Crawl Space Characterization [2005]

| Characterizing Crawl Spaces as Sources of Mold in the Home Environment |

PREPARED BY ADVANCED ENERGY

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Executive Summary

The overall purpose of this Duke University study was to evaluate the importance of typical wall vented crawl spaces as sources of fungal species (mold) in the livable parts of the home environment. Duke University conducted bioaerosol sampling in 187 homes in North Carolina. Duke contracted with Advanced Energy to conduct a building science evaluation to characterize the conditions of typical wall vented crawl spaces in 45 homes in Durham, New Hanover, Wayne and Wilson counties, a subset of the homes studied by Duke. This is one of several reports written for this study. The other reports capture the bioaerosol sampling results and the long-term crawl space temperature and relative humidity results.

Indoor air quality researchers have increasingly focused on mold as a household pollutant. Because crawl spaces experience periodic high levels of moisture, they are very likely building areas where mold can be found. However, it is unclear whether the presence of crawl space mold results in mold exposure to occupants of these houses. To answer this question, Advanced Energy conducted a building science characterization on 45 houses. The characterization protocol recorded a wide variety of data including:

- Homeowner interview
- Combustion safety checks
- Building pressure diagnostics to quantify the air leakage paths and driving pressures throughout the building envelope and mechanical systems
- Documentation of topographical and exterior water transport issues
- Visual inspections and recordings of crawl space moisture history
- Wood moisture meter reading
- Drawings and notes of the house foundation and crawl space construction
- Insulation quality

Duke University conducted the bioaerosol sampling, testing five locations for levels of fungal spores.

The study documented that typical wall vented crawl spaces possess these characteristics:

- Presence of liquid water, moisture vapor and associated moisture issues
- Presence of fungal spores
- Measured holes between the crawl space and living space
- Forces (natural and mechanical) that drive crawl space air across the holes
- Measured transmission of fungal spores from the crawl space to the living space

When these characteristics exist together, the study indicates that contaminants (fungal spores and moisture vapor) present in the crawl space are being transmitted through holes in the floor by natural or mechanical forces to the livable parts of the home. This situation exposes occupants to potentially harmful crawl space contaminants. These results show that crawl spaces are important sources of mold in the home environment. Improved wall vented crawl spaces or alternative foundation designs such as closed crawl spaces should be implemented to reduce or eliminate the moisture and indoor air quality problems associated with typical wall vented crawl spaces.

Introduction

The purpose of this study was to evaluate the importance of crawl spaces as sources of mold species in the livable part of the home environment. Duke University received a Housing and Urban Development (HUD) grant to perform this work and contracted with Advanced Energy to conduct deliverables associated with the building science/crawl space characterization and long-term temperature and relative humidity analysis.

TABLE 1 Overall study goals and objectives of the research

Goal /Objective	Responsible Organization
Conduct fungal sampling in 125 – 150 homes with crawl spaces in three study locations in North Carolina.	Duke University
Conduct crawl space characterizations in 40 – 50 homes drawn from the Duke University fungal sample homes.	Advanced Energy
Provide long-term monitoring data on the temperature and relative humidity conditions in the crawl space characterization homes.	Advanced Energy
Provide study participants with a report on findings from their home.	Duke University and Advanced Energy
Evaluate the relative contribution of crawl spaces to mold species in the livable part of the home	Duke University with support from Advanced Energy
Evaluate the causes for transport of mold species from the crawl space to the livable part of the home environment.	Duke University with support from Advanced Energy

This project was divided into three tasks:

- Orientation
- Fungal sampling
- Crawl space characterization

During the orientation task, Duke University and Advanced Energy researchers reviewed the research objectives, schedules and deliverables with HUD headquarters staff. Duke University conducted fungal and bioaerosol sampling in 125-150 homes (see Duke University reports). Advanced Energy conducted the crawl space characterizations which included building science characterization and long-term temperature and relative humidity data on 40-50 houses, a subset of the Duke University houses. This report documents the results of the crawl space characterization.

Objectives of crawl space characterization

The principal objectives of the crawl space characterizations were to collect building science and crawl space information used in characterizing the conditions of typical, wall-vented, crawl spaces across at least three counties in North Carolina. The characterization protocol included the following components to better understand thermal, moisture and air leakage data associated with ventilated crawl spaces[1]:

- Homeowner interviews to better understand how homeowners operate houses and crawl spaces and to determine any potential indoor air quality related health issues
- Air leakage and zone pressure testing, used to calculate air flow
- House characteristics such as house measurements, topography, heating, ventilation, air conditioning (HVAC), other equipment and existing moisture control strategies

[1] The Crawl Space Characterization protocol and accompanying instructions can be found in Appendix III.

- Crawl space characteristics such as evidence of past moisture problems (wood rot, condensation, mold, puddles on vapor barrier, etc.), wood moisture content to evaluate the potential of wood for supporting mold growth, temperature measurements of the ground, water pipes, ductwork, air handling cabinet and floor framing temperature to assess surface condensation potential
- Long-term temperature and relative humidity data for the crawl space compared to outside

Background

Researchers studying indoor air quality have increasingly focused on mold as a household pollutant. As a result of their periodic high levels of moisture, crawl spaces are a very likely building area 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.

Effect of building dampness and mold

Mounting evidence suggests that exposure to mold in damp buildings is an important risk factor for childhood respiratory illness.[2] The strongest identifiable risk factor for the development of asthma appears to be exposure to environmental allergens, including indoor and outdoor pollutants.[3] Moreover, child allergies are closely associated with asthma expression. Children living in flood plains may experience increased risks from exposure to allergens and asthma triggers. The North Carolina coast and piedmont areas have been subjected to a number of flooding events during the past several years, including the effects of Hurricane Floyd.

Crawl spaces as sources of mold and building dampness

Crawl space foundations are cheap to build, functional in terms of providing a level foundation for flooring on sloping sites and popular as spaces to locate plumbing, ductwork and heating systems. Builders have avoided building crawl spaces without these vents for fear of causing moisture problems. For more than a century, home builders in North America have built crawl spaces with wall vents on the premise that these vents help dry crawl spaces.

While wall ventilation of crawl spaces may work in some climates during some times of the year, researchers have documented that many wall vented crawl spaces experience serious moisture problems. Measurement of humidity in North Carolina shows that outside summer air has more water vapor than crawl space air. Therefore venting crawl spaces in the summer offers no potential for drying and can actually cause moisture problems such as standing water on top of plastic ground covers, water condensation on ductwork and pipes, wet insulation and stained foundation walls due to moisture and visible mold. Crawl spaces in North Carolina and in regions with climates similar to North Carolina may be more prone to surface mold problems than crawl spaces in other states as a result of more humid weather. Wall vented crawl spaces have been shown to stay damp with relative humidity above 70 percent for long periods of time. When this happens, the excess moisture encourages mold to grow on wood and other organic material such as cardboard, dust and paper-faced sheetrock.[4]

Wall ventilated crawl spaces in existing homes are often dangerously wet. Papers presented at the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) symposium on moisture control in crawl spaces expressed a need to document and validate the poor performance factors that are reported in existing homes.[5] Building mold has emerged as a major issue for the entire home building industry. The issue stems from thousands of insurance claims and lawsuits, including successful multi-million dollar settlements that identify building mold as a health problem for tenants and homeowners.

The association between conditions in the crawl space and mold species in the home environment was previously identified during indoor air quality investigations in the homes of health-impacted patients being treated at Duke University Medical Center.[6] A subsequent pilot study undertaken jointly by Duke University and Advanced Energy expanded the mold contamination characterization and assessment protocol. This pilot study confirmed crawl spaces as potentially

[2] Etzel, Ruth et al. 1999. "Indoor Mold and Children's Health." *Environmental Health Perspectives.* Vol. 107 (Supplement 3): 463-468.
[3] National Institutes of Health. 1995. Global Initiatives for Asthma. National Heart and Blood Institute Publication Number 95-3659.
[4] Building Air Quality: A Guide for Building Owners and Facility Managers, Appendix C. EPA 402-F-91-102. http://www.epa.gov/iaq/largebldgs/graphics/iaq.pdf
[5] ASHRAE Symposium Recommended Practices for Moisture Control in Crawl Spaces. 1994.
[6] W.R. Thomann, M.L. Miranda, M. Stiegel, and A. Overstreet. "Shared Air: Examining the Contribution of Mold from Home Crawl Spaces to Home Interiors." Proceedings of the Fifth International Conference on Bioaerosols, Fungi, Bacteria, Mycotoxins and Human Health. December 2004.

important reservoirs of mold species that may be transported into livable parts of the home environment. In addition, all pilot study homes were found to have significant air leakage pathways between the crawl space and the home through duct and floor holes. The results indicate that crawl spaces may represent a more important exposure source than previously anticipated.[7]

This study allowed for a more complete characterization of the relative risk associated with mold growth in crawl spaces. Understanding the scope of this problem, as well as the mechanism for transport of mold species, is critical to providing guidance on establishing healthier home environments.

[7] Davis, Bruce and William Warren. Characterization Study Final Report: A Field Study Comparison of the Energy and Moisture Performance Characteristics of Ventilated Versus Sealed Crawl Spaces in the South. Advanced Energy. June 22, 2005. www.crawlspaces.org.

Procedures and Methods

All characterization data for this study, excluding the long-term temperature and relative humidity readings, represent conditions existing at a single point in time. A brief evaluation of the characterization protocol and lessons learned can be found in the Appendix. This study does not include multi-point, ongoing characterization data for each house. The sampling methodology described below took place in four North Carolina counties: Durham, New Hanover, Wayne and Wilson (see Figure 1 for location). The counties are representative of the coastal and piedmont locations that have been subjected to flooding. Methodology headings below follow the order in which the tasks were conducted in the field.

FIGURE 1 Location of four North Carolina counties where sampling took place

Background

General methodology

From 2002-2004 Duke University recruited 187 houses in Durham, New Hanover, Wayne and Wilson counties for fungal/bioaerosol sampling. These homes varied in size and age. From this pool of houses, Duke identified 58 for crawl space characterization through letters and phone calls. Advanced Energy then contacted the homeowners to further describe the crawl space characterization project and the time commitment required to participate.

For the crawl space characterization, a researcher spoke with the homeowner to ensure their home qualified for the study. Based on the following qualifications, 45 houses were selected for testing:

- Willingness of homeowner participation
- Only one duct system in the crawl space

Homeowners were additionally asked about the following issues:

- Adequate crawl space access to allow for testing equipment
- No standing water in the crawl space due to safety considerations
- No total obstruction in the crawl space that would inhibit testing

Sampling timeframe

The original intent of the study was to study and characterize all the homes during the humid season, May through September 2004. In the Southeast, the humid season is the most likely time when problems related to moisture are visible. During this time it is common to see puddles on the crawl space vapor retarder, condensation on pipes and duct work, and elevated wood moisture content. However, because of hiring and training delays actual sampling did not begin until July 2004 and subsequently extended into December 2004.

Project staffing and training

The project was overseen by a project manager, with input and assistance from other technical resources. Bi-weekly conference calls were scheduled between Advanced Energy and Duke University project teams to maintain open lines of communication. Initially, the study protocol estimated that two field technicians could conduct two house characterizations per day. However, because of the detail required by the protocol, an accurate study would allow for only one house characterization per day by the two field technicians. In a few instances, three field technicians were present and as a result of increased staffing, two house characterizations per day were conducted. Project staff found it most efficient to have the same lead field technician present on each site visit with an interchangeable second field technician to assist.

All project staff received a Human Subjects certificate for completing ethics training. All field technicians received technical training on the field protocol from technicians who participated in the pilot studies. Field technicians performed several “test runs” of the protocol on practice houses before performing the characterization on study homes.

Data storage and management and confidentiality

A Microsoft Access database was created to store and sort all study data, scheduling and logistics. All data were entered into this database. Periodic quality assurance checks were completed to ensure accuracy. The database was also password protected to protect the confidentiality of the homeowners. Only study staff had access to homeowner records and all the homes were given a unique identifier. The unique identifier was used in reporting so that data was not tied to specific homes. The project staff thoroughly explained the confidentiality procedures and obtained participant signatures for the consent forms.

Crawl space characterization protocol

The study team used a pilot-tested and Institutional Review Board (IRB)-approved protocol that allowed all homes to be similarly characterized. The protocol was divided into several sections: initial safety checks, homeowner interviews, building pressure diagnostics, building and lot dimensions and surroundings and crawl space characterizations. The full field protocol and accompanying instructions are found in the Appendix. Details of the protocol methods are below.

General data collection

The goal of the data collection was to have consistent and accurate data about each house. A field check list was created to ensure all necessary data was collected (see Appendix). Technicians were directed to take pictures and make notes of any significant situations they encountered. All study drawings were done to scale and measurements were captured using English units. Adequate space was created throughout the protocol to allow for additional comments on any section. Each picture taken was labeled on the protocol sheet as it corresponds to the number on the digital camera. All photographs and measurements were taken as technicians moved to the right from the main door or crawl space access when looking at the entrance from outside, continuing all the way around the building. Study technicians documented all comments and recommendations made to homeowners for future reference. The following is a list of situations in which researchers found it necessary to immediately notify the homeowner of a serious problem or issue:

- Life safety issues (CO levels, flame rollout)
- Disconnected ducts
- Saturated insulation around ducts
- Lack of filters
- Major holes in ducts
- Major floor rot
- Electrical arcing
- Dead animals
- Termites/ants

- Incorrect dryer venting
- Drainage under house
- Plumbing leak

Homeowner interview

The goal of the homeowner interview was to gain an understanding of how the occupant operates the house and crawl space and to determine any perceived indoor air quality and health-related issues. The interview began with a review and completion of the consent forms, including study consent and permission to take and use pictures. The remainder of the interview questioned the homeowner about the history of the home through obtaining the following information:

- Date the house was first occupied
- Date the current occupants moved in
- Crawl space use and frequency
- Service or repair work completed
- Operation of the crawl space vents
- Thermostat settings during the day and night
- Fan operation: on or auto setting
- Perceived health-related issues of occupants (asthma, allergies, etc.)
- Perceived change in health condition since moving into current house or being away from the house for a period of time

Combustion safety

Upon walking up to the house, an initial carbon monoxide reading was taken to ensure a safe environment for study staff and the home's inhabitants. All other safety measures were performed after the homeowner signed the consent form. Before performing any portion of the characterization protocol, all combustion equipment in the conditioned space was turned to pilot, and the fire place dampers and doors were closed and sealed. Fireplaces were sealed using a large piece of cardboard and duct mask tape. Fireplaces were sealed during testing to prevent ashes or debris in the fireplace from being sucked into the room when a negative pressure was applied to the home.

Temperature and relative humidity

Following the safety checks, indoor, outdoor, and crawl space temperature and relative humidity readings were taken using a calibrated handheld meter. These readings were completed before proceeding with the indoor air leakage testing. As one technician was indoors preparing the equipment for air leakage testing, the second technician took the crawl space and outdoor temperature and relative humidity (RH) readings and relayed them inside so they could be recorded. When obtaining the crawl space reading, the technician put on crawl space safety gear, went into the crawl space, closing the door behind him- or herself, and moved to the center of the crawl space. The technician in the crawl space used a two-way radio to communicate the readings to the technician in the house.

Building pressure diagnostics

The goal of the following pressure testing procedure was to quantify the "holes" between the house and outside, the crawl space and the house, the air conditioning unit (the air conditioning unit included the air handler and all ducts, takeoffs, boots and registers coming from the air handler) and the crawl space that might allow moisture and airborne particle transport. To obtain these air leakage flows with the most accuracy and precision, our testing set-up included an Automated Performance Testing (APT) System with one Minneapolis Blower Door™ system for the house and another for the crawl space and one Minneapolis Duct Blaster™ system to test the air conditioning unit (ducts included) located in the crawl space. Energy Conservatory TECLOG software was used to record the data generated by the APT system.

Prior to the study, an Excel spreadsheet was created and tested during a 10 to 12 house project pilot. The spreadsheet automatically converted the binary TECLOG data files to text and calculated flows based upon fan pressure and ring configuration. The spreadsheet converted pressure measurements across either the blower door fan or duct blaster fan into flows using the calibration formulas provided in the operation manual by the Energy Conservatory.

The first steps of the pressure testing protocol call for installing a clean filter in the air-conditioning system, ensuring all ceiling and bathroom fans are turned off, closing all windows, exterior doors and attic hatches and opening all interior doors.

Equipment set up

The APT system, laptop and all pressure taps were set up according to Table 1, using the definitions illustrated in Figure 2 as a guide. Figures 3 and 4 display the blower door set up for the crawl space and the house.

TABLE 2 APT pressure tap and hose setup

Pressure Tap #	Tap Measurement	Input Hose Color	Reference Hose Color
1	House	<open tap>	Green (Outside)
2	House Blower Door	Red (Fan Pressure)	<open tap>
3	Crawl Space	Purple	<open tap>
4	Crawl Blower Door	Orange (Fan Pressure)	Purple (Crawl Space)
5	Closest Supply Duct to Air Handler	Blue	<open tap>
6	Duct Blaster	Red2 (Fan Pressure)	Clear (Fan Reference)
7	Return Duct	Yellow	<open tap>

FIGURE 2 Flow definitions for APT pressure tap setup

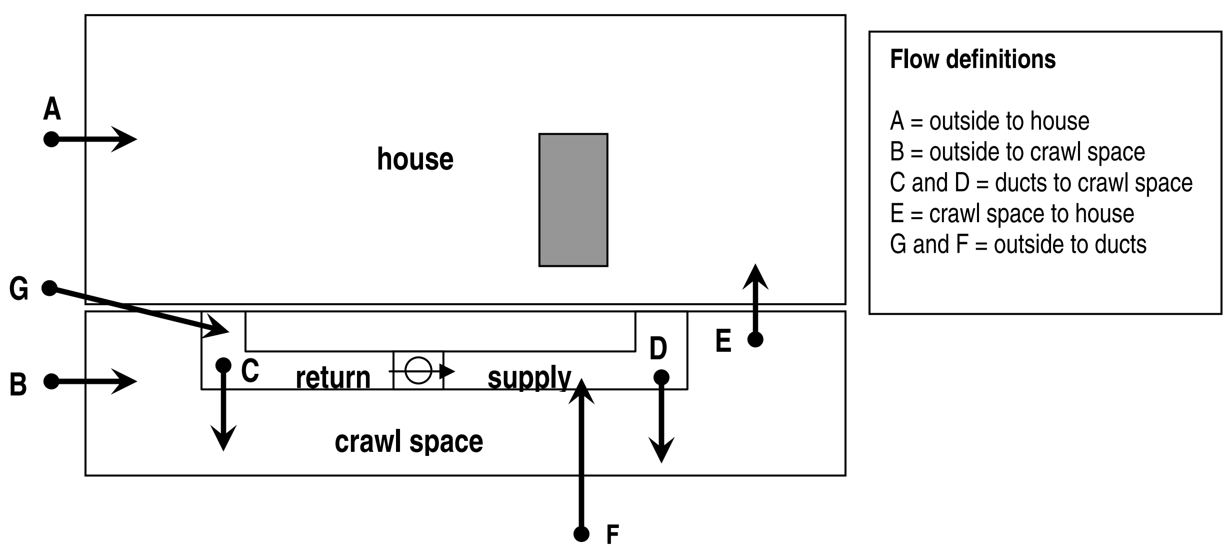
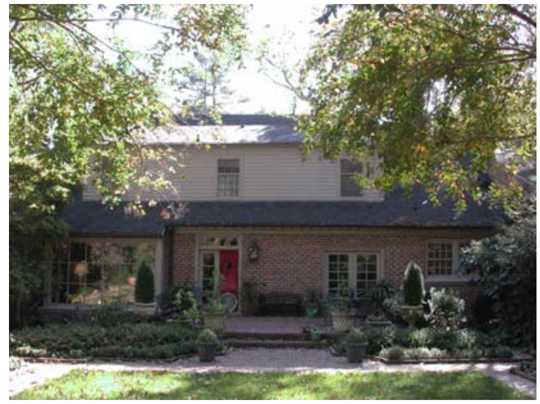


FIGURE 3 **Crawl space blower door set up**

FIGURE 4 **House blower door set up**



After the testing components and pressure hoses were set up, the following tests were run and data was recorded during minute-long intervals by the TECLOG software running on a laptop:

TEST 1 Baseline air leakage – HVAC system off

With the HVAC system and any other fans off, all windows closed and the crawl space access closed, the baseline pressures were recorded.

TEST 2 Total house air leakage – blower door test

Next the standard house leakage test was run and recorded through a blower door test (a single-point CFM50 test). After performing the single point blower door test, the fan cover was replaced before continuing further.

TEST 3 House, crawl and ducts

This test incorporated the use of three pieces of equipment. As the duct blaster and the blower door for the crawl space were installed, the floor registers and foundation vents were temporarily sealed with duct mask. The three fans were run simultaneously while the APT recorded the multi-point pressure differences. Single point pressures and ring configurations for each fan were also recorded.

In order to document the multipoint pressure differences, it was necessary that the house, crawl space and ducts be taken to -50 Pa with respect to outside. Additionally, the crawl space must be at 0 Pa with respect to the house with the house at -50 Pa with respect to outside on the TECLog display. This process is most efficient if the outside technician has a manometer to measure the crawl space-to-outside pressure. If both the crawl space and house are at -50 Pa with respect to the outside they should be at 0 Pa with respect to each other. If any location (crawl space, house or ducts) could not be brought to -50 Pa before the equipment reached its maximum setting, the weakest Pa measurement was used to balance the pressure. As an example, if the ducts can only be brought to -35 Pa, the crawl space and house should be brought to -35 Pa. The spreadsheet will use the equation in the blower door manual to compensate the air flow calculation if 50 Pa can not be reached.

TEST 4 House and ducts

The next test involved opening the crawl space door and allowing the pressure of the crawl space to stabilize with that of the outside, and then running the house blower door and duct blaster together. The house and ducts were taken to -50 Pa with respect to (WRT) the outside. For this test, the APT was still recording the air pressure within the crawl space because if the ducts or air handler were leaky and sucking air from the crawl space, a negative pressure WRT the outside and house could be recorded. If the ducts or air handler were blowing air into the crawl space a positive pressure WRT the outside and house could be recorded. Single point pressures and ring configurations were noted again. If any location could not be taken to -50 Pa, the weakest pressure for each location was used, as described above.

TEST 5 Baseline - HVAC system on

The final pressure test was completed after all the fans were taken down, all the temporary tape was removed and the air conditioning system filter was replaced. With the air conditioning system in operation, this final test measured any pressure differences in the home and crawl space caused by the use of the system.

Following the test procedure the house was flushed with outside air by opening windows and doors and turning the blower door fan on so that it would pull outside air into the house.

House description

Once the pressure testing was complete, the researchers noted points of interest on the exterior and interior of the house. Researchers created a scale drawing of the house footprint, including house orientation, structural details such as porches, decks, garages and sheds. From these, exterior footprint measurements, square footage, volume and surface area were calculated for the conditioned and some unconditioned space. Notes about house type and ceiling height were also made.

Topography and exterior water transport issues

In order to identify any topographical issues that might impact the transport of liquid water into the crawl space, researchers included the following in drawings and notes:

- All impervious surfaces within 50 feet of the house
- Direction of drainage or slope around the house
- Significant slopes or grading
- Water spigot and lawn sprinkler influences
- Standing water, erosion, or drainage issues
- Presence and conditions of gutters and downspouts and whether they drain away from the crawl space

Mechanical equipment and appliances

The heating, ventilation and air conditioning (HVAC) and other equipment details were recorded at each location. Potential condensing surfaces associated with the equipment were also recorded. This information included:

- HVAC equipment model number, manufacturer, type and location
- Location of the supply and return ducts and the air handler
- Location of condensate drain termination
- Presence and location of humidifier and/or dehumidifier
- Water heater type, location and pressure relief valve drainage
- Venting of dryer hose (none, fully vented, vented to crawl space)
- Pictures of the air handler. Depending on time and accessibility air handler components such as the drain pan, insulation, blower wheel and coil were examined for signs of water damage, dirt build up and coil fouling that would indicate the potential for mold sources originating inside the HVAC system.

Moisture history

In order to document possible causes of past or current moisture problems, data was collected to indicate wet or previously wet areas. These included visual inspections, recording air temperatures and relative humidity as well as recording surface temperatures. Significant past or current moisture problems were reported to the homeowner and photographed as well.

Visual inspection

Researchers described the location of any issues of concern and indicated the extent of the issue (significant, some, minimal). The issues of concern included, but were not limited to, the following.

TABLE 3 **Interior and exterior crawl space issues**

Crawl space interior	Crawl space exterior
Puddles on ground vapor retarder	Gutter spillover
Drip lines on the soil	Saturated soil immediately around house
Moisture discoloration on walls (front, back, left, right)	Plants next to foundation
Efflorescence salts leaching through walls	Wood rot
Condensation on duct or pipe surfaces	
Waterlogged ducts	
Signs of past plumbing leaks	
Visible mold (front, back, left, right, center)	
Wood rot	
Termite mud tunnels	
Animals, type and number	

Air temperature and relative humidity

- An air temperature reading and a relative humidity reading were taken in the middle of the crawl space, immediately outside the house, and inside the house.

Surface temperature[8]

- Using a Raytek Raynger ST20 non-contact thermometer, temperatures were recorded from spots on the ground, water pipes, ductwork and the surface of the air conditioner coil cabinet.
- The temperature of the ground was recorded by pulling back the plastic crawl space liner (if present) in a central location of the crawl space.
- In order to measure the cold water pipe line it was necessary to place a piece of black electrical tape on the pipe to decrease reflectance and then use the spot radiometer for temperature measurement.
- Black electrical tape was also used to reduce reflectance while measuring the air conditioning coil cabinet and ductwork. It was also important to be sure that the ductwork was measured away from the air handler cabinet to gain more accurate readings.

Wood moisture

To measure wood moisture content of the framing material, moisture readings and wood surface temperatures were recorded at 10 to 12 locations within the crawl space using a Delmhorst BD-2100 and a Raytek Raynger ST20 non-contact thermometer. Following each manufacturer's manual, this process included first identifying the wood species, then testing the surface temperature of each sample location before pushing the moisture meter into the wood for a reading. The general locations sampled included: the sill plate next to the crawl space access, the band joist next to the access, the floor joist next to the access below insulation, the floor joist next to the access above insulation, the sill plate at the worst or lowest location, the band joist at the worst or lowest location, the center floor joist above insulation, the center floor joist below insulation, the center beam, the floor joist at the worst location below insulation, the floor joist at the worst location above insulation and the sub floor in the middle of the floor.

[8] A Raytek Raynger ST20 non-contact thermometer was used for all surface temperature readings

Detailed locations for the measurements included:

- Sill plate and band joist next to access | Researchers determined that measurements made next to the access should be made two feet to the right or left of the access door and that sill plate measurements should be made on top of the plate halfway between the band joist and edge of the sill plate. Band joist measurements were to be taken one inch above the sill plate but below the floor insulation.
- Joist above and below insulation next to the access | The measurements at the access should be either two feet left or right from the main crawl space access and two feet from the exterior wall.
- Center joist above and below insulation | Center joist should be chosen to be the most central joist location in the house. All beam and joist measurements should be made one inch from the bottom but below the insulation and one inch from the sub floor but above the insulation.
- Sill plate, band joist and joist above and below insulation at worst or lowest point | Measurements at the lowest clearance or worst location should be made at what is determined to be the potentially worst moisture problem site. Look for other worst area measurements such as near vents or on the support beam.
- Sub floor in middle | The sub floor measurement should be made above the insulation evenly spaced between two joists approximately in the center of the crawl space.
- Other | Technicians took readings from any other site of significance regarding mold and moisture.

Foundation and crawl space construction
After the crawl space layout was recorded, details were noted on drawings, including the location of piers, height of vents above grade, percent the vents were open, number of vents, percent ground covered by vapor barrier, location of HVAC equipment, water treatment or water heating equipment, location of crawl space fans or any other mechanical equipment and condition and nominal value of insulation. The goal of this level of detail was to characterize the construction of the crawl space and to note what construction practices were used that increase or decrease moisture transport into the crawl space. Researchers recorded the following data:

- A cross sectional diagram including elevation, material details and the information below:

    - Footing type
    - Insulation
    - Sheathing
    - Vapor barrier – include gaps, percent coverage and condition (excellent, acceptable, poor)
    - Wall water proofing
    - Sill gasket or seal
    - Facade type
    - Water proofing
    - Termite flashing
    - Average height to floor joist
    - Elevations
    - Drainage system (yes, no, inconclusive) and location

- A footprint drawing including:

    - Layout of crawl space piers
    - Sump pump presence & location
    - Elevation changes between outside and inside. Starting immediately to the right of the crawl space access looking from the outside, record the distance between the earth and the bottom of the vents. Continue moving to the right to the corner or any

significant change in grade slope. Record height, mark location on drawing and approximate distance from last measurement. Continue process until measurements are made around the entire perimeter of the house and then repeat the measurements inside the crawl space going in the same direction and recording at the same locations. On the outside corners, account for the wall thickness so inside measurements line up with outside measurements.

- Calculated area and volume

Crawl space ventilation
For each crawl space vent the following was recorded in order to quantify the amount of effective crawl space ventilation.

- Vent type (fixed, manual or automatic)
- Manufacturer name or model number if found
- Dimensions in inches (typical vents are 8” by 16”)
- Clearance above the ground (measured by block/brick)
- Percent damper open (100 percent = completely open – 0 percent = completely closed)

Heating, Ventilation and Air-Conditioning (HVAC) and other equipment
Information about the first floor duct system was also noted, including ducting material and insulation levels. If more than 20 percent of the supply and/or return duct system for the first floor zone were located in the crawl space, it was concluded that the supply and/or return duct system was in the crawl space. Other equipment installed to work with the HVAC system was also noted. For crawl space duct systems, the type of ducts used and approximate square footage of voids in the duct insulation was recorded.

Crawl space insulation
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 tension wires (tiger claws) were used to mount the batts, the average wire spacing was estimated. Particular attention was paid to documenting insulation problems, such as fallen or poorly fitted batts, insulation compression, gaps, voids and bypasses. Researchers were directed to record the extent (significant, some, minimal) of each issue below.

- Insulation type (faced batt, unfaced batt, other)
- Direction the paper backing on the fiberglass insulation was facing (toward house floor, toward crawl space floor)
- R-Value
- Mounting technique (tension wires, others)
- Frequency of tension wires (per ft)
- Presence of wet insulation
- Visible unplanned holes
- Compression caused by the tension wires. Minimal/none includes less that one inch compression everywhere. Some includes between one inch and two inches and/or less than 10 percent with two inches to three inches compression. Any compression more than listed above is significant
- Fallen insulation and its quantity
- Number of batts that are hanging because of missing supports, their spacing and number of tension wires missing
- Presence of delaminated batt
- Missing insulation
- Compromised insulation at floor penetrations
- Significant bypasses

Bioaerosol/fungal spore sampling
Duke University conducted the bioaerosol/mold sampling. For this sampling, each homeowner agreed not to run the HVAC system that served the first floor for four hours prior to the sampling. In each home, a minimum of two sets of samples were taken during the test. First, before the HVAC system fan was turned on, three samples were taken. One was taken near the return grill for the HVAC system, one in the crawl space and one outside the house. Then the system fan was turned on and allowed to run for at least five minutes before two additional samples were taken, one near the return grill and one at the supply air diffuser (or register). The supply diffuser sample was collected inside a short polyethylene tube that was temporarily taped around the supply register. The tube isolated the supply air from the potential contaminant sources within the house, thus allowing characterization of the relative contribution of the HVAC system to the total bioburden within the house. The sampling was conducted by two trained indoor air quality technicians using Andersen two-stage cascade impactors, which collect and separate both non-respirable and respirable size particles. The sampler was connected to a vacuum pump calibrated to collect air samples at the rate of one cubic foot per minute. Equipment calibration was conducted at the beginning of sampling, at mid-day and at the end of the day. A sampling period of 3.5 minutes was used for the outdoor air sample and all samples collected within the houses. The sampling period for the crawl space samples was one minute. 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 back 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. Fungal identification was accomplished by macroscopic examination of colony morphology and microscopic examination of fungal elements. More information on bioaerosol/fungal sampling methodology is provided in reports submitted by Duke University.

Comments made to homeowner
Researchers documented conversations involving corrective recommendations they had with homeowners to ensure the project team had record of the discussion. Corrective recommendations were only made in the case of incidents outlined in the Appendix. Field staff also kept records of issues to include in the homeowner reports.

Install data loggers
HOBO Pro Series temperature and relative humidity data loggers were attached to floor framing in a central location in the crawl space.[9] A property notification was attached to the HOBO indicating the reason for its presence and who to contact about the device.

[9] HOBO Pro Series data loggers from Onset Computer Corporation. Model number H08-032-08

Results

Summary characterization data are described in the following section. Specific data on all variables might not have been possible to collect, so in some cases less than 45 samples are represented below. When possible, the extent of the variable was stated (poor/acceptable/excellent or minimal/some/significant). This variable classification was consistently assessed by the lead field technician. Among the recommendations stated in the future research section, one evaluation of the characterization protocol was to define each classification to ensure consistency of data. Presentation of the results follows the layout of the field checklist found in the Appendix.

Homeowner interview

Sampling timeframe and location

Thirty-eight percent of the study sampling was conducted during the humid season (May through September). The 62 percent conducted from October through December was considered to be during the non-humid season. Figure 5 shows the sampling breakout by month. Figure 6 displays the number of houses sampled in each county.

FIGURE 5 **Sampling time frame**

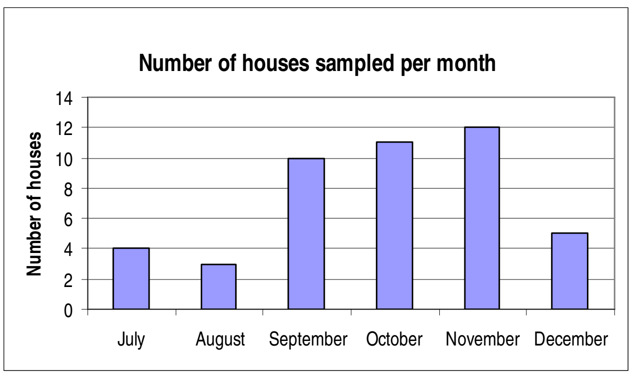
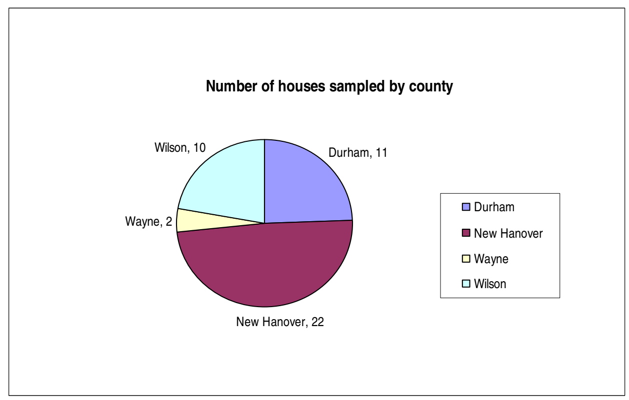


FIGURE 6 **Number of houses sampled by county**



House age and occupancy

The house ages ranged from 2 to 60 years, with 27 years being the average. The average length of occupancy in that current home was 16 years but ranged from one to 60 years. Sixteen of 45 homeowners were the original owners. Only 10 percent (four) of homeowners were involved in the construction of their homes. Three occupants per house was average for this study but ranged from one to five people per household.

Use of crawl space

Table 4 shows the frequency of crawl space usage and Figure 7 illustrates a crawl space being used for storage of paints.

TABLE 4 **Crawl space usage**

Crawl use	Never	Rarely (1/yr)	Occasionally (1/month)	Often (1/wk)	Total
#	6	24	10	4	44
% of total	14%	55%	23%	9%	100%

FIGURE 7 Gas and paint containers stored in the crawl space can release fumes that can travel through holes in the floor and ducts into livable parts of the house

Of the homeowners who used their crawl spaces, 56 percent used them for storage and 44 percent for plumbing repair or maintenance of the HVAC components, water heater or other equipment. 77 percent of homeowners did not operate their crawl space vents. The vent operation measure was based purely on responses from homeowners.

Perceived health by homeowner

Twenty-four households reported to have a family member with allergies and 13 households reported a family member with asthma. Five of these households reported both asthma and allergies.

Operation of heating and cooling systems

Table 5 displays the thermostat settings results reported by the homeowner for the winter heating and summer cooling seasons. Homeowners were asked in general, if they change their thermostats at night and how they operate HVAC fans. Responses are shown below. Heating and cooling season-specific information was not captured.

Do you change your thermostat at night?

Yes 56%
No 44%

How do you operate your HVAC fan?

On 7%
Auto 84%
Combination auto/on 9%

TABLE 5 Thermostat settings for heating and cooling seasons

Thermostat setting	Heating season (•F)	Cooling season (•F)
Average	70	75
Range	66 -79	68 - 80

House description

The majority of houses in this study were one-story ranch homes (51 percent). Forty-four percent of the homes were two-story and four percent (two houses) were one and a half stories. Figure 8 shows estimated house square footage. Twenty-five houses had brick exteriors, 14 had siding and five had a combination of brick and siding.

FIGURE 8 **Number of houses in each square footage category**

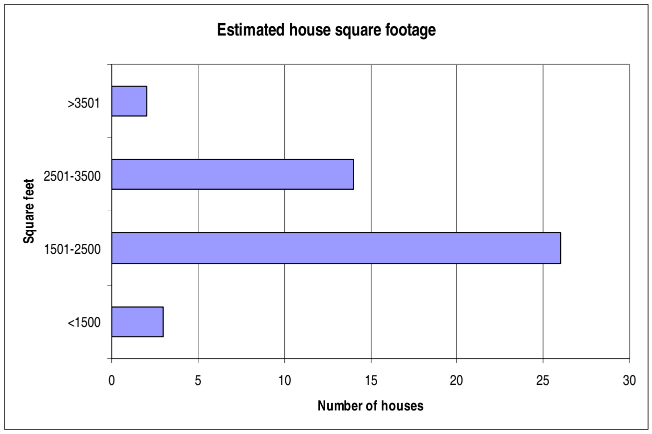


Table 6 displays the square foot area, volume and perimeter of conditioned living space (house) and the crawl space. Also shown, is the area of the unconditioned space, such as garages. These calculations were based on exterior measurements of the house and estimates on floor to ceiling height.

TABLE 6 **House and crawl space area, volume, and surface area measurements**

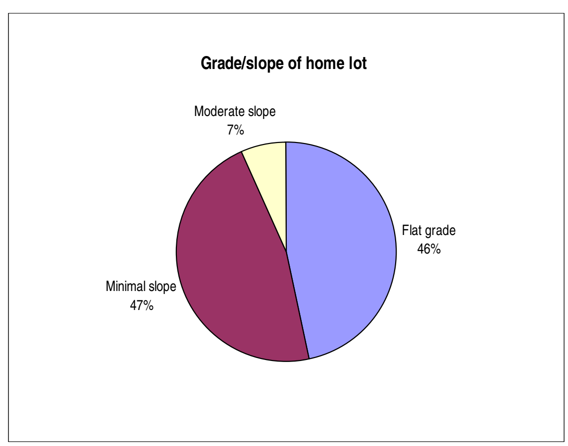
	Crawl space			Conditioned living area			Unconditioned area
	Area (ft^2)	Volume (ft^3)	Perimeter (ft)	Area (ft^2)	Volume (ft^3)	Surface area (ft)	Area (ft^2)
Mean	1551	4230	183	2299	20400	5841	489
High	2511	7104	307	4138	37056	9582	674
Low	858	2059.2	118	858	6864	2660	299

Topography and exterior water transport issues

Figure 9 shows a yard sloping toward the house. Figure 10 summarizes the grade or slope of the study home lots. Of the lots with minimal or moderate grades, 10 were sloped away from the house and 23 had slopes higher on one side of the house than the other.

FIGURE 9 **The slope of this yard into the front of the house could allow liquid water to run towards the house and its foundation.**

FIGURE 10 **Grade/slope of home lot**



Seventy-seven percent of the houses had both gutters and downspouts. This total does not indicate adequate installation of each feature, simply that both are present. Of the homes with gutters, 30 percent were observed to have gutter clogging or spillover at the time of the visit (see Figure 11).

FIGURE 11 **Clogged gutters and downspouts can inhibit free flow of water away from the house.**

Only 26 percent of the houses possessed sprinkler systems next to the house foundation. Ninety-six percent of the houses had spigots fastened to the house foundation wall. Saturated soil was visible next to the foundation of 31 percent of the houses. Eighty-four percent of the houses had plants next to the foundation.

HVAC and other equipment

Fifty-five percent of the HVAC units were heat pumps, 34 percent were gas packs, seven percent were furnace-air conditioning packs and the remaining five percent fell into the other category comprised of a geothermal and a hydronic heating coil unit.

Air handler and duct work

Thirty-three percent (15) of the houses had the air handler in the crawl space. Of these, three had condensate drains going uphill and leaking. All but one house had the supply and return ducts in the crawl space. Table 7 shows the breakdown of duct type.

TABLE 7 **Supply and return trunk and run out types**

Type	Supply trunk	Supply run out	Return trunk	Return run out
Flex	3	24	22	13
Metal-internal insulated	2	0	0	0
Metal-external insulated	19	9	7	0
Duct board	7	0	1	3
Metal uninsulated	0	5	11	8
Panned	0	0	0	0
Mixed	5	5	2	0
Total	36	43	43	24

Other equipment

Seven houses had a dryer venting into the crawl space and 34 were fully ducted to the outside. Figure 12 illustrates a dryer venting into the crawl space instead of being ducted to the outside.

FIGURE 12 This dryer was not vented to the outside and introduced lint and moisture into the crawl space.

Of the 43 houses for which there was humidifier data, two had a humidifier attached to the duct system in the crawl space. Of the 41 houses with dehumidifier data, two had a dehumidifier located in the conditioned space.

Figure 13 shows the percent of water heaters by type. Figure 14 displays water tank locations.

FIGURE 13 Percent of water heaters by type

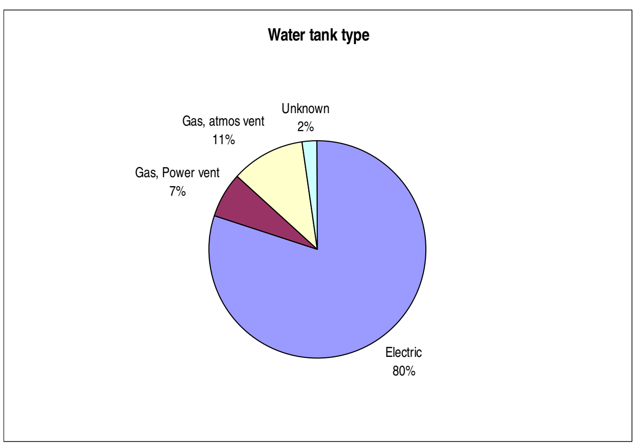
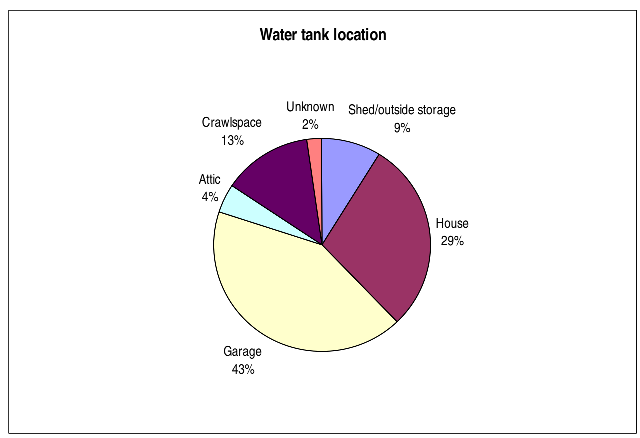


FIGURE 14 Percent of water heaters by location



Temperature and relative humidity

Table 8 represents the temperature, relative humidity and dew point data for one measurement taken at the time of visit. For long-term data refer to the Long-term Temperature and Relative Humidity Report, as part of this study.

For the houses sampled in July and August, the outside dew point temperature was higher than the crawl space dew point temperature. In September, half of the houses sampled had higher outside dew points than crawl space dew points, four houses had lower outside dew points and one house had equal crawl space and outside dew points.

TABLE 8 Temperature, relative humidity and dew point of crawl space and outside at time of visit

		Crawl space			Outdoor		
	#	Temperature (°F)	Relative humidity (%)	Dew point	Temperature (°F)	Relative humidity (%)	Dew point
July	4	74	82	68	82	75	73
August	3	73	83	68	77	80	70
September	10	81	63	67	76	71	66
October	11	71	68	60	64	73	55
November	12	65	59	50	60	58	45
December	5	67	60	53	59	64	47

Surface temperature on crawl space components

Table 9 displays the mean, maximum and minimum surface temperatures for the crawl space ground, water pipes and duct work. Table 10 shows temperature by month.

TABLE 9 Crawl space ground, water pipe and ductwork

Study temperature (°F)			
	Ground	Water pipes	Duct work
Mean	68	71	70
High	76	90	81
Low	61	61	62

TABLE 10 Crawl space ground, water pipe and duct work temperature by month

Mean temperature by month (°F)				
	# houses	Ground	Water pipe	Duct work
July	4	70	75	72
August	3	71	74	74
September	10	71	74	72
October	11	69	71	72
November	12	64	68	66
December	5	65	67	68

Surface moisture on crawl space components

- **Ground**. Two of the houses were found to have wet crawl space ground at the time of the visit. Two were borderline damp to wet, nine were damp or moist and 19 were found dry.
- **Water pipes**. One of the houses was classified as having wet water pipes while three were damp or moist and 15 were found dry.
- **Ductwork**. Of the 20 houses with information on duct work moisture, three were wet, nine were damp or moist and nine were dry. Figures 15 and 16 illustrate conditions found in a wet crawl space.

FIGURE 15 **Dark-staining in the crawl space is an indicator of long-term wetness.**

FIGURE 16 **Significant amount of water pooling along perimeter of crawl space wall**

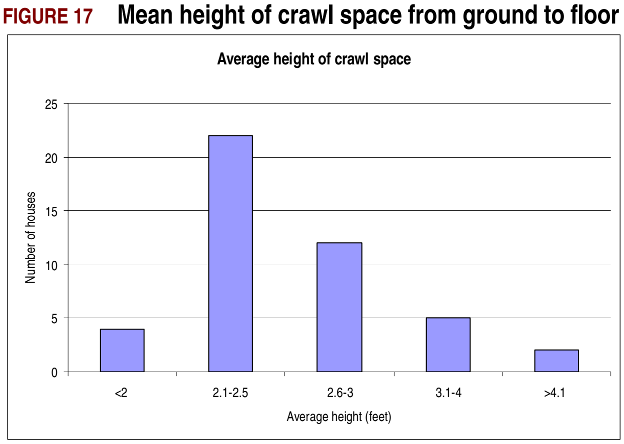
Basic crawl construction information

Table 11 shows mean, high and low measurements of crawl space area, volume, perimeter and height to floor joist. Figure 17 displays the numbers of houses with a given range of crawl space height.

TABLE 11 **Crawl space area, volume, perimeter, and height**

House #	Area (ft2)	Volume (ft3)	Perimeter (ft)	Average height to floor joist (ft)
Mean	1551	4230	183	3
Height	2511	7104	307	6
Low	858	2059	118	2

FIGURE 17 **Mean height of crawl space from ground to floor joist**



Exterior and interior of crawl space

Twenty-six crawl spaces had interior walls made of brick, 13 of concrete block and four of a brick and concrete block combination. Forty-one crawl space exteriors were made of brick and two were made with concrete block.

Crawl space components

- Figure 18 displays the percentage of houses with corresponding ground vapor retarder. Sixty-nine percent had six mil poly, four percent had four mil poly, and 27 percent had no ground vapor retarder. Table 12 below depicts the coverage of poly in the crawl space. One hundred percent lacked full coverage, 84 percent had less than 90 percent coverage. Ground vapor retarders were classified as being in poor, acceptable or excellent condition (see Figure 19 for percentages).

FIGURE 18 **Percent of crawl spaces with ground vapor retarder**

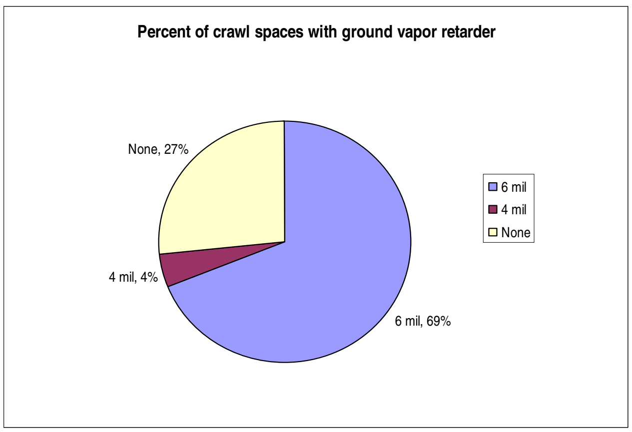


FIGURE 19 **Classification of crawl space vapor retarder condition**

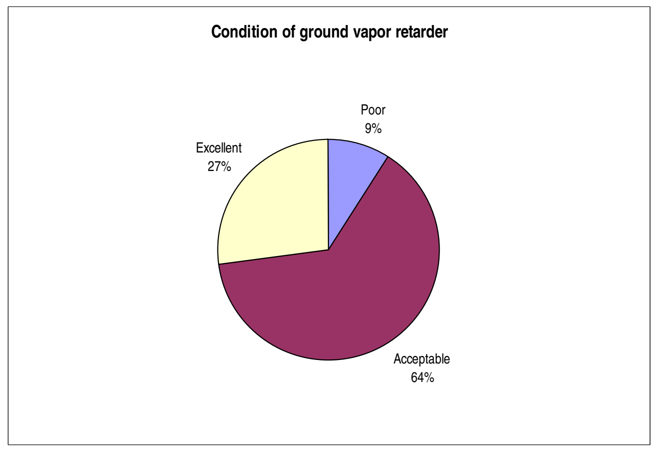


TABLE 12 **Percent of ground covered with ground vapor retarder**

% ground covered	• 50%	51-80%	81-90%	• 91%	Could not determine	Total
# of crawl spaces	20	9	8	7	1	45
% of crawl spaces	44%	20%	18%	16%	2%	100%

- Of the 28 houses for which sump pump information was obtained, 22 homes did not have a sump pump. All 33 houses for which we have sill gasket information lack a sill gasket.
- Of the 27 houses for which water proofing data was available, 25 crawl spaces did not have water proofing on the exterior.
- Of the 43 houses for which crawl space drain information was obtained, 53 percent did not have a crawl space drain.
- Thirty-one of 32 houses for which termite shield information was available had no shield.

Ventilation

The average number of vents per house was 13 with the maximum being 22 and the minimum being four vents per house. Figures 20 and 21 display the number of houses found with vents open, closed or both and the number of crawl spaces with manual/fixed and automatic vents when examined by a field technician.

FIGURE 20 **Percent of homes with crawl space vents open and closed**

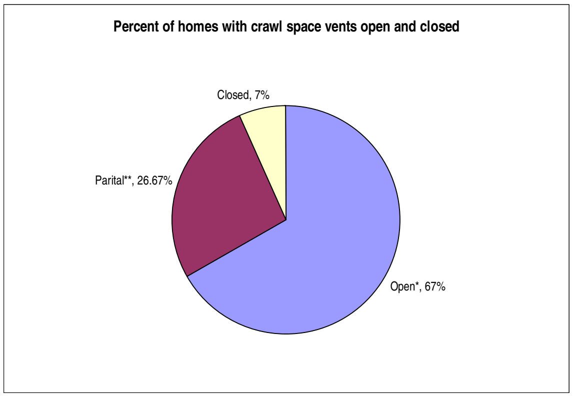
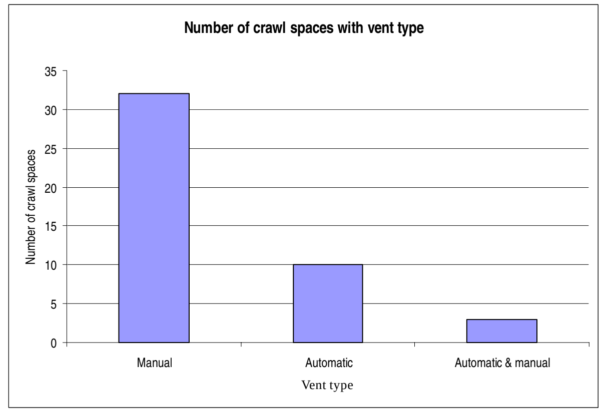


FIGURE 21 **Number of crawl spaces by vent type**



Moisture history of the crawl space

- **Gutter spillover**. See section on Topography and exterior water transport issues.
- **Saturated soil**. See section on Topography and exterior water transport issues.
- **Plants next to foundation**. See section on Topography and exterior water transport issues.
- **Ground vapor retarder**. Of the 33 crawl spaces with ground vapor retarders, 14 have puddles on the ground vapor retarder, see Figures 22 and 23.

FIGURE 22 **Percent of crawl spaces with vapor retarders with observed puddles**

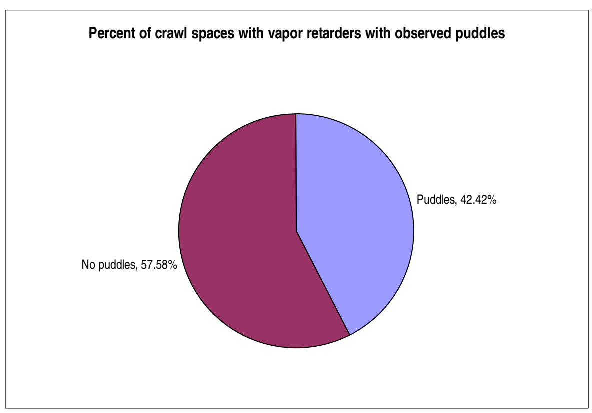
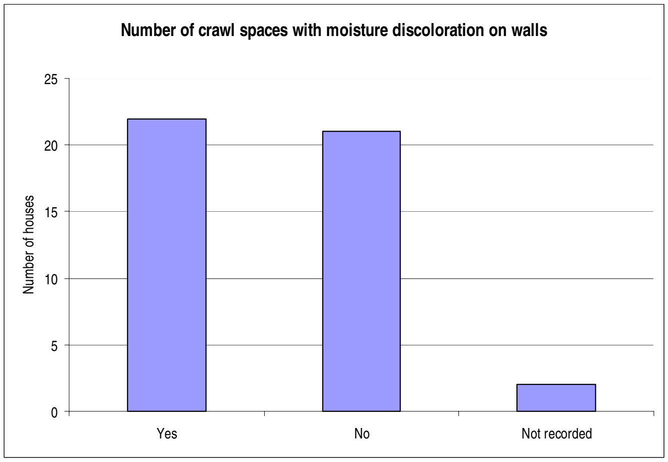


FIGURE 23 **Due to bulk water infiltration or significant dripping from condensation, water can pool on the surface of the ground vapor retarder**

- **Drip lines**. 22 percent (10) of the houses had drip lines on the soil in the crawl space at the time of sampling. Of these houses six of 10 were sampled in the humid season (June through September).
- **Discoloration**. Figure 24 illustrates a block wall with discoloration. Figure 25 shows the number of houses with evidence of moisture discoloration on the walls. Of these 22 houses, nine had discoloration on three or more crawl space walls. Data for four of these houses were not captured. Thirteen of the houses with discoloration were classified as either having significant, some or minimal discoloration; two houses had significant discoloration; six some discoloration and five minimal discoloration.

FIGURE 24 **Through capillary action liquid water is absorbed into the masonry and migrates to the surface, creating discoloration**

FIGURE 25 Number of crawl spaces with moisture discoloration on walls



- **Efflorescent salts**. Forty-four percent (19) of the crawl spaces studied had signs of efflorescent salts leaching through the walls. Of these 19 crawl spaces, seven were sampled during the humid season. Of those with efflorescence, 10 exhibited minimal evidence, four some evidence and five were not classified. Figure 26 shows efflorescent salts leaching through the foundation wall.

FIGURE 26 When water evaporates it leaves behind the efflorescent minerals that show up as whitish coloring on foundation blocks

- **Condensation**. Thirty-three percent of the houses showed condensation on duct or pipe surfaces. Twelve of the 15 houses with condensation present were sampled during the humid season.
- **Waterlogged ducts**. Sixteen percent of the houses exhibited waterlogged ducts. Of these seven homes, five were sampled in the humid season.
- **Plumbing leaks**. Thirty-one percent of the houses were found to have plumbing leaks at time of the visit. Figure 27 illustrates the problem plumbing leaks could cause on wood surfaces.

FIGURE 27 **A plumbing leak led to saturated and rotting wood framing and sub floor**

- **Visible mold (fungi)**. Figure 28 illustrates the percentage of houses noted to have visible mold. The determination of presence of mold was by visual inspection only. Fungal spore counts conducted by Duke University can be found below in the Bioaerosols – fungal spores section**.** Of the 62 percent (28) of houses with visible mold noted, 10 had minimal amounts of mold, seven had some amounts of mold, two had significant amounts of mold and nine were not classified. Twelve of 28 houses with mold were sampled during the humid season; 19 had mold located in the center of the crawl space. Of the crawl spaces that had visible mold in only one location, 79 percent recorded that location as the center of the crawl space. Figures 29 and 30 show growth on a floor joist.

FIGURE 28 **Percent of crawl spaces with visible mold**

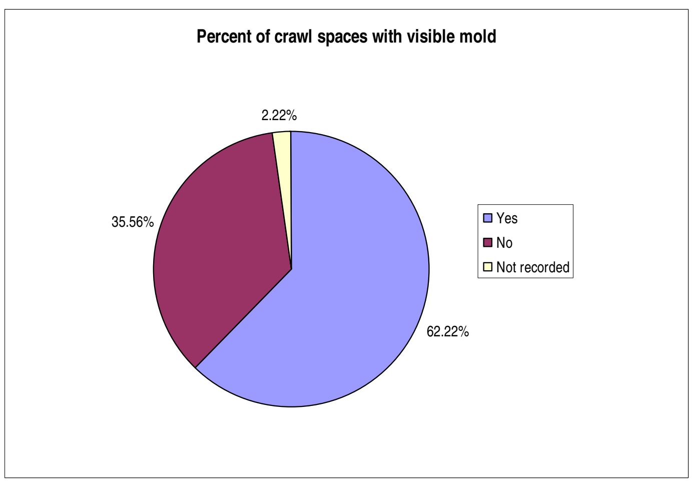


FIGURE 29 **Visible mold growth on floor framing**

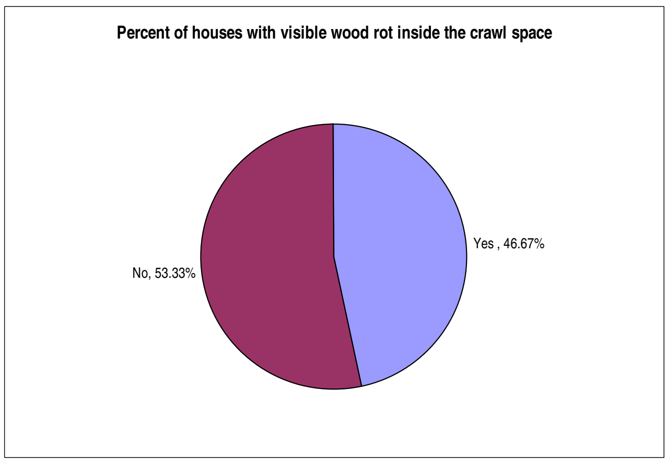
FIGURE 30 **The wood moisture meter reading of 20.6 is at mold-forming levels and could explain the growth on the wood framing**

- **Wood rot**. Figures 31 and 32 illustrate crawl spaces with wood rot. Figure 33 shows the percentage of crawl spaces that have visible wood rot inside the crawl space. Twenty-two percent had wood rot external to the crawl space.
    - The county breakdown of crawl space wood rot was as follows: seven in Durham, 10 in New Hanover, none in Wayne and four in Wilson.

FIGURE 31 **A pen is able to penetrate the rotted sub floor**

FIGURE 32 **The rot illustrated in this picture could have resulted from a condensation event**

FIGURE 33 **Percentage of houses with visible wood rot inside the crawl space**



- **Termite tunnels**. Two of the crawl spaces were found to have termite tunnels.
- **Animals and insects.** Thirty-six percent of crawl spaces were found to have evidence or sightings of animals. Most frequently seen were insects (crickets, roaches, other) and frogs, and evidence of rats, cats, a bird and a snake. Figure 34 displays a spider found in a crawl space.

FIGURE 34 **Bugs were commonly seen in crawl spaces. Camel crickets were the most frequently found.**

Wood moisture

Table 13 shows the results of wood moisture meter readings for all houses. The table displays the number of readings at the mold-supporting level (•19 percent) and at the wood rot-supporting level (• 25 percent).[10] Figure 35 displays the wood moisture meter reading maxed out in a moisture-ridden floor joist. Figures 36 and 37 display wood moisture meter readings indicating mold growth and wood rot by county and month respectively.

TABLE 13 **Percent and number of wood moisture meter readings indicating potential for mold growth and wood rot**

	# readings for all houses			% of readings	
Location	**Potential for mold growth (• 19%)**	**Potential for wood rot (• 25%)**	**Total**	**Potential for mold growth (• 19%)**	**Potential for wood rot (• 25%)**
Sill (access)	6	0	37	16%	0%
Joist (access)	5	0	45	11%	0%
Joist (access, below insulation)	11	0	45	24%	0%
Joist (access, above insulation)*	3	0	36	8%	0%
Center joist (below insulation)	17	4	43	40%	9%
Center joist (above insulation)*	4	2	34	12%	6%
Sill (worst)	11	1	34	32%	3%
Joist (worst)	13	4	43	30%	9%
Joist (worst, below insulation)	20	7	43	47%	16%
Joist (worst, above insulation)*	10	3	35	29%	9%
Sub floor	13	7	43	30%	16%
Other worst	17	8	29	59%	28%
Total	**130**	**36**	**467**	**28%**	**8%**

* For houses with no insulation in the floor, there was not an above-insulation wood moisture reading. A reading was taken for below insulation.

[10] Moisture Control and Prevention Guide. N.C. State University and North Carolina A&T University Cooperative Extension. 1998.www.ces.ncsu.edu/depts/fcs/housing/pubs/fcs486.html.

FIGURE 35 **The wood moisture meter reading is maxed out at 99.9, well over mold and rot-forming levels. The surrounding insulation is sopping wet.**

67 percent of all houses have wood moisture meter readings at mold-supporting levels (•19 percent)

36 percent of all houses have wood moisture meter readings at wood rot-supporting levels (• 25 percent)

FIGURE 36 **Wood moisture meter readings indicating potential for mold growth and wood rot by county**

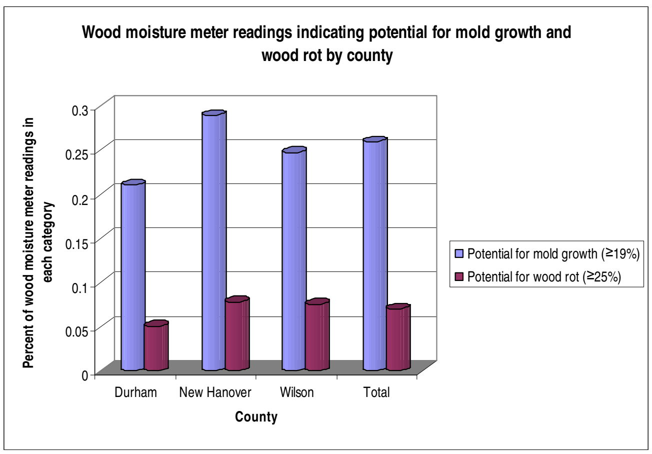
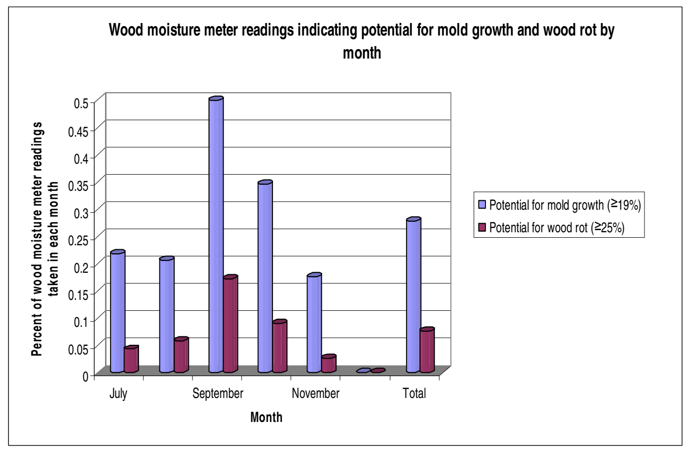


FIGURE 37 **Wood moisture meter readings indicating potential for mold growth and wood rot by month**



Crawl space insulation

Presence

Eighty percent of the crawl spaces have insulation under the subfloor in the crawl space. Sixteen percent had no insulation and four percent (two crawl spaces) had insulation on the foundation walls, although the walls were still vented. Of the crawl spaces with subfloor insulation, 26 houses had Kraft-faced batts and 10 had unfaced batts. Of the 26 crawl spaces insulated with Kraft-faced batts, 23 had insulation facing toward the house floor, two toward the crawl space floor and one crawl space had some of the Kraft facing oriented both directions. Twenty houses had an estimated value of R-19 and 16 had an estimated value of less than R-19.

Installation

All crawl spaces with floor insulation used tension wires (tiger claws) as the mounting technique. Most tension wires (22 crawl spaces) were mounted every 2 to 3 feet. Two houses used tension wires every 1 to 2 feet, eight houses fastened every 3 to 4 feet and one house rarely had tension wires, mounting them every eight feet. A full assessment of one house could not be completed due to the safety hazard associated with the presence of snake skin. As a result, the following characterizations are based on 35 instead of 36 houses with insulation in the floor:

- 26 percent of insulation was found wet (see Figure 38 for an illustration)
- 60 percent of insulation had visible unplanned holes

- 23 percent of insulation had significant compression due to tension wires (57 percent some, 20 percent minimal/none)
- 60 percent had some fallen insulation (see Figure 39 for illustration)
- 71 percent had some hanging batts
- 54 percent had some delaminated batts (see Figure 39 for illustration)
- 74 percent had compromised insulation at band joist
- 26 percent had compromised insulation at floor penetration (see Figure 40 for illustration)
- 11 percent had insulation with significant bypass

FIGURE 38 Floor joists, surrounded by wet insulation, display fungal growth on the wood framing.

FIGURE 39 Fallen insulation reveals a floor penetration.

FIGURE 40 Fallen insulation found on crawl space floor.

Air leakage

Monitoring air leakage between various parts of the home helps determine the potential for transport of air and airborne contaminants. Three leakage paths were measured in this study: total house air leakage, air leakage between the house (living space) and crawl space and air leakage between the duct work and crawl space. Each leakage path is measured in cubic feet per minute at 50 Pascals (CFM 50). From these measurements, an equivalent hole size was calculated as a way to help visually understand the leakage.

Total house air leakage

Total house air leakage quantifies the amount of air leakage resulting from holes in the building envelope, measured in CFM 50. This measurement was achieved using calibrated fans to reach 50 Pascals of pressure difference between the inside and outside of the house.

CFM 50 per square foot of surface area

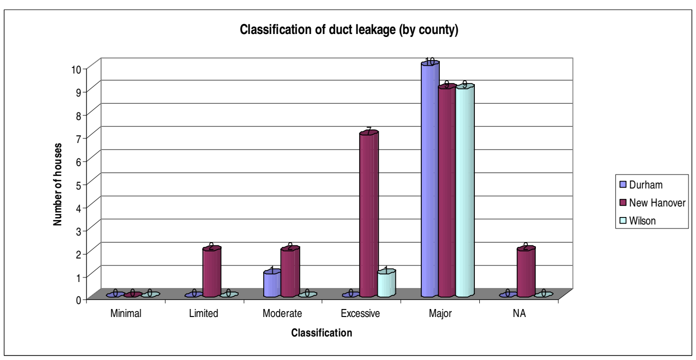
Researchers typically measure total house air leakage in CFM 50 per square foot by dividing the CFM 50 reading by the total surface area of the house measured in square feet.[11] Using a standard building science scale, the CFM 50 per square foot results have been classified according to the scale in Table 14.

TABLE 14 Classification of CFM 50 per square foot of surface area

CFM 50 per square foot of surface area	Classification
<0.25	Minimal
0.26-0.45	Limited
0.46-0.60	Moderate
0.61-0.75	Excessive
>0.76	Major

Thirteen percent (six) of the houses had major leakage, 20 percent (nine) had excessive leakage, 42 percent (19)had moderate leakage, 24 (11) percent had limited leakage and zero percent had minimal leakage. Figure 41 shows the breakdown of these classifications by county.

FIGURE 41 Classification of total house air leakage by county



Equivalent hole size

The mean equivalent hole size for total air leakage was three square feet with a range of 1.2 to 8.1 square feet. A breakdown by county is in Table 15.

[11] CFM 50 per square foot is a common measurement used by Advanced Energy in assessing building performance.

TABLE 15 Total air leakage equivalent hole size by county

Equivalent hole size (ft^2)	Mean	High	Low	# of houses
All counties	3.0	8.1	1.2	45
Durham	2.9	4.0	2.2	11
New Hanover	3.0	5.4	1.2	22
Wayne	1.9	2.2	1.6	2
Wilson	3.3	8.1	1.3	10

Crawl space to house air leakage
This leakage path quantifies the amount of air exchange resulting from holes in the floor between the crawl space and house. Air exchange between the crawl space and house can allow contaminants, such as mold spores and water vapor, to enter livable parts of the house through these holes, affecting indoor air quality and potentially leading to moisture issues.

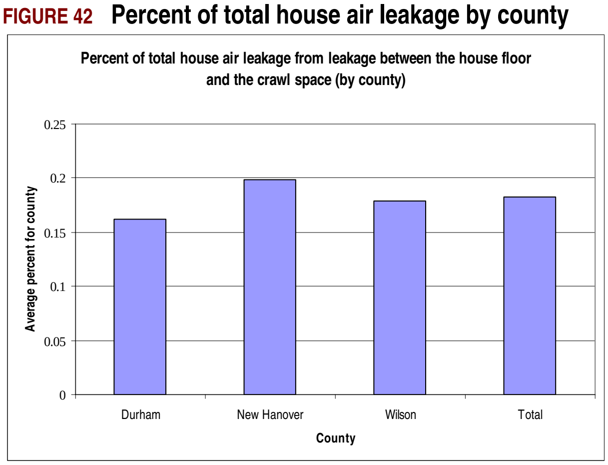
Percentage of total house air leakage
This measurement represents how much of the total house air leakage is from the crawl space through holes in the house floor. A standard building science scale does not exist for this measurement. Summary findings for this measurement are in Table 16. Figure 42 shows the county breakdown of this measurement.

TABLE 16 Percent of total house air leakage from the crawl space

% of total house air leakage	# Houses
31-40%	3
21-30%	13
11-20%	18
0-10%	6
No results due to inability to reach target pressure*	5
Total	45

* These five houses were too leaky to reach target pressure

FIGURE 42 Percent of total house air leakage by county



Equivalent hole size

The mean equivalent hole size for air leakage between the house and crawl space was 0.5 square feet with a range from 0-2 square feet. A breakdown by county is in Table 17.

TABLE 17 House to crawl space air leakage equivalent hole size by county

Equivalent hole size	Mean	High	Low	NA*
All counties	0.5	2.0	0.0	5
Durham	0.5	1.1	0.1	1
New Hanover	0.4	1.3	0.1	4
Wayne	0.3	0.5	0.2	0
Wilson	0.6	2.0	0.0	0
*NA indicates numerical data could not be calculated due to difficulty in reaching target pressure.				

Air leakage in crawl space ducts

Air leakage in crawl space ducts represents the amount of air in CFM passing through holes or gaps in the ductwork. This measurement is achieved using calibrated fans to achieve 25 Pascals of pressure difference between the inside and outside of the ductwork. Figure 43 illustrates a source of duct leakage.

FIGURE 43 A broken supply leads to duct leakage, introducing crawl space air into the livable parts of the house.

CFM 25 per square foot of floor area

By dividing the CFM reading by the house floor square footage served by the system, the houses can be compared using the standard CFM25 per square foot scale shown in Table 18. Figure 44 displays the percentage of houses that fall into each classification. Figure 45 shows the number of houses by county in each of the classifications.

TABLE 18 Classification of duct leakage

Percentage	Classification
< 3%	minimal
3.1-5%	limited
5.1-8%	moderate
8.1-12%	excessive
> 12%	major

FIGURE 44 **Percent of houses in each duct leakage classification**

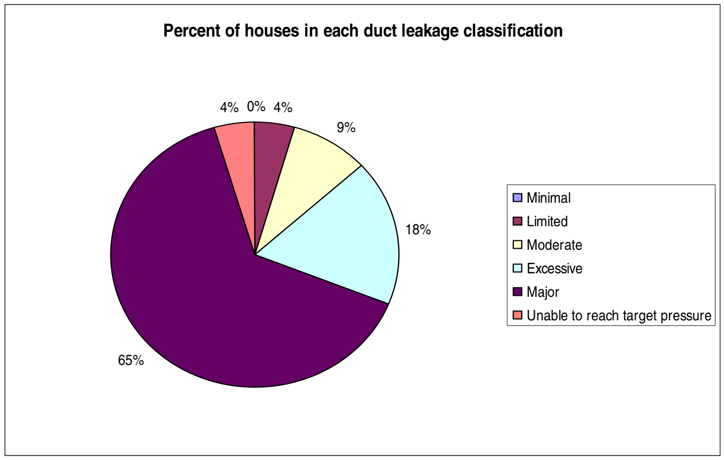
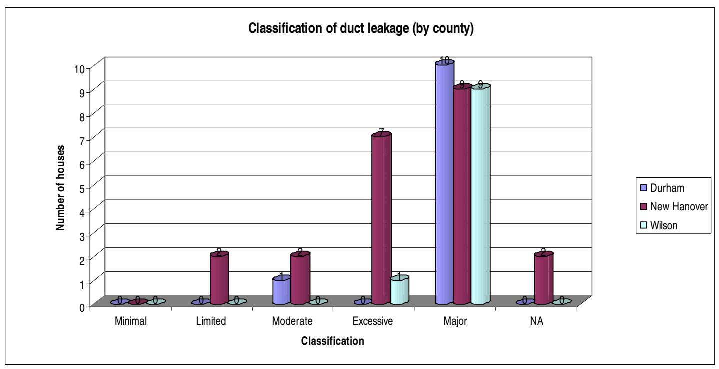


FIGURE 45 **Classification of duct leakage by county**



Equivalent hole size

Table 19 displays the hole size corresponding to the leakage from crawl space ducts.

TABLE 19 **Percent of houses in each duct leakage classification Equivalent hole size solely from crawl space ducts**

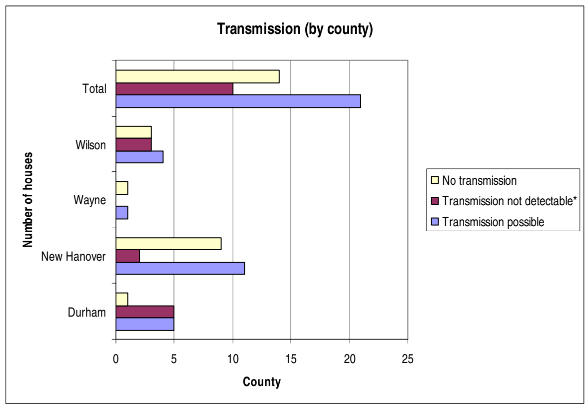
Of total hole size, equivalent hole size solely from crawl space ducts (ft2)	Mean	High	Low	NA	# of houses
All counties	0.4	1.5	0.1	2	45
Durham	0.5	1.4	0.1	0	11
New Hanover	0.3	1.5	0.1	2	22
Wayne	0.2	0.3	0.1	0	2
Wilson	0.4	0.8	0.1	0	10

Transmission of air

Initial assessment of transmission of crawl space air and its contaminants, including fungal spores and moisture vapor, into the living space was determined to be present if two conditions held true. First, the concentration of the fungal samples had to be higher in the living space once the HVAC system was turned on compared to the level of spores with the HVAC system off. Second, the mix and rank order of the indoor samples with the HVAC system running shifted to reflect the dominant mold species present in the crawl space sample and the rank order of species was different from the outdoor sample. If only one condition held, the house was classified as “transmission not detectable” and if neither condition held true, the house had no transmission.

Transmission of air and its contaminants was present in 21 of the houses characterized (47 percent). In 10 (22 percent) houses, transmission was not detectable or rather only one of the two conditions held true. No transmission was found in 14 or 31 percent of the houses. Figure 46 shows transmission by county.

FIGURE 46 Transmission by county



Bioaerosols – fungal spores

Bioaerosol samples provide an evaluation of the total number of breathable fungal spores, reported in colony forming units per cubic meter of air and the most common species of mold found. Table 20 shows the summary of bioaerosol results by the possibility of transmission and sample location. Figure 47 displays the bioaerosol levels for houses with the possibility of transmission. Figure 48 illustrates bioaerosol levels for all houses by location.

TABLE 20 **Summary bioaerosol results**

Sample	# Observ.	Mean	Std. Dev.	Max	Min
Transmission possible (B)			In CFU/m3		
Crawl space (HVAC off)	21	**30163**	16230	41146	1348
Indoor (HVAC off)	21	861	1233	5802	146
Outdoor(turn on HVAC here)	21	3235	3862	11756	349
Indoor (HVAC on)	21	1761	2425	11756	373
Diffuser(HVAC on)	21	1822	2607	11756	166
Transmission not detectable (A)			In CFU/m3		
Crawl space(HVAC off)	10	161	508	1607	0
Indoor (HVAC off)	10	55	173	548	0
Outdoor(turn on HVAC here)	10	2033	2524	8418	40
Indoor (HVAC on)	10	176	556	1759	0
Diffuser(HVAC on)	10	1415	2282	11756	0
No transmission (C)			In CFU/m3		
Crawl space(HVAC off)	14	16041	15144	41146	105
Indoor (HVAC off)	14	1323	3045	11756	71
Outdoor(turn on HVAC here)	14	3427	4630	11756	146
Indoor (HVAC on)	14	645	765	3219	124
Diffuser(HVAC on)	14	556	1101	4326	71
All homes			In CFU/m3		
Crawl space(HVAC off)	45	19102	18179	41146	0
Indoor (HVAC off)	45	825	1911	11756	0
Outdoor(turn on HVAC here)	45	3027	3836	11756	40
Indoor (HVAC on)	45	1061	1837	11756	0
Diffuser(HVAC on)	45	1062	2011	11756	0

FIGURE 47 **Mean bioaerosol levels for houses with transmission possible**

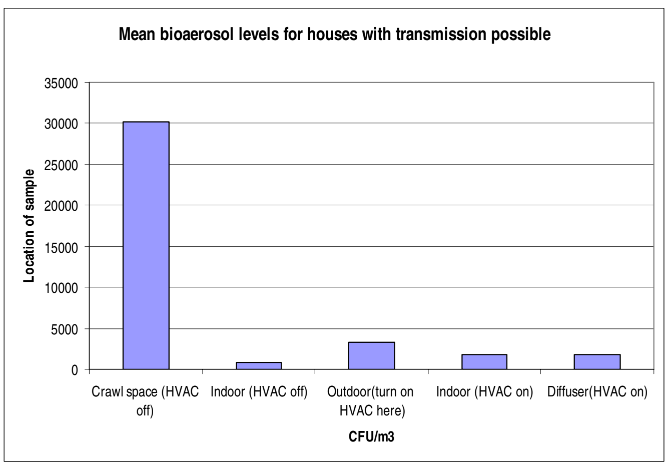
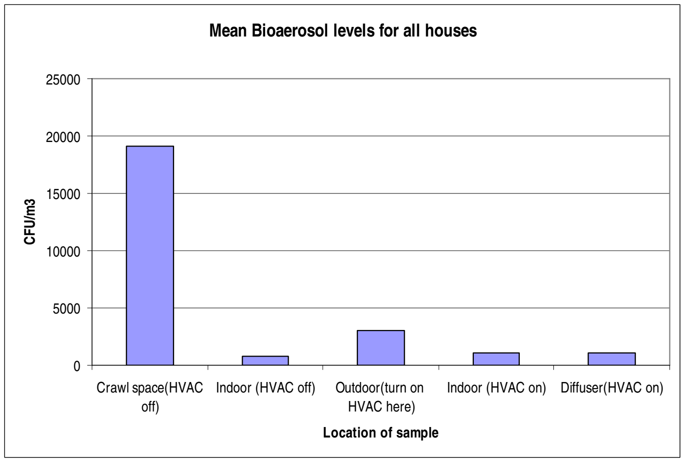


FIGURE 48 **Mean bioaerosol levels for all houses (by location)**



Discussion

This study was purely an observational study. The measurements reviewed below demonstrate the failures associated with typical wall vented crawl spaces in North Carolina.

Vented crawl spaces have moisture problems
According to the results of this study, crawl spaces were wet to the point of failure in a variety of ways: moist outdoor air was entering the crawl space and high percentages of crawl spaces had evidence of past or present liquid water intrusion through visible wood rot, visible mold, efflorescent salts leaching through the foundation walls and discoloration.

Moist outdoor air is entering the crawl space
The concept of venting crawl spaces with outdoor air assumes that the outside air will be drier than crawl space air and help dry out the crawl space upon entry. This study indicates that during humid months this is not an accurate assumption. As shown by dew point temperatures in Table 21, outside air in the humid months of July, August and part of September was actually wetter than the crawl space air. This means, in humid months, wet outdoor air was entering the crawl space and condensing on surfaces with temperatures at or below the dew point. Further exploration of the relationship between dew point and condensation potential can be found in the Long-term Temperature and Relative Humidity report.

TABLE 21 **Dew point temperatures**

Sampling month	#	Crawl space dew point	Outdoor dew point
July	4	68	73
August	3	68	70
September	10	67	66
October	11	60	55
November	12	50	45
December	5	53	47

Crawl spaces commonly had wood rot
Forty-seven percent of all sampled crawl spaces had visible wood rot. Thirty-six percent of houses have wood moisture meter readings at wood rot-supporting levels of 25 percent or greater. Some of the difference in observed wood rot and wood moisture meter readings could be due to houses with water leaks that lead to wood rot. Of the 21 (47 percent) crawl spaces with wood rot, 11 had a plumbing leak. Regardless, both percentages represent a significant number of houses with wood rot.

Sixty-two percent of crawl spaces had visible mold
Twenty-eight (62 percent) of the crawl spaces were observed to have visible mold (fungi). Sixty-seven percent (30) of the crawl spaces had wood moisture meter readings at mold-supporting levels of 19 percent or greater. Given the fact that mold forms require significant moisture to grow, the presence of mold indicates the presence of water.

Crawl spaces had efflorescent salts and discoloration as indicators of past and present liquid water
Forty-nine percent of houses sampled showed moisture discoloration on walls and 42 percent had efflorescent salts leaching through the foundation walls. Both of these measures are leave-behind indicators of the presence of water in a wall system. Through capillary action liquid water is absorbed into the masonry and migrates to the surface, creating discoloration. When the water evaporates, it leaves behind the efflorescent minerals. The fact that efflorescent salts and discoloration were present is an indication of past or present water in the crawl space.

Crawl spaces contained contaminants that may be harmful to people's health
The fungal counts (bioaerosol results) showed higher levels of colony forming units in the crawl space than other locations sampled, especially outdoor samples (see Table 22). Fungal spores were present in the crawl space. This is consistent with the visible mold in the **Vented crawl spaces have moisture problems** section.

TABLE 22 **Mean spore count for crawl space and outside samples**

	# houses	Crawl space (CFU/m3)	Outside (CFU/m3)
Transmission possible	21	30,163	3,235
Transmission not detectable	10	161	2033
No transmission	14	16,041	3,427
All homes	45	19,102	3,027

The crawl space and living space were connected through holes in the floor
The average equivalent hole size measured between the crawl space and the livable parts of the home was 0.5 square feet. The majority of houses (31) had somewhere between 11 percent and 30 percent of their total house air leakage coming from holes in the floor between the crawl space and the house. These measurements indicate that the crawl space and living space are connected through holes in the floor.

Pressures drive air across the holes between the crawl space and living space
The summary of total house air leakage as illustrated in Table 23 shows that 72 percent of the houses tested had moderate, excessive or major air leakage. As stated above, the majority of houses had 11-30 percent of this leakage coming through holes in the floor from the crawl space to the house. The rest of this air leakage (70-89 percent for the majority of houses) was taking place above the crawl space. Through the stack effect, warm air in the house rises and exits through holes in the ceiling and upper walls. Cool air is then drawn through holes in the floor and lower walls, brining contaminants (fungal spores, water vapor) from the crawl space along. Natural building physics is a cause of air movement between the crawl space and living space.

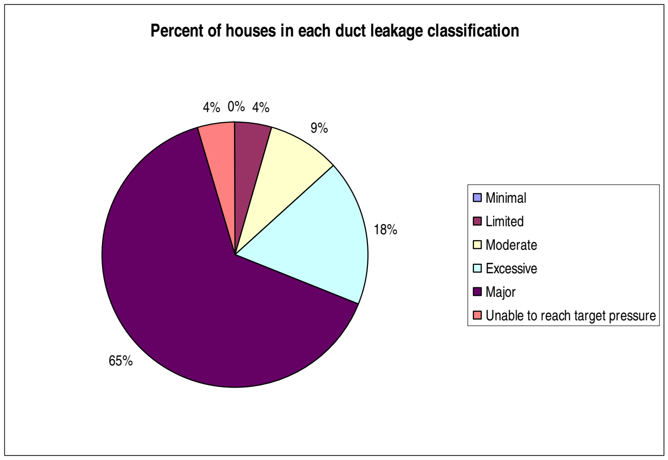
TABLE 23 **Classification of total house air leakage**[12]

Classification	% of houses
Major	13%
Excessive	20%
Moderate	42%
Limited	24%
Minimal	0%

The duct systems were very leaky, therefore, introducing crawl space air and its contaminants to livable parts of the home. Sixty-five percent of houses had major duct leakage (see Figure 49 for a summary of duct leakage). Return duct leaks pull in airborne pollutants, spores and water vapor into the duct work and redistribute these indoor air quality hazards into the livable parts of the house. Supply duct leaks cause the house to pull crawl space air through holes in the floor. When the HVAC system is on, causing air to be distributed through the leaky ductwork, it is a mechanical force causing crawl space air to be introduced to livable parts of the home.

[12] Does not equal 100% due to rounding.

FIGURE 49 **Percent of houses in each duct leakage classification**



Crawl space contaminants were entering the livable parts of the house

In 47 percent of houses sampled, transmission of fungal spores between the crawl space and living space could be confirmed by bioaerosol measurements. As described in the previous two sections, the house and the crawl space were connected through holes in the floor and duct forces were present to drive air across the holes. Therefore, fungal spores and water vapor in the crawl space were being introduced through these holes into the livable parts of the house, even when bioaerosol sampling could not confirm the transmission.

Conclusion

This study was intended to more completely document moisture characteristics of typical wall vented crawl spaces as well as to measure their importance as sources of mold in the living space. By documenting the performance of wall vented crawl spaces in North Carolina, this study confirmed that crawl spaces experience mold and moisture problems that can result in indoor air quality problems. These problems can be introduced from the crawl space into livable parts of the house through measured holes, by natural building physics and by mechanical forces created by HVAC systems.

According to dew point analysis, outside summer air had more water than crawl space air, offering no drying potential for the crawl space. In fact, current construction practice could result in a number of issues such as those found in the sample houses:

- 49% had moisture discoloration
- 62% had visible mold
- 67% had wood moisture meter readings at mold-supporting levels; 36% had wood moisture meter readings at wood rot-supporting levels

Sampling indicated the existence of higher numbers of colony forming units of fungal spores in the crawl space than outside, an indication that crawl spaces contained contaminants that could be harmful to people's health. This also confirms the observed visible mold in 62 percent of the crawl spaces sampled.

Building pressure diagnostics documented that on average, there was a hole on the order of 0.5 square feet between the crawl space and living space. The presence of these holes confirms that the crawl space and the living space are connected. For the majority of houses sampled, crawl space to house air leakage represents 11-30 percent of the total house air leakage. The remaining 70-89 percent of air leakage occurs above the crawl space where natural building physics of the stack effect and very leaky ducts introduce contaminated crawl space air to the livable parts of the house. Natural building pressures and mechanical HVAC systems are two drivers causing air to be moved across the holes in the floor between the crawl space and the house.

Analysis of bioaerosol samples determined that fungal spores were being transmitted from the crawl space to the house in 47 percent of houses. Therefore, crawl space air and its contaminants, both fungal spores and water vapor, are being introduced into livable parts of the home.

This study combined the documentation of available paths, driving forces, measured transmission and characteristics that support growth and delivery of contaminants (fungal spores and moisture vapor) from the crawl space to the livable parts of house. When these characteristics exist together, the study indicates that contaminants present in the crawl space are being transmitted through holes in the floor by natural or mechanical forces to the livable parts of the home. This situation exposes occupants to potentially harmful crawl space contaminants. These results show that crawl spaces are important sources of mold in the home environment. At minimum improved wall vented crawl spaces construction should be used. Although, this improvement will not address the air borne water vapor sources that will cause problems. To fully address the crawl space moisture issues identified in this study, closed crawl space foundations construction techniques would be necessary.

Appendices

I Sample homeowner report
II Pictures from homeowner reports
III Advanced Energy characterization protocol instructions
IV Advanced Energy characterization protocol checklist
V Homeowner consent forms
VI Evaluation of characterization protocol and lessons learned
VII Future research questions and observations