Characterization Study Final Report

A Field Study Comparison of the Energy and Moisture Performance Characteristics of Ventilated Versus Sealed Crawl Spaces in the South

Instrument # DE-FC26-00NT40995

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DISCLAIMER

ACKNOWLEDGEMENT STATEMENT

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Lead agency: **Advanced Energy**, a nonprofit organization whose primary mission is to create environmental and economic benefits through innovative approaches to energy use. Established in 1980 by the North Carolina Utilities Commission, the organization is funded by member energy utilities and fee for service contracts.

Project Director: **Bruce Davis**, Research Director at Advanced Energy, is a nationally recognized building science expert. His early research on the impacts of duct leakage and repair are recognized as milestones in applied building science. He is senior diagnostician for Advanced Energy's building diagnostic services. Specialty areas include combustion safety, residential ventilation systems, and moisture diagnostics.

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Duke University, Durham, NC, supervised and conducted indoor air quality protocols, as well as recruited homes for the Characterization Study. The key team member is **Wayne Thomann**, Dr. PH, Director, Occupational and Environmental Safety. Wayne is a microbiologist and a co-principal investigator of the *Mapping for Prevention: Developing GIS-Based Risk Models for Directing Children's Environmental Health Programs study.*

North Carolina Solar Center, Raleigh, NC, supervised field work for the Characterization, Field and Hygrothermal Studies through June 2003. The key team members were Shawn Fitzpatrick, M.S. M.Eng., and Christine (C.C.) Maurer. Rob Stevens, M.S. Mechanical Engineering, served as initial crawl space site supervisor.

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Heartfelt thanks and praise go to the advisory committee comprised of the sub-contractors and consultants. This committee met at the beginning of the project to establish the overall study design and objectives, and provided further guidance at critical decision points in the project. Some field study modifications (most notably those implemented in 2004) were reviewed by NETL but not by the advisory committee. Special appreciation goes to William Rose and Terry Brennan for their invaluable technical review and contributions to this report. The contributions to and technical reviews of the study by the members of the committee do not constitute or imply an endorsement of this report.

1. Executive Summary

For more than a century, home builders in North America have built crawl spaces with wall vents on the premise that these vents keep crawl spaces dry by dissipating excess moisture accumulation to the outside air. However, anecdotal information suggests that moisture problems are prevalent in wall vented crawl spaces, particularly in the humid climate of the Southeast.

While passive ventilation of crawl spaces through the use of wall vents may work in theory, researchers have noted that many wall vented crawl spaces have serious moisture problems. The 1994 ASHRAE Symposium (Recommended Practices for Moisture Control in Crawl Spaces) reported that wall ventilated crawl spaces in existing homes are often dangerously wet. Speakers at the symposium expressed a need to document and validate the poor performance factors that are reported in existing homes. This pilot study establishes a framework for providing such a validation.

Using a variety of instrumentation and first hand observation, this study characterizes wall ventilated crawl spaces with respect to moisture, thermal and indoor air quality performance factors in ten houses located in the central Piedmont region of North Carolina.

Findings revealed that all ten crawl spaces had multiple moisture problems, unexpectedly high levels of respirable, viable mold spores, and compromised thermal performance due to poor insulation performance and excessive shell and duct leakage. All ten buildings readily communicated air between the crawl space and the house. All ten homes had significant air leakage pathways measured across the floor system that separates the crawl space air from the house air. Further, in the nine crawl spaces that had duct systems in the crawl space, all had measurable duct leakage that mechanically mixes the crawl space air with the house air.

These preliminary findings presented in this report appear to confirm the supposition that wall vented crawl spaces as they are currently designed and built are not sufficient to remove moisture in many instances. Findings suggest the need to consider additional controls to prevent exposure and to reduce the source strength of crawl space molds. The strong moisture and mold findings support the adoption of dry crawl space construction techniques, most notably sealed crawl spaces. Any adoption of dry construction techniques necessitates that improvements be made to the thermal performance characteristics of crawl space systems.

2. Introduction

The purpose of this task, as was defined in the Statement of Project Objectives, is to conduct a study that will characterize, for the first time ever, the moisture, thermal and indoor air quality conditions found in typically constructed, wall vented crawl spaces.

The surveyed homes, which ranged in age from two to ten years, were located in the Chatham, Orange and Durham counties in North Carolina.

The authors hope these findings will prompt the home construction industry to increasingly employ dry construction techniques as a means of improving the performance of crawl space systems.

This study is being conducted as a part of a larger project funded by the U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL), and co-funded and managed by Advanced Energy Corporation. Two concurrent project studies, a field study and a hygrothermal study, along with a technology assessment, will help complete the picture on crawl space performance. The field study is testing the moisture, thermal and indoor air quality performance characteristics of dry crawl space technology versus traditional wall vented crawl spaces in as-built homes. The hygrothermal performance study, conducted with Oak Ridge National Laboratory (ORNL), involves the development of a computer program to analyze crawl space designs with respect to moisture and thermal performance. Application of this model should lead to the development of design guidelines and the formulation of performance-based, building code provisions that will minimize moisture and indoor air quality problems, and, at the same time, improve the thermal performance for crawl space systems. The objective of the technology assessment is to assess the performance of residential crawl space construction in the United States with respect to moisture control, thermal integrity, and indoor air quality.

Reports on the pilot phases of all three studies and the technology assessment were submitted to DOE/NETL in December 2001. This project will utilize the study findings and technical assessment to commercialize improved guidelines and building code provisions for wall vented and dry technology crawl spaces. This final task will involve disseminating the developed information, guidelines, code inquiries, etc. to targeted audiences utilizing a variety of technology transfer instruments.

2.1 Objectives

The principal objective of this study was to collect thermal, moisture, and indoor air quality performance data on wall ventilated crawl spaces as they are currently being built by the residential construction industry. The data will be used to quantify typical problem areas in this type of construction.

As much detailed information as possible was to be collected on each house in a half-day protocol. The study is intended to develop and evaluate field characterization protocols.

2.2 Background

For more than a century, home builders in North America have built crawl spaces with wall ventilation on the premise that these vents allow moisture rising from the crawl space ground to dissipate to the outside air. Builders have avoided building crawl spaces without these vents for fear of causing moisture problems.

Builders rely almost exclusively on wall vents, and to lesser extent ground moisture barriers, for crawl space moisture control. On the assumption that these measures are sufficient, builders tend to pay less attention to such measures as waterproofing below grade than they do when constructing basements and slabs.

While ventilation of crawl spaces may work in theory, researchers have noted that many wall vented crawl spaces have serious moisture problems. The 1994 ASHRAE Symposium (Recommended Practices for Moisture Control in Crawl Spaces) reported that wall ventilated crawl spaces in existing homes are often dangerously wet. Speakers at the symposium expressed a need to document and validate the poor performance factors that are reported in existing homes.

Since 1994, researchers studying indoor air quality have increasingly focused on mold as a household pollutant. Because of their high levels of moisture, crawl spaces are the mostly likely building area in which to find visible molds and mold odors. However, it is unclear how much of a problem crawl space mold presents to occupants of these homes.

2.3 House selection criteria

Ten homes with wall ventilated crawl spaces and without any basements or slab areas were selected for this study. The participant homes were recruited from a group of word-of-mouth referrals and from homes that participated in a Duke University study entitled "Mapping for Prevention: Developing GIS-Based Risk Models for Directing Children's Environmental Health Programs." The latter is a large, ongoing study characterizing environmental risk factors in North Carolina housing.

The selection criteria called for houses to be two-to-ten years old. Two years was selected as the minimum age to ensure that a history of moisture problems, should any be present, would be established. Newer homes were not chosen on the thought that moisture problems commonly evident over time might not yet have appeared. A ten year limit was established to exclude homes built under outdated building codes.

A variety of homes, ranging from small "starter" homes to larger-sized homes, were chosen for this project. The actual size range was 1,300 to 3,200 square feet. The homes were all located in the Research Triangle area of North Carolina (specifically Chatham, Durham and Orange counties) and typical of current home construction practices in this Southeastern climate.

The willingness of the homeowners to participate in the study was a key factor in the selection process, as the fieldwork was intrusive and time consuming. Homeowners that participated received a detailed report that summarized the characterization data. Copies of these reports are included in an appendix at the end of this report.

3. Procedures and Methods

3.1 General

A protocol was developed to allow all of the homes in this study to be similarly characterized. The initial protocol was pared down and refined during characterization of twelve homes in the companion Field Study and prior to being used to characterize the ten homes in this study. The intent of the protocol was to allow a two-person team to characterize two homes per field day.

Initial home survey visits were made from June to September 2001, during the humid summer season in the Southeast. Researchers wanted to observe homes during that time of year when problems related to moist outdoor air – condensation on ducts and pipes, floor puddles on ground moisture barrier, and elevated wood moisture content – would likely be most visible. Follow-up home visits were made to a subset of six homes to attempt a second round of bioaerosol testing, which focused on the air distribution system.

The protocol was split into several sections: homeowner interview, exterior building and lot dimensions and characteristics, crawl space characterization, and building pressure diagnostics.

The homeowner interview provided information about the history of the home and its operation, and any health issues of the occupants. The homeowner provided the date the house was first occupied and when the current occupants moved in. Crawl space use, frequency of use, service or repair in the crawl space, and operation of crawl space vents were determined. Homeowners were asked how they operate their thermostat, what temperature it was set at during the night and during the day, and whether the fan was set to “on” or “auto.” The homeowner gave a description of any respiratory problems in the family, such as asthma or allergies, and a relative statement about whether these problems were better, worse, or the same after moving into this home.

Researchers then characterized the house exterior and lot. They executed a scale drawing of the footprint of the house. All impervious surfaces within 50 feet of the house were noted and drawn. Also included on this drawing were details about the orientation of the house, crawl space construction, vent location and height, and direction of drainage or slope around the house. Using a level, grades were measured within four feet of the house at the corners in both directions perpendicular to house. Significant slopes, interesting grading, or any problems were noted or photographed as necessary. All measurements were made using feet and inches, except grade, which was measured in degrees.

The position of the lot relative to the surrounding neighborhood was examined and the house was noted as either low, medium, or high in the local watershed. Any unusual problems such as standing water, erosion, or drainage issues were noted. Researchers noted whether the house had gutters and downspouts that drain away from the crawl space. The roof overhangs were estimated.

Pictures were taken of the four main sides of the house and more, if necessary. The type of house was noted. Based on inside measurements, researchers calculated the square footage of the conditioned space, unconditioned space, and conditioned space surface area, as well as cubic feet of conditioned space.

A base floor plan of all crawl space walls was drawn, noting the location of the joist beam pier.

The primary crawl space dimensions were recorded. Starting immediately to the right of the crawl space access looking from the outside, elevation changes were recorded inside. These changes were based on the measured height to the bottom of the joist, which was noted at each corner. This process was continued until measurements were made around the entire perimeter of the house. The average height and volume of the crawl space were determined from these measurements.

3.2 Energy

The protocol was designed to collect a wide range of energy performance data. The key measured data utilized pressure testing to quantify air leakage characteristics.

The Researchers noted the HVAC equipment type, location, and size. The purpose of acquiring this data was to indicate the potential for cabinet air leakage and condensing surfaces associated with the equipment. If available, make and model was noted and also whether it was a gas pack, heat pump, furnace and air conditioning (A/C) unit, or other type.

Information about the first floor duct distribution system was noted, including duct type and insulation levels. If more than 20% of the supply and/or return duct system for the first floor zone was located in the crawl space, it was concluded that the supply and/or return duct system was in the crawl space.

Other types of equipment found in the crawl space were noted. Water heaters were characterized as electric, gas with power vent, or gas with atmospheric vent. It was noted if the water tank pressure relief valve drained to the outside, and if the dryer hose vented to the outside or to the crawl space.

General information about the insulation and quality of installation was documented, including insulation type, presence and direction of faced batts, R-value, and mounting technique. If insulation wires were used to mount the batts, the average wire spacing was estimated. Particular attention was paid to documenting insulation problems, such as fallen or poor fitting batts, insulation compression, gaps, voids and bypasses.

The goal of the following pressure testing procedure was to quantify the “holes” between the crawl space and the house, house and outside, and duct to crawl space that might lead to moisture transport and to measure the driving forces (pressures) that are created by the

HVAC equipment. To obtain these air leakage flows with the most precision, the setup included the Automated Performance Testing (APT) System with one Minneapolis Blower Door™ System for the house and another for the crawl space, and the Minneapolis Duct Blaster™ System to test crawl space ducts.

Pressure Tap #	Input Tap Location	Input Tap Hose Color	Refer. Hose Color
1	House		Green (Outside)
2	House Blower Door	Red (Fan Pressure)	
3	Crawl Space	Purple	
4	Crawl Blower Door	Orange (Fan Pressure)	Purple
5	Closest Supply Duct to Air Handler (#1)	Blue	
6	Duct Blaster	Red2 (Fan Pressure)	Clear (Fan Reference)
7	Return Duct	Yellow	
8	Furthest Supply Duct from Air Handler (#2)	Green	

Table 1: Hose configuration for the APT System

Indoor and outdoor temperatures were recorded to correct for the difference in air density due to temperature. First, the standard House CFM50 test was run using TECTITE Ver. 2 (Win 95/98) Airtightness Testing Software. This test is conducted with the air handler off, all windows closed, and the crawl space access closed. TECTITE measures building leakage by taking 100 data points at 50Pa, 45Pa, 40Pa, 35Pa, 30Pa, 25Pa, 20Pa, and 15Pa. The purpose of taking the measurements at several pressures is to allow a flow equation exponent to be determined. TECTITE uses this test data to determine the CFM50 leakage. In addition, the hoses were setup as shown in Table 1 to obtain zone pressures for the crawl space, the supply and the return during the House CFM50 test.

All of the other tests were conducted using TECLOG Ver 1.04 from the Energy Conservatory with the hose configuration shown in Table 1. First, all pressures were logged for one minute with the exterior windows and doors closed and without the HVAC system running. The logged pressures are the baseline pressures. Then, the air handler fan was turned on and pressures were logged for at least one minute. During this time, each zone was again monitored for reaction to the operation of the HVAC system. During windy or inclement weather, each test period was increased to two or three minutes.

As the duct blaster and the second blower for the crawl space were setup, the floor registers were sealed before conducting test 1. Foundation vents may or may not be completely sealed during testing, depending upon whether 50Pa can be reached without sealing the crawl space. To run through the tests as described below, start time and ring configuration for both blower doors and the duct blaster of each test was recorded. An Excel spreadsheet was created to automatically convert binary TECLOG data to text and calculate flows based upon fan pressure. The manual for the APT system was consulted in the design and creation of this spreadsheet (EC 1998). The spreadsheet converts pressure measurements across either the blower door fan or duct blaster fan into flow using the calibration formulas provided in the operation manual by the Energy Conservatory as shown in Table 2.

Fan Type	Fan Configuration	Calibration Formulas for Flow (CFM)
Blower Door	Open	Flow = 490*(Fan Pressure)$^{.4945}$
	Ring 1	Flow = 180.7*(Fan Pressure)$^{.4948}$
	Ring 2	Flow = 57.2*(Fan Pressure)$^{.5065}$
Duct Blaster	Open	Flow = 104.38*(Fan Pressure)$^{.5000}$
	Ring 1	Flow = 39.25*(Fan Pressure)$^{.5000}$
	Ring 2	Flow = 15.31*(Fan Pressure)$^{.5000}$
	Ring 3	Flow = 6.26*(Fan Pressure)$^{.5000}$

Table 2: Calibration formulas for flow across the Blower Door and Duct Blaster.

The following figures go through the testing procedure and the theory of how each flow was calculated. Leakage paths between the house, outside, ducts, and crawl space are illustrated in Figure 1. These leakage paths are based upon relations between flow measurements that are defined in Figures 2 and 3.

The hole sizes can be quantified as follows:

Outside to Crawl space = **B**

Outside to House = **A**

Crawl space to House = **E**

Crawl space to Ducts = **C** + **D**

Outside to Ducts = **G** + **F**

Crawl space to Return Ducts = **C**

Crawl space to Supply Ducts = **D**

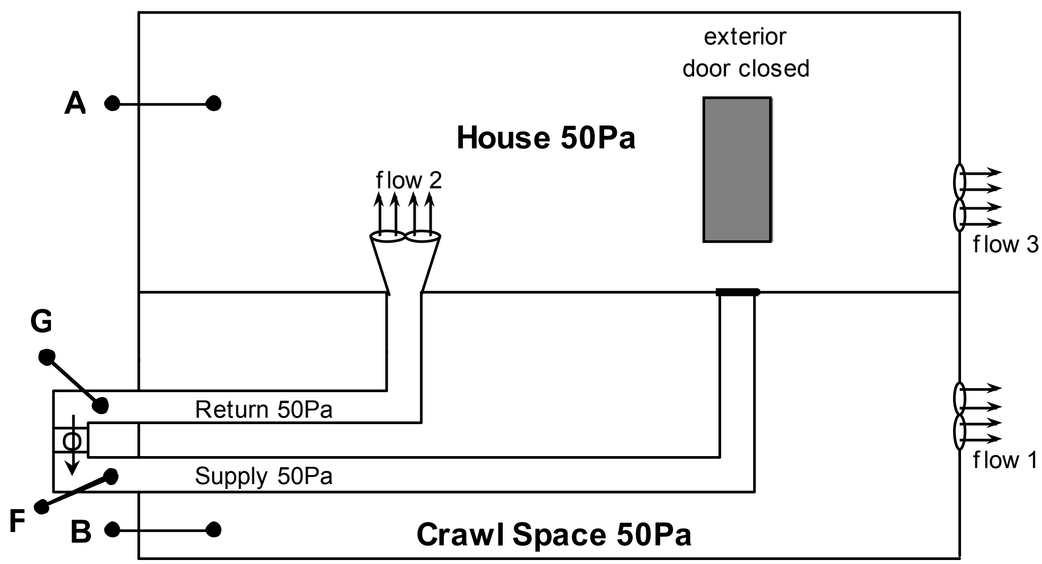

Figure 1: Leakage paths determined from series of pressure tests conducted on homes

Test #1 was conducted with registers sealed and the house door closed. The house, crawl space and ducts were depressurized to -50 Pa with respect to outside. Because the house, ducts and crawl space are at essentially the same pressure in this test, the outside to duct flow (G+F), outside to crawl flow (B), and outside to house flow (A) could be calculated from this configuration.

Flow 1 = **B**

Flow 2 = **G** + **F**

Flow 3 = **A** + Flow 2 = **A** + **G** + **F**

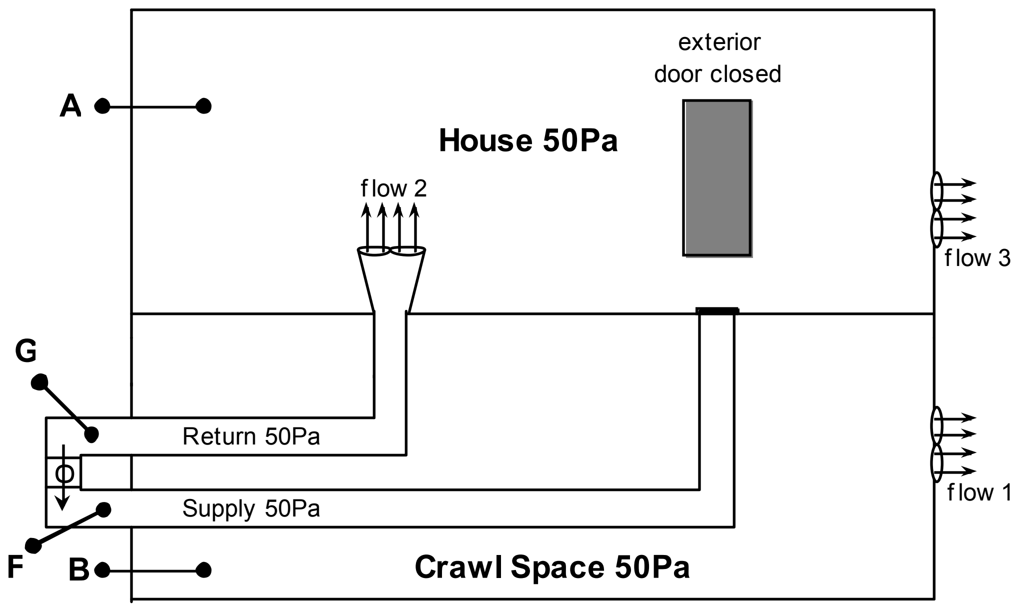

Figure 2: Illustration of flow and air leakage path definitions used during Test 1

Test # 2 was conducted to quantify floor system leakage (E) and crawl space to duct leakage (C+D) as shown in Figure 3. The ducts and house were both depressurized to -50 Pa with respect to outside. The crawl space access door was left open allowing the crawl space to be at the same pressure as outside. Flow 4 in this test represents duct leakage. The outside to duct leakage determined in Test 1 can now be subtracted from duct leakage to quantify crawl to duct leakage. Similarly, the floor leakage is determined by subtracting outside to house leakage (Test 1) and duct leakage from flow 5.

Flow 4 = **G** + **F** + **C** + **D**

Flow 5 = **A** + **E** + Flow 4

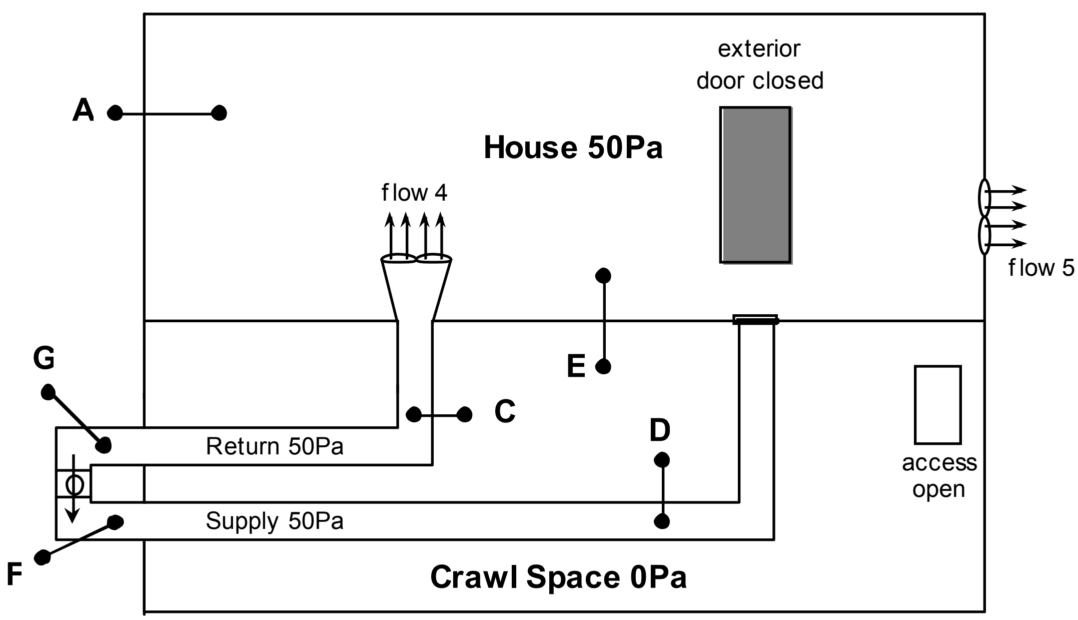

Figure 3: Illustration of flow and air leakage path definitions used in Test 2

3.3 Moisture

A detailed description of the crawl space was created based on several aspects, including visible moisture problems and vapor barrier, construction, insulation, heating and air conditioning equipment, and wood moisture readings. The relative humidity and dry-bulb temperatures were recorded in the middle of the crawl space, outside, and inside the house.

The type of vapor barrier and a rough estimate of percent of ground coverage was estimated. If there was not a vapor barrier, the ground cover was recorded. Location of gaps in the vapor barrier were documented, such as around HVAC equipment, water heater, edges, or piers. The vapor barrier was deemed either poor, acceptable, or excellent based on how well it was installed and whether there is reason to believe coverage will deteriorate with use.

A list of existing or past moisture problems was recorded and investigated. This list included the presence of drip lines in the crawl space, visible mold, wood decay, termite mud tunnels, efflorescent salts leeching through the walls, moisture discoloration on the walls, puddles on the vapor barrier, condensation on duct or pipe surfaces, waterlogged ducts, signs of past plumbing leaks, gutter spillover, and saturated soil immediately around house. Visible signs of significant past or current moisture problems were photographed.

Many aspects were examined to characterize the construction of the crawl space and to note construction practices that appear to decrease or increase moisture transport into the crawl space. Details of all the materials used in the foundation, including footing type, insulation, termite shield, sill seal, brick veneer, sheathing, siding, vapor barrier, and wall waterproofing were noted.

All details about the crawl space wall vents were noted, including vent size, manufacturer/model, number of installed vents, location, height above outside grade, vent type (fixed, manual, or automatic), and damper position.

The crawl space floor was inspected for the presence of an internal drainage system. Although difficult to determine, existence of drainage pipe was noted if found.

To measure wood moisture content, pin moisture reading and wood surface temperatures were measured at ten locations within the crawl space. First, the wood species was noted. Then, measurements were made for the sill plate next to the access, the band joist next to the access, the sill plate at the worst location, the band joist at the worst location, the center beam, floor joist next to the access below insulation, floor joist next to the access above insulation, floor joist at the worst location below insulation, floor joist at the worst location above insulation, and the subflooring in the middle.

Measurements recorded next to the crawl space access were made two feet to the right or left of the access door. Sill plate measurements were made on top of plate approximately halfway between the band joist and the edge of the sill plate. Band plate measurements were made about one inch from the bottom of the plate, but below the insulation. Measurements at the worst location were made at what was determined to be the potentially worst moisture problem site. Usually, the worst location was determined to be the point of lowest clearance in the crawl space, unless there was an obvious moisture problem at another location. Joist measurements were made above and below the floor insulation approximately one inch from the edges. Joist beam measurements were made close to the middle of the house approximately one inch from the bottom edge. The subfloor measurements were made above the insulation close to the approximate center of the crawl space, usually above the center beam measurements. An average overall wood moisture was used to compare study groups. For the average wood moisture numbers, the subflooring readings were not included because the subfloor plywood or oriented strand board are not pure wood products.

The wood moisture measurements on the first three homes were done using a Delmhorst J-4 moisture meter with uninsulated pins. The Delmhorst moisture meter was calibrated for Douglas Fir at 70ºF, therefore, the pin readings were adjusted according to the temperature and wood species correction tables provided with the Delmhorst meter (Delmhorst 1999). First, the readings were adjusted for temperature. An equation was determined using Microsoft Excel Solver to model the correction for temperature. To determine this equation, only corrections for 40ºF to 100º were used in the meter reading range of 6-30%. The temperature correction equation is as follows:

$$MR_{corr}=A1+A2*T+A3*MR+A4*MR*T \qquad (3.1)$$

MR_{corr} = the meter reading corrected for temperature
A1 = -1.08513
A2 = 0.01603
A3 = 1.521056
A4 = -0.00752
T = Temperature
MR = Meter reading in field

Next, measurements were corrected for southern yellow pine using the following correction factor based on a plot of the values provided by the Delmhorst table determined this equation.

$$M_{SYP} = 1.1407*M_{DF} + 0.4085 \qquad (3.2)$$

M_{SYP} = Moisture content for southern yellow pine
M_{DF} = Moisture content for Douglas Fir

Readings were taken on homes C04 through C10 with a Protimeter, due to a broken pin on the Delmhorst. The instrument is calibrated for wood at 68^{o}F (20^{o}C). Temperature compensation is approximated by the following corrections. For every 9^{o}F (5^{o}C) above 68^{o}F, ½ % is subtracted from the meter readings. For every 9^{o}F below 68^{o}F, ½ % is added to the meter reading (Protimeter 2000). Protimeter had a direct reading for our species, therefore, these readings do not reflect any adjustment for yellow pine. The manual does state that readings may be 1 to 2 % higher if measuring treated wood. Therefore, measurements on the sill plate may be slightly high. For both types of meters, the subfloor was only corrected for temperature.

3.4 Indoor air quality

The house characterization protocol exclusively addressed the observation of visible molds and bioaerosol sampling for viable mold spores.

As part of Characterization Study, air samples were taken in the living space, crawl space and outdoors of 10 homes. The sampling results were used to characterize the levels of viable mold spores found in the crawl space, and to investigate if there was any linkage between the levels and types of mold found in the house and crawl space.

The bioaerosol sampling involved the use of an Andersen two-stage cascade impactor connected to a vacuum pump that had been calibrated to collect air samples at the rate of one cubic foot per minute. Equipment calibration was conducted before beginning and after completing the sampling.

Initially, a sampling period of 3.5 minutes was used for all samples collected in houses 1, 2, 3, and 4. However, the number of mold spores collected from the crawl space samples exceeded the quatifiable limits in three of the four homes. Therefore, the sampling period was reduced to 1.0 minute in the crawl spaces of the remaining 6 houses, while the 3.5 minute sampling time remained for outdoor and indoor samples. Even at the 1.0 minute sampling period, mold spores counted exceeded the equipment's limit for two of the remaining 6 homes.

The collection medium used for impaction of fungal spores was Malt Extract Agar, an aciduric mycologic medium designed for the collection of environmental fungi. After sampling, the culture plates were transported to Duke University and incubated at ambient temperature for 96 hours prior to enumeration and identification. The samples were protected from temperature extremes during transportation. Identification was accomplished by macroscopic examination of colony morphology and microscopic examination of fungal elements.

The basic investigation of the test homes involved an inspection of the crawl space and the collection of three bioaerosol samples: one in the crawl space, one in an indoor location near the HVAC system return grill, and an outdoor air sample for comparison. The purpose of the basic test was to document viable spore levels in the crawl space and house and compare these results to the outside reading to see if there was evidence of mold growth (amplification) within the house or the crawl space. In addition, the sampling was designed to "screen" whether the crawl space was contributing fungal contamination to the living space.

As the initial homes were being sampled, the researchers decided to attempt a second sampling protocol. Consequently, a second sampling visit, which is referred to as the duct test, was made to homes 1 through 7 (except for #5). The researchers wanted to further evaluate homes where there was an equivocal result in the first test. The purpose of the duct test was to determine if air leakage in the crawl space duct system transports viable mold spores from the crawl space into the home breathing air. To conduct this test, the homeowner agreed not to run the crawl space heating and cooling system the night before the duct test. Two sets of samples were taken during the test. First in phase 1, three samples were taken before the air handling unit system fan was turned on: one at the return grill in the house, one in the crawl space, and one outside. In phase 2, the system fan was turned on and allowed to run for at least 5 minutes before two additional samples were taken at the return grill and a supply diffuser (or register). The supply diffuser sample was taken inside a short polyethylene tube that was temporarily taped around the supply register. The purpose of the tube was to "isolate" the supply air from contaminant sources within the house.

4. Results

4.1 General

4.1.1 Age of home and crawl space use/purpose

The age of homes, current occupant move-in date, house square footage and number of floors, the frequency of crawl space use, crawl space purpose, and repairs done in crawl space are presented in Table 3.

The age of these houses ranged from two to nine years old with an average of 4.7 years. No homeowner has lived in the home for more than five years and one occupant moved in only one year prior to our characterization. The homeowners varied in the frequency of their crawl space use. Four homeowners claimed they used the crawl space once a week, three used it once a month, and the other three used their crawl space less frequently than once a month.

The most common use of the crawl spaces was storage, especially of lawnmowers and tools. It was recommended to homeowners to stop storing lawnmowers or gas in the crawl space. Other observed storage concerns were wood and cardboard boxes as these items contain cellulose, absorb moisture and can grow mold.

House	Age of home (yrs)	Current occupant move-in date	House square footage	Number of floors	Frequency of crawl space use	Crawl space purpose	Service done/date
C01	4	Aug 97	2913	2	1/wk	Store tools and lawnmower	None
C02	2	Sep 99	2948	2.5	2/yr	Fix banging pipes, not really used	Yearly HVAC and termite inspection
C03	4.25	Aug 00	3178	2	1/mo	Filter change and storage	Pipe repairs at move-in
C04	4.75	Dec 96	1698	1.5	1/wk	Store wood, lawn–mower, and tools	Pipe near crawl door had leak in 1997
C05	8.75	Dec 92	1354	2	1/mo	Lawnmower storage	Vapor barrier installed 1997
C06	3.25	Jun 98	2136	2	2/yr	None	Fix floor joists and dirt fill under fireplace
C07	5	Jan 00	1517	2	1/mo	Storage of seldom used items such as camping supplies	Replace nozzles on furnace, install space–guard filter, repaired blocked French drain in crawl
C08	2.5	Mar 99	2478	2	4/yr	None	None
C09	7	May 97	1689	2	1/wk	Lawnmower and yard supply storage	Termite inspection
C10	5	Aug 97	3147	2	1/wk	Storage	HVAC (1 – 2 times per year for humidifier)

Table 3: General information about age of house and crawl space usage.

Also, homeowners were asked about any service done or problems in their crawl spaces. Two homeowners reported past plumbing problems, although by the time of the site visits there were no signs of plumbing leaks in any of the houses. In addition, one homeowner reported that prior to moving into the home, there was a blocked French drain in the crawl space. He reported that the blocked drain caused water pools up to 18” deep in the lowest corner. The drain was repaired before the homeowners moved into the home.

4.1.2 Crawl Space Area and Volume

All inspected crawl spaces were full crawl spaces. In addition to the crawl space most homes also had adjacent, poured floor slabs for attached garages. The crawl spaces’ areas, volumes, wall perimeters, and average heights to floor joist are shown in Table 4. There was a wide range of sizes and heights in our study. The average height to floor joist was anywhere from 2.0 ft to 7.2 ft. These numbers are a weighted average based on measurements made along the perimeter of the crawl space. The area was determined from outside measurements with the 8 inches subtracted for the block in the wall. Therefore, the area is an inside measurement, which varied from 609 ft to 2611 ft. The crawl space volume was determined from the inside area and average height to floor joist. The numbers presented in the chart do not exactly multiply together because volume was calculated before rounding off height. As shown in the table, the volumes varied by a factor of 10, from just under 1192 ft^3 to 12, 871 ft^3. Outside measurements were used to determine wall perimeter.

	Crawl space area (ft^2)	Crawl space volume (ft^3)	Average height to joist (ft)	Wall perimeter (ft)
C10	1783	12871	7.2	209
C01	2611	9098	3.5	219
C03	1570	7770	5.0	169
C06	1171	5425	4.6	139
C04	907	4869	5.4	150
C08	1100	4831	4.4	153
C09	1187	3305	2.8	160
C02	1244	2904	2.3	152
C07	852	2830	3.3	136
C05	609	1192	2.0	114

Table 4: Area, volume, wall perimeter, and the average floor joist height.

The most informative factor presented in the table is average height to joist column. The larger the number, the more the building site is sloped, whereas small numbers identify flat building sites. Houses 2 and 5 have very low headroom crawl spaces that made it difficult to crawl through and inspect. In this sample, most of the homes were built on sloped sites. Consequently these crawl spaces had acceptable to high clearance headroom in most areas.

4.2 Energy

4.2.1 HVAC and Equipment

Heating ventilation and air conditioning equipment and water heater type were evaluated in all the homes. Results are displayed in Table 5.

	HVAC Type Zone 1	HVAC Type Zone 2	Supply and return in crawl	Air handler in crawl	Condensate drain	Humidifier	Water heater in crawl
C01	Heat Pump	Heat Pump	yes	yes	yes	no	Electric
C02	Heat Pump	Heat Pump	yes	yes	no	no	None
C03	Heat Pump	Heat Pump	yes	yes	yes	no	Electric
C04	Combo heater-A/C	NA[1]	yes	yes	yes	no	None
C05	Heat Pump	NA[1]	yes	yes	yes	no	None
C06	Gas Pack	Gas Pack	yes	no	yes	no	None
C07	Furnace-A/C	NA[1]	yes	yes	yes	no	Electric
C08	Gas Pack	Gas Pack	yes	no	yes	no	None
C09	Furnace-A/C	Furnace-A/C	no	no	yes	no	None
C10	Heat Pump	Heat Pump	yes	yes	yes	yes	Gas

[1]HVAC system serves both upstairs and downstairs

Table 5 : Types of HVAC and other equipment in the crawl spaces.

Nine of the houses had supply and return duct systems in the crawl space. Seven of the homes also had their air handling unit in the crawl space. Any duct leakage in wall vented crawl spaces is air leakage to outside.

Gas appliances were found in three crawl spaces. C07 and C09 had gas furnaces and C10 had a gas water heater, all of which took their make up combustion air from the crawl space.

4.2.2 HVAC Settings and filter location

Table 6 shows the temperature and fan settings for operation of the heating and air conditioning systems in the houses. On average, homeowners set their thermostat to about 68 to 70 during the winter and 75 to 76 in the summer. Five homeowners claimed to setback their thermostat at night, during the day, or when away on vacation. The HVAC fan in most homes was set to auto. In two homes, the fan was sometimes operated all the time. In house C07, the auto setting is used most of the year but it is switched to full-time on during times of high pollen count to filter the air with the high efficiency air filter that was installed. In the table Zone 1 is the first floor or whole house zone. Homes that have values for Zone 2 are homes with two HVAC systems; Zone 2 equates to the second floor HVAC system. The table also identifies where the return air filter is located.

	HVAC Settings						Fan Filter Location(s)	
	Heat Zone 1	Heat Zone 2	A/C Zone 1	A/C Zone 2	Setback Thermostat?	Fan Operation (Auto or On)	Air Handling Unit	House
C01	65	65	79	79	no	Auto	yes	yes
C02	68	68	77	77	yes	Auto	yes	no
C03	70	70	76	74	yes (80 at night)	Auto	yes	no
C04	70	n/a	78	n/a	no	Auto	no	yes
C05	68	n/a	75	n/a	no	Auto and On	no	yes
C06	69	69	78	78	no	Auto	no	yes
C07	72	n/a	76	n/a	yes (68 at night or	Auto and On	yes	no
C08	80	n/a	70	n/a	no	Auto	no	yes
C09	69	n/a	72	n/a	yes (68 at night or when away)	Auto	no	yes
C10	69	69	73	73	during day or if away	Auto	no	yes
Average	**70**	**68**	**75**	**76**				

Table 6: HVAC temperature and fan settings and filter location.

All 10 homes regularly use air conditioning, 3 homes maintain low cooling set points (below 74ºF), and 9 of 10 homes have duct systems in the crawl space. The significance of these interrelated conditions is that 9 crawl spaces have large duct surface heat loss areas that are located in a tempered outdoor space. Duct heat loss would be dramatically reduced if ductwork was located in conditioned space. In addition, when cooling, these surface areas will produce water droplet condensation for prolonged time periods in the summer moisture season.

Given the high levels of bioaerosols measured in the crawl spaces, the filter location ap– pears to be critical. Given that significant duct leakage was measured in all ten crawl spaces, the filter should be located at the air handling unit and not at the return grilles in the house. Further it may be advisable to install a high efficiency air filter at the air handling unit.

Only four out of ten houses had filters located at the air handling unit.

4.3 Insulation

For insulation to be effective in achieving it's rated R-value, it must be installed continuously, without compression, gaps, voids or bypasses. Information about the floor insulation in study homes is described in Table 7.

	R-Value	Mounting Technique	Insulation Type	Fallen Insulation	Installation Job
C09	19	Tiger Claw	Faced Fiberglass Batt	yes	Poor
C01	19	Tiger Claw	Unfaced Fiberglass Batt	yes	Acceptable
C03	19	Tiger Claw	Unfaced Fiberglass Batt	yes	Acceptable
C07	19	Tiger Claw	Faced Fiberglass Batt	yes	Acceptable
C02	19	Tiger Claw	Unfaced Fiberglass Batt	no	Acceptable
C04	19	Tiger Claw	Faced Fiberglass Batt	no	Acceptable
C05	19	Tiger Claw	Unfaced Fiberglass Batt	no	Acceptable
C06	19	Tiger Claw	Faced Fiberglass Batt	no	Acceptable
C08	19	Tiger Claw	Unfaced Fiberglass Batt	no	Acceptable
C10	19	Tiger Claw	Faced Fiberglass Batt	no	Acceptable

Table7: Characterization of floor insulation type and conditions

All homes had typical floor insulation. R-19 fiberglass batt insulation was installed in the joist cavities and held in place with insulation wires spaced between 18" to 24". By default, the use of insulation wires compresses the insulation batts.

The floor insulation performance in House C09 was rated as poor. This house had wood I-beam floor framing which made the spacing between the joist centers about one inch wider than the length that the insulation wires were designed for. Although this home did not have a large number of batts that had fallen out, there were air bypasses in virtually every joist cavity, where batt ends had sagged within the joist cavities.

Small amounts of batt insulation had fallen out of the floor in three other homes.

All homes had typical, varying amounts of insulation compression by the insulation wires and gaps around plumbing, duct and electrical floor penetrations.

In summary, all homes had floor insulation problems that significantly degraded the effectiveness of the installed insulation batts.

It is also noted that five houses had faced batts (rated vapor barrier surface facing up) and five had unfaced batts. This even split reflects the confusion that exists about insulation vapor barriers. Based on the amount of moisture load found in these crawl spaces, theoretically all 10 crawl spaces should have faced batts facing down. However, the air leakage pathways that were documented through the insulation would likely trap moisture in the batt above the batt vapor barrier.

4.4 Standard pressure testing results

In addition to the new testing protocols that were developed for this project, results are presented below for several standard shell, zone and duct testing procedures.

4.4.1 LBL ACH Factors

Standard Lawrence Berkeley Laboratory (LBL) correction factors (N) were used to convert the measured air changes per hour (ACH) at 50 Pascals test pressure into natural infiltration (ACH natural) values. The (N) values used for each house are presented in the Table 8.

	Number of Stories	Exposure	LBL Correction Factor (N)
C01	2	normal	17.2
C02	2.5	normal	16.2
C03	2	well shielded	20.6
C04	1.5	normal	19.4
C05	2	normal	17.2
C06	2	normal	17.2
C07	2	normal	17.2
C08	2	normal	17.2
C09	2	normal	17.2
C10	2	normal	17.2

Table 8: LBL natural infiltration ACH correction factors.

4.4.2 ACH at 50Pa and natural infiltration

Standard blower door test results are presented in Table 9. This pressure test measures the combined effect of all shell and duct air leakage pathways. The results of this test are presented in reference to the home geometry in four different ways. The table is ranked based on the last column, which divides the CFM50 reading by the total square feet of envelope surface area.

	CFM50 Total House Leakage	ACH @ 50Pa	ACH Natural	CFM50/ ft^2 floor area	CFM50/ ft^2 envelope surface
C09	2714	13.1	0.68	1.61	0.61
C03	3594	8.2	0.40	1.13	0.57
C10	3835	8.2	0.48	1.22	0.56
C01	3745	8.2	0.51	1.29	0.53
C04	2077	8.6	0.44	1.22	0.47
C06	2197	7.5	0.44	1.03	0.44
C05	1372	7.4	0.43	1.01	0.41
C08	2479	7.2	0.42	1.00	0.41
C07	1506	6.8	0.39	0.99	0.38
C02	1000	2.5	0.15	0.34	0.17
Average	**2451**	**7.8**	**0.43**	**1.08**	**0.46**

Table 9: House CFM50 test results and ACH due to natural infiltration.

Nine houses had a grouped, total air leakage characteristic ranging from 0.38 to 0.61 CFM50/sf of envelope surface area, which is typical performance for homes built in the area.

C02, with only 0.17 CFM50/sf of envelope surface area, is a clear outlier to the group. This home was built with advanced air sealing techniques, including air-tight drywall gaskets.

4.4.3 CFM50 zone pressures

Table 10 summarizes several zone pressure differences with reference to the house main body at a standard 50 Pascal pressure difference between the house and outdoors.

	Crawl Space (P3)	Supply #1 (P5)	Return Duct (P7)	Supply #2 (P8)
C01	48.84	0.33	0.98	0.05
C02	47.90	0.13	0.09	0.23
C03	48.56	0.30	1.76	0.27
C04	51.99	0.07	0.23	0.06
C05	49.58	0.70	1.53	0.31
C06	49.56	0.23	0.38	0.30
C07	49.48	1.00	0.92	0.23
C08	49.51	0.24	0.33	0.24
C09	49.48	-0.01	-0.02	0.00
C10	49.89	2.43	2.86	2.39

Table 10: Zone pressures at 50 Pascals with respect to house

Not surprisingly, zone pressures in these wall vented crawl spaces ranged from 47.9 to 51.99, when the house to outside pressure difference was being maintained at 50 Pascals. This means that, for all intents and purposes, the crawl spaces function as outdoor spaces.

4.4.4 Air handling unit fan effect on zone pressures

The effect of running the air handling unit fan on house and crawl space pressures was measured by logging the pressures of the house and the crawl space with the fan off and then with the fan on. Table 11 shows the change in pressure in the two zones caused by the operation of the HVAC system serving the first floor. In all homes but C09, this was the HVAC system with ducts located in the crawl space. In C09, there was no HVAC system located in the crawl space; it was located in the house and attic.

	House Change (Pa) WRT Outside	Crawl Space Change (Pa) WRT Outside	Crawl Space Change (Pa) WRT House
C01	0.45	-0.20	-0.65
C02	0.11	0.24	0.12
C03	0.16	0.05	0.25
C04	-0.66	-0.60	0.06
C05	-0.10	-0.04	0.06
C06	0.12	0.64	1.22
C07	0.09	-0.09	-0.18
C08	-0.07	0.09	0.16
C09	-0.46	-0.38	0.08
C10	-0.21	-0.08	0.14

Table 11: House and crawl space pressure changes caused by operating HVAC system fan

The positive values in the last column show pressure difference that result in airflows into the house through holes in the floor plane. The outlier in the group is C06, which had the crawl space pressurized to 1.22Pa by the fan.

4.4.5 Total duct leakage

Duct leakage was measured for the crawl space duct systems. Duct leakage is a measure of the flow from the crawl space and outside into the duct system when the ducts are depressurized with respect to the crawl space and outside. Since all of the homes in this study had fully ventilated crawl spaces, the crawl space and outside were at essentially the same pressure during the duct leakage test.

Duct leakage is typically measured at 25Pa depressurization. The pressure testing protocol for this study dictated that the duct leakage testing pressure differential be at 50Pa in order to be consistent with the rest of the testing protocol. The duct leakage testing results for 50Pa were translated to the usual 25Pa results using the standard flow equation and an exponent (n) of 0.65, that suggested in the Energy

Conservatory Duct Blaster manual. Total duct leakage test results are presented in Table 12.

	Duct leakage CFM at 25Pa	Duct leakage CFM/ft² floor area served
C09	n/a	n/a
C01	388	18.1%
C03	191	11.0%
C07	167	11.0%
C05	138	10.2%
C10	167	9.7%
C04	140	8.2%
C02	96	7.6%
C06	59	5.5%
C08	60	5.4%
Average	**156**	**9.6%**

Table 12: Total duct leakage at 25 Pascals.

No house had a tight duct system. All ducts tested as having moderate to major, total duct leakage.

At 18.1%, house C09 had major duct leakage stemming in large part due to the fact that there was three panned return plenums used in the crawl space.

C03, C07, C05 and C10 had excessive duct leakage ranging from 9.7% to 11%

The remaining four houses, C04, C02, C06 and C08 had moderate duct leakage ranging from 5.4% to 8.2%.

C09 did not have any ductwork in the crawl space. The attic-based duct system in C09 was not measured for duct leakage.

4.5 Component air leakage testing

As was presented in Chapter 3, new protocols were developed for this project. These protocols were designed to allow researchers to isolate and differentiate between air leakage pathways across the floor plane between the house and crawl space and to determine the source of duct leakage in the crawl space or to the outside. Results are summarized below.

4.5.1 TECTITE data

The TECTITE software measures house leakage at several pressures as described in Chapter 3. This allows the software to determine the flow equation exponent (n) and the corresponding flow equation coefficient (C). In addition, the software calculates the equivalent leakage area for the house to two standards, the Canadian EqLA @10Pa and the LBL ELA @4Pa. The equivalent leakage area represents the cumulative size of the holes and cracks in the building's envelope. Table 13 presents these software's calculated values for all of the homes in this study.

	Canadian EqLA @ 10Pa (in^2)	LBL ELA @ 4Pa (in^2)	Flow Equation Coefficient (C)	Flow Equation Exponent (n)
C01	390.0	208.3	300.6	0.645
C03	367.0	193.9	275.2	0.657
C10	366.2	186.3	249.4	0.699
C09	271.5	141.8	197.7	0.670
C08	235.9	119.8	160.0	0.701
C06	209.6	106.6	142.6	0.699
C04	201.8	103.7	141.0	0.688
C07	147.2	75.9	103.7	0.684
C05	131.5	67.0	90.1	0.696
C02	93.5	47.0	61.8	0.712
Average	**241.4**	**125.0**	**172.2**	**0.685**

Table 13: Selected TECTITE testing results for study homes.

4.5.2 Leakage path coefficients

The flow equation coefficients that were calculated from the test results for each home are presented below in Table 14.

	CFM50 House Leakage Coefficient	Wall/Ceiling Leakage Coefficient	Floor Leakage Coefficient	Crawl Duct Leakage Coefficient	Outside Duct Leakage Coefficient
C01	295	218	30	47.6	0.2
C02	79	56	12	11.6	0.3
C03	283	249	14	19.9	3.7
C04	163	124	15	9.7	7.6
C05	108	71	16	7.4	9.6
C06	173	153	14	6.6	0.7
C07	118	87	6	13.7	6.8
C08	195	149	34	4.8	2.6
C09	213	185	21	n/a	n/a
C10	302	226	52	16.9	3.8
Average	**193**	**152**	**21**	**15**	**4**

Table 14: Flow equation coefficients.
(based on flow equation exponent n = 0.65)

4.5.3 Summary of component air leakage

Table 15 summarizes the component air leakage pathways. The table breaks down house (total) leakage by percents into four leakage components: wall/ceiling, floor (between the crawl space and house), crawl ducts and outside ducts. The table also summarizes the total crawl space leakage component by adding the floor and crawl space duct columns.

Note that the duct leakage percents in this table are at 50 Pascals and not at 25 Pascals. It should also be noted that the duct leakage % refers only to duct systems located in the crawl space. Leakage from any other duct system (typically attic based duct systems) is represented as part of the wall and ceiling leakage percentage.

	Total CFM50	Wall and Ceiling Leakage	Floor Leakage	Crawl Ducts	Outside Ducts	Total (Crawl Ducts plus Floor)
C02	1000	70.4%	14.7%	14.5%	0.4%	29.2%
C01	3745	73.6%	10.2%	16.1%	0.1%	26.3%
C10	3835	75.6%	17.4%	5.7%	1.3%	23.1%
C05	1372	68.1%	15.7%	7.0%	9.2%	22.7%
C08	2479	78.3%	17.7%	2.5%	1.4%	20.2%
C07	1506	76.8%	5.1%	12.1%	6.0%	17.2%
C04	2077	79.4%	9.5%	6.2%	4.9%	15.7%
C06	2197	87.6%	8.3%	3.7%	0.4%	12.0%
C03	3594	86.9%	4.9%	6.9%	1.3%	11.8%
C09	2714	89.7%	10.3%	n/a	n/a	10.3%
Average	**2452**	**78.6%**	**11.4%**	**8.3%**	**2.8%**	**18.9%**

Table 15: Components of house CFM50 leakage flow rate.

The significant data in this table are highlighted. In a standard blower door test, the ten homes had 18.9% of the total house air leakage coming from the crawl space, through floor holes and crawl space duct leakage. Crawl space duct leakage is prominent, representing 44% percent of this total contribution.

All of the homes except C09 had duct systems in the crawl space that served the first floor. C09 had an attic based duct distribution. In some cases, this duct system also served a second floor.

4.6 Moisture

4.6.1 Relative Humidity and Temperature

The measured relative humidity and dry bulb temperatures are shown in Table 16. These measurements are also presented as graphs in Figures 4, 5 and 6.

The inside relative humidity range was 50% to 64% with an average of 57%. Inside dry bulb temperatures varied from 70ºF to 81ºF. These temperatures were used to correct for air density differences due to temperature in the pressure testing of the houses. The outside relative humidity ranged from 48% to 87% (measured just before it started to rain). The outside dry bulb temperature varied from 63ºF to 91ºF.

All 10 crawl spaces had high relative humidity levels (73% to 88%). No reading is given for House C10 because heavy rains affected measurements (probable reading would have been greater than 85%). In all cases the crawl space relative humidity was higher than the outside relative humidity.

The temperatures in the crawl spaces were 2 to 14 degrees cooler than the outdoor air temperature in all homes except for house 9.

	Crawl RH (%)	Crawl Dry Bulb (°F)	Crawl Dew Point (°F)	Outside RH (%)	Outside Dry Bulb (°F)	Inside RH (%)	Inside Dry Bulb (°F)
C01	76	77	68	60	91	60	76
C02	83	74	68	76	86	53	78
C03	88	71	66	76	75	62	78
C04	76	76	66	48	86	52	81
C05	77	78	70	59	87	60	78
C06	85	73	68	76	77	50	77
C07	79	69	63	61	72	57	70
C08	73	76	66	57	78	61	80
C09	74	64	55	57	63	55	70
C10	NA[1]	NA[1]	NA[1]	87	74	64	73
Average	**79**	**73**	**66**	**66**	**79**	**57**	**76**

[1]Did not get accurate measurements due to pouring rain at time of inspection.

Table 16: Relative humidity and dry bulb temperatures.

The dew point temperatures in the crawl space were estimated using a psychometric chart for pressure at 1 atm. The estimated temperatures ranged from 55°F to 70°F. The smallest temperature difference between dry bulb and dew point was 5°F while the largest was 10°F.

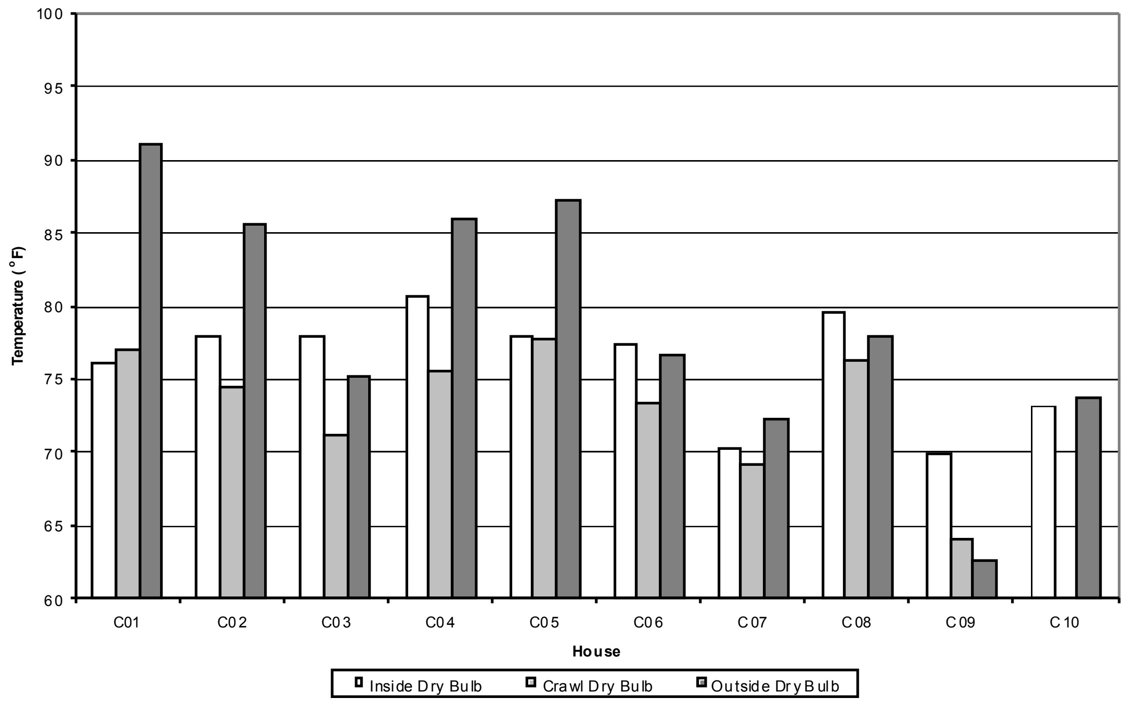

Figure 4: Dry bulb temperatures inside, outside and in the crawl spaces.

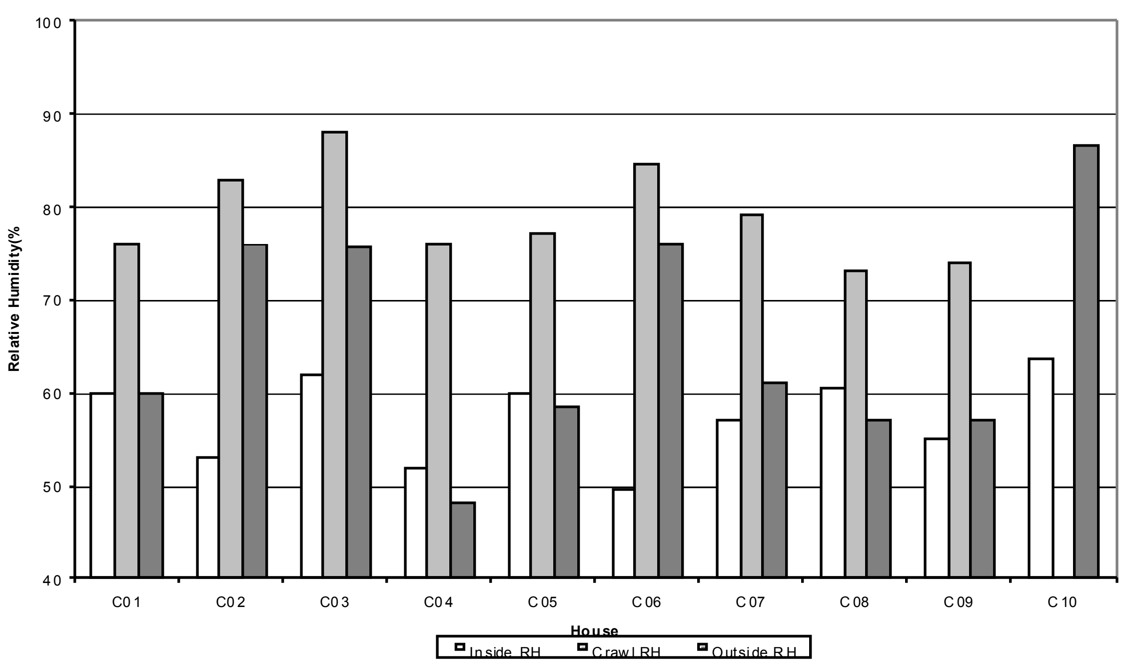

Figure 5: Relative humidity inside houses, outside houses, and in the crawl spaces.

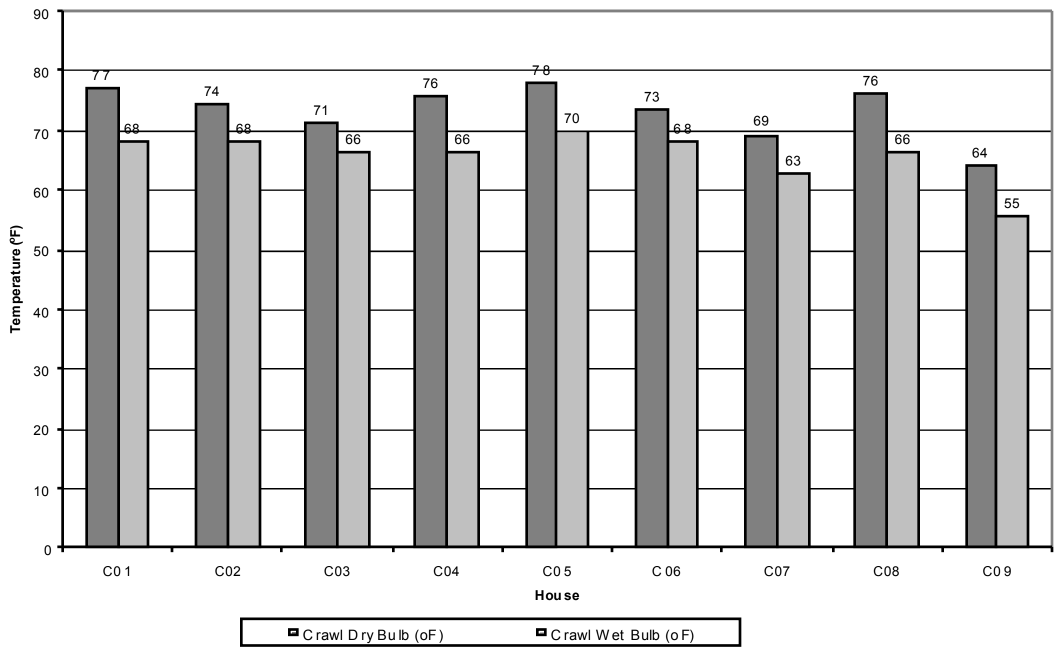

Figure 6: Dry bulb and dew point temperature in crawl spaces.

4.6.2 Ground Moisture Barrier

A description of the ground moisture barriers and the extent of their coverage of the crawl space floors is displayed in Table 17.

	Vapor Barrier Description	Percent Vapor Barrier Coverage	Gaps in Vapor Barrier	Meets ICC coverage requirement
C05	6 mil	95	Edges	Yes
C02	6 mil	95	Edges	Yes
C07	6 mil	85	Edges, piers	No
C06	6 mil	80	Edges	No
C08	6 mil	75	Edges, piers	No
C10	4 mil	70	Edges	No
C09	4 mil	60	Around HVAC, edges, piers	No
C01	None	0	NA	No
C03	None	0	NA	No
C04	None	0	NA	No

Table 17: Ground moisture barrier conditions.

The key observation is that three homes had no ground moisture barrier whatsoever.

Only two homes (C02 and C05) had ground moisture barriers that were deemed to comply with the BOCA interpretation of ICC Residential Code provision for full coverage of ground vapor barriers. These 2 homes had an estimated 95% of the earth floor covered with 6 mil polyethylene. The uncovered floor area occurred at gaps along the edges or the walls of the crawl space. Generally these gaps range from about six inches to one foot.

Five homes had partial coverage barriers. In addition to the above mentioned edge gaps, these crawl spaces had coverage gaps around the beam piers and/or HVAC equipment. If there were a long line of piers, then the vapor barrier could be missing from the entire sections between piers.

Where ground moisture barriers were present, the material used was either 6 mil or 4 mil polyethylene, and was acceptable in terms of not showing signs of degradation such as holes or tears.

4.6.3 Condensation

It is common to find puddles and water droplet condensation in crawl spaces during humid weather. The most common observation is condensation droplets collecting on ductwork and cold water pipes. If the condensation persists, puddles will accumulate on the ground below, particularly if there is a ground moisture barrier. Drip lines tell where condensation drops have made erosion marks in bare earth. Drip lines can also show where puddles have dried up on top of the ground moisture barrier. A summary of observed condensation problems is presented in Table 18.

	Puddles on ground moisture barrier	Drip lines	Condensation on ducts or pipes
C01	n/a	yes	yes
C02	yes	no	yes
C03	n/a	yes	yes
C04	n/a	yes	yes
C05	yes	no	yes
C06	no	no	no
C07	yes	no	no
C08	no	yes	no
C09	no	yes	no
C10	no	no	yes

Table 18: Condensation, puddles and drip lines.

Five crawl spaces had water drip lines eroded on exposed earthen floor areas. The presence of water drip lines indicates a history of water droplet condensation off of cold surface cold water piping ductwork and air handling unit cabinets.

Water puddles were found collecting on top of the ground moisture barrier in three of the seven houses that had installed ground moisture barriers.

Water droplet condensation was seen on the ductwork and/or cold water pipes in six of the ten houses. This condition ranged from isolated drops to large surface areas covered with drops and droplets falling to the crawl space floor.

4.6.4 Type and operation of wall vents

Vent type and operation are shown in Table 19. All houses had wall vents with manual dampers that were 8 inches high by 16 inches wide. Homeowner operation of these vents varied. Six houses always had their vents open. One home had all vents closed intentionally except one. Three homeowners said that they try to close the vents in winter and open them in the summer.

	Vent Type	Vent Operation	Vents Located Near Ground
C01	Manual 8" X 16"	Open	yes
C03	Manual 8" X 16"	Open	yes
C07	Manual 8" X 16"	Open	yes
C09	Manual 8" X 16"	Open	yes
C02	Manual 8" X 16"	All closed except one	no
C04	Manual 8" X 16"	Open	no
C05	Manual 8" X 16"	Easily accessed ones are closed during winter and open during summer	no
C06	Manual 8" X 16"	Open in summer and close in winter	no
C08	Manual 8" X 16"	Open	no
C10	Manual 8" X 16"	Close in winter if remember	no

Table 19: Wall vent type, operation and location.

The last column of Table 19 reveals whether the houses had any vents located at or near ground level. To define this parameter, vents were considered at or near ground level if the bottom edge were within about two inches from the exterior ground level.

Four houses had low wall vents. Most of the wall vents in C09 were too low; several of which were below grade, and none had vent wells. Vent wells are used to provide a dam edge around the vent. Moisture tracks on the inside walls below these low vents as well as ground erosion along the interior wall perimeter in C09 demonstrated a long history of bulk water penetration through the vent openings. The flooding source is rainwater accumulating along the exterior wall edge.

Three other homes had one or more low crawl space vents. However all such vents had vent wells, some of which were drained by gravel filled pathways leading to foundation drains. House C03 had a patio that was at or above the elevation of the crawl space vents. All these low vents had corrugated vent wells and were believed to have French drains on the exterior to divert water runoff away from the crawl space.

4.6.5 Amount of crawl ventilation

Table 20 shows the necessary information to determine whether crawl spaces met code ventilation recommendations.

	Number of Vents	Vent Net Free Area (in^2)	Crawl Space Area (ft^2)	Total Vent NFA (ft^2)	Presence of Vapor Barrier (VB)	Fraction of Total NFA to Crawl Area	Meets 1/150 Code Provision	Meets 1/1500 Code Provision
C05	9	75	609	4.7	full	1/130	yes	yes
C08	15	68	1100	7.1	partial	1/155	no	no [3]
C04	12	68	907	5.7	no	1/160	no	no [3]
C06	15	68 [2]	1171	7.1	partial	1/165	no	no [3]
C10	20	68 [2]	1783	9.4	partial	1/189	no	no [3]
C03	17	68 [2]	1570	8.0	no	1/196	no	no [3]
C07	9	68 [2]	852	4.3	partial	1/201	no	no [3]
C09	12	68 [2]	1187	5.7	partial	1/210	no	no [3]
C02	13 [1]	64	1244	5.8	full	1/215	n/a	yes
C01	16	68 [2]	2611	7.6	no	1/346	no	no [3]

[1] All vents fully closed except one on west side
[2] Net free area estimated based on manufacturers data for similar vents
[3] Non-compliant because of partial or missing ground vapor barrier

Table 20: Estimated fraction of vent area to crawl area.

Crawl space vents were drawn on the foot print drawing during the site visit. The vent net free area was read off the vents at four of the houses and was in the range of 64 to 75 in^2. Vent net free area was not recorded for six homes because it was either not visible or was overlooked. For these six homes, a value of 68 in^2 was assumed for analysis work. The North Carolina Residential Building Code is taken from the CABO code. The basic ventilation requirement calls for at least 1 square foot of net free area per 150 square feet of crawl space area. If an approved vapor barrier material is used for the ground moisture barrier, the 1/150 ratio may be reduced to 1/1500.

Only C05 was found to meet the 1/150 provision; whereas C05 and C02 met the 1/1500 provision. The other eight houses had ratios that met the 1/1500 provision, however the venting was deemed non-compliant because of the absence of a full coverage ground moisture barrier.

4.6.6 Site grading and drainage

To summarize a description of each house site, the relative location in the local watershed, slope of lot, and the noted impervious surfaces within 50 ft of the house are shown in Table 21. Only one house was determined to be located low in the local watershed because it had a creek running through the backyard. The two houses that were specified as high in the local watershed were elevated relative to surrounding lots.

			Impervious Surfaces around House	
	Location in Local Watershed	Description of Slope of Lot	Driveway	Other
C10	high	steep	concrete	none
C04	middle	steep	concrete	concrete sidewalk
C06	middle	slight slope	concrete	concrete sidewalk
C08	middle	slight slope	concrete	concrete sidewalk
C09	middle	slight slope	concrete	short concrete sidewalk
C03	high	steep	gravel	patio
C01	low	steep	gravel	none
C05	middle	flat	gravel	none
C07	middle	slight slope	gravel	concrete sidewalk
C02	middle	slight slope	gravel	none

Table 21: House location in watershed and impervious surfaces around house.

Four of the houses were located on a steep lot, five lots were slightly sloped, and one was flat. In large part because of the prevalence of sloped grading conditions, none of the houses were in danger of crawl space flooding due to their location.

Five of the homes had gravel driveways and the other five had concrete driveways. Several homes also had concrete walkways. None of these impervious surfaces posed a serious runoff threat to the crawl spaces.

4.6.7 Rain Water Control: gutters/downspouts/overhangs

Table 22 summarizes the methods of rainwater control from roofs of houses and away from crawl spaces. All houses had some overhangs, but C09 only had overhangs on front and back and not along the sides. The size of the overhangs was estimated from ground level.

	Roof overhang (in) [1]	Gutters	Downspouts away from crawl space
C02	18	yes	yes
C03	18	yes	yes
C01	16	yes [3]	yes
C04	16	yes	yes
C10	16	yes	yes
C06	12	yes	yes
C07	12	yes	yes
C08	12	yes	yes
C05	10	yes	no
C09 [2]	6	yes	yes

[1]All overhangs are estimated.
[2]Overhangs on front and back, none on sides.
[3]Gutters along back only.

Table 22: Methods of rain water control from roofs of houses.

All homes had gutters, but C01 only had gutters along the back of house where the elevation was already lower than the rest of the house. Nine of the homes had gutter downspouts and included a drainpipe that emptied at least 3 feet from the foundation wall. C05 had downspouts but they emptied at the elbows at the bottom of the downspouts, within a foot of the foundation wall.

Relative to the pilot group characterization, the use of gutters and downspouts was the most widely used bulk moisture control strategy.

4.6.8 Foundation components

A foundation description, the façade type, and the presence of a crawl space or foundation drain are reported in Table 23.

	Foundation description	Façade type	Crawl space drain
C01	Concrete block	Brick	yes
C02	Concrete block	Stucco	yes
C03	Concrete block	Stucco	yes
C04	Framing and concrete block	Siding/Block	yes
C05	Concrete block	Stucco	inconclusive
C06	Framing and concrete block	Brick	yes
C07	Concrete block	Brick/Stucco	yes
C08	Framing and concrete block	Brick	yes
C09	Framing and concrete block	Stucco	inconclusive
C10	Framing and concrete block	Brick	yes

Table 23: Description of foundation, façade, and presence of crawl space drain.

Five of the homes had all concrete block all the way up to the floor joist. The other five had one or more foundation walls that combined concrete blocks at the bottom with wood framed walls at the top. The crawl space vents were located at the top of the block wall in all crawl spaces except C04 and C08. The crawl space vents in these homes were located under one course of brick or about two and a half inches from the top of the block. The façade types included stucco, brick, and siding.

Eight of the houses were found to have interior foundation drains. The inspections could not determine if the other two houses had crawl space drains. Generally the drain would be a large pipe opening laid in gravel with the line sloped to an outdoor discharge. The purpose of the drain is to control major flooding in the crawl space. However the crawl space floors had little if any intentional grading that would direct water to the drain spot. Without interior drainage grading, puddles of water can be trapped on top of the ground moisture barrier.

4.6.9 Below grade walls

Large areas of below grade walls in crawl spaces may represent a significant moisture load on the space. The below grade wall refers to the portion of wall that is exposed on the inside and is below the surface grade on the exterior. This wall area is prone to capillary moisture transport from ground water adjacent to the wall exterior. Crawl spaces located on sloped sites are more likely to have significant amounts of below grade walls, particularly when there is some interior excavation work.

Measurements were taken in the crawl space and outside at major corners to allow the determination of the crawl space floor elevation with respect to the outside grade. This was done by measuring the height from the outside grade to the top of nearby crawl space vents at major corners around the perimeter of the house. Also, the height from the crawl space floor to the top of nearby foundation vents and to the bottom of the floor joist was taken inside at major corners. The crawl space wall area from earth floor to bottom of floor joists was calculated using the length of the wall and the height measurements. Also, the outside wall area from grade to the bottom of the floor joist was calculated. Using these measurements, the inside crawl space wall area and the corresponding above and below grade crawl space wall areas were calculated. The crawl space wall area includes the inside block wall area and any framed wall area up to the bottom of the floor joist. The results of these measurements are presented in Table 24.

	Crawl space Wall Area (ft^2)	Crawl space Wall Area Above Grade (ft^2)	Crawl space Wall Area Below Grade (ft^2)	Crawl space Wall Below Grade %	Wall Salt Deposits	Wall Moisture Stains
C10	1340	933	407	30%	no	yes
C03	813	530	283	35%	no	yes
C04	785	542	243	31%	no	yes
C08	766	542	224	29%	yes	yes
C07	444	279	165	37%	no	no
C01	813	650	163	20%	no	no
C06	692	546	146	21%	no	yes
C09	430	342	88	20%	yes	yes
C02	336	260	76	23%	yes	yes
C05	217	164	53	24%	no	yes
Average	**664**	**479**	**185**	**27%**		

Table 24: Below grade walls.

The key information from this characterization is believed to be the amount of wall area below grade. The larger the number, the more likely it is that the below grade walls will contribute a significant moisture load on the space.

The last two table columns summarize observations of below grade wall moisture loading effect. These signs, which can be seen on the inside wall surfaces, are darkened water stain areas and efflorescent salt buildups. In crawl space masonry, white efflorescence is a water-soluble salt that is brought to the surface by groundwater that has penetrated the wall. Eight crawl spaces had water stains and/or efflorescence on below grade wall areas.

Only C01 and C07 did not have any visible signs of wall water stains or white salt deposits. This might indicate that these two homes had effective moisture proofing on the exterior of the crawl space walls.

4.6.10 Wood Moisture

For reference, all wood surface temperature readings and the average, maximum, and minimum are exhibited in Table 25.

	C01	C02	C03	C04	C05	C06	C07	C08	C09	C10
Sill Plate (Access)	68.0	71.0	69.6	71.9	72.1	69.8	63.6	68.1	64.0	71.6
Band Joist (Access)	71.0	74.0	71.0	71.2	73.4	71.2	64.0	65.3	64.0	73.4
Sill Plate (Worst)	64.0	70.0	64.0	70.0	71.2	70.8	64.9	69.0	64.4	72.3
Band Joist (Worst)	66.0	74.0	71.2	73.4	69.6	70.7	66.0	68.0	63.5	73.4
Center Beam	60.0	70.0	n/a	71.9	73.4	70.8	66.7	67.8	68.1	70.7
Joist (Access Below Insulation)	64.0	71.0	70.7	64.5	72.1	71.7	68.1	63.1	67.8	72.6
Joist (Access Above Insulation)	62.0	71.0	69.8	63.8	69.6	71.9	68.7	63.5	71.6	71.9
Joist (Worst Below Insulation)	66.0	70.0	71.7	69.0	69.6	70.5	68.5	66.5	67.8	73.6
Joist (Worst Above Insulation)	63.0	70.0	74.3	72.3	68.7	74.3	70.8	69.0	68.1	74.1
Subflooring	61.0	76.0	n/a	74.6	70.3	75.3	68.9	72.0	71.7	75.0
Average	64.5	71.4	71.2	70.3	71.0	71.7	67.0	67.2	67.1	72.9
Maximum	71.0	74.0	74.3	74.6	73.4	75.3	70.8	72.0	71.7	75.0
Minimum	60.0	70.0	69.6	63.8	68.7	69.8	63.6	63.1	63.5	70.7

Table 25: Wood surface temperature readings.

The temperature readings in each house ranged from an eleven degree difference in C01 to a four degree difference in C02.

The purpose of taking wood surface temperatures was to calibrate the pin moisture readings. However it is noted that these surface temperatures are generally below the space temperatures that were measured in the crawl spaces. This indicates higher relative humidities and air moisture loads adjacent to the wood framing.

The corrected field wood moisture readings are presented in Table 26. The maximum, minimum, and average wood moisture readings are shown in Table 27. The average, minimum, and maximum do not include subfloor readings because the reading on plywood or OSB could be misleading. Moisture readings over 19% are highlighted.

	C01	C02	C03	C04	C05	C06	C07	C08	C09	C10
Sill Plate (Access)	15.0	14.0	18.0	12.8	15.8	14.8	14.2	14.9	17.1	16.0
Band Joist (Access)	14.0	14.0	16.0	13.7	15.6	15.2	15.0	13.5	16.4	11.0
Sill Plate (Worst)	19.0	17.0	20.0	13.8	17.1	21.9	15.6	17.9	14.5	17.2
Band Joist (Worst)	21.0	15.0	15.0	13.2	15.8	23.5	14.9	15.5	19.2	14.7
Center Beam	21.0	16.0	NA	14.7	20.3	17.9	19.2	14.2	18.8	16.2
Joist (Access Below Insulation)	16.0	15.0	18.0	14.7	16.5	16.0	15.3	14.2	20.5	15.0
Joist (Access Above Insulation)	14.0	13.5	14.5	12.5	11.3	13.6	10.8	12.1	16.2	11.6
Joist (Worst Below Insulation)	22.0	20.0	20.0	15.8	19.5	18.9	19.2	15.7	21.0	19.0
Joist (Worst Above Insulation)	17.0	15.0	12.0	12.0	12.8	14.3	17.2	12.3	18.4	15.2
Subflooring	12.0	18.0	NA	10.5	16.6	14.1	16.7	16.6	15.6	15.8
Average 1-9,11	17.7	15.5	16.7	13.7	16.1	17.3	15.7	14.5	18.0	15.1
Maximum	22.0	20.0	20.0	15.8	20.3	23.5	19.2	17.9	21.0	19.0
Minimum	14.0	13.5	12.0	12.0	11.3	13.6	10.8	12.1	14.5	11.0

Table 26: Temperature and species corrected wood moisture readings.

Seven houses had one or more corrected wood moisture readings above 19%, which is the moisture level threshold generally accepted as supporting mold growth. However, none of the homes had an average reading above 19%.

Not shown in the table are the 50%+ wood moisture content readings that were taken under the floor rotting fireplace area of C06. Wood fibers are saturated above 25% wood moisture content.

The maximum, minimum, and average wood moisture readings are displayed graphically in Figure 7. As can be seen in Figure 7, there was a fairly wide range of readings measured in each crawl space.

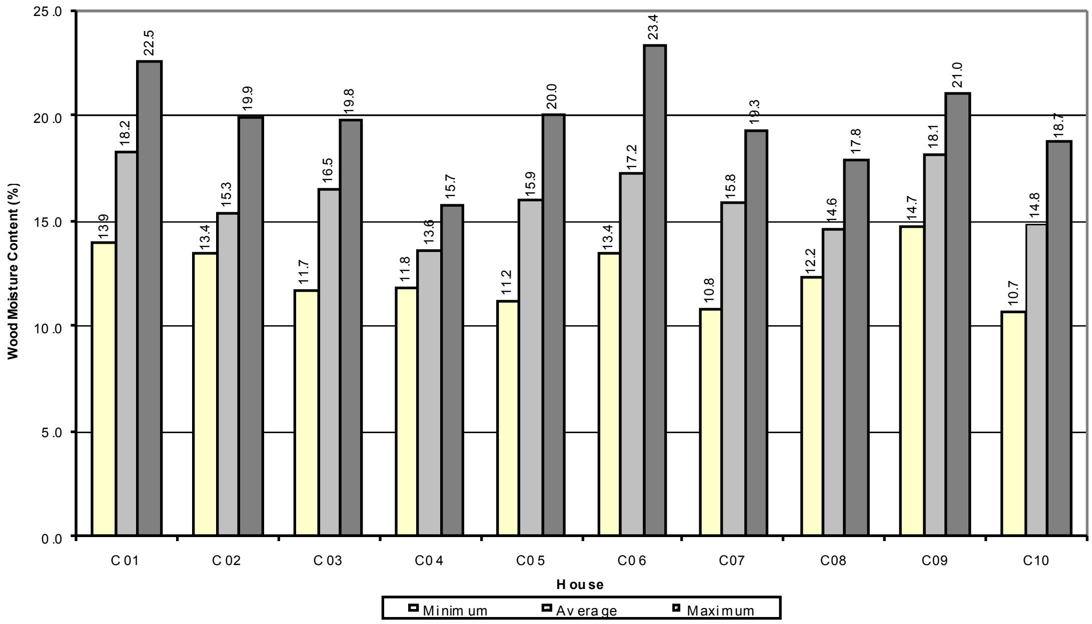

Figure 7: Maximum, minimum, and average wood moisture content in all study houses

	Location of highest wood moisture reading
C01	Joist worst below insulation (22.5)
	Center beam (22.3)
C02	Joist worst below insulation (19.9)
C03	Sill plate worst (19.8)
	Joist worst below insulation (19.7)
C04	Joist worst below insulation (15.7)
C05	Center beam (20.0)
	Joist worst below insulation (19.4)
C06	Band joist worst (23.4)
C07	Center beam (19.3)
	Joist worst below insulation (19.2)
C08	Sill plate worst (17.8)
C09	Joist worst below insulation (21.0)
	Joist access below insulation (20.5)
C10	Joist worst below insulation (18.7)

Table 27: Location of worst wood moisture reading in study crawl spaces.

In nine of the houses, the maximum moisture reading was found to be at the joist at the worst location below the insulation. The worst location was taken to be the lowest clearance area of the crawl space. The center beams had high moisture content in three of the houses.

4.7 Indoor Air Quality

4.7.1 Allergies

The incidence and description of homeowner allergies is shown in Table 28. Eight of the homeowners reported someone in their house having allergy problems and no one reported asthma. Most reported allergies to mold, mildew, or pollen. Two homeowners said that the allergies were serious. The occupants of C07 had serious allergy problems in their previous home until a deep pleated media filter was installed at the air handling unit. Problems started again in their present home, and they installed the same type filter, but reported that they are not as allergy-free as in their previous home. These were the only occupants that claimed their allergies were currently worse than before they moved into the current home. The homeowner of C06 described her son's allergies as serious and said that he has a runny nose all the time.

	Asthma / allergies	Description	Allergy problems exist before?	Allergies better / worse / same
C07	yes	Serious for all three occupants, runny nose	yes	worse
C02	yes	Seasonal allergies	yes	same
C03	yes	Mold and mildew cause itchy eyes	yes	same
C04	yes	Sinus allergies	yes	same
C06	yes	Mold, mildew, grasses, cats; son has serious allergies with runny nose all the time	yes	same
C10	yes	Not major	n/a	n/a
C09	yes	Allergies to dust mites, worse in spring	yes	better/same
C01	yes	Mold, mildew, pollen	yes	better
C05	no	n/a	none	n/a
C08	no	n/a	none	n/a

Table 28: Presence and description of allergy problems of occupants in houses.

Eight of ten households reported allergy problems; three of which were specific to mold allergies.

4.7.2 Visible mold

Observations of fungal growths found in the crawls spaces are summarized in Table 29. Three categories were used to characterize the relative amount of mold observed.

- High: Visible mold was found throughout the crawl space.
- Medium: Visible mold was found in several areas, but not in the entire crawl space.
- Low: One or more isolated mold spots was found.

For comparison purposes, the table also includes the percentage of ground moisture barrier coverage as well as the viable spore count measurements in colony-forming units per cubic meter of air (CFU/m^3).

	Amount of Visible Mold on Floor Framing	Crawl Space Viable Mold Spores CFU/m^3	Percent Ground Moisture Barrier Coverage	Mushrooms/Fungus on Floor
C01	High	>11,756	0	yes
C02	High	>11,756	95	yes
C05	High	5,740	95	no
C03	Medium	>11,756	0	yes
C06	Medium	>41,146	80	no
C07	Medium	5,138	85	yes
C04	Low	>11,756	0	no
C08	Low	5,285	75	no
C09[1]	Low	4,571	60	no
C10	Low	41,146	70	no

[1]House had I-beam laminated plywood floor framing, all other homes had southern yellow pine.

Table 29: Summary of visible and viable mold spores in crawl spaces.

All ten houses had visible mold growing on the wood framing, and four houses had ground fungus growths such as mushrooms.

It is noteworthy that houses C02 and C05 had high levels of visible mold despite the fact they had 95% coverage vapor barriers as ground moisture barriers. The implication of this correlation is that full coverage ground moisture barriers do not prevent surface mold growth.

The visible mold and viable spore counts were not highly correlated. The high amount of visible mold in C05 was not reflected in the viable spore count. On the contrary, the biological sampling in C02 and C05 showed high amounts of viable spores in crawl spaces that had low amounts of visible mold. It may be important to advise homeowners that high numbers of viable spores can be present in a crawl space and not be visible.

4.7.3 Results of Initial Air Sampling Protocol

The results of the initial air sampling protocol are as follows. Five types of mold were found to predominate in the tested homes. These included *Cladosporium* sp., *Penicillium* sp., *Acremonium* sp., *Aspergillus* sp., and *Aspergillus niger*. These are all molds commonly found in both the indoor and outdoor environment. The results of the bioaerosol sampling are presented in Table 30.

	Colony-forming units per cubic meter of air (CFU/m3)		
House	**Outdoors**	**Crawl space**	**Indoors**
CO1	831 C*	>11,756 P, C, An	1,142 C, P
CO2	1,251 C, P*	>11,756 C, P, Ac*	536 C, P
CO3	1,642 C, P	>11,756 C, P	548 C, P
CO4	361 C, P	>11,756 P, C	1,935 P, C
CO5	>11,756 C, P, An*	5,740 P, Asp*, C	536 P, Asp, C
CO6	510 C, P	>41,146 P, C	188 C, P
CO7	1,620 C, P	5,138 P, C	1,962 C, P
CO8	988 C, P	5,285 P, C	585 P, C
CO9	>11,756 C, P, An	4,571 C, Asp, P	222 C, Asp, P
CO10	1,288 C, P	>41,146 P, C	924 C, P

*Asp = *Aspergillus*, An = *Aspergillus niger*, Ac = *Acremonium* sp., C = *Cladosporium* sp., P = *Penicillium* sp

Table 30: Summary of bioaerosol sampling results.

All ten crawl spaces had significant viable spore counts in the basic test. Respirable, viable spore concentrations ranged from a low of 4,571 CFU/m^3 (colony-forming units per cubic meter of air) to >41,146 CFU/m^3. Six of the 10 crawl spaces had levels that exceeded the counting capability of the sampling period; which for 3.5 minute samples is >11,756 CFU/m^3 and for 1.0 minute samples is 41,146 CFU/m^3. The other 4 homes had viable spore counts ranging from 4,571 to 5,138 CFU/m^3.

While there are no regulatory standards for fungal spore concentrations in crawl space environments, the high crawl space spore counts and the corresponding high ratios of crawl space to outdoor spore concentrations are significant and warrant further study. All but 2 of the tested crawl spaces contained 3 to >80 times the amount of spores found in outdoor air. The ratios of crawl space spores to outdoor spores are presented in Table 31.

House	Outdoors CFU/m3	Crawl Space CFU/m3	Crawl Space / Outdoors Ratio
CO6	510 C*, P*	>41,146 P, C	80.7
CO4	361 C, P	>11,756 P, C	32.6
CO10	1,288 C, P	>41,146 P, C	31.9
CO1	831 C	>11,756 P, C, An	14.1
CO2	1,251 C, P	>11,756 C, P, Ac*	9.4
CO3	1,642 C, P	>11,756 C, P	7.2
CO8	988 C, P	5,285 P, C	5.3
CO7	1,620 C, P	5,138 P, C	3.2
CO5	>11,756 C, P, An*	5,740 P, Asp*, C	0.5
CO9	>11,756 C, P, An	4,571 C, Asp, P	0.4

*Asp = *Aspergillus,* An = *Aspergillus niger,* Ac = *Acremonium* sp., C = *Cladosporium* sp., P = *Penicillium* sp

Table 31: Ratio of crawl space spores to outdoor spores.

While there are no regulatory standards for fungal spore concentrations in indoor environments, one generally accepted guideline for assessing the “acceptability” of indoor air is that the indoor concentration is no more than one-half to one-third of the outdoor concentration and the genera of fungal spores indoors are similar to the mix (rank order) of spores found outdoors. The ratios of indoor spores to outdoor spores are presented in Table 32.

House	Outdoors CFU/m3	Indoor CFU/m3	Indoor / Outdoors ratio
CO4	361 C*, P*	1,935 P, C	5.4
CO1	831 C	1,142 C, P	1.4
CO7	1,620 C, P	1,962 C, P	1.2
CO10	1,288 C, P	924 C, P	0.7
CO8	988 C, P	585 P, C	0.6
CO6	510 C, P	188 C, P	0.4
CO2	1,251 C, P	536 C, P	0.4
CO3	1,642 C, P	548 C, P	0.3
CO9	>11,756 C, P, An*	222 C, Asp*, P	0.0
CO5	>11,756 C, P, An	536 P, Asp, C	0.0

*Asp = *Aspergillus,* Ac = *Acremonium* sp., C = *Cladosporium* sp., P = *Penicillium* sp

Table 32: Ratio of indoor spores to outdoor spores.

Table 32 results can be characterized as follows:

House number 4 not only had indoor concentrations of mold spores more than 5 times greater than outdoor concentrations. This suggests that mold may be growing somewhere in the home. The environment within the sample area in the home clearly exceeds the guideline conditions that the indoor concentration of mold spores be no more than one-half to one-third the outdoor concentration. The mix of organisms found indoors was consistent with the predominant genera in the outdoor air.

For home 1, the basic investigation revealed indoor concentrations higher than the outdoor concentration (a ratio greater than 1.0). These findings may have resulted from the windows and doors having been opened before the testing. Fungal spores that enter the indoor air will stay "airborne" for an extended period of time. These findings may indicate mold growth somewhere within the house. It also had a type of mold (*Penicillium* sp.) indoors not recorded in the outdoor environment.

For home 7, the basic investigation revealed indoor concentrations higher than the outdoor concentration (a ratio greater than 1.0). Again, these findings may have resulted from the windows and doors having been opened before the testing and may also indicate mold growth somewhere within the house. The mix of organisms found indoors was consistent with the predominant genera in the outdoor air.

House 5 had a relatively low concentration of fungal spores indoors, but the rank order of fungal species was significantly different than the species in the outdoor air. More importantly, the *Aspergillus* sp. identified in the indoor air was morphologically identical to the species isolated from the crawl space, suggesting that the crawl space was a source of contaminants in the living space.

Houses 8 and 10 had indoor concentrations of mold spores somewhat lower (a ratio of 0.5-1.0) than the outdoor concentration. The mix of organisms found indoors was consistent with the predominant genera in the outdoor air. The environment within the sample area in the home marginally exceeds the recommended guideline conditions.

For homes 2, 3, 6, and 9, the basic investigation revealed indoor concentrations of mold that were significantly lower than the outdoor concentration (a ratio of less than 0.5). The mix of organisms found indoors was consistent with the predominant genera in the outdoor air.

4.7.4 Results of the Modified Air Sampling Protocol (Duct Test)

In addition to the basic test, researchers returned to a subset of the 10 homes to conduct a second test, this one measuring mold spores inside the house with the HVAC system off and with it running (on). Time constraints allowed the team to revisit and evaluate six homes with the new protocol in October and November. The purpose of the "duct test" was to determine if air leakage in the crawl space duct system and/or heating and cooling unit transports viable mold spores from the crawl space into the home breathing air. The results of the bioaerosol sampling are presented in Table 33.

	Colony-forming units per cubic meter of air (CFU/m3)				
House	Outdoors	Crawl space	Indoors at Return Grill (HVAC Off)	Indoors at Return Grill (HVAC On)	Indoors at Supply Diffuser (HVAC On)
CO1	>11,756 C*, P*	>41,146 P, C	434 C, P	1,553 P, C	1,532 P, C
CO2	1,532 C, P	>41,146 P, C, Ac*	573 C, P	723 C, P	446 C, P
CO3	>11,756 C, P	2,156 C, P	459 C, P	877 C, P	434 C, P
CO4	484 C, P	>41,146 P, C	113 C, P	2,984 P, C	1,090 P, C
CO6	1,178 C, P	>41,146 P, C	244 C, P	210 C, P	51 C, P
CO7	772 C, P	623 P, C	256 C, P	302 C, P	102 C, P

* Ac = *Acremonium* sp., C = *Cladosporium* sp., P = *Penicillium* sp

Table 33: Summary of duct test bioaerosol sampling results.

The duct test sampling results showed that two houses (1 and 4) tested positive, particularly house 4. It should be noted that when the duct test was conducted in drier weather in the fall, homes 3 and 7 had significantly reduced crawl space spore levels.

The ratios of the two phases of the bioaerosol duct testing are presented in Table 34.

House	Indoors (HVAC Off) CFU/m3	Indoors (HVAC On) CFU/m3	Diffuser (HVAC On) CFU/m3	Ratio (Indoors HVAC On / HVAC Off)	Ratio (Diffuser / Indoors HVAC Off)
CO4	113 C*, P*	2,984 P, C	1,090 P, C	26.4	9.7
CO1	434 C, P	1,553 P, C	1,532 P, C	3.6	3.5
CO3	459 C, P	877 C, P	434 C, P	1.9	1.0
CO2	573 C, P	723 C, P	446 C, P	1.3	0.8
CO7	256 C, P	302 C, P	102 C, P	1.2	0.4
CO6	244 C, P	210 C, P	51 C, P	0.9	0.2

* C = *Cladosporium* sp., P = *Penicillium* sp

Table 34: Ratios of duct test bioaerosol testing.

Table 34 results can be characterized as follows:

The first ratio compares viable spore counts before and after the air handling unit fan is turned on. Both samples were collected at the same location near a return air grille in the home.

For homes 1 and 4, results suggest that the crawl space duct system and/or heating and cooling unit are contributing a significant amount of viable mold spores to the indoor environment. The source of the mold could be crawl space mold simply being transported by air leakage in the duct system and/or fungal growth inside the ductwork or air-handling unit, particularly around the cooling coil. The recommended actions to minimize this transport include sealing the crawl space ductwork to eliminate air leakage as well as inspecting and, if necessary, cleaning the interior of the air handling unit to remove identified mold growth. The homeowner should also consider installing a higher efficiency filter at the air handling unit.

For house 6 and 7, the results of the duct test were classified as “negative”, with no significant change when the crawl space heating and cooling system was turned on.

For houses 2 and 3, the results of the duct test were inconclusive. Mold levels were slightly elevated when the HVAC system was running and the concentration of fungal spores in the diffuser sample were relatively high. Additional testing would be required to fully assess potential contributions from the crawl space.

The second ratio compares viable spore counts taken at the diffuser with the air handling unit turned on, with the samples that were taken near a return air grill before the air handling unit was turned on.

For houses 1 and 4, the test results are strongly positive. Spore levels in the supply air stream are significantly higher than the house levels measured before the air-handling unit was turned on. In addition, *Penicillium* sp. became the predominant species in both the indoor and diffuser samples.

For the remaining houses (2, 3, 6 and 7), the test results are negative. Spore levels in the supply air stream are lower than the house levels, which were measured before the air-handling unit was turned on. However it should be noted that the actual concentrations detected at the diffusers in houses 2 and 3 were relatively high.

5. Evaluation of Characterization Protocols

The purpose of this evaluation was to define refinements and changes to the protocol for use in future studies. The protocols developed for this study were a "work in progress," evolving over the course of the study for each of the ten homes.

Two keys changes were made to the original protocol. One change involved a second bioaerosol duct test. This was done to test differences in mold spore counts with the HVAC system on and with it off. This test required a second visit and was conducted on six of the ten homes.

The second change was a shortening of the bioaerosol sampling time in crawl spaces. Levels of spores sampled at the 3.5-minute timeframe overloaded the equipment's counting capability.

The protocols took almost twice as much time as planned for. The protocols involved the collection of large amounts of data, but to do this required added time in the field—four-to-six hours for researchers from North Carolina State University and two visits for Duke. The result is that, using this method, only one house per day can be surveyed. Streamlining is needed to make the data collection process more cost effective. Teams should be able to do at least two or three homes per day. The goal is to move towards a broader statistical base by analyzing a large number of homes.

Streamlining efforts will target the development of simplified checklists that catalog the insulation, wall, and moisture conditions. Where a number of detailed field measurements were taken in the pilot protocol, the main study will rely on estimates. For example, instead of drawing a crawl space floor plan to scale, a rough sketch (not to scale) will be used. Instead of taking numerical grade level readings around the perimeter, the basic grade will be noted on each side of the building. Finally, the percentage of above and below grade wall will be estimated and not measured.

A significant amount of effort was needed to prepare the homeowner reports, copies of which are attached in the appendices. While they are detailed and informative, the lengthy reports took far more time to compile than was budgeted for. Streamlining efforts are likewise needed in this deliverable. The revised reporting method would consist of a checklist left at the time of the visit, with some standard supporting documentation. The checklist would be followed with a mailing of the bioaerosol sampling results after the samples are cultured.

For this study, homeowners were easy to recruit and very willing to participate. They were particularly interested in the mold and indoor air quality aspects of survey. Homeowners put up with the four-to-six-hour hour main visit. Six homeowners put up with second duct mold test. Researchers originally planned to provide a $50 honorarium for homeowners to encourage participation. However, participants stated that the inspection work performed was of significant value to them. Subsequently, the honorarium offer was not needed or made.

6. Findings

This study demonstrates that the characterization protocol that was developed for this project is effective. A large amount of measured and observed information can be readily collected in a single visit to a test house. Further, homeowners are quite willing to participate in the program, despite the inconvenience and intrusion of the data collection. It should be noted, however, that the site visits took up to twice as long to complete as anticipated.

These preliminary findings presented in this report appear to confirm the supposition that wall vented crawl spaces as they are currently designed and built are not sufficient to remove moisture in many instances, and to corroborate the 1994 ASHRAE Symposium (Recommended Practices for Moisture Control in Crawl Spaces) finding that wall ventilated crawl spaces in existing homes are often dangerously wet. All ten crawl spaces displayed a variety of moisture problems and symptoms.

Despite the fact that ground moisture barriers have long been identified as the most important crawl space moisture control strategy, only two homes had full barriers. Three homes had no ground moisture barriers whatsoever. Further, in the two homes that had full ground moisture barriers, the barriers were ineffective in protecting the crawl spaces from above ground sources of moisture problems such as rainwater and duct condensation. Both of these crawl spaces had visible mold covering most of the wood framing.

All ten buildings readily communicated air between the crawl space and the house. The component pressure testing results revealed that the ten homes had, on average, 18.9% of the total house air leakage coming from the crawl space, through floor holes and crawl space duct leakage. Crawl space duct leakage is prominent, representing 44% percent of this total contribution. In addition, all homes had floor insulation problems that significantly degraded the effectiveness of the installed insulation batts.

All 10 crawl spaces had significantly elevated levels of viable, respirable mold spores. If similar bioaerosol levels were found inside the homes, the homeowners may be advised to evacuate the building. All ten crawl spaces had unexpectedly high levels of respirable, viable mold spores. The strength of the bioaerosol results clearly warrants further evaluation of the potential bio-burden that crawl space environments may pose to the home occupants, and of the need to consider additional controls to prevent exposure and to reduce the source strength of crawl space molds. The pilot data is suggestive that residential crawl spaces may have a greater impact on indoor air quality than previously appreciated. It may be important to begin including the crawl space environment as part of residential building indoor air quality investigations.

In summary the findings revealed that all ten crawl spaces had multiple moisture problems, unexpectedly high levels of respirable, viable mold spores, and compromised thermal performance due to poor insulation performance and excessive shell and duct leakage. Table 35 lists the identified problem areas.

	C01	C02	C03	C04	C05	C06	C07	C08	C09	C10
Duct leakage CFM25 / ft^2 floor area served	18.1%	7.6%	11.0%	8.2%	10.2%	5.5%	11.0%	5.4%	NA	9.7%
Air leakage (crawl ducts and floor) / total house at CFM50	26.3%	29.2%	11.8%	15.7%	22.7%	12.0%	17.2%	20.2%	10.3%	23.1%
Insulation problems	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Major	Yes
Crawl relative humidity over 70%	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Full ground moisture barrier	None	Yes	None	None	Yes	No	No	No	No	No
Condensation on ducts or pipes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes
Puddles on vapor barrier	NA	Yes	NA	NA	Yes	No	Yes	No	No	No
Drip lines	Yes	No	Yes	Yes	No	No	No	Yes	Yes	No
Wood moisture content over 19%	26.1	23.1	23.0	None	20.0	50.0	19.3	No	21.0	No
Low crawl space vents	Yes	No	Yes	No	No	No	Yes	No	Yes	No
Moisture discoloration on crawl wall	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Visible mold	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
High viable mold spores	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 35: Summary of thermal, moisture and indoor air quality problems.

7. Recommendations

It is strongly recommended that the protocols developed for this study be utilized in future work efforts. The study results clearly exceed the expectations of the Scope Of Project Objectives description for this task. The study has established a characterization methodology that can be cost effectively utilized to document the as-built moisture, thermal and indoor air quality characteristics and shortcomings of wall vented crawl space systems. Further the strong moisture and mold findings support the adoption of dry crawl space construction techniques, most notably closed crawl spaces. Any adoption of dry construction techniques necessitates that improvements be made to the thermal performance characteristics of crawl space systems.

The field protocol should be streamlined to make the data collection process more cost effective in future work efforts. Survey teams should be able to do at least two or three home characterizations per workday in order to create a broader statistical database by analyzing a large number of homes.

Future efforts should consider installing a Hobo data logger in some or all crawl spaces that are characterized. The objective would be to collect one year of temperature and humidity data on a large number of crawl spaces. The collected data would be valuable in aiding researchers to determine what the long term annual wetting and drying cycles are for wall vented crawl spaces.