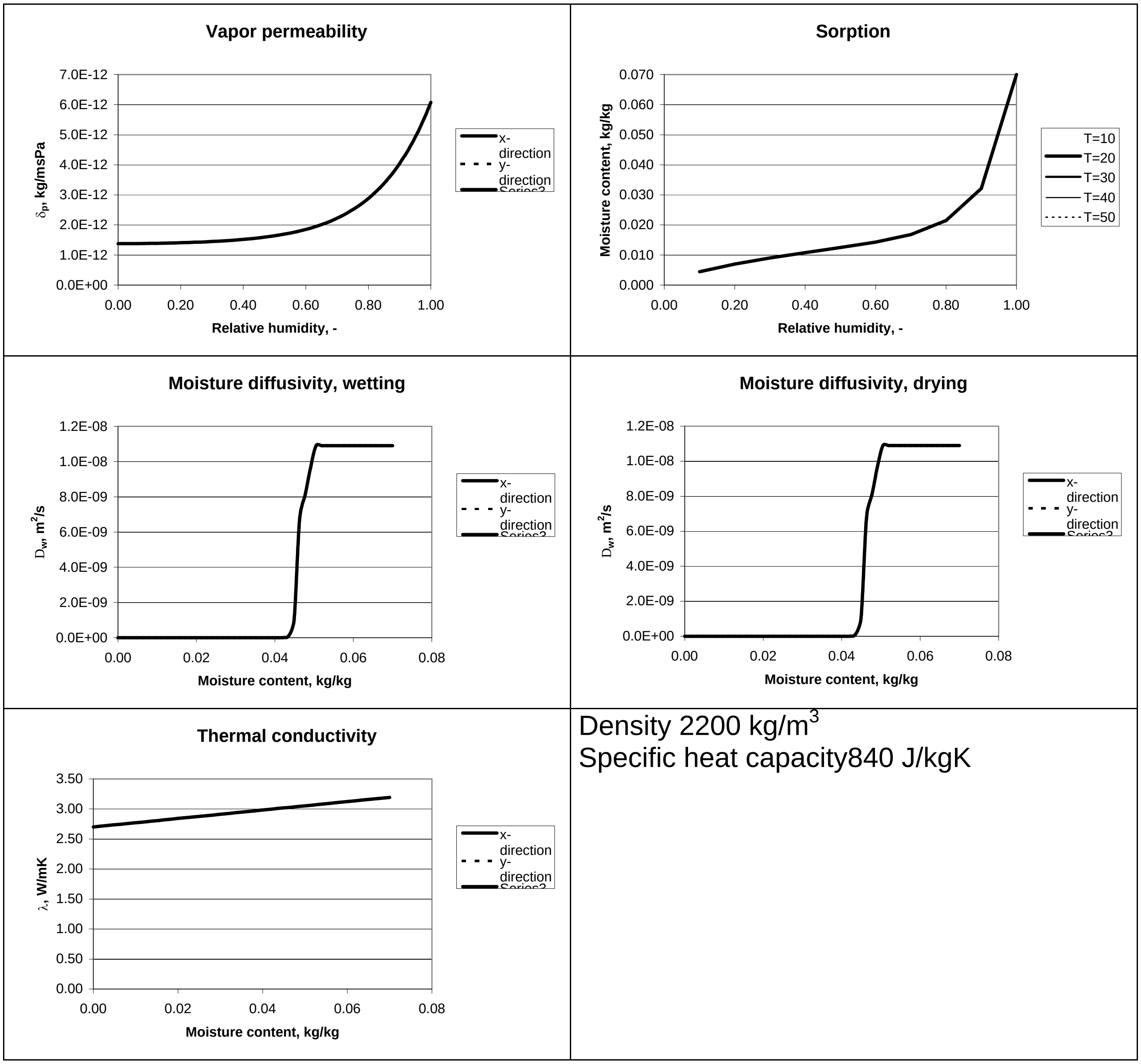
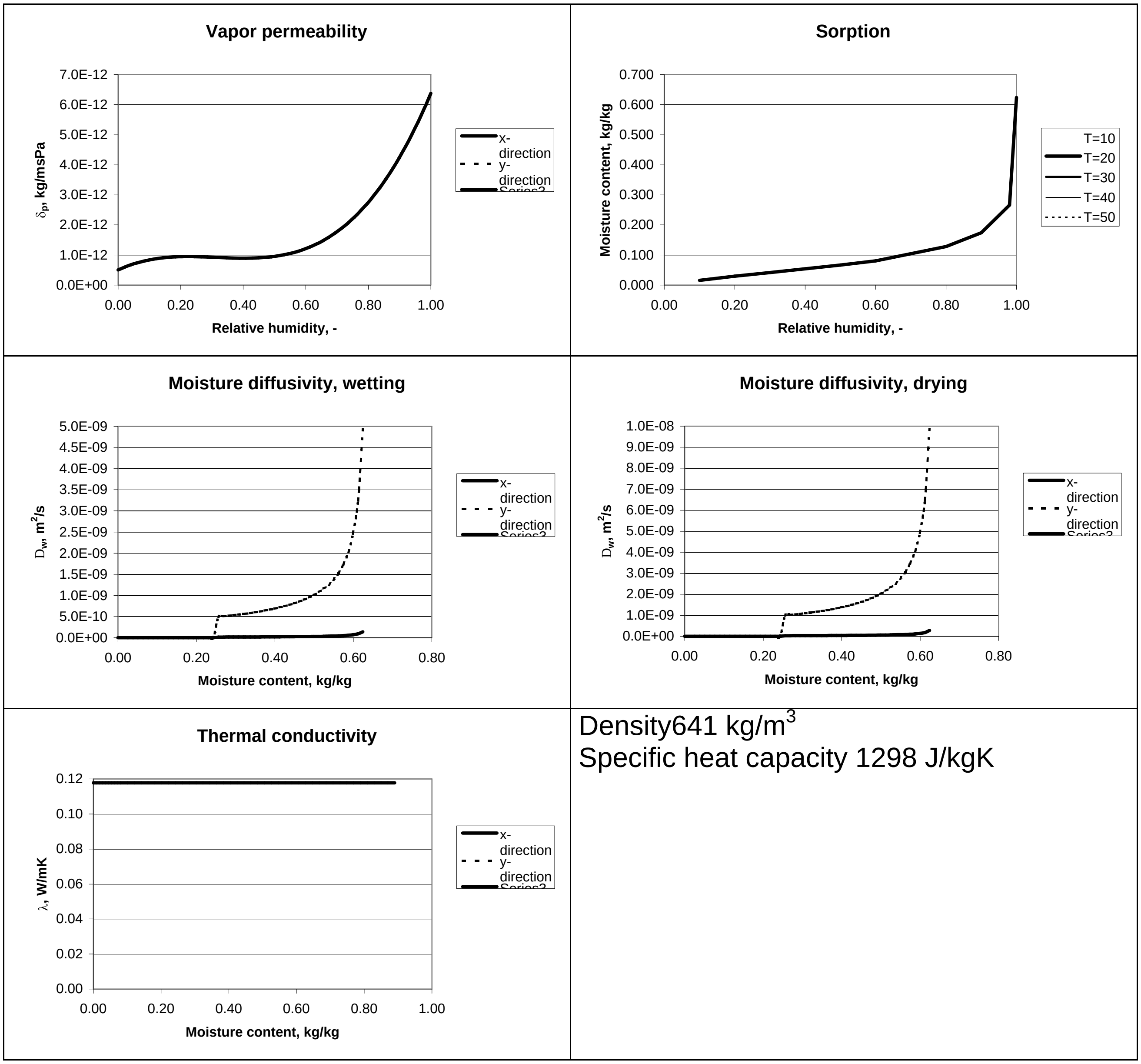


Figure 30: Hygrothermal Material Properties for Concrete

Oriented Strand Board (OSB)



Density641 kg/m^3
Specific heat capacity 1298 J/kgK

Figure 31: Hygrothermal Material Properties for OSB

Gypsum board

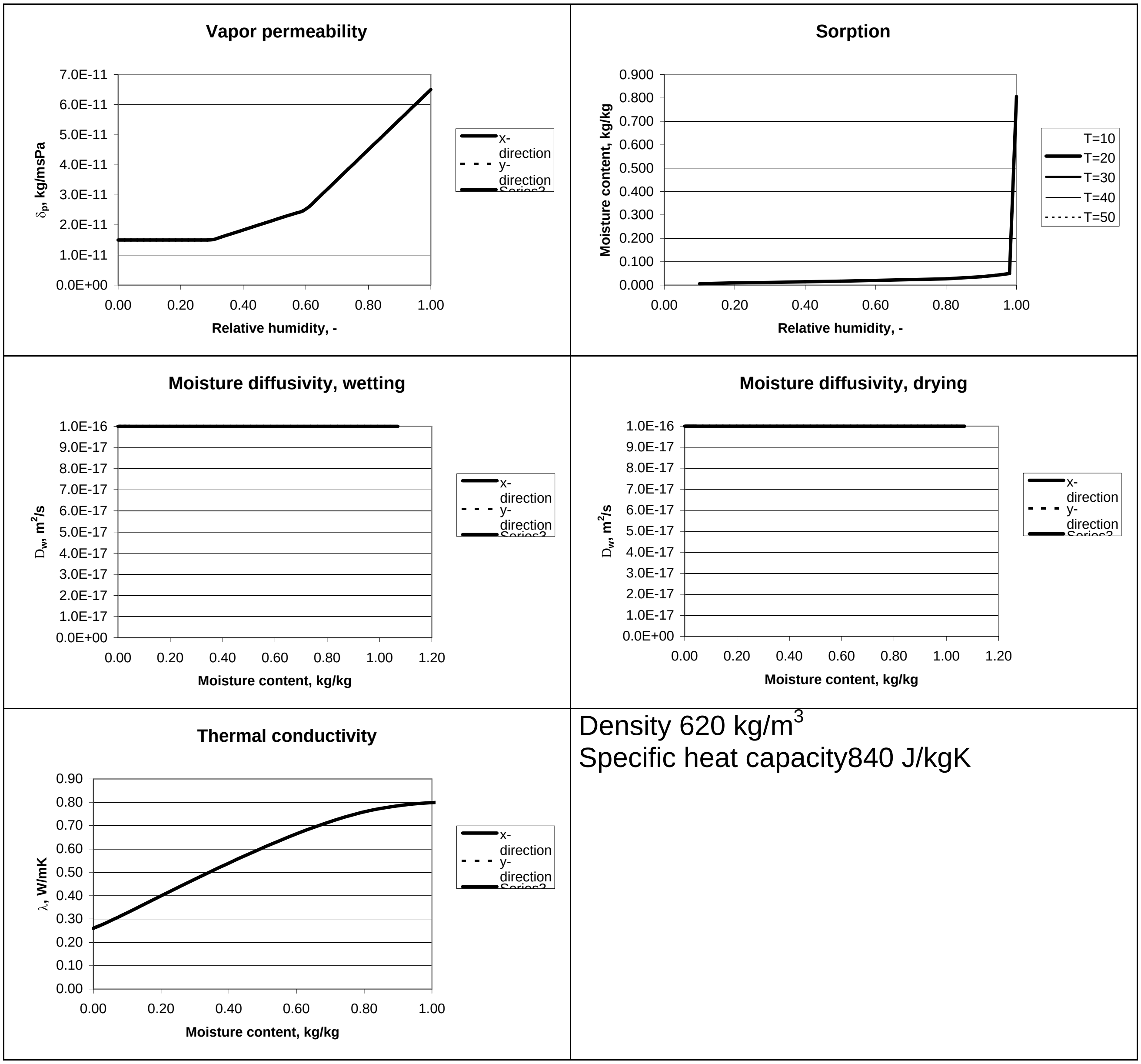


Figure 32: Hygrothermal Material Properties for Gypsum Board

Description of the Hygrothermal Model

The MOISTURE-EXPERT hygrothermal model developed by [Karagiozis, 2001] at ORNL was used in this work. The model was developed to predict the dynamic one-dimensional and two-dimensional heat, air, and moisture transport in building envelope geometries. The model treats vapor and liquid transport separately. The moisture transport potentials are vapor pressure and relative humidity, and temperature for energy transport. The model includes the capability of handling temperature-dependent sorption isotherms and liquid transport properties as a function of drying or wetting processes.

MOISTURE-EXPERT model accounts for the coupling between heat and moisture transport via diffusion and natural and forced convective air transport. Phase change mechanisms due to evaporation/condensation, freezing/thawing are incorporated in the model. The model includes the capability of handling internal heat and moisture sources, gravity-driven liquid moisture, and surface drainage capabilities. The model also captures experimentally-determined system and sub-system performances and anomalies of the building envelope. One of the model's unique features is its capability to handle temperature dependent sorption isotherms, water penetration and directional and process-dependent liquid diffusivity. For these wall simulations, a majority of the simulations were performed both in one-dimensional and two-dimensional enhanced versions. The moisture transfer equation, including contributions from liquid, vapor air flow and gravity assisted transfer is:

$$\dot{m}_M = -D_\phi(u,T,x,y)\nabla\phi - \delta_p(u,T)\nabla P_v + v_a\rho_v + K(u)\rho_w\vec{g} \quad \text{(Equation1.)}$$

Where
$\dot{m}$ = mass flux, kg/m2·s ()
ρ0 = dry density of porous material, kg/m3
Dϕ = liquid moisture transport coefficient, m2/s
u = moisture content, kgw/kgd
T= temperature, oC
δp = vapor permeability, kg/s·m·Pa
P_v = vapor pressure, Pa
va= velocity of air, m/s
ρv= density of vapor in the air, kg/m3

K= moisture permeability, s

ρw = density of liquid water, kg/m3

g= acceleration due to gravity, m/s2.

ϕ= relative humidity (-)

Exterior Environmental loads

Climate

North Carolina has a humid subtropical climate, with precipitation in all seasons and few temperature extremes.

Temperature

In January temperatures average 4° to 7°C (40° to 45°F) in most areas, except in the mountains, where the range is from 1° to 3°C (34° to 38°F). There cold raw weather lasts much of the winter. In the Coastal Plain and the Piedmont, cold spells are brief. On the highest peaks, January averages are well below freezing and heavy snowfalls occur. July temperatures range from an average of about 20°C (about 68°F) in the mountainous regions to as high as 27° C (80°F) in the Coastal Plain. Hot days are common at lower elevations, and temperatures occasionally rise into the upper 30°s C (lower 100°s F). Summers are cooler in the mountains. The hourly temperatures are shown in Figures 33, 34 and 35 for a period of two years starting January 1, for Wilmington, Charlotte, and Raleigh. Hourly relative humidities, and rainfall are plotted out in Figures 36 to 41. From these figures (temperatures, relative humidity and rainfall) and Figures 42, 43, 44 (yearly rain loads) it is evident that a characteristic differences are present in the exterior environmental loads. In Figures 45, 46 and 47 the results show that the wind speed and orientation from the wind rose data. It is evident that the winds speeds are above average and indeed are very similar to each other. In Figure 48 a rain fall map for North Carolina is depicted showing higher rainfall at both the eastern and western parts of the state with lower precipitation in the central zone.

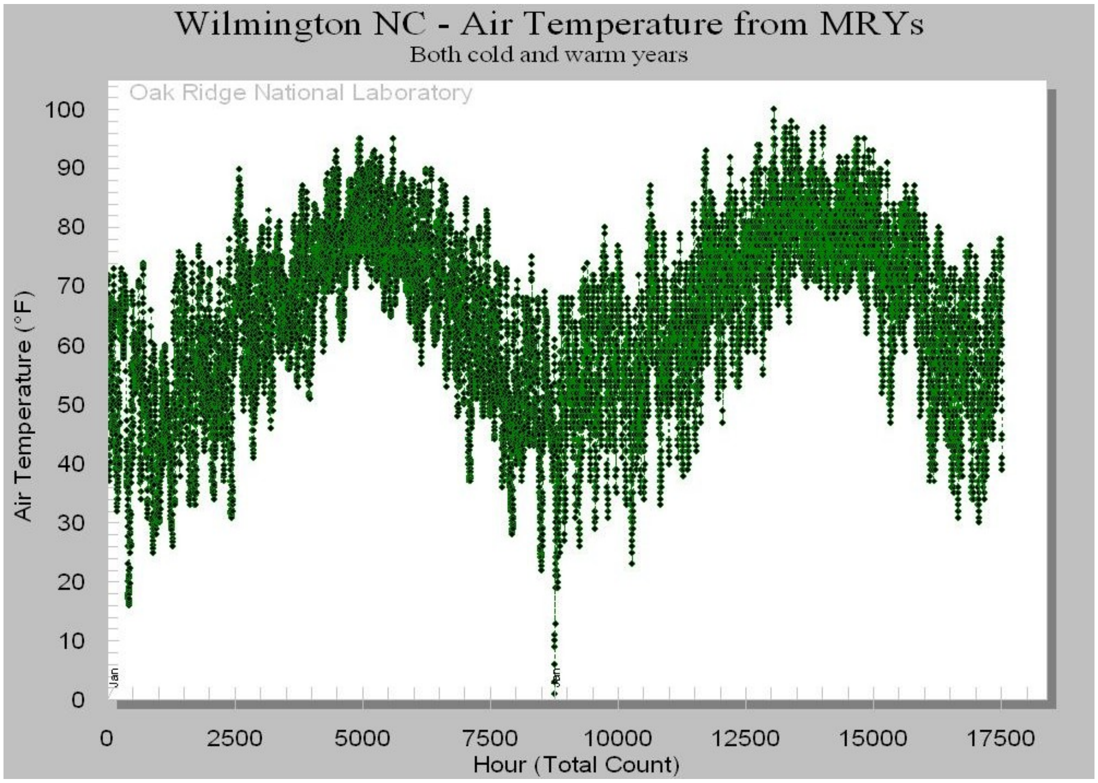


Figure 33: Wilmington Hourly Temperatures

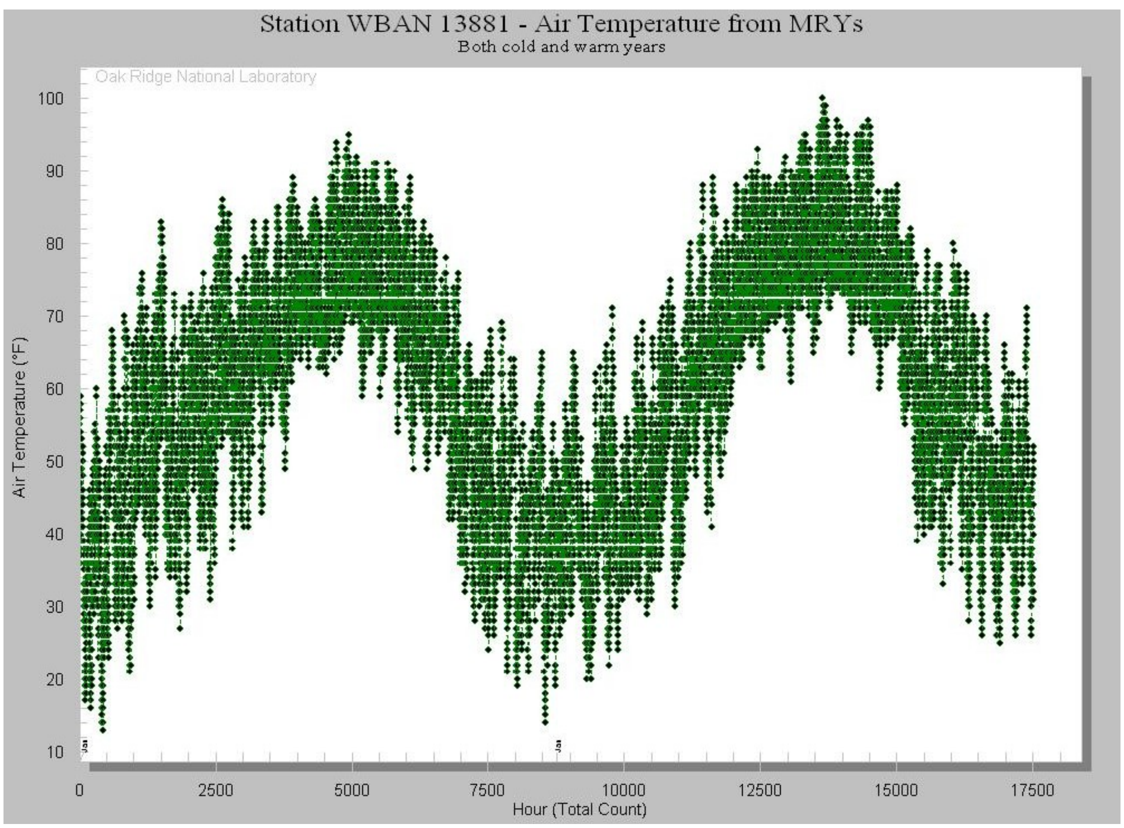


Figure 34: Charlotte Hourly Temperatures

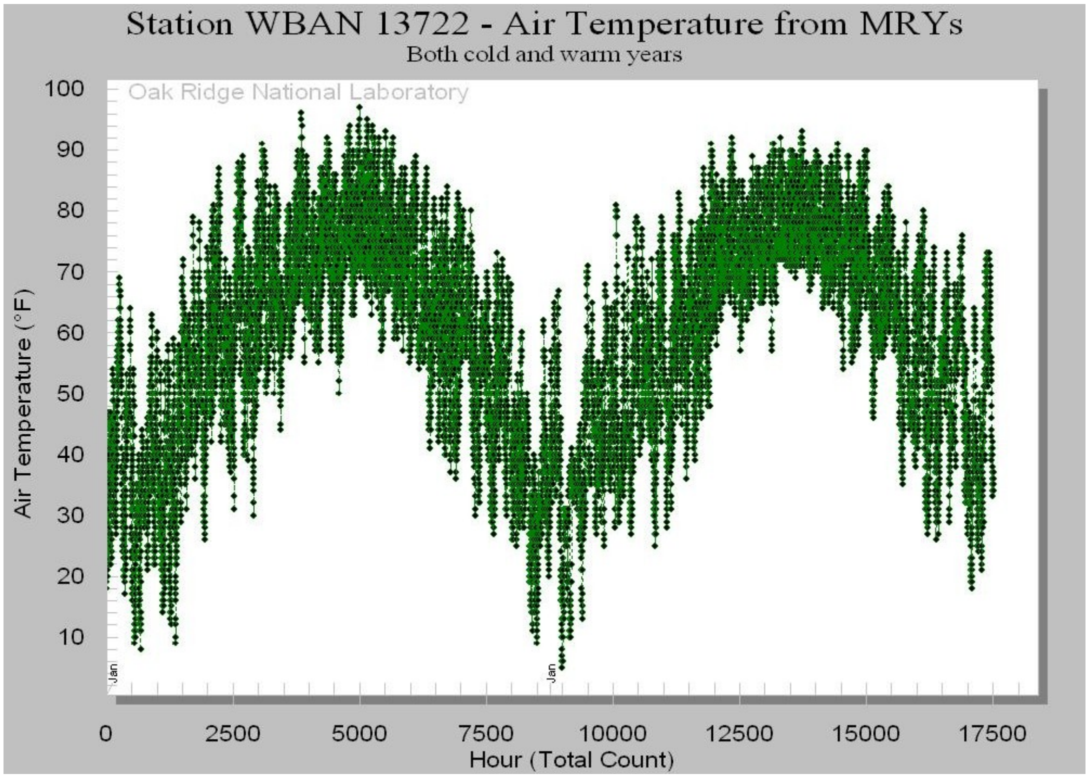


Figure 35: Raleigh Hourly Temperature

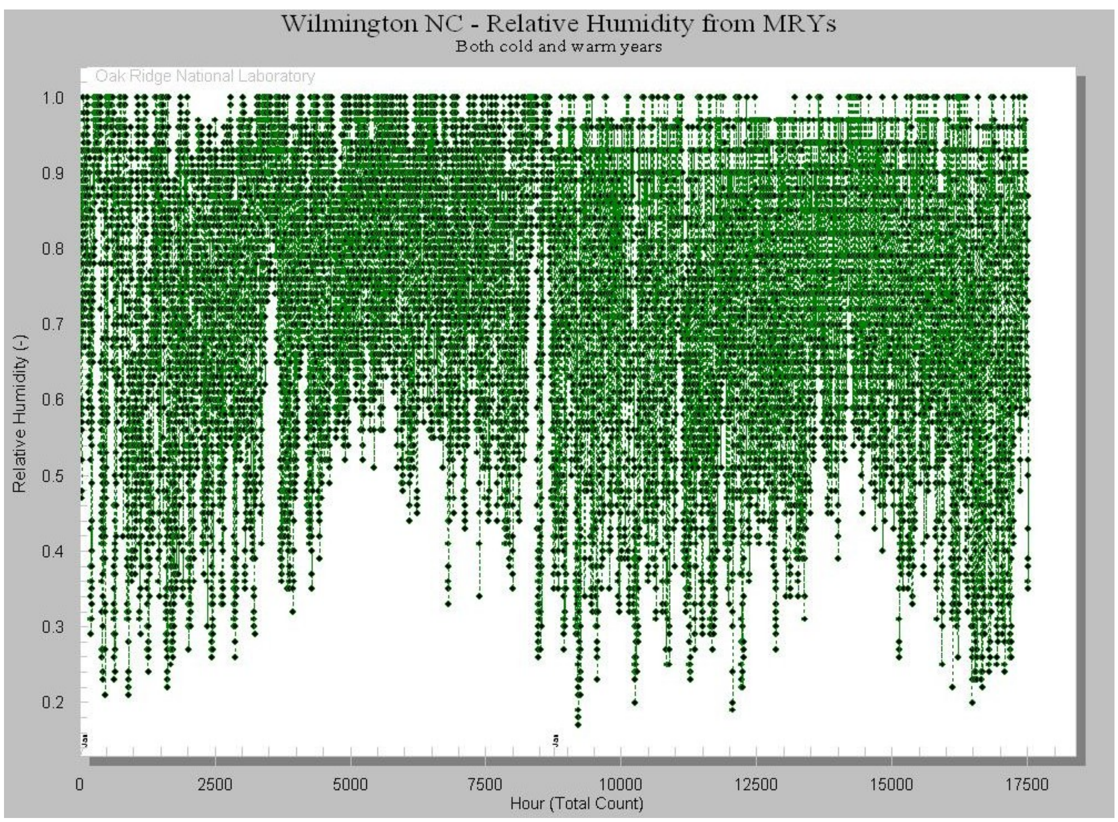


Figure 36: Wilmington Hourly Relative Humidity

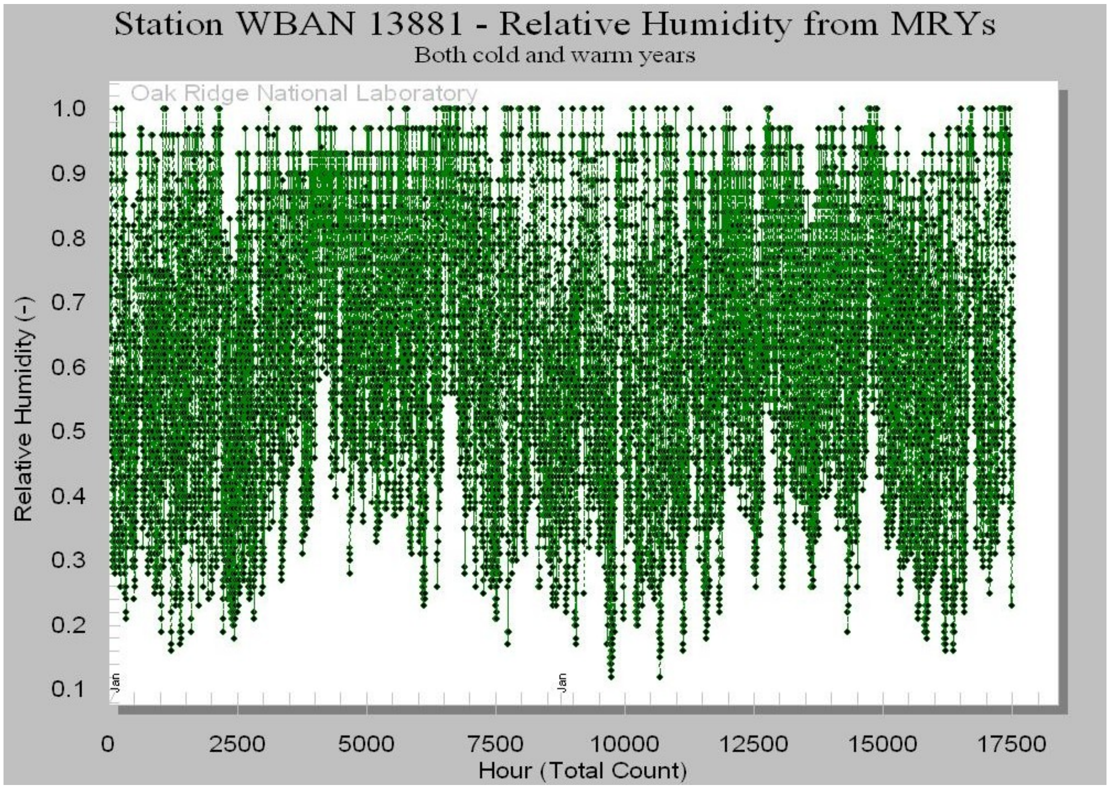


Figure 37: Charlotte Hourly Relative Humidity

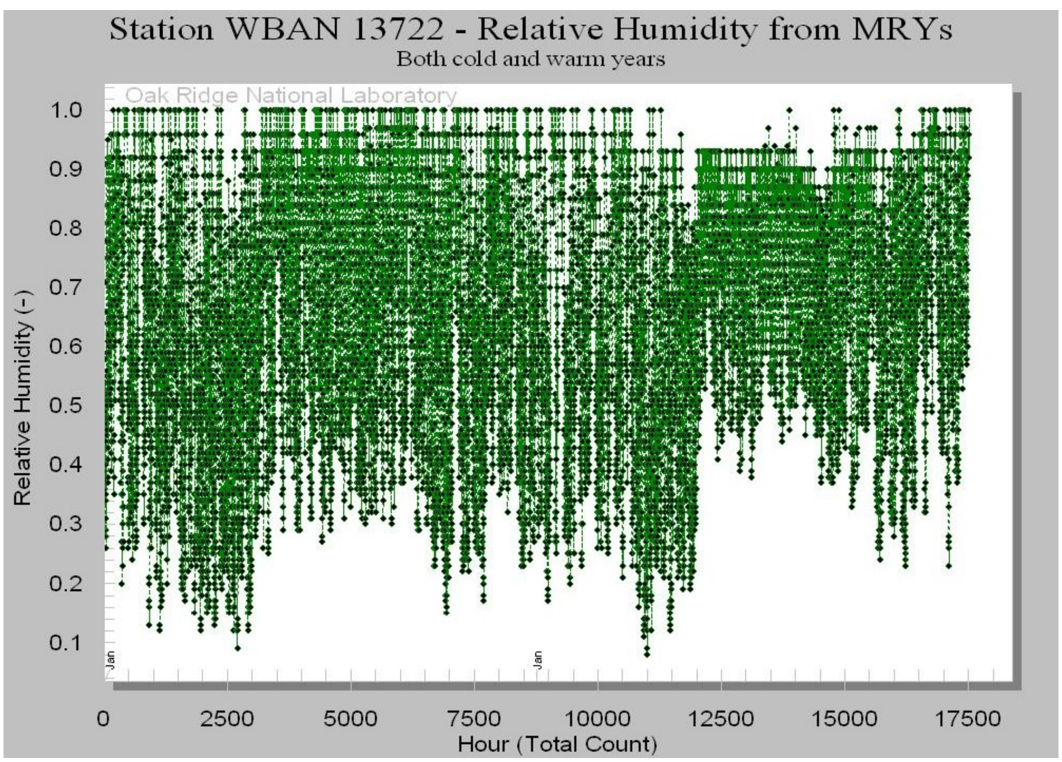


Figure 38: Raleigh Hourly Relative Humidity

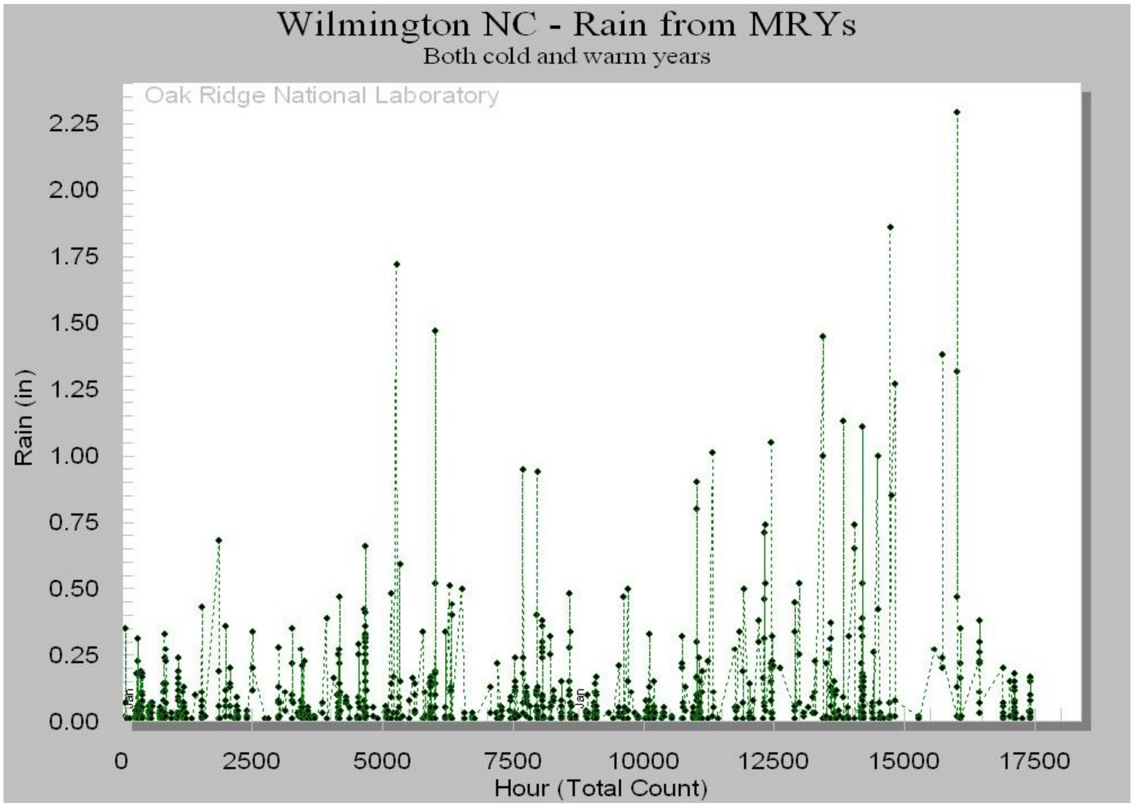


Figure 39: Wilmington Hourly Rainfall

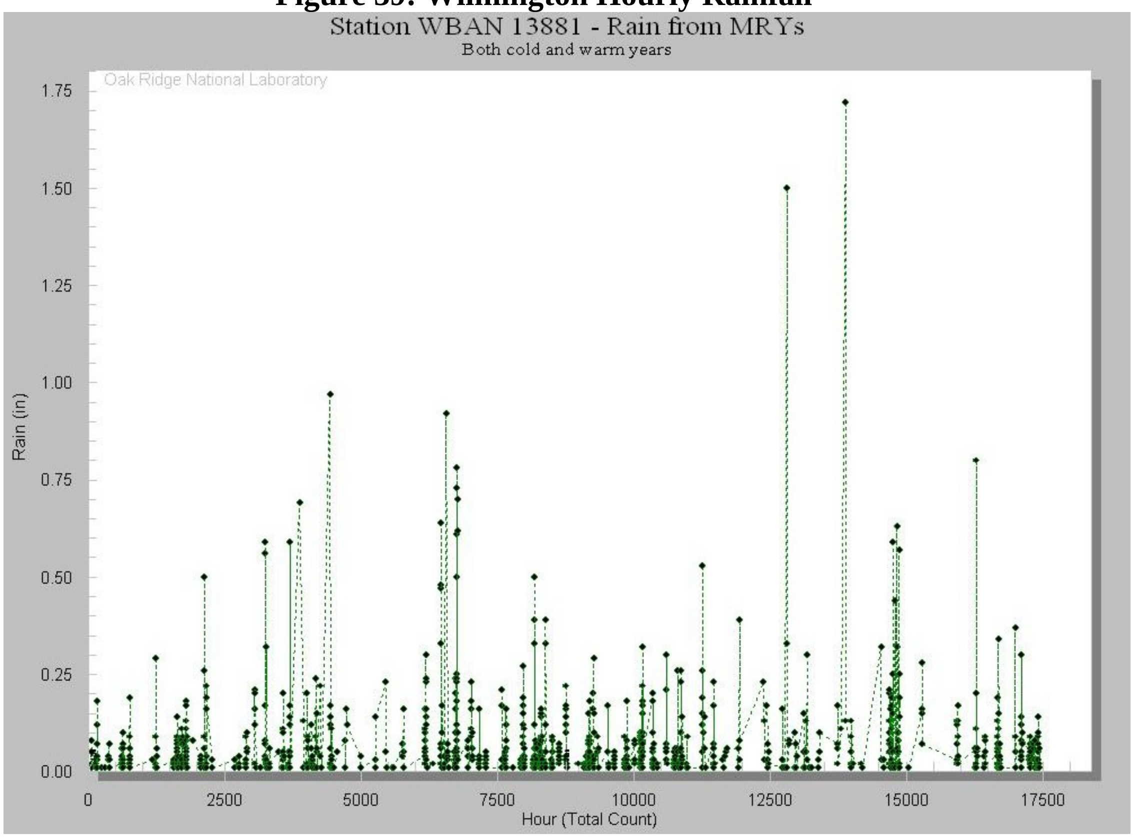


Figure 40: Charlotte Hourly Rainfall

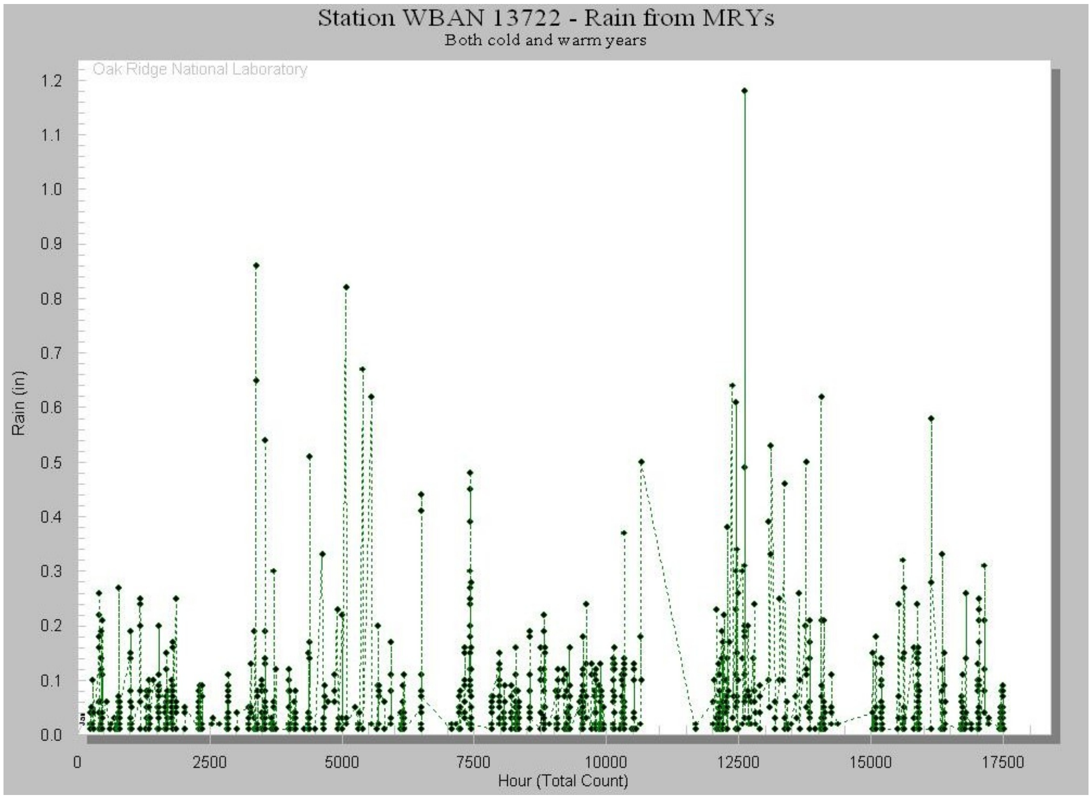


Figure 41: Raleigh Hourly Rainfall

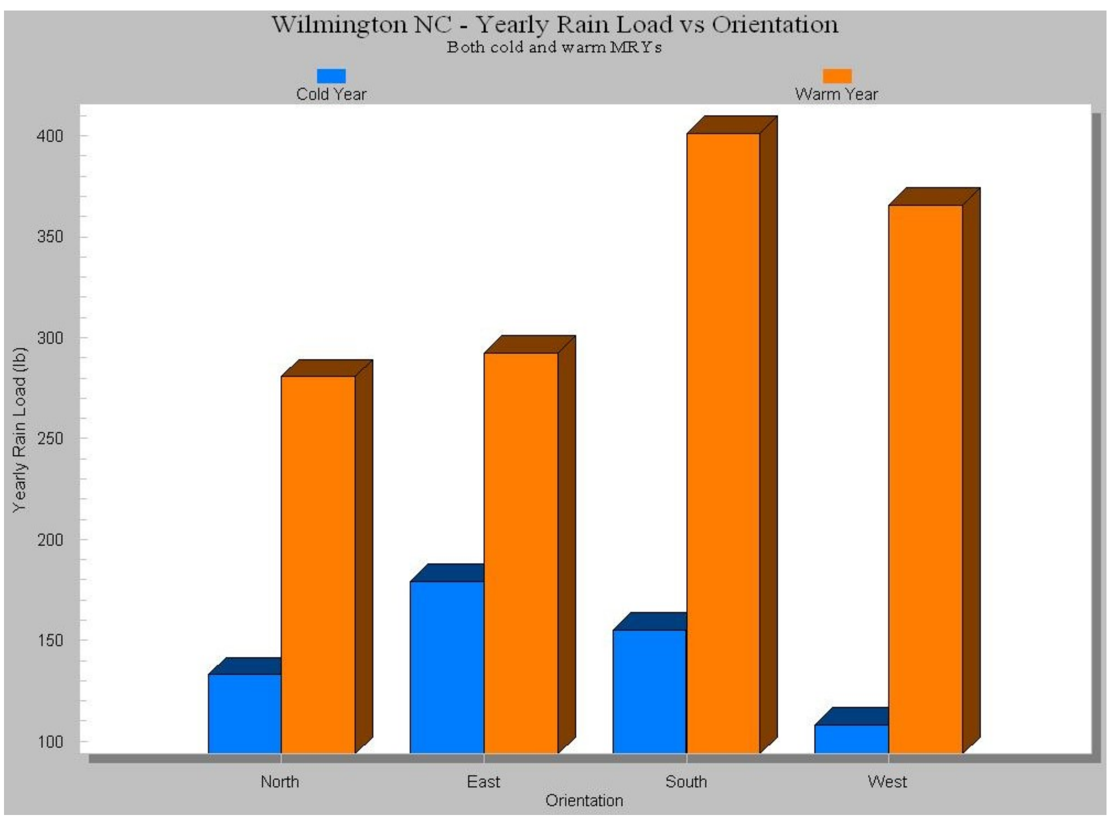


Figure 42: Wilmington Yearly Wind Driven Rain Loads

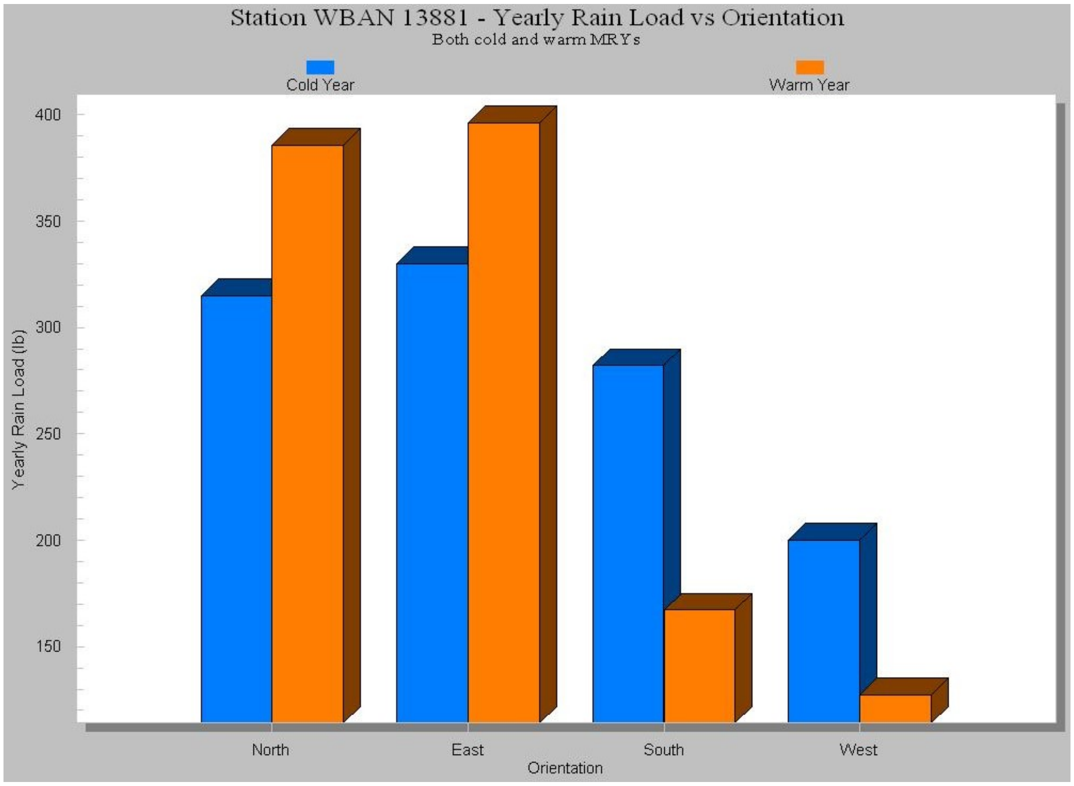


Figure 43: Charlotte Yearly Wind Driven Rain

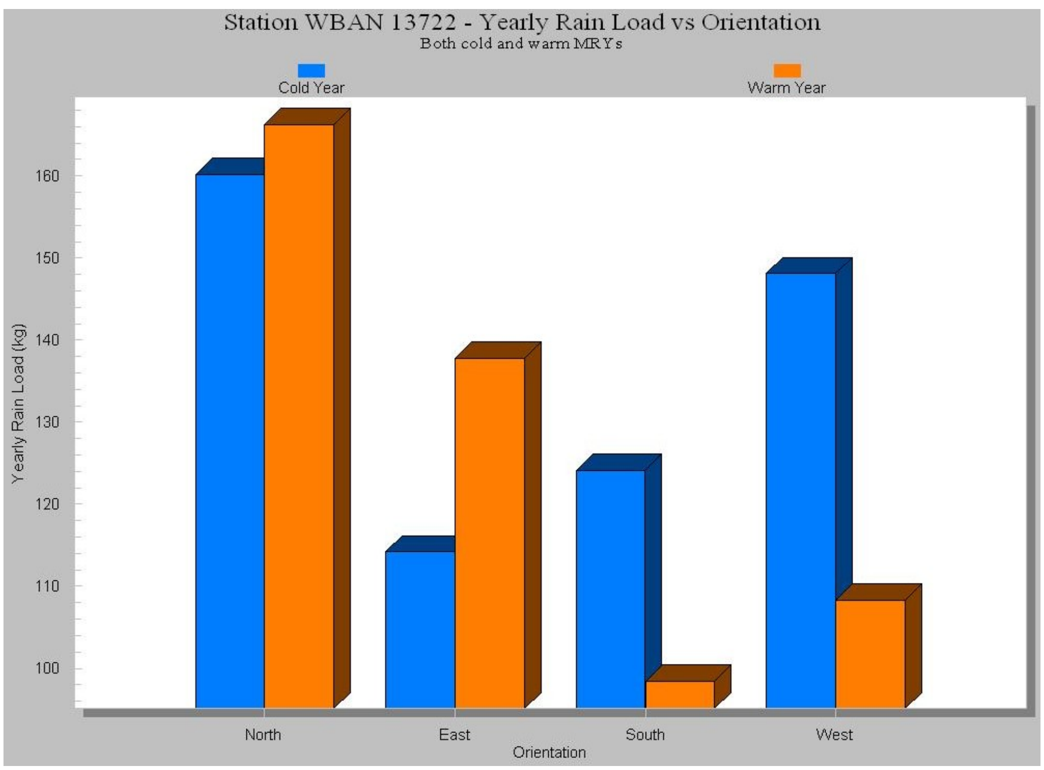


Figure 44: Raleigh Yearly Rain Load

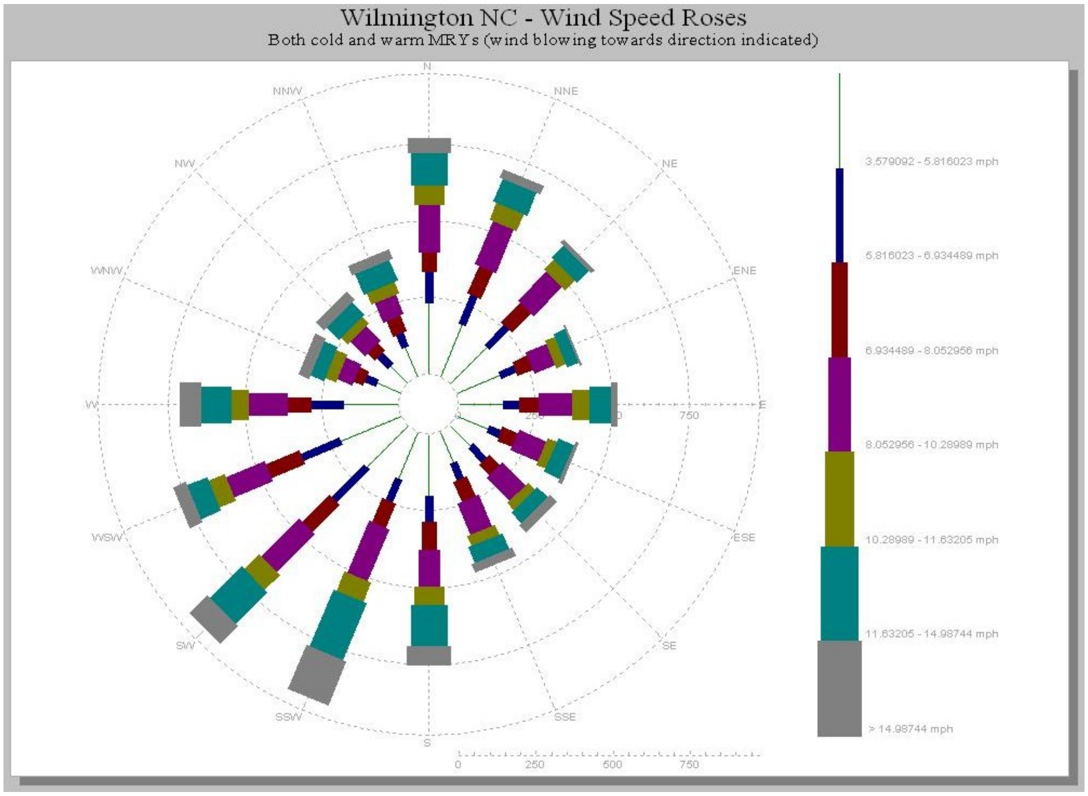


Figure 45: Wilmington Wind Roses

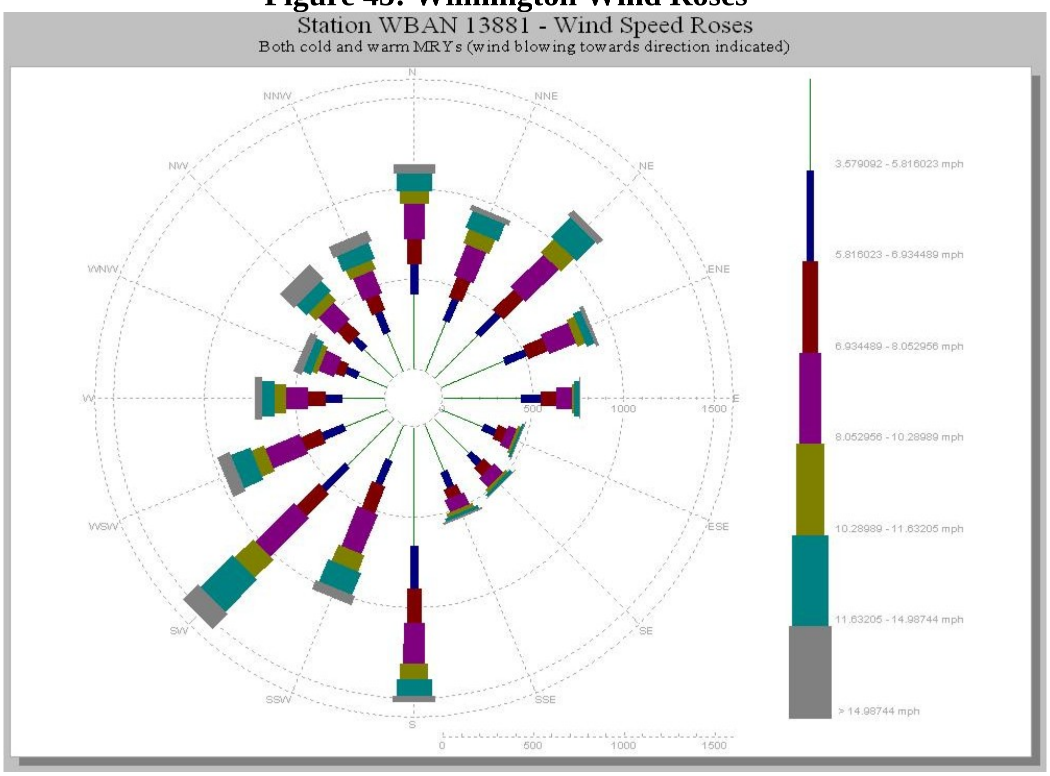


Figure 46: Charlotte Wind Roses

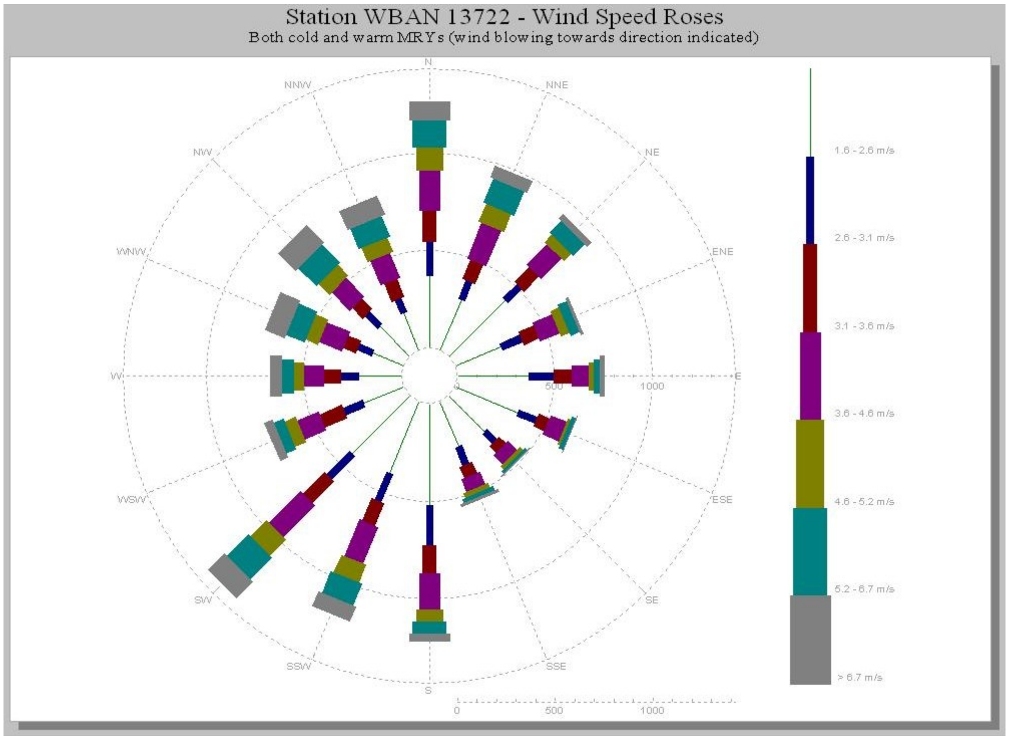


Figure 47: Raleigh Wind Roses

Precipitation

Yearly precipitation averages 1,000 to 1,300 mm (40 to 50 in) over most of the Atlantic Coastal Plain and the Piedmont. The sheltered basins and mountain valleys receive 1,000 mm (40 in). The southern-facing slopes of the mountains in the extreme southwestern part of the state receive about 2,000 mm (80 in) due to the moist prevailing winds blowing northward from the Gulf of Mexico. Summer is the rainiest season, and autumn is generally the driest, except that near the coast, autumn can be very rainy because of tropical storms and hurricanes. Snowfall ranges from 25 to 250 mm (1 to 10 in) a year over the Atlantic Coastal Plain and the Piedmont. In the mountains annual snowfall averages as much as 1,300 mm (50 in) in places, and the snow cover can last for several weeks at a time

In Figure 49, a comparison is given for the monthly rain precipitation for Raleigh and Charlotte.

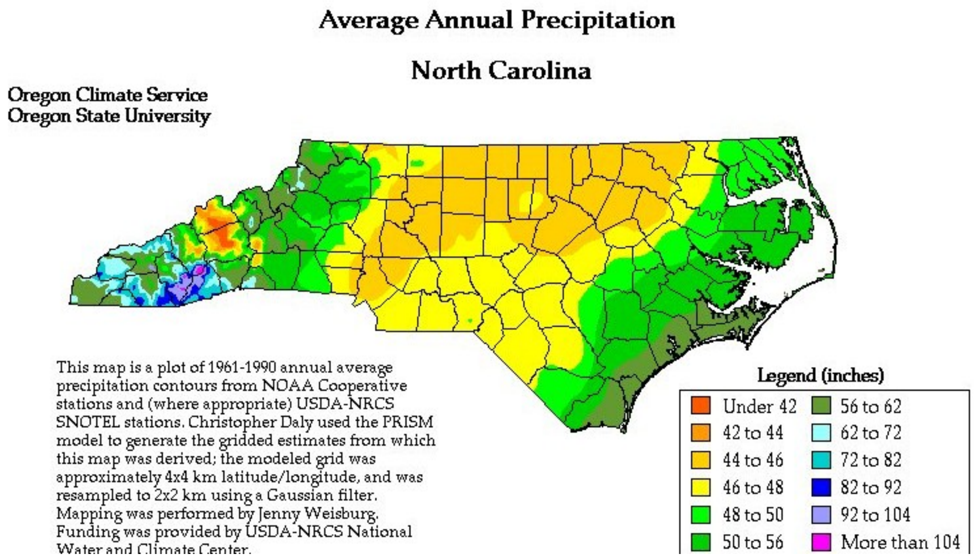


Figure 48: Annual Precipitation

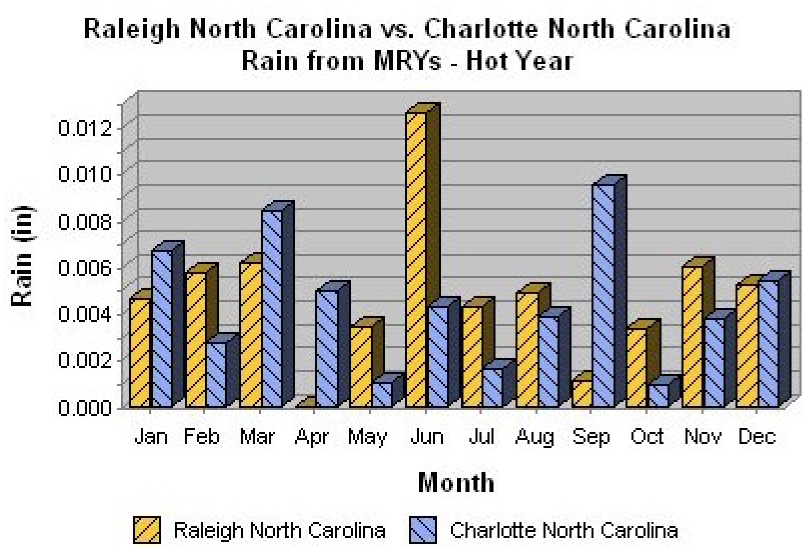


Figure 49: Comparison of Raleigh and Charlotte Monthly Rainfall

Modeling Assumptions

Several assumptions were implemented at different levels of the input parameters. Input parameters related to weather loads, interior moisture loads, material properties, and system and sub-system performance attributes were used. Assumptions were made that were consistent with the purpose of the project: that was, to provide relative performance of walls in terms of their response to the same hygrothermal loads and inputs.

A few of the assumption made are:

- Material properties used in the simulations are representative of material used. The exact composition is not known for each material layer.
- Weather data were developed from 30 years of hourly data by choosing the 10th percentile coldest and hottest years. This approach has been developed at IEA Annex 24 and has been used extensively in North America (ASHRAE is proposing this approach for SPC 160P)
- System imperfections were not included, and gross workmanship defects not examined.
- In this project, the effect of ageing of materials was not included due to the lack of any data. Therefore, durability changes and influences were not included in this project.

With any engineering analysis, the loads used are assumed substantially higher than average loads. While this statement is not absolute, and exceptions may exist, imposing higher than normal hygrothermal loads and tracking the performance of the walls is one way to design systems with an added safety factor.

Description of the Mold Index

The mold growth model and involved mathematical equations are presented in more details in another paper (Hukka & al., 1998) and only short introduction is given here. Quantification of mold growth in the model is based on the mold index used in the experiments for visual inspection. The mold growth model is based on mathematical relations for growth rate of mold index in different conditions including the effects of exposure time, temperature, relative humidity and dry periods. The model is purely mathematical in nature and as mold growth is only investigated with visual inspection, it does not have any connection to the biology in the form of modeling the number of live cells. Also the mold index resulting from computation with the model does not reflect the visual appearance of the surface under study, because traces of mold growth remain on wood surface for a long time. The correct way to interpret the results is that the mold index represents the possible activity of the mold fungi on the wood surface.

The model makes it possible to calculate the development of mold growth on the surface of small wooden samples exposed to fluctuating temperature and humidity conditions including dry periods. The numerical values of the parameters included in the model are fitted for pine and spruce sapwood, but the functional form of the model can be reasoned to be valid also for other wood-based materials.

Table 2: The mold index scale

Mold Index Values and Their Meaning.

Index	Descriptive meaning
0	no growth
1	some growth detected only with microscope
2	moderate growth detected with microscope
3	some growth detected visually
4	visually detected coverage more than 10%
5	visually detected coverage more than 50%
6	visually detected coverage 100%

Simulation Results

In this section results of the 2-D hygrothermal simulations for all three locations will be presented. These simulation were very CPU expensive as they took approximately 2 weeks of dedicated time to execute on a personal computer with 3.0 GHz clock speed.

Table 3 : Parametric Analysis

	Parametric Analysis A- Effect of Insulation placement (Interior versus Exterior) B- Effect of Vapor Barrier Placement (None-ground-Walls+ground) C- Sensitivity of Sealed Crawlspace to Water Penetration (None and 0,0001 % of pipe leak) D- Effect of Ventilation Strategy (Sealed or Ventilated System E- Effect of Water Table Level (Two Levels, 6.5 m or 3.25 m)									
Cities	*A*		*B*			*C*		*D*	*E*	
Wilmington	√	√	√	√	√	√	√	√	√	√
Charlotte	√	√	√	√	√	√	√	√	√	√
Raleigh	√	√	√	√	√	√	√	√	√	√

In Figure 51 a cut of the crawlspace is show and the location of interest is shown in the figure. This graph depicts the precise location of the nodal point that was 1mm into wood floor joist. This wood joist is the closest one to the wall vents when the crawlspace was ventilated. The geometries used in the crawlspace was chosen to be for an average size home in the south east with approximately 1200 ft^2. The crawlspace vents sizes were taken from the sizes installed in the Princeville crawlspaces.

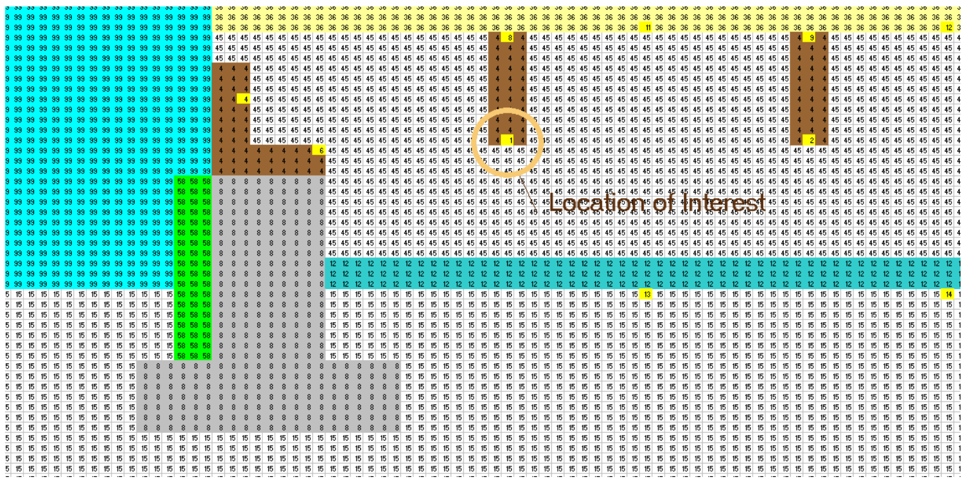


Figure 50: Point of interest in crawlspace assembly

In Figure 52 the full crawlspace representation is show. In this cut the same amount of wood, insulation, concrete, etc present in an actual crawlspace was modeled (both for volume and surface exposure). The total number of control volumes originally employed was 266 x 128 followed by 133 x 64 to establish the minimum threshold for numerical accuracy (+/- 0.05 %) in temperature and RH. In subsequent simulation the number of control volumes deployed was reduced when only specific analysis was required. In total over 80 core simulations were conducted and another 30 or more additional for further analysis. As such, not all results will be presented only those that allow one to analyze the trends and the related back to the transport physics. Figure 53 shows an exploded view for the 133x64 grid size close to the left ventilation opening.

Effect of Ventilation on Crawlspace Performance

In Figure 54 the time dependent temperature evolution within the ventilated crawlspace system is shown for Wilmington, NC. Several locations are simultaneously plotted out to show the variation within the crawlspace at any given point in time. The results show hourly temperature and 8760 data points are plotted out. All simulations have started at time zero equivalent to May 1. The air temperature are also plotted out. It is important to notice the dynamic performance of the ventilated crawlspace. The temperatures in the crawlspace follow with a small lag (depending on the specific location up to 40 minutes in the joists and 3 weeks in with the ground (3 inches within the ground surface) the outdoor excitations (amplitudes). This dynamic thermal performance may provide positive or negative impacts for moisture control. In Figure 55, the time dependent temperature evolution within the sealed crawlspace system, the floor joint insulation has been removed) is also shown for Wilmington, NC. Here, it is evident that the coupling between the outside excitations are dampened. The temperature seem to follow interior conditions that was controlled by a temperature controller (not humidistat).

In Figure 56, 57 and 58 the temperatures at various locations within the crawlspace (2 locations at the tip of the wood joists location 1 and 2 and, at the location of the OSB floor. The results clearly depict the beneficial performance of sealing the crawlspace for the Wilmington Climate. The fluctuations that exist in the ventilated crawlspace temperature sometimes occur very rapidly this has cause liquid moisture movement towards the surface of the wood joists making the surface wet. In this manner a sufficient amount of water exist close to the wood surfaces that may provide enough water for mold to occur.

In Figure 59 and 60 the relative humidity is plotted out for a year for both the ventilated and sealed crawlspaces for the OSB and joist 1 tip respectively. The simulated results start May 1 and clearly show the fast response of the moisture pick-up at the surface of the wooden materials. Already a very high amount of moisture exist in the air during the beginning of the simulation (May 1), this only increases during the summer months. Indeed the relative humidity in the air can become close to 100 % during the summer months. If any duct leakage, with cold air occurs then the already moist air increases in RH. The simulations also show that for the OSB sub floor, the relative humidity does decrease during the winter months to dry conditions even for the ventilated cases. However for more than a period of 120 days, the relative humidity has exceeded a relative humidity of 80 %. From Figures 56, 57 and 58 show that the temperature conditions exist that are favorable for the onset of mold for the ventilated cases. This however is not the case for the sealed crawlspace with interior perimeter insulation. In those cases the relative humidity does not attain an equilibrium moisture content higher than 16 %.

Comparison of the effect of location (Wilmington, Charlotte and Raleigh)

Figure 60 and 61 compares the effect of climatic location on the performance of the crawlspace system. Figure 60 displays the transient relative humidity at joist 2 for all the three climatic locations chosen. Results are plotted out for Wilmington, Charlotte and Raleigh, North Carolina. Results show that the tip of wooden floor joist at location 2 has higher relative humidities in Wilmington than the other two cities. A maximum difference of the order of 15 % was present. Temperature are also higher in Wilmington than Charlotte or Raleigh. In Raleigh, the temperature was the coldest at location 2.

Similar conditions were found for all other locations. Indeed since such as similarity was found, it become apparent that for the second round of simulations that city of Wilmington be used. This is particularly important as the energy analysis of the benefits of sealed crawlspaces has not been quantified in a modeling manner previously.

In Figures 62 and 63 the air change and air change frequency plots are shown for the ventilated crawlspace for Wilmington NC. As found in the experimental analysis of the pilot house, the ventilation is predominately about 3.5 to 5 air changes per hour.

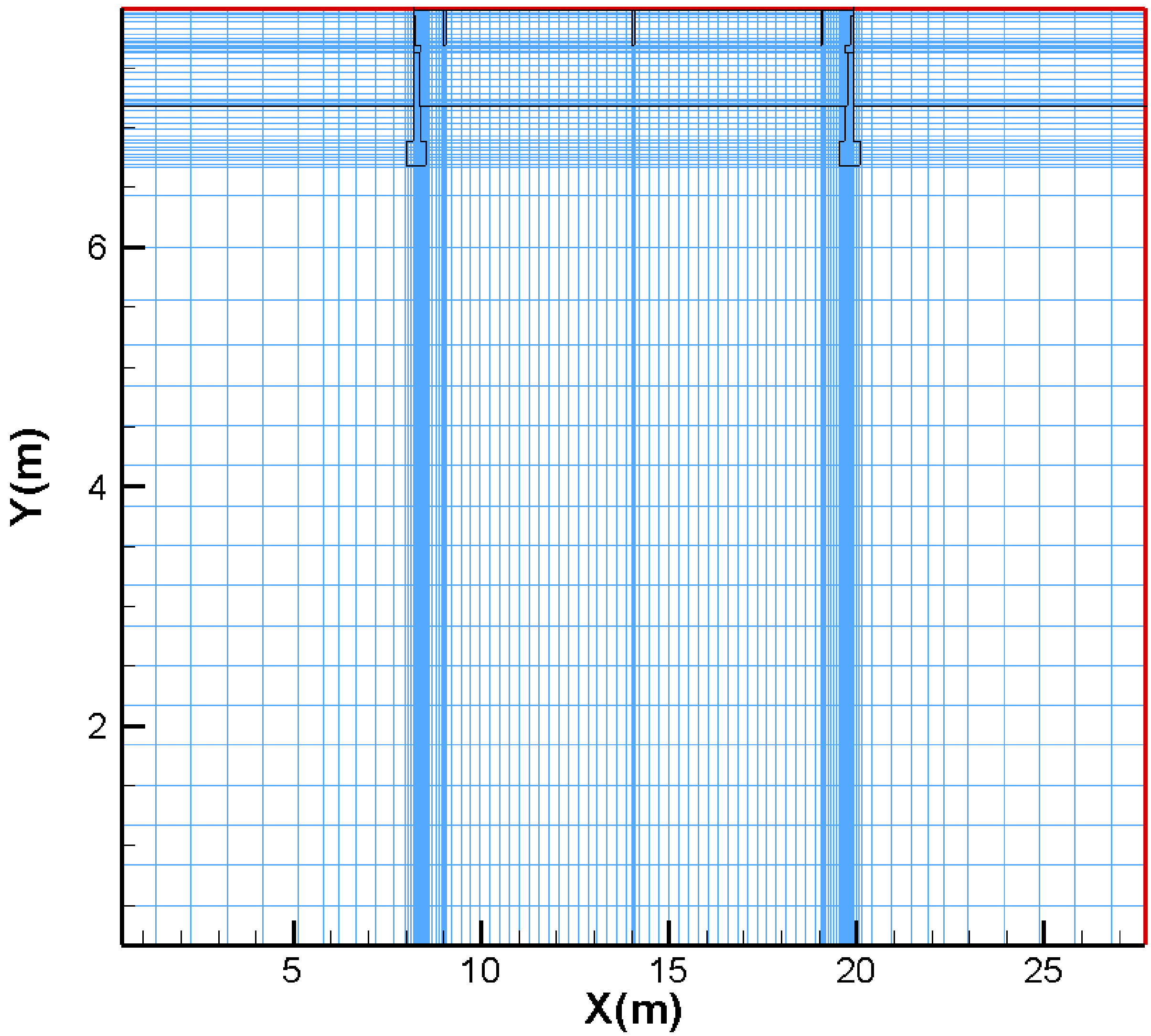


Figure 51: Intermediate grid size distribution in crawlspace assembly

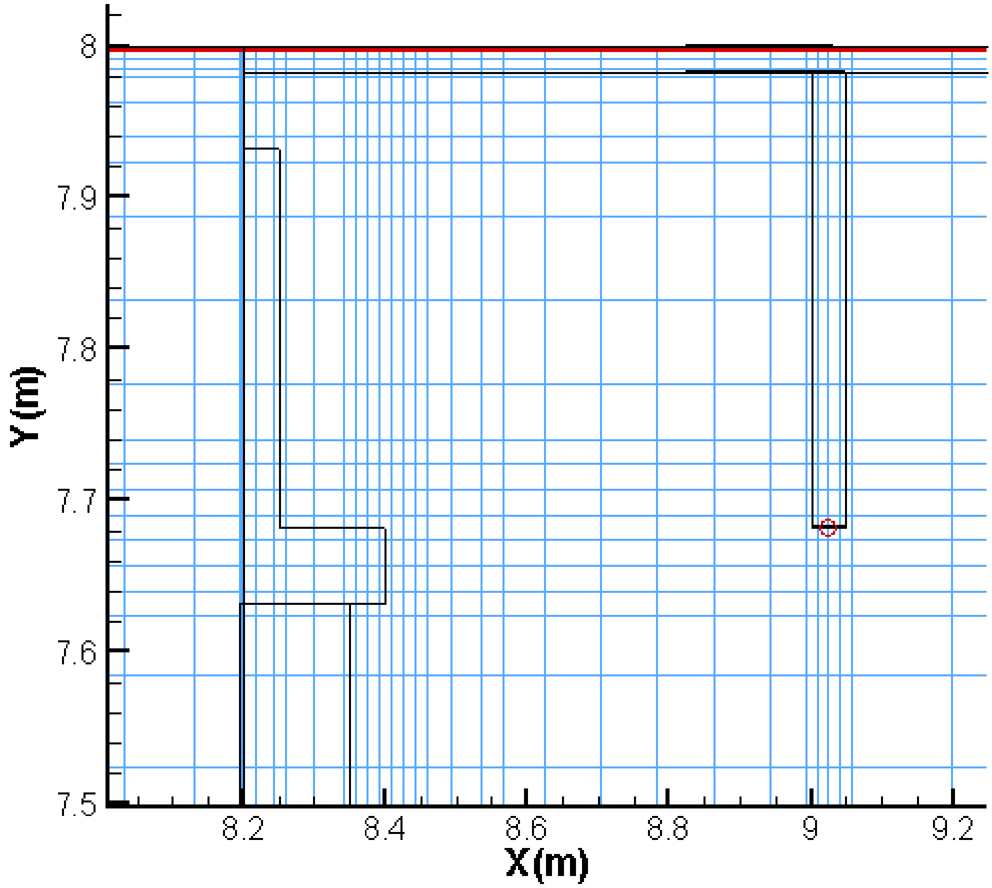


Figure 52: Close up for uninsulated crawlspace with vents

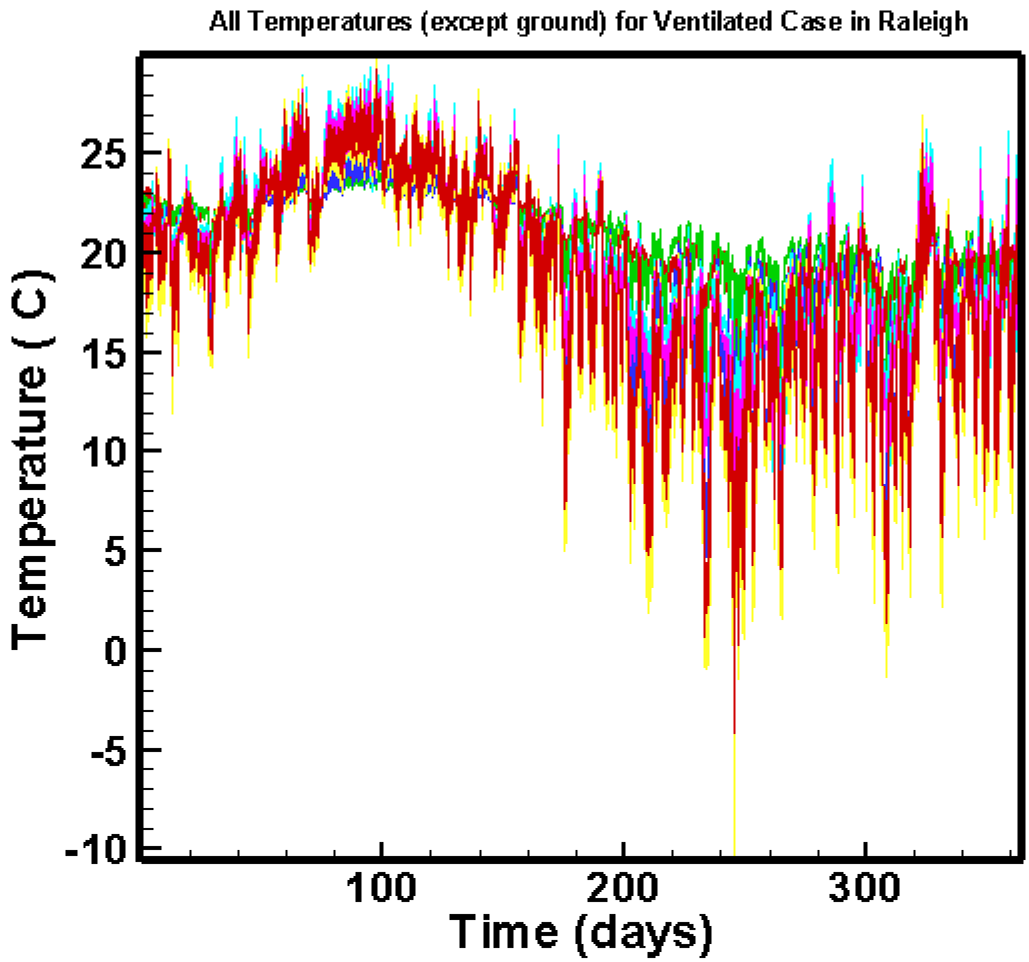


Figure 53: All Temperature for Ventilated Case in Wilmington NC

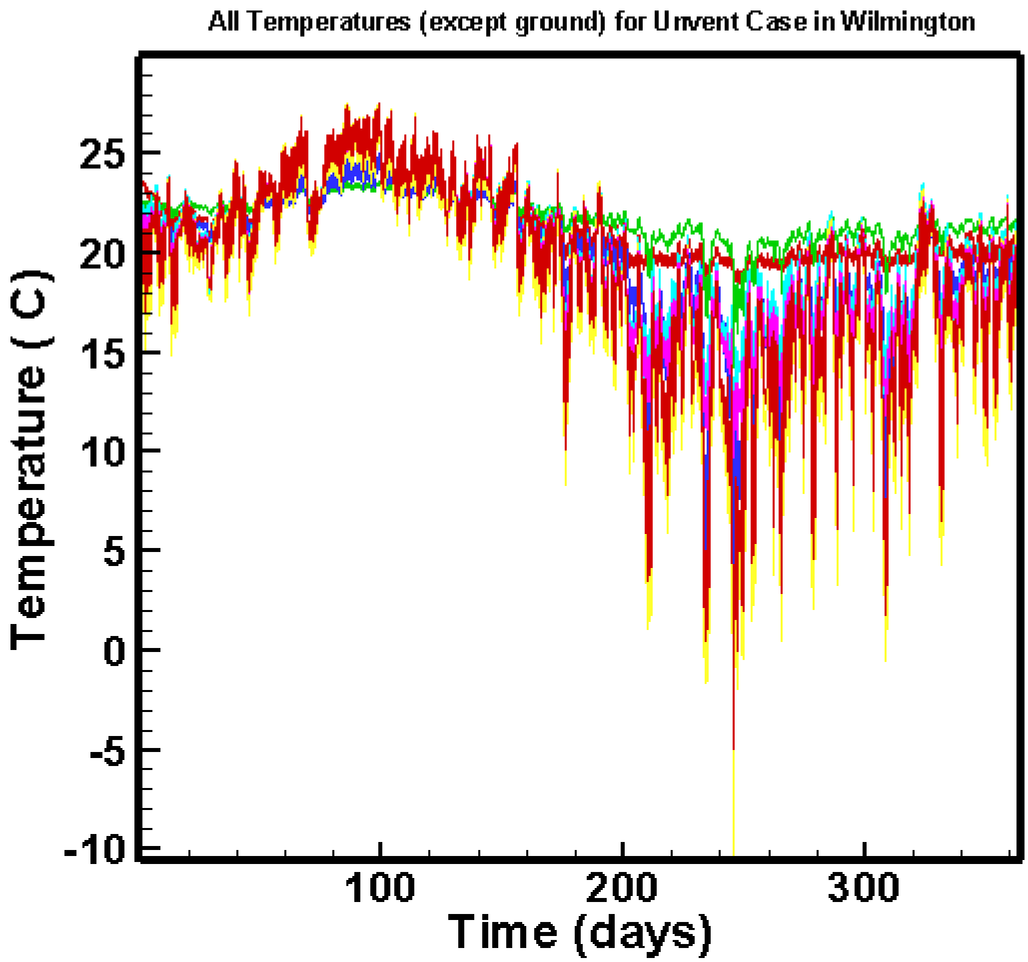


Figure 54: All Temperature for Sealed Case (Includes Outside air) in Wilmington NC

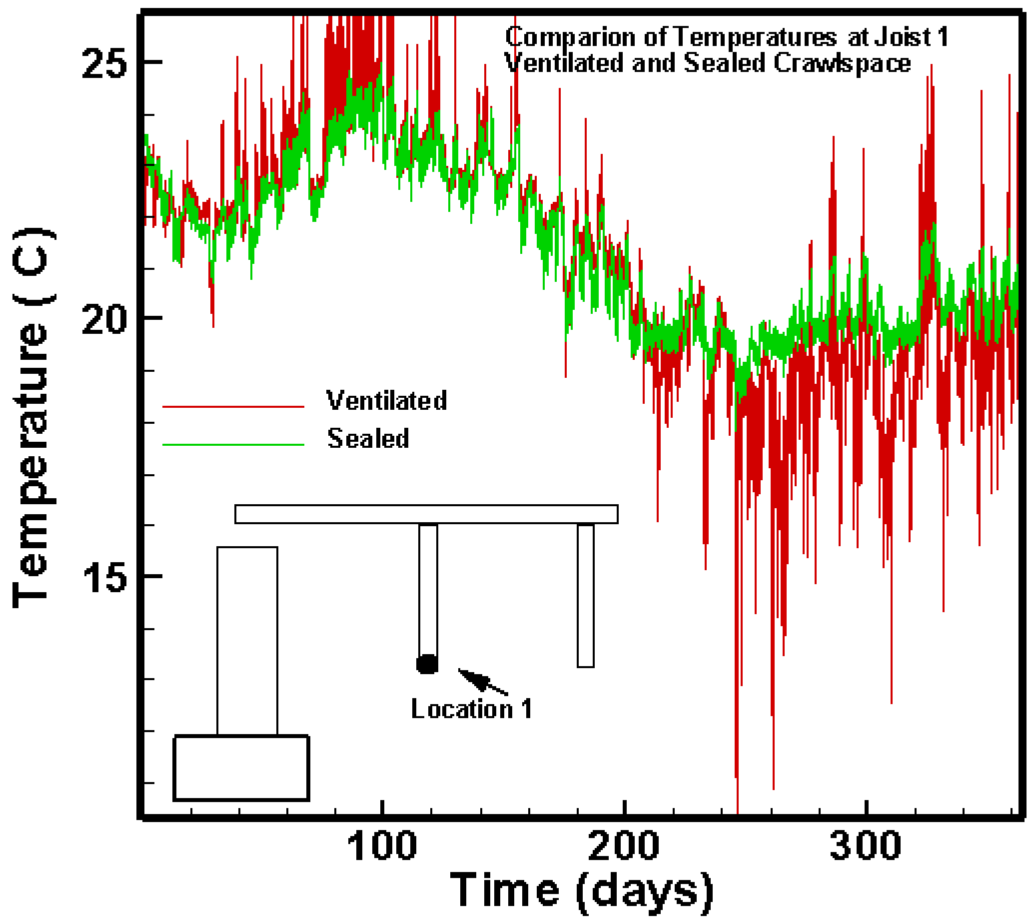


Figure 55: Comparison of Temperature at Joist 1 for Ventilated and Sealed Crawlspace

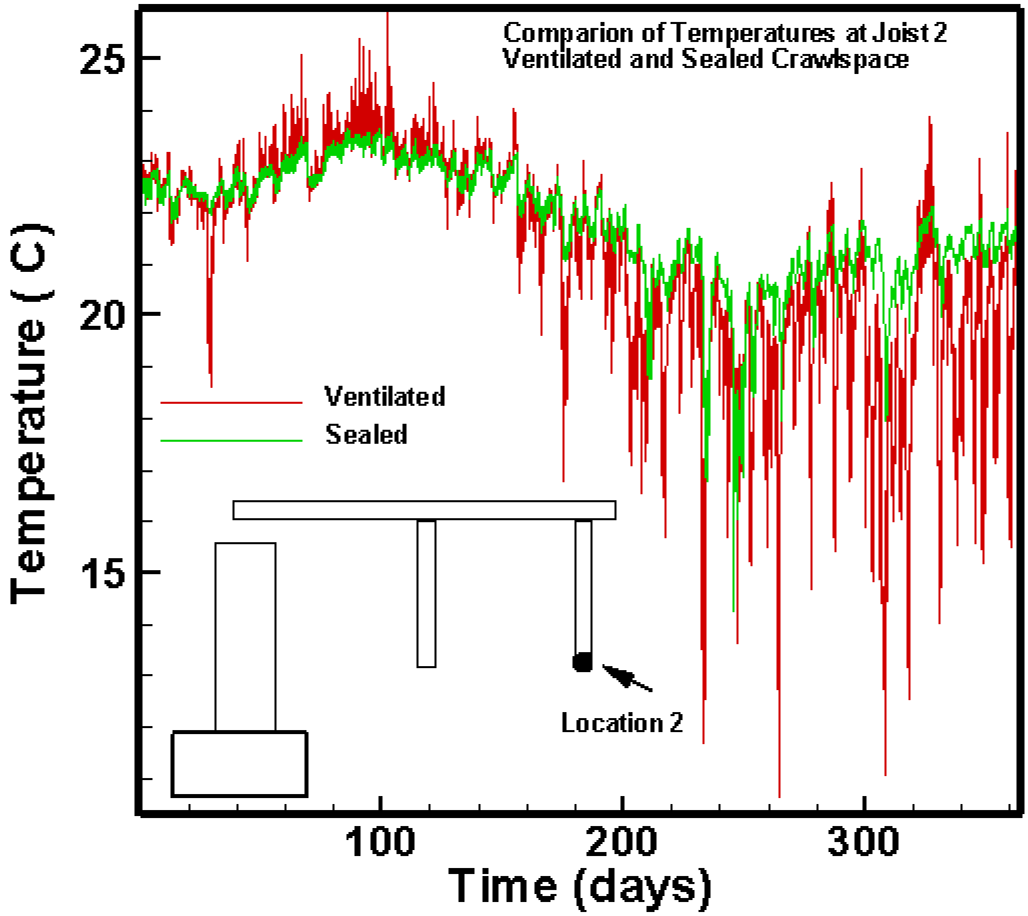


Figure 56: Comparison of Temperature at Joist 2 for Ventilated and Sealed Crawlspace

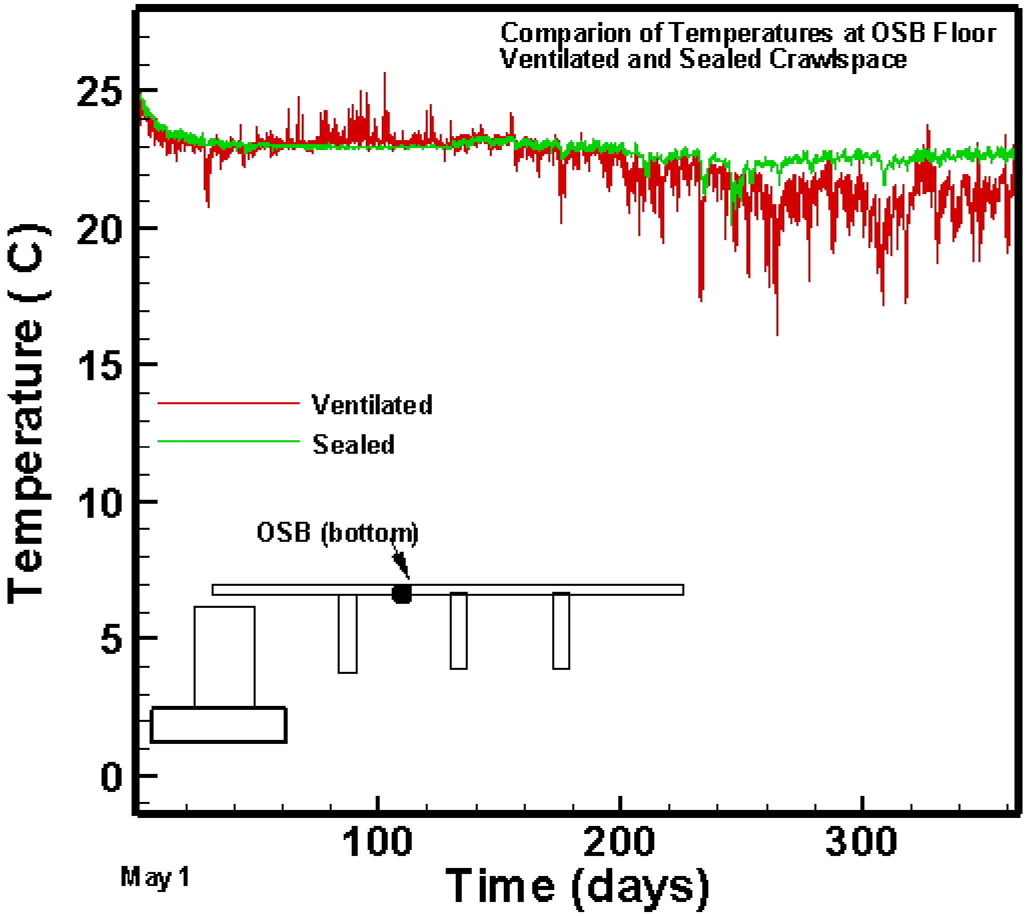


Figure 57: Comparison of Temperature at OSB (bottom surface) for Ventilated and Sealed

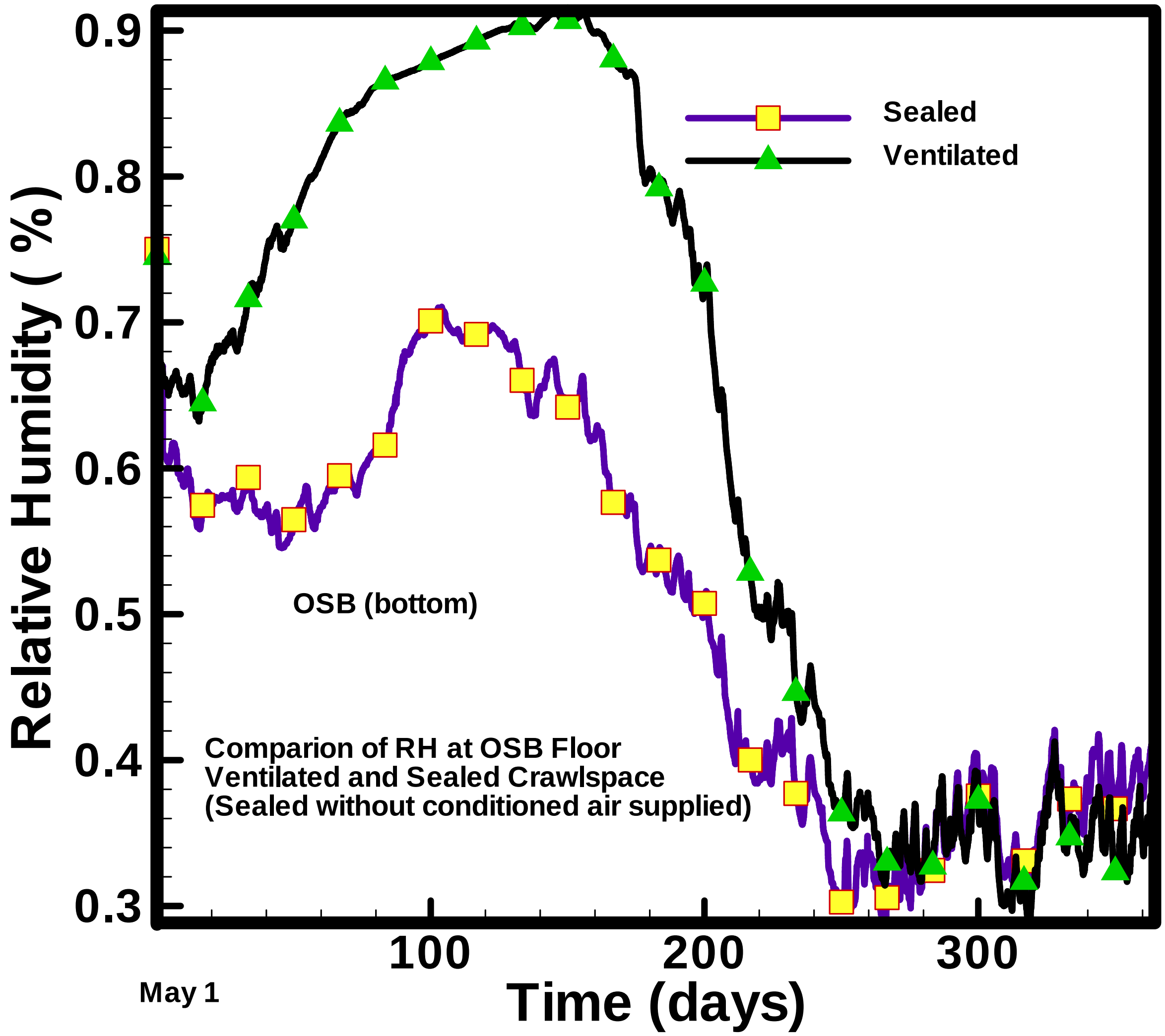


Figure 58: Comparison of RH at OSB (bottom surface) for Ventilated and Sealed

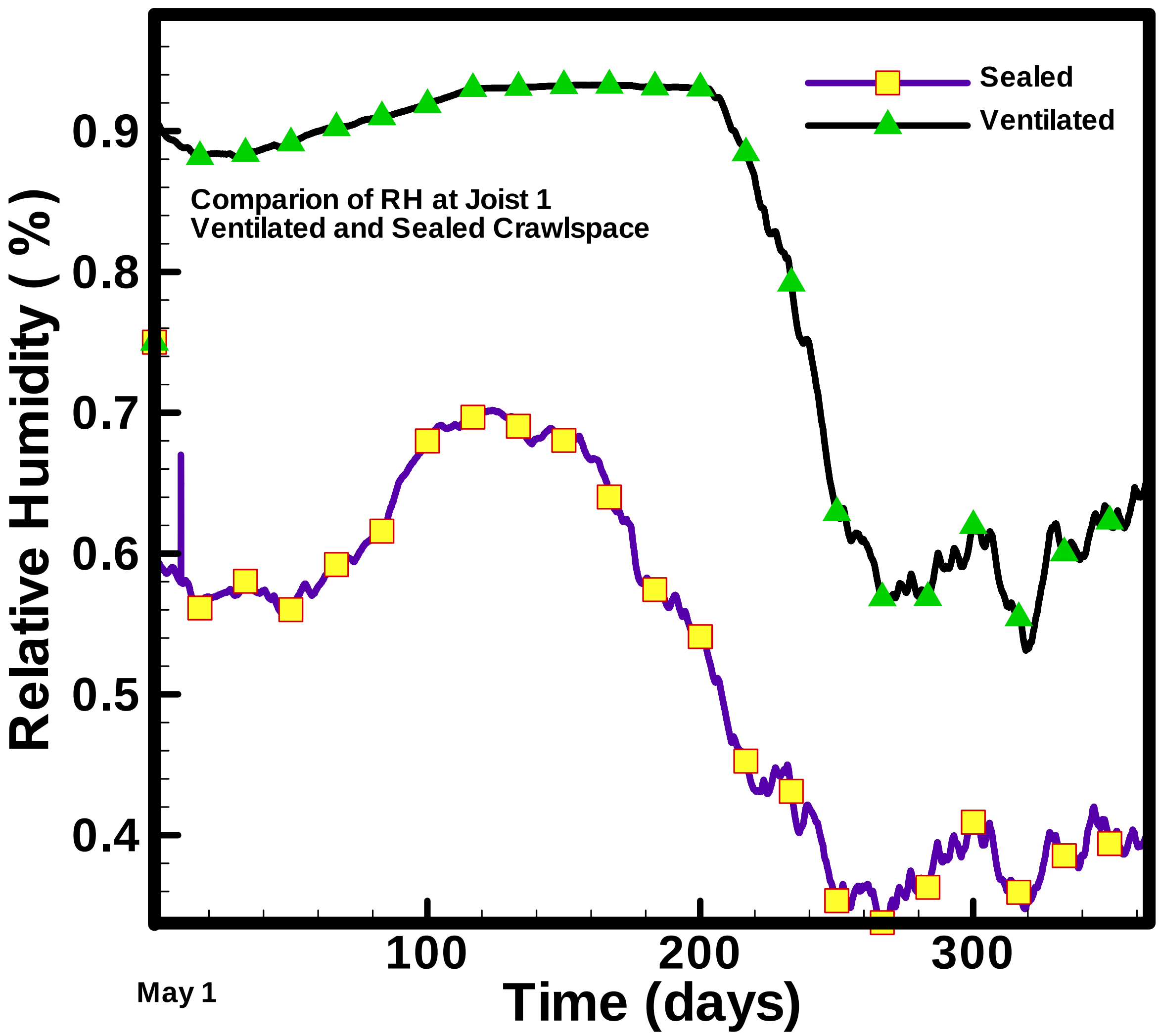


Figure 59: Comparison of RH at OSB (bottom surface) for Ventilated and Sealed

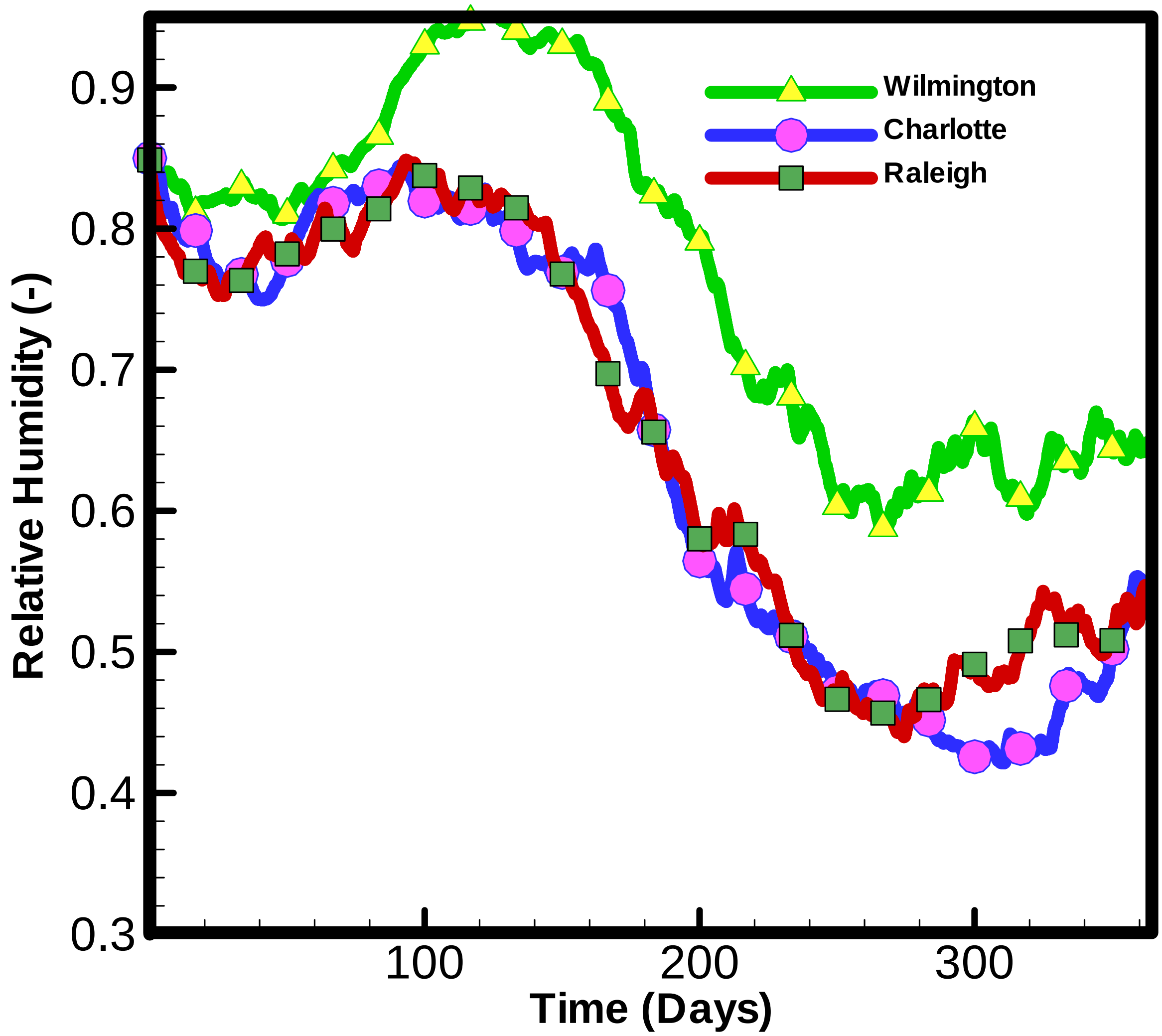


Figure 60: Comparison of RH at Joist 3 tip for Wilmington, Charlotte, Raleigh for Ventilated

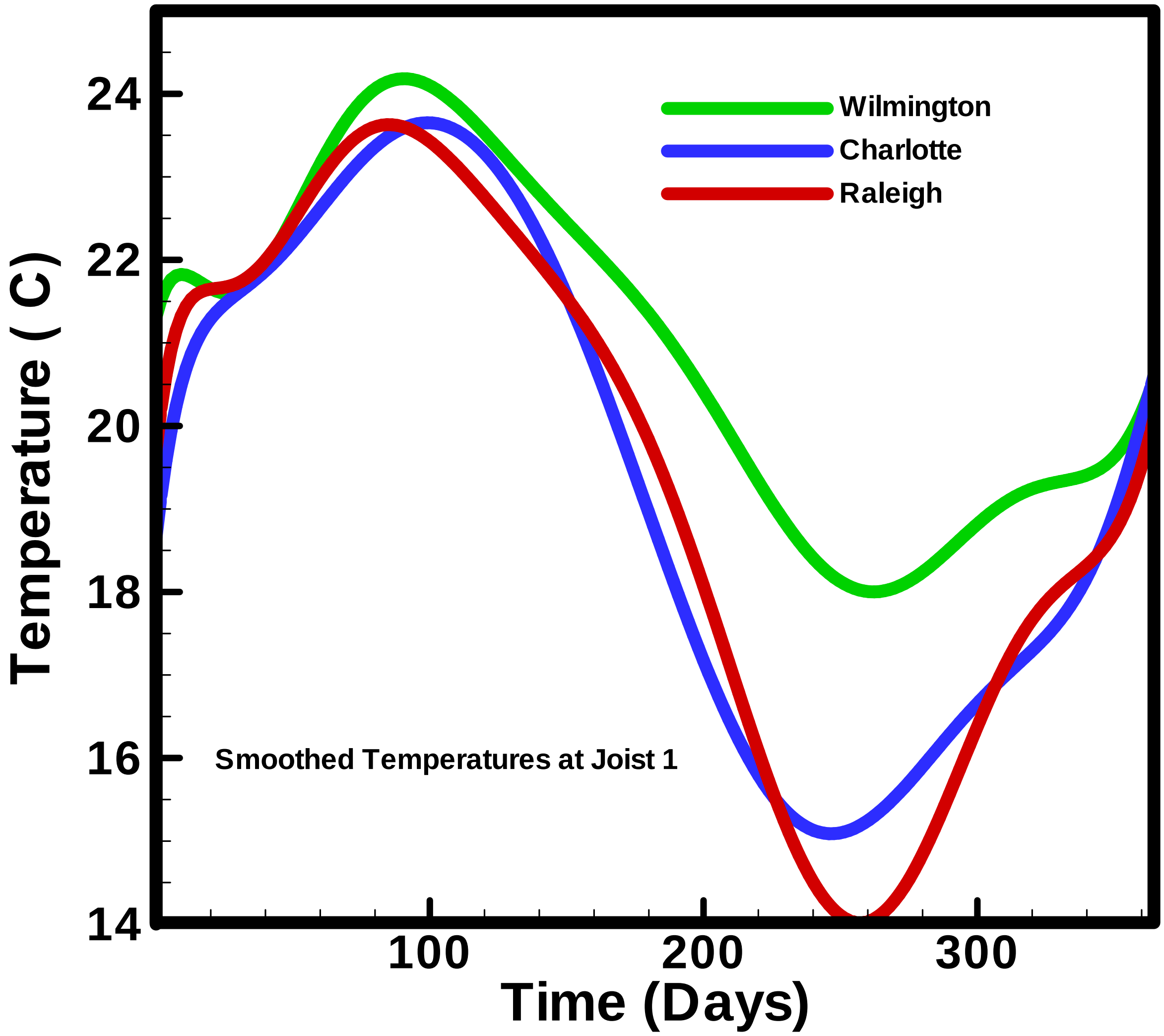


Figure 61: Comparison of Curve fitted Temperatures at Joist 3 tip for Wilmington,

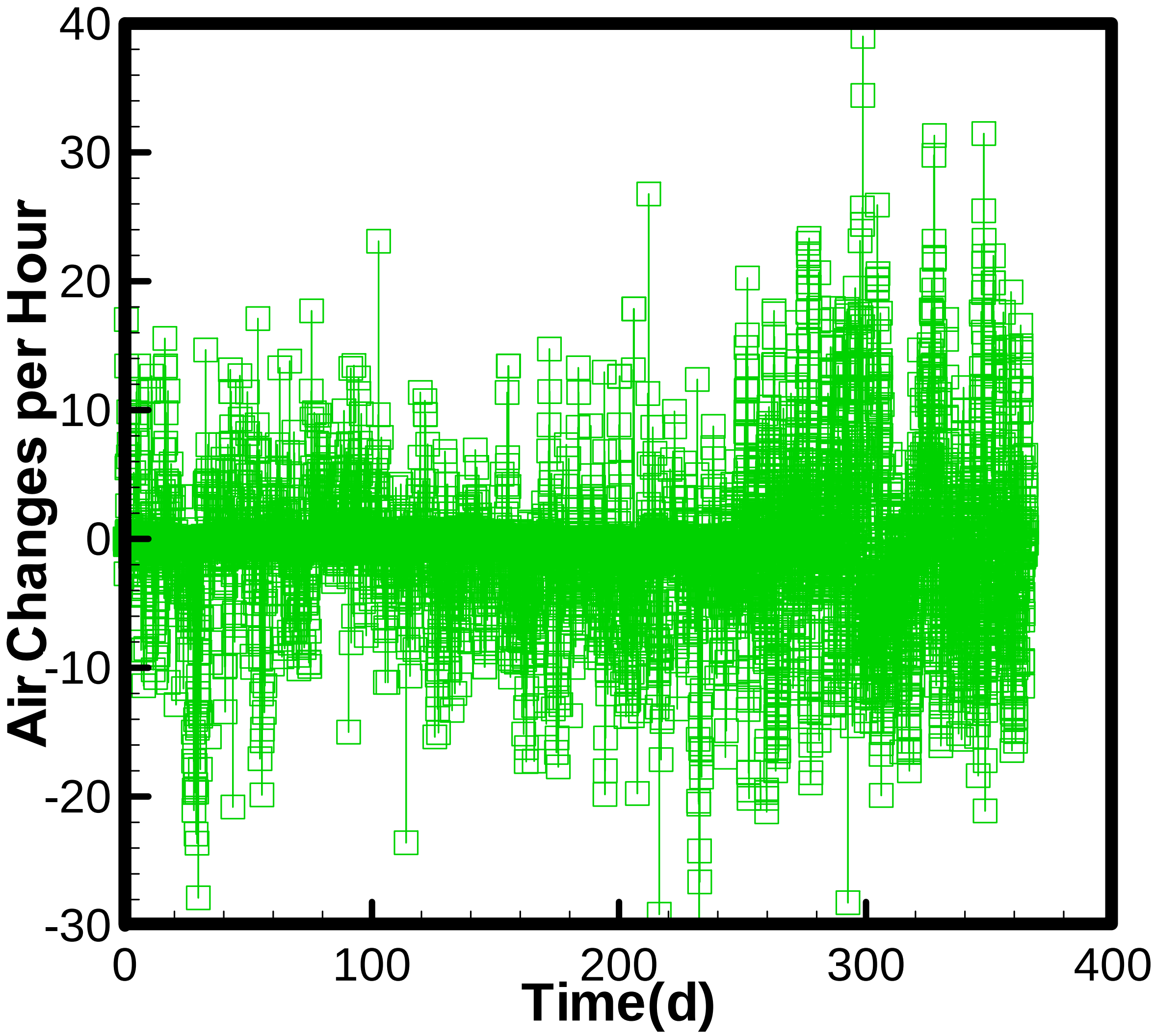


Figure 62: Air Changes Per Hour in Ventilated Cavity

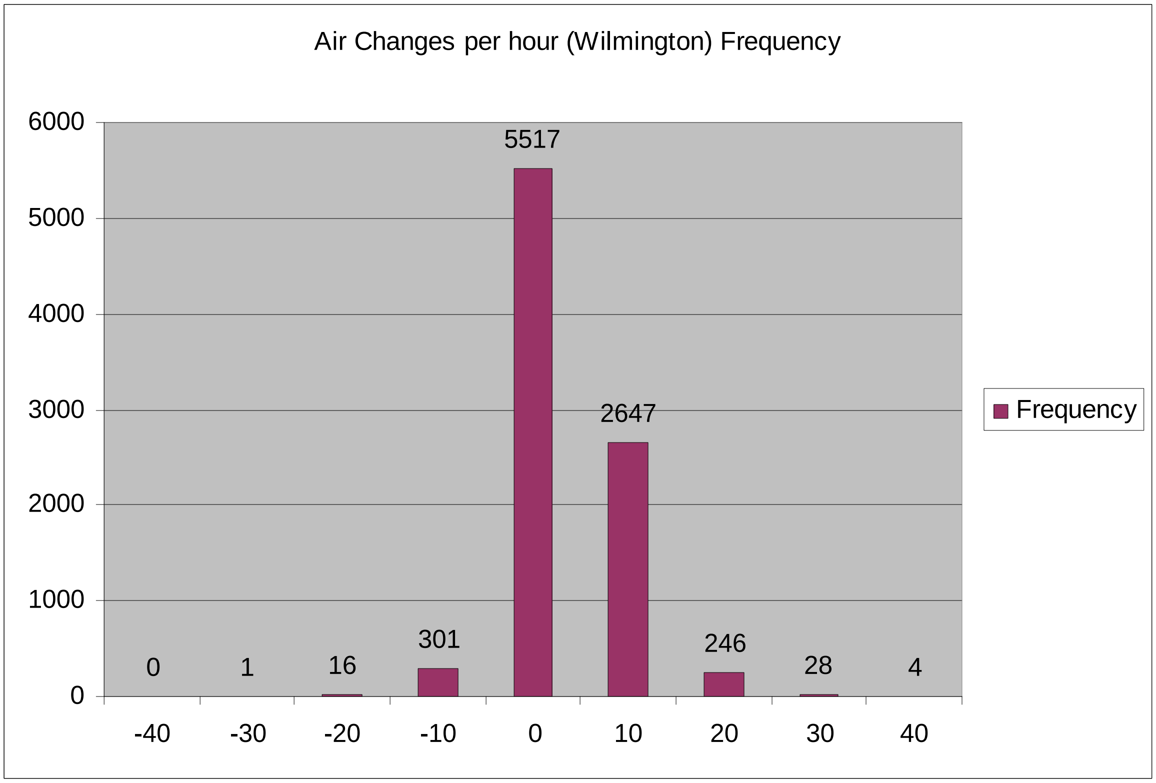


Figure 63: Simulated Yearly ACH Frequency (minus sign indicating direction)

In Figure 64 the relative energy impact is shown for a number of energy retrofits for ventilated and sealed crawlspaces. Heat loss through the floor is approximately 1/3 when the floor is insulated. In Figure 65 the effect of perimeter insulation on the crawlspace air temperature is shown. The results show the benefits of higher temperatures of about 2 C. The moisture content of the middle joist is depicted in Figure 66. Good agreement is shown between measured moisture contents and simulated results, at both locations in the crawlspace joists. The temperature in the crawlspace air is predicted in Figure 67. Here the temperature is lower in the simulated results because of the lower ambient temperatures employed in the weather files. Figure 68, clearly shows the good agreement in the relative humidity predictions and calculations using the hygrothermal model. The weather data comparison is shown in Figure 69. In Figure 70, the heat loss through the floor is reduced in the winter when insulation is added to the perimeter. In Figure 71 the transient hourly heat flows through the vertical insulated wall section as a function of time starting in October is shown. Insulation is shown to reduce the heat loss (negative heat loss) but it also reduces the heat gains to the crawlspace in the warmer months.

In Figure 72 shows the heat loss through the open uninsulated 8 in concrete block is less than 0.1 % of the heat loss through the floor surface. Figure 73 plots out the moisture content in the concrete block in the lower parts of the wall. In Figure 74, the temperature contour plot is shown for an insulated crawlspace edge near the vent. Figure 75 shows the contour plot of the previous crawlspace but showing a larger section. In Figures 77 and 78 the relative humidity distribution for insulated and uninsulated crawlspaces systems.

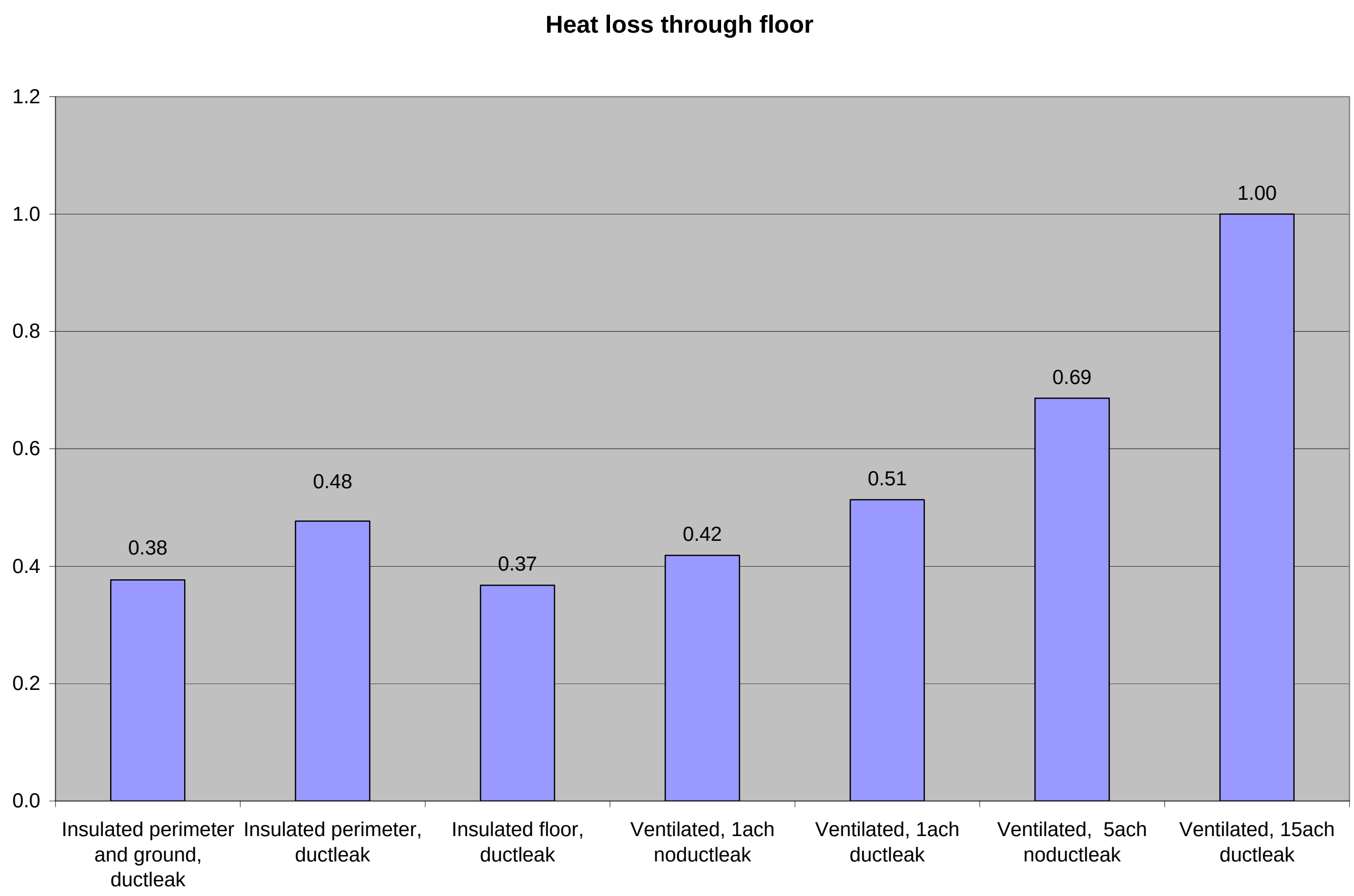


Figure 64: The base case for heat loss comparison is a situation where the crawlspace is ventilated, with and without floor or perimeter of the crawlspace insulation.

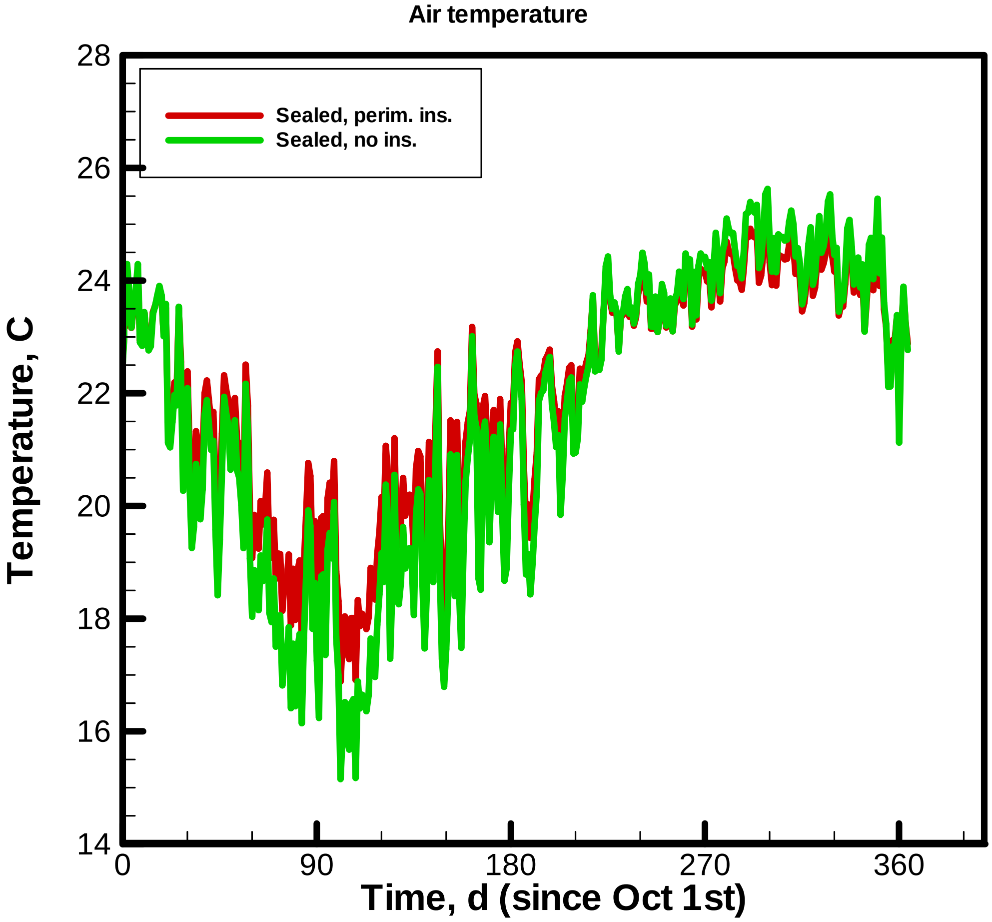
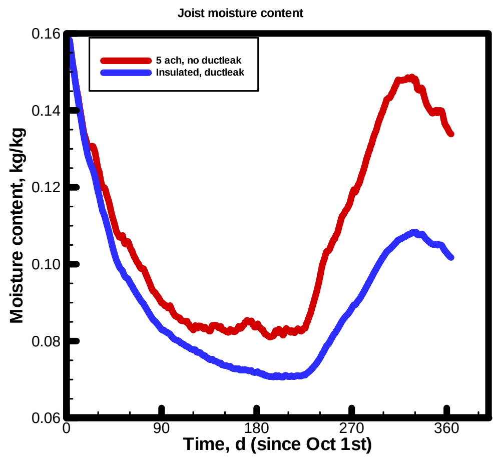
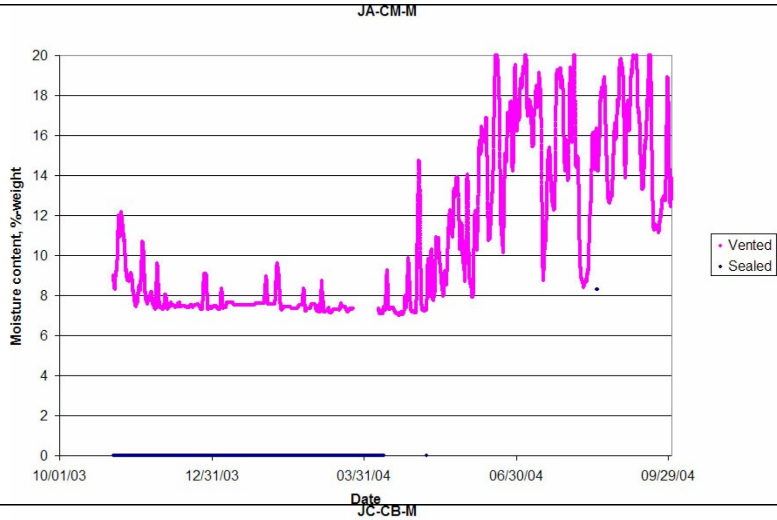


Figure 65: Crawlspace air temperature with and without perimeter insulation.

A



B



C

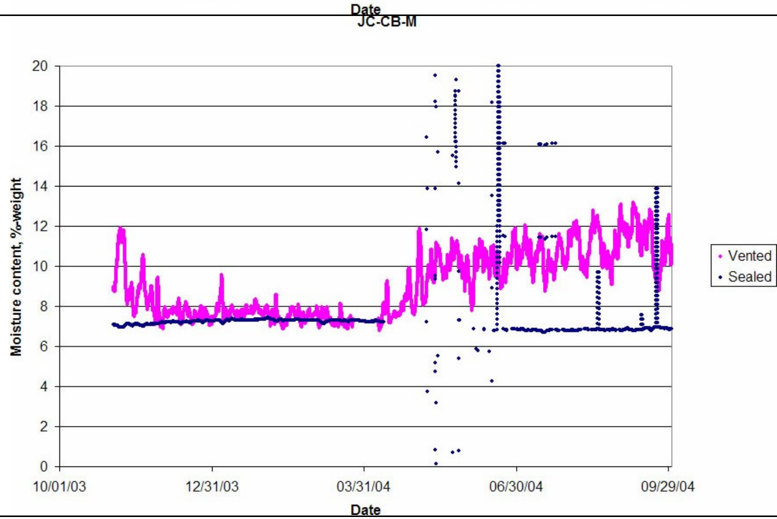


Figure 66: Moisture content of a joist in the middle of the crawlspace. Simulation results for the vented and the sealed crawlspace (A) and the measured results for the middle of a joist (B) and the bottom of a joist (C).

Validation of simulation model

Comparison of measured and simulated air temperatures

The weather data used in the simulations was a weather file created for Moisture Expert heat, air and moisture transport model from 30 years of simulation data representing cold and hot moisture reference years. This weather data set and the actual data measured at the location do not exactly match and therefore differences exist in the simulation and the measured results already based on different ambient boundary conditions.

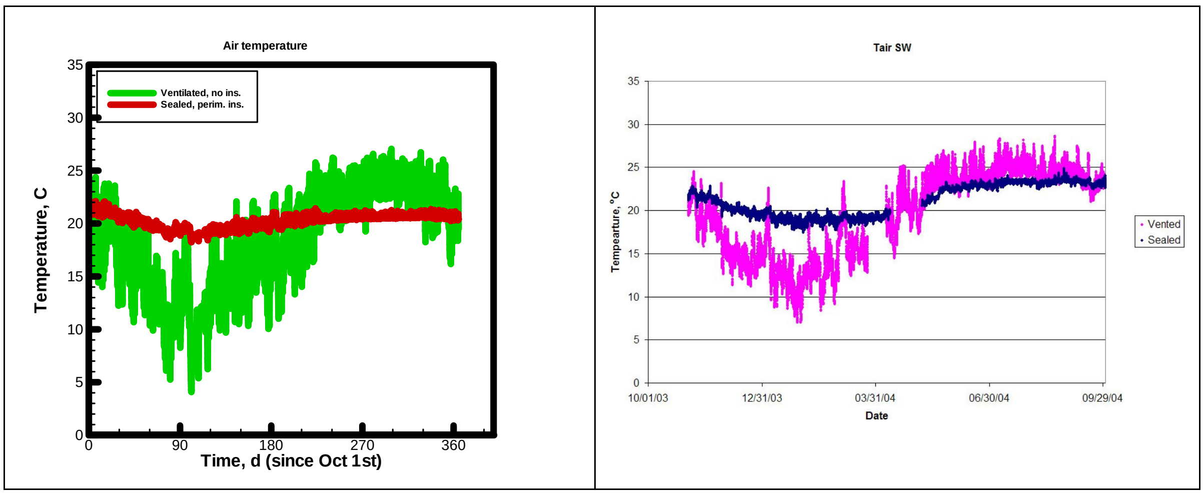


Figure 67: The temperature in the crawlspace air as predicted by the simulations (left) and as measured at the actual location.

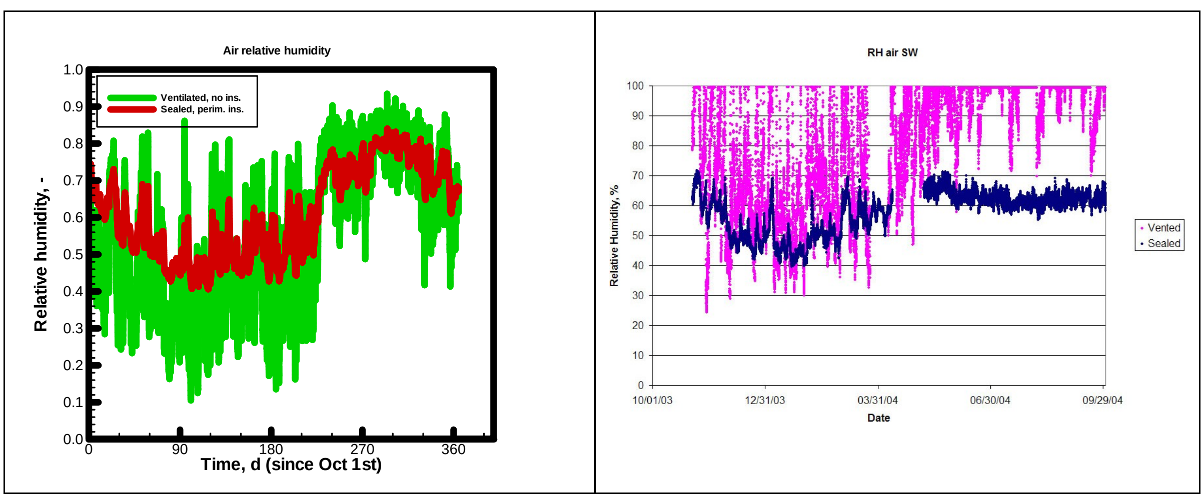


Figure 68: The relative humidity in the crawlspace air as predicted by the simulations (left) and as measured.

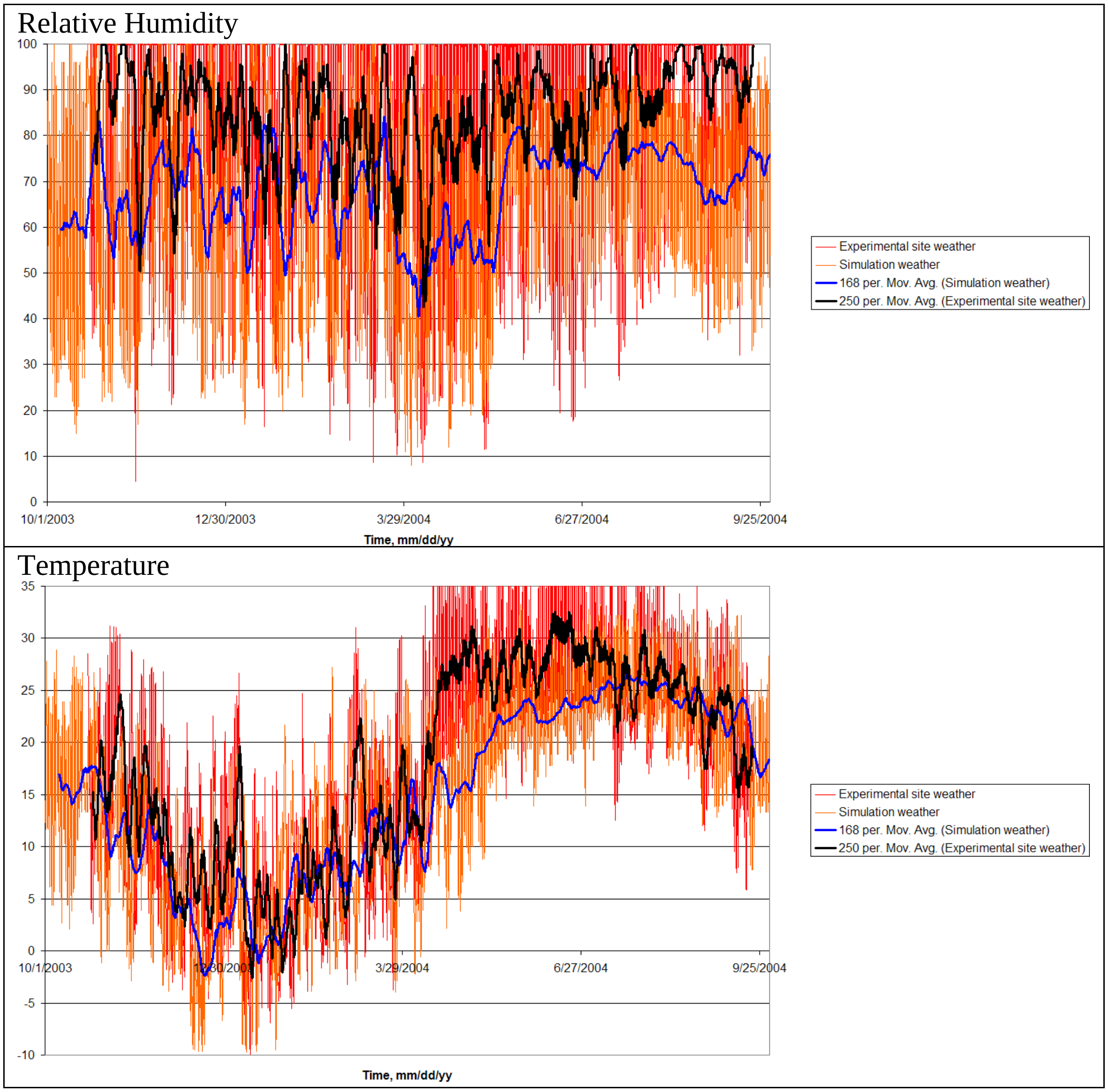


Figure 69: The comparison of the weather data measured at the site and the weather data used in simulations.

In Figure 69 the weather at the Princeville location is more humid and warmer (in the summer) than those in the NCDC weather data file used in the simulations. This is the prime reason why the humidity in the crawlspace is not as high as in the measurements during the summer months.

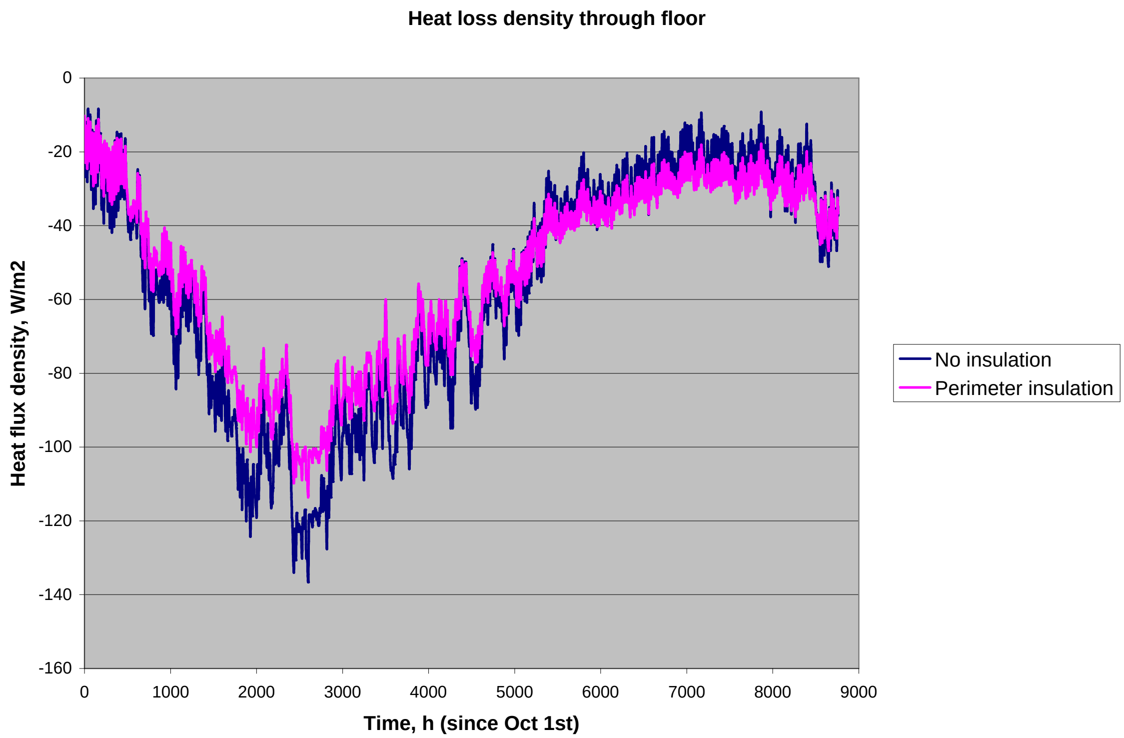


Figure 70: Heat loss through the floor is reduced in the winter when insulation is added to the perimeter walls.

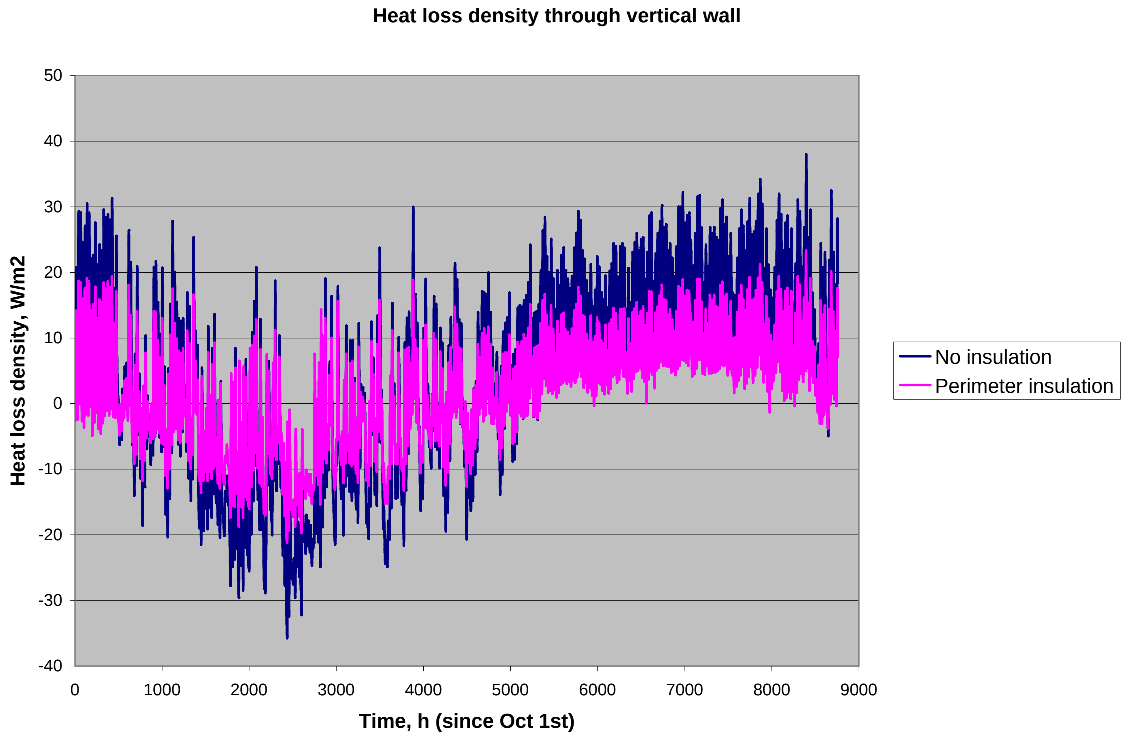


Figure 71: The hourly heat flow through the vertical insulated wall section as a function of time starting from October shows that while the insulation reduces the heat loss (negative flow) it also reduces the heat gain to the crawlspace in the warmer months.

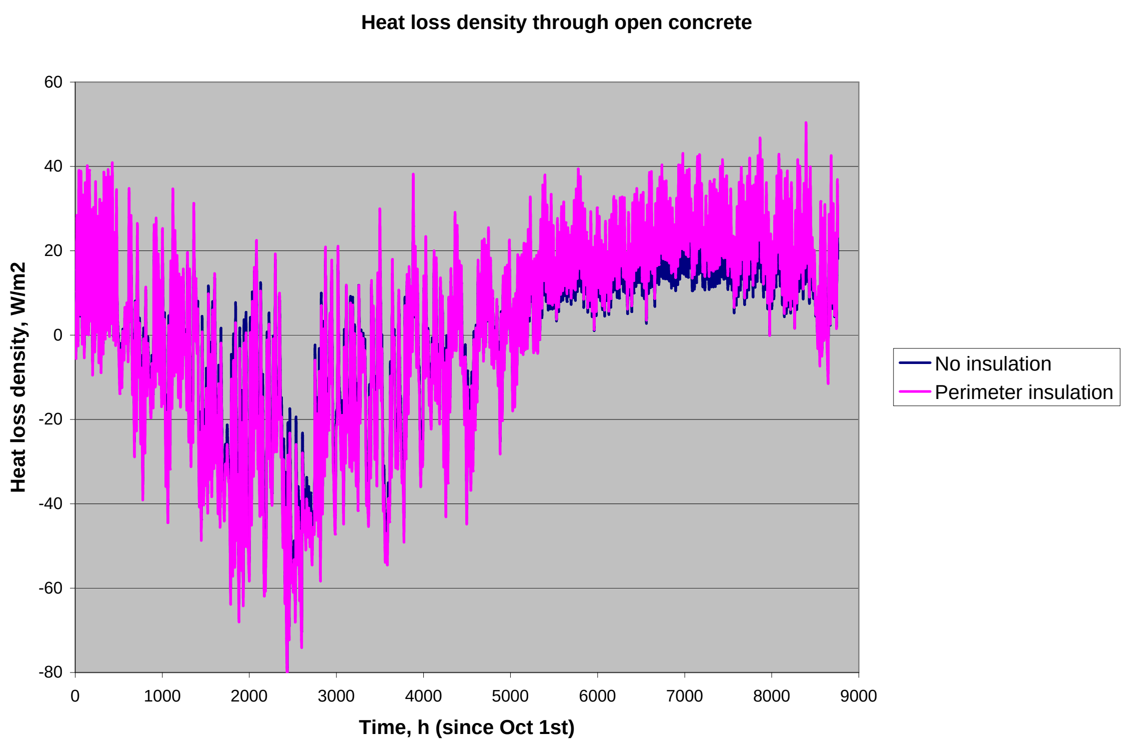


Figure 72: The heat loss through the open uninsulated 4" concrete block surface is less than 0.1% of the heat loss through the floor surface.

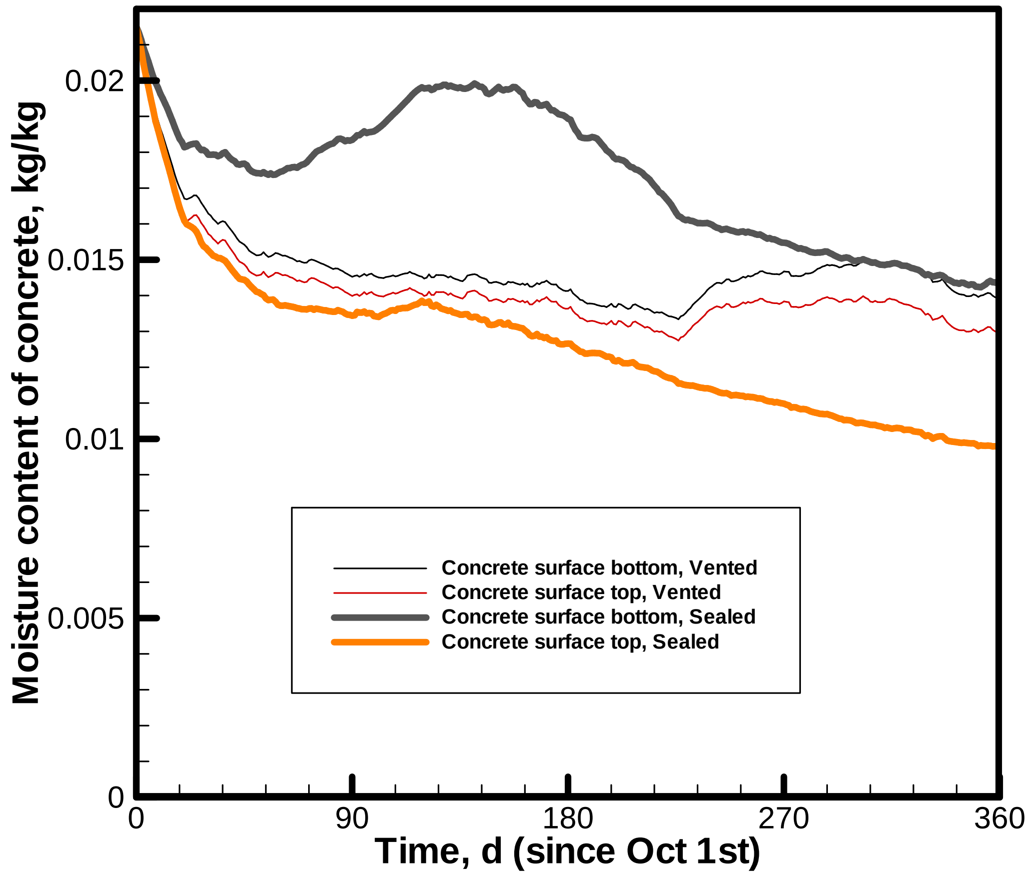


Figure 73: Moisture content of the concrete blocks in the lower part of the crawlspace wall and on top (uninsulated area in the sealed crawlspace).

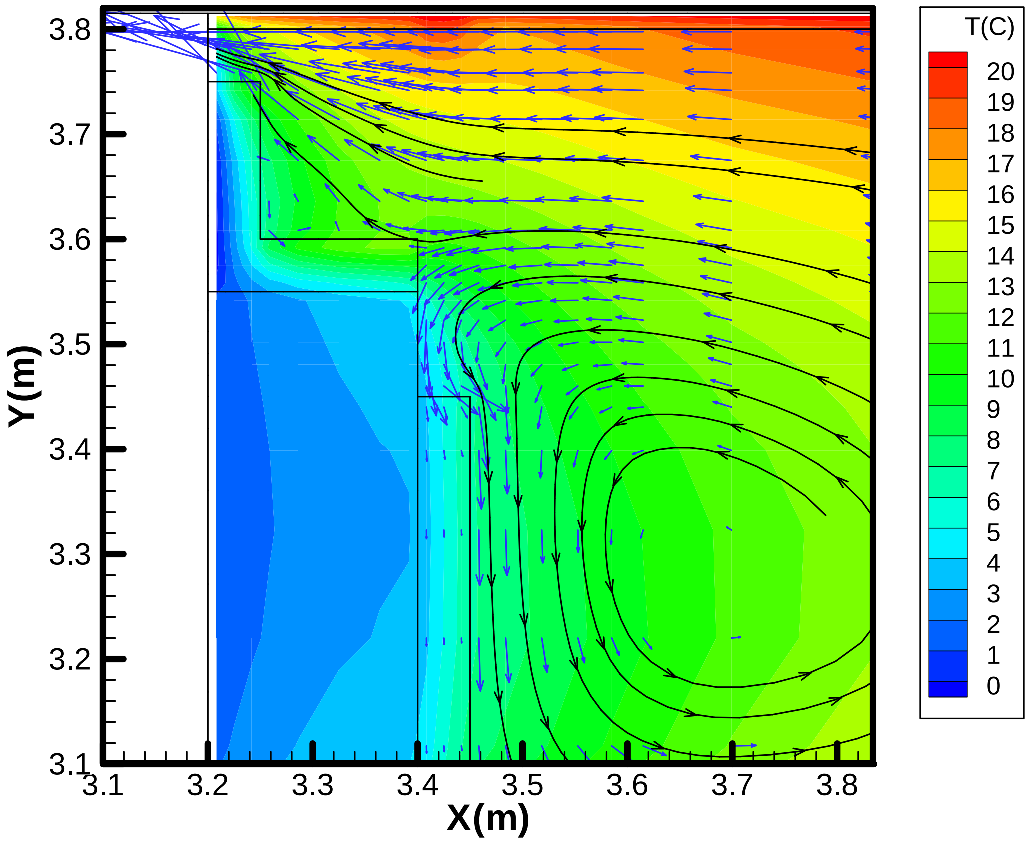


Figure 74: Contour T plot after 15 weeks from October 1st for the insulated crawlspace edge near the vent (Vent is provided to exhaust the air from duct leakage).

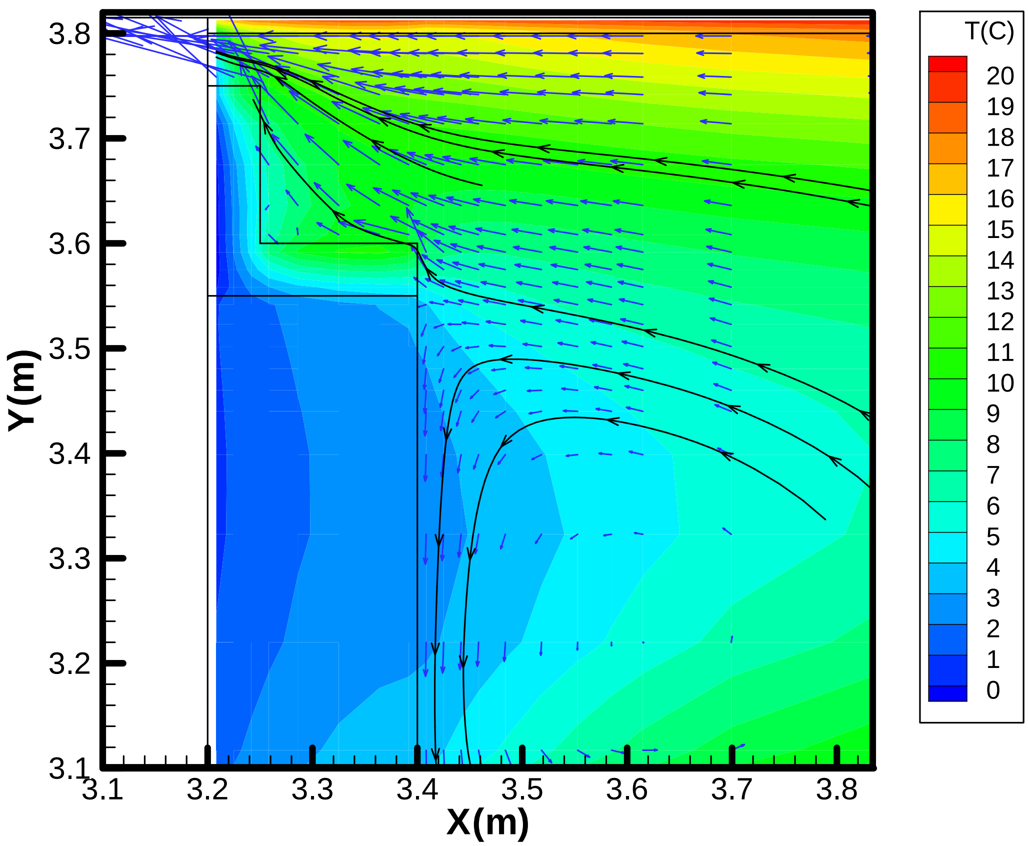


Figure 75: Contour plot after 15 weeks from October 1st for the insulated crawlspace edge near the vent.

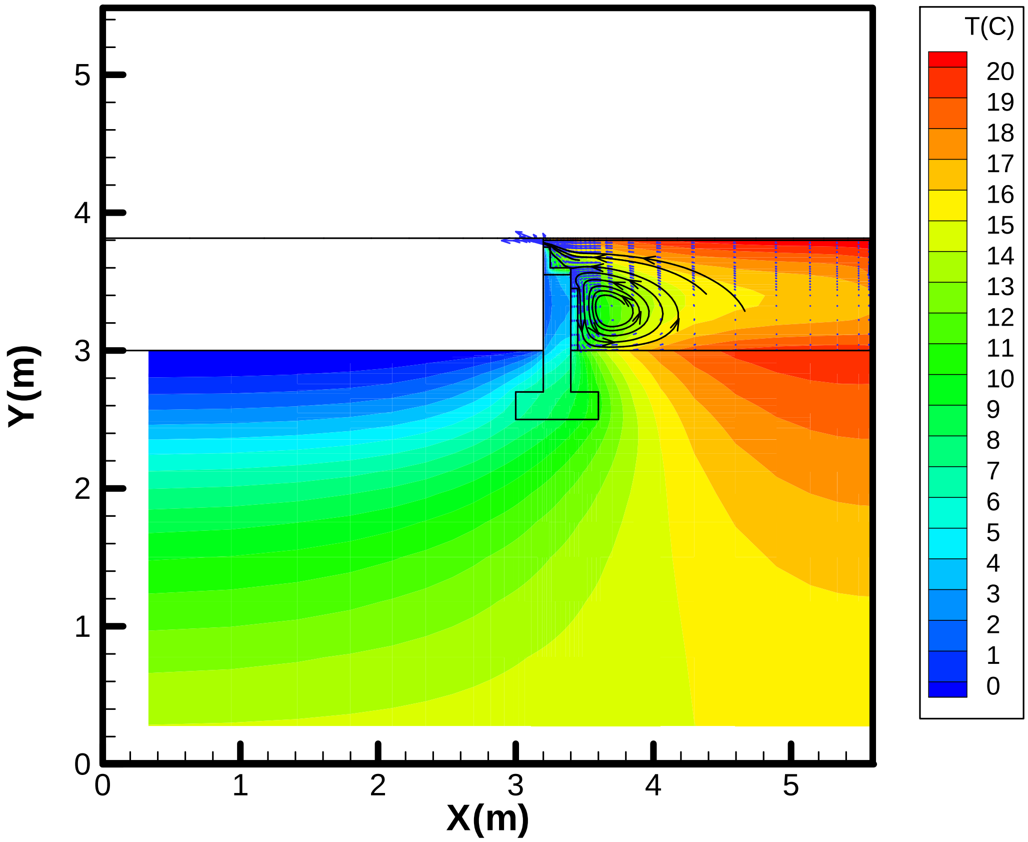


Figure 76: Contour plot of the temperature after 15 weeks from October 1st.

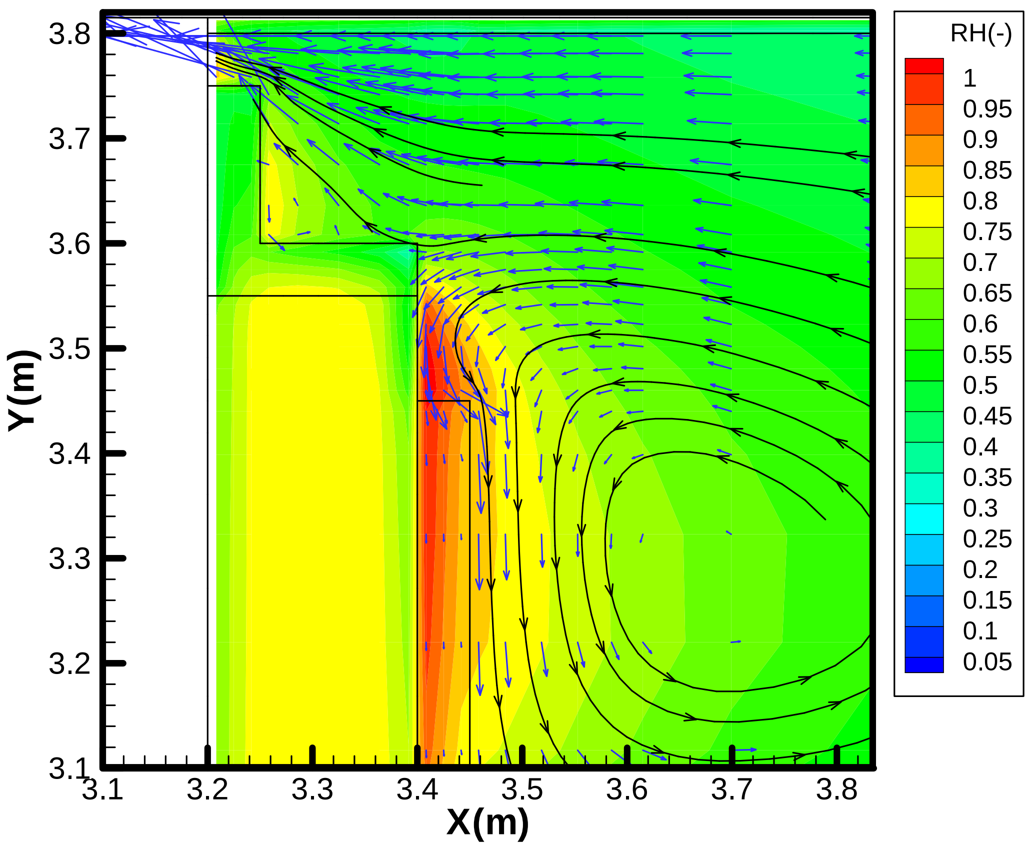


Figure 77: Contour plot of the relative humidity after 15 weeks from October 1st for the insulated crawlspace case.

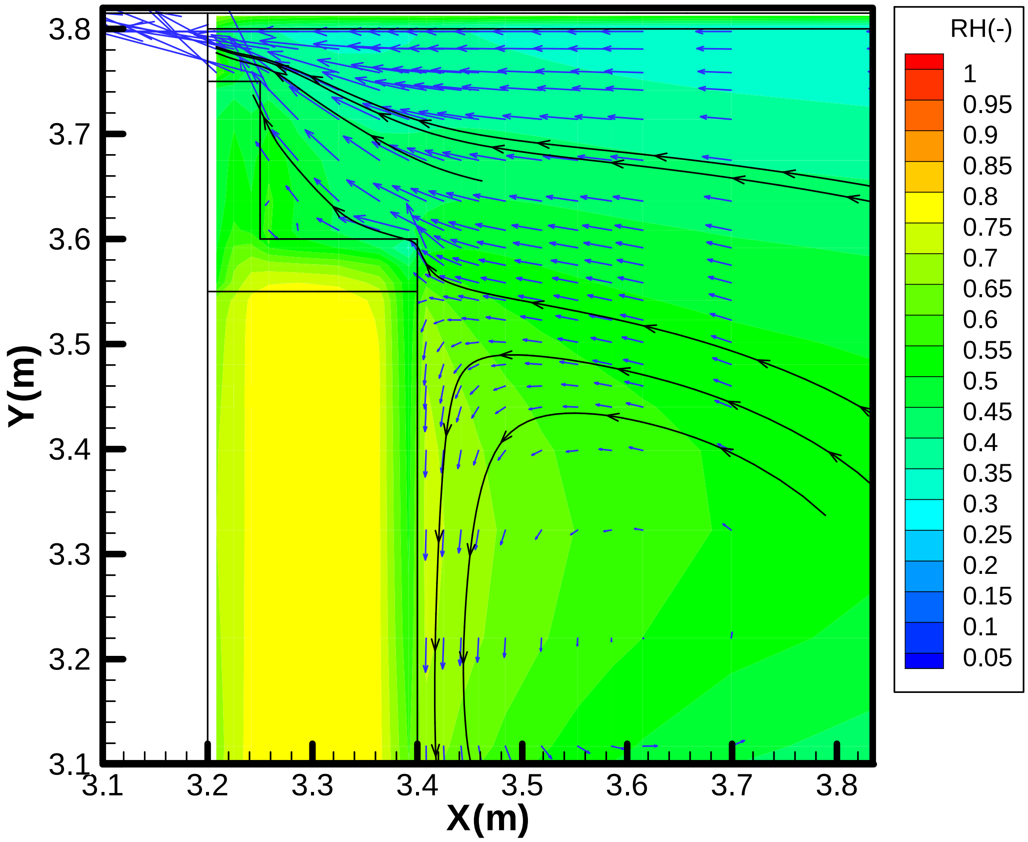


Figure 78: Contour plot of the relative humidity after 15 weeks from October 1st for the uninsulated crawlspace case.

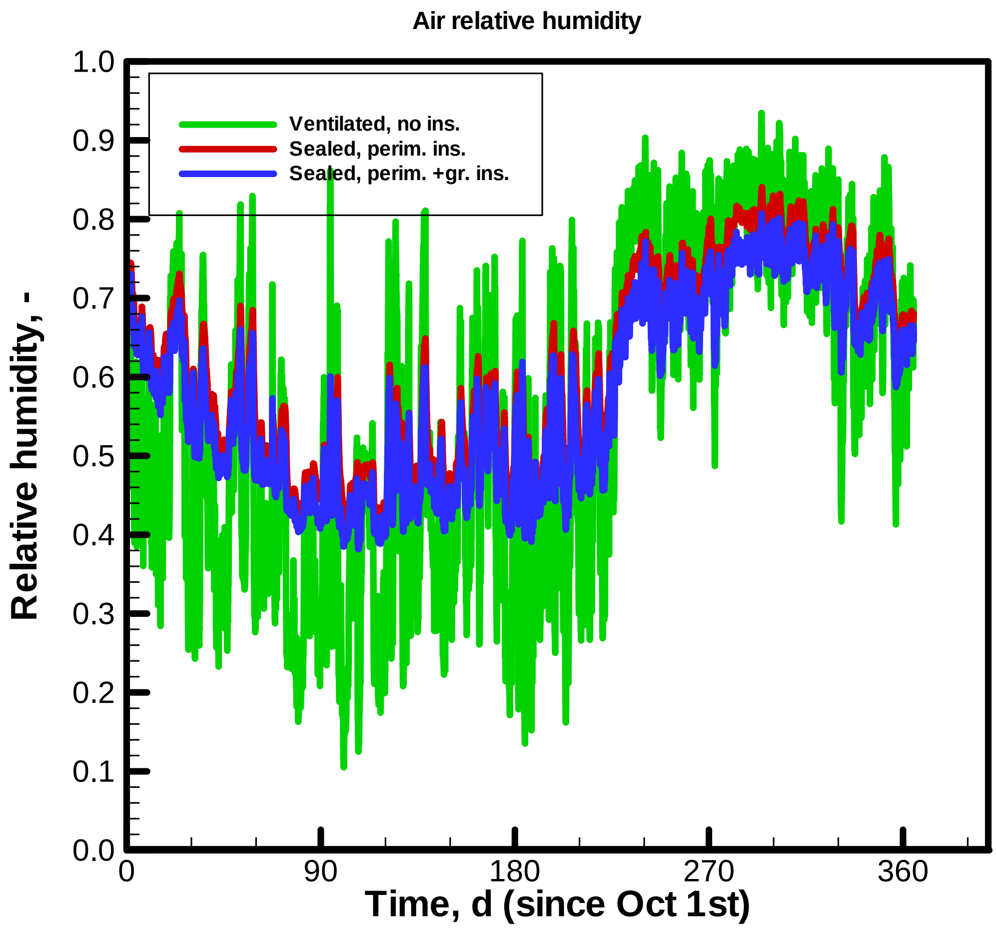


Figure 79: The air relative humidity in the crawlspace air in ventilated and non-insulated crawlspace versus the insulated sealed crawlspaces (perimeter insulations / perimeter insulation and ground insulation).

The ground has likely still had some effect on the heat loss during the first year. The ground near the perimeter has still some effect on the heat loss through the floor since the distance from the exterior environment (climate) to the crawlspace through the soil is not that large and heat can still be lost around the perimeter through the ground.

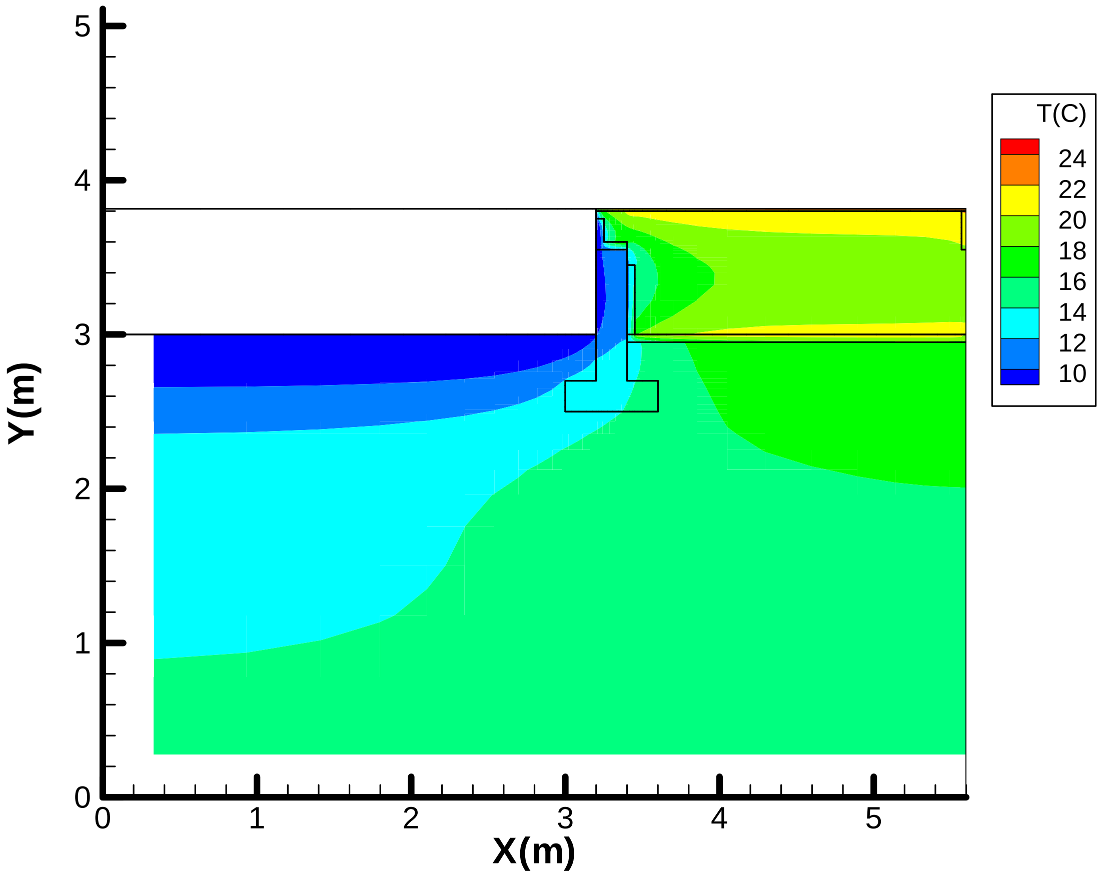


Figure 80: Temperature profile in the middle of the winter with ground insulation.

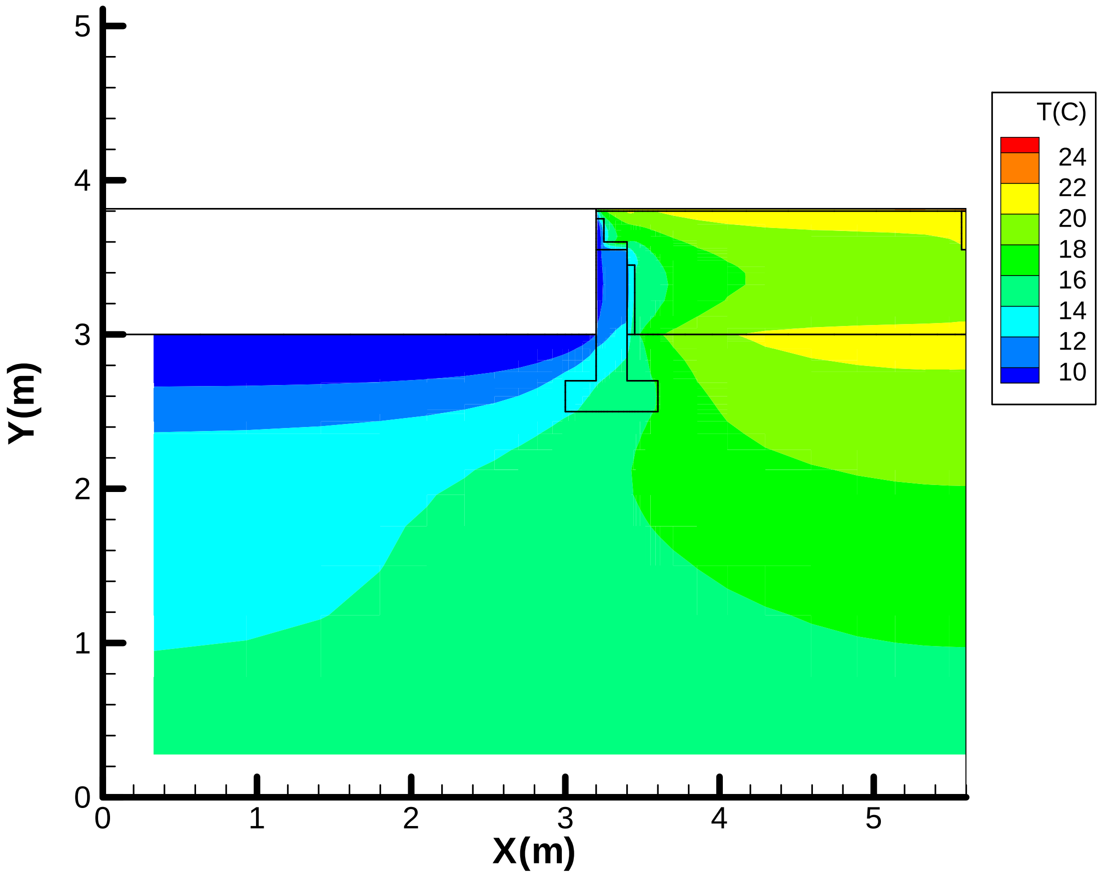


Figure 81: Temperature profile in the middle of the winter without ground insulation.

CONCLUSIONS

In this report submission, the Phase II of the AE/DOE Hygrothermal Pilot Study is presented. ORNL has fully satisfied the assigned responsibilities to monitor and analyze the two side by side crawlspaces houses, one vented and the other sealed, as specified in the Standard User Agreement between ORNL and AE. The goal was to develop an intermediate level of experimentation and monitor the hygrothermal performance of the sealed and ventilated crawlspaces, and provide better scientific understanding through the use of modeling. This goal has been achieved. The monitored data and the subsequent hygrothermal modeling have provided a definitive differentiation in performance of these two crawlspace systems for the mixed to hot and humid climates found in the south east climate zone.

The crawlspace modeling using the model developed by Dr. Karagiozis has demonstrated strategic importance in this project. This model was been validated on various aspects of the complex heat and moisture transport physics in both the sealed and ventilated crawlspace. The model was found in good agreement with the experimental monitored data for both the sealed and ventilated crawlspace. This is the first application of a hygrothermal model to simulate North American crawlspace performances.

Experimental results followed the trends and behavior found during the previous period from August, 2001 till December 2001. The sealed crawl space system was found to have lower hygrothermal loads than were found in the ventilated one. The sealed crawlspaces for the particular buildings investigated clearly showed superior performance in comparison to the ventilated crawlspace system for both hygric and thermal performance. The benefits of the sealed crawlspace applications in the South East with climatologically conditions were found in Charlotte, Wilmington and Raleigh. Conditions were found to be drier than the corresponding ventilated system.

However, with the conditions examined (especially modeling), with adequate drainage and low water table level, the ventilated crawlspace did not enter the catastrophic failure region. However, the surface moisture contents at certain locations in the crawlspace floor did exceed the values of 16 % for wood. The results observed in this climate should not be extrapolated for other climate zone unless additional experimental and modeling analysis is performed. In both the field set-up and modeling analysis no catastrophic performance analysis such as flooding or water pipe leakage was considered. All research performed employed representative conditions as found in other buildings construction in the area was used.

The experimental investigation has demonstrated the mold growth potential for the ventilated crawlspace, while none was observed for the sealed crawlspace configuration. One of the more successful applications of this advanced model has been it ability to predict the energy consumption of various ventilation and energy retrofit strategies. Indeed using the modeling analysis it was concluded that the crawlspace energy performance is benefited more when the joist floor is insulated rather than the perimeter wall for the sealed cases. Insulated perimeter though provides a slightly higher temperature and enhances the moisture performance.

From the analysis of the weather data using the SPC 160P methodology and the National Climatic Data Center weather data, showed that during the 2003-2005 years, the measured weather data were more humid by approximately 8 % .

The modeling results have shown the importance of the presence of an effective vapor retarder on all ground surfaces and wall surfaces. Up to 25 % of the moisture entering into the crawlspace may come through the walls. Without an effective vapor barrier, the sealed crawlspace may lead to moisture accumulation especially when the ground water table level is high.

In warm climates such as those simulated, during the summer months a net positive pressure exists in the crawlspace trying to exfiltrate air towards the exterior. In these circumstances special attention should be given to air seal the crawlspaces. In addition, attention should be given to the type of insulation used in the perimeter. During the winter periods a net outward vapor pressure is occurring and condensation may occur at the interface of the insulation and polyethylene vapor retarder.

As fibers, pollutants, radon gas, dust particles may accumulate with time in the crawlspace attention should be taken to have pressures in the crawlspace that should be lower than in those in the house. While this concern is a minor one, especially with our current construction practice (mold & high air leakage) this might be a concern to investigate further.

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