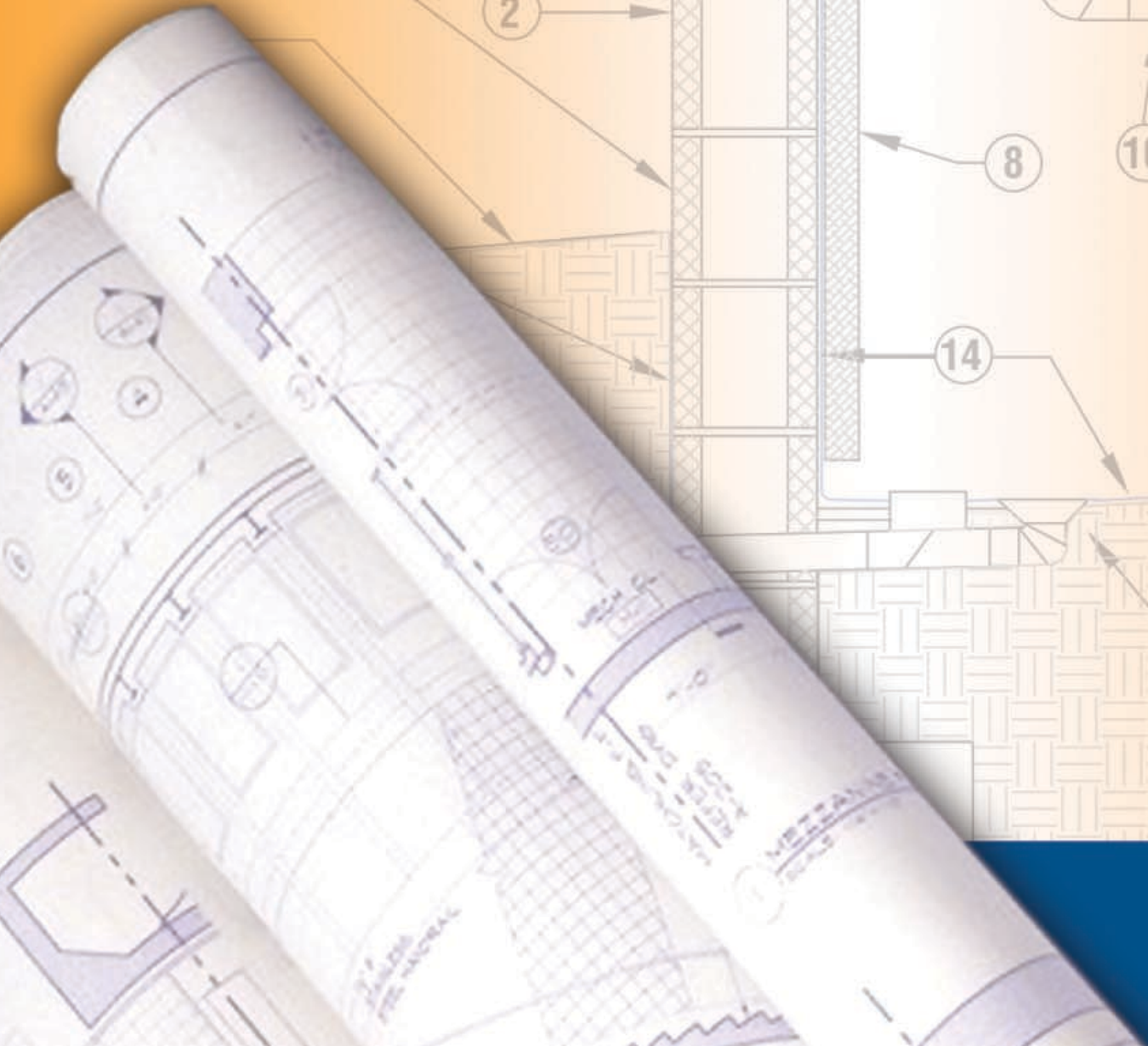
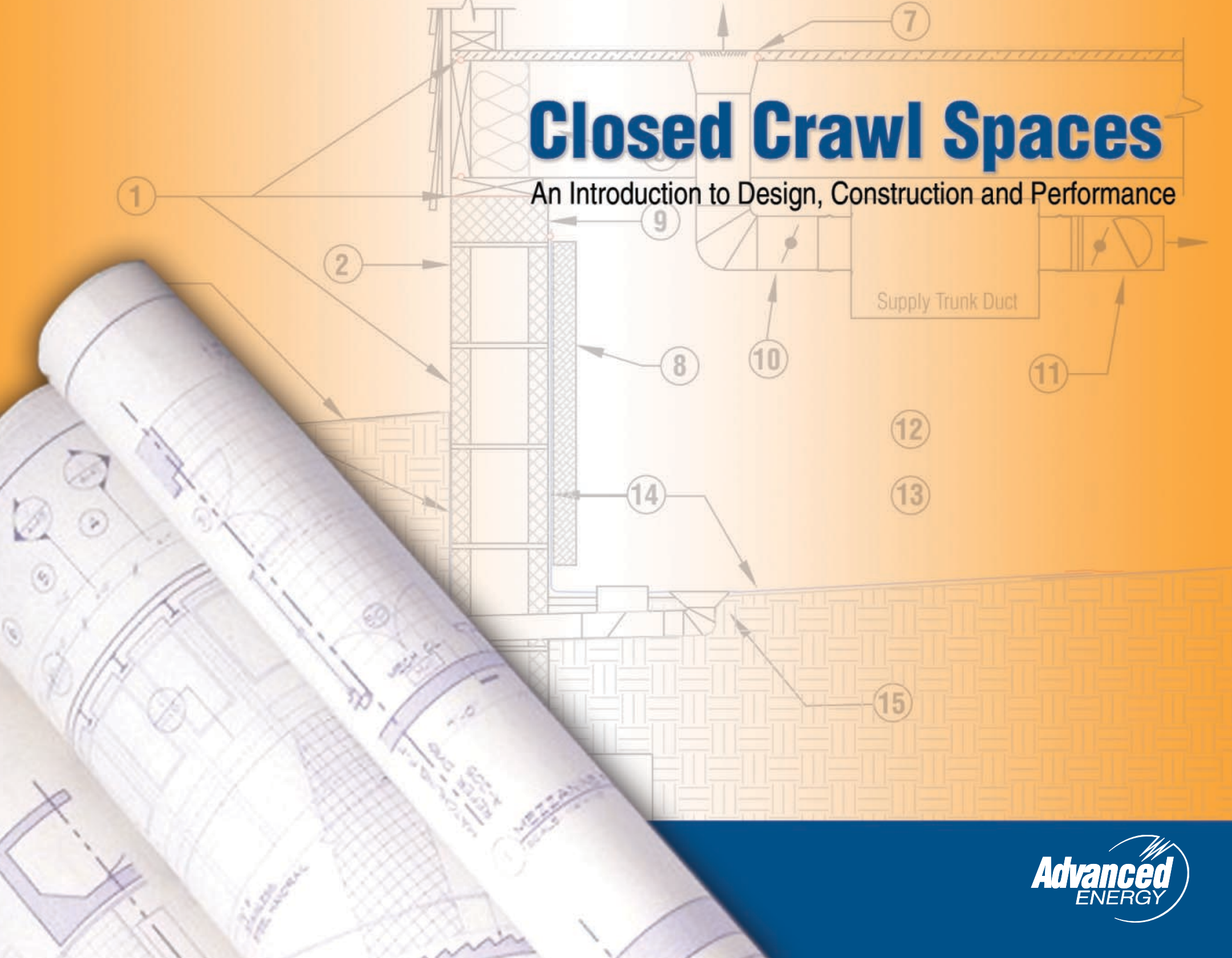


Closed Crawl Spaces

An Introduction to Design, Construction and Performance



CLOSED CRAWL SPACES

An Introduction to Design, Construction and Performance



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INTRODUCTION

This guide is an introduction to the design components, field implementation, code requirements, and measured performance of crawl space construction in central and eastern North Carolina. While a short section describes steps that builders or property owners can take to improve traditional wall-vented crawl spaces, the majority of this guide focuses on a new design: closed crawl spaces that are not ventilated with outside air.

Many of the guidelines and much of the background information presented in this guide comes from the results of an ongoing Advanced Energy research project, started in the eastern North Carolina town of Princeville in 2001. The Princeville research project compares the performance of wall-vented and closed crawl space foundations in a controlled study. Additional recommendations come from other Advanced Energy research projects, including investigations of crawl space failures, and from collaboration with closed crawl space installers across North Carolina.

The Princeville research project has shown that closed crawl spaces do a much better job of controlling crawl space moisture levels than do well-built wall-vented crawl spaces. While relative humidity in the wall-vented crawl spaces exceeds 80% for the majority of the spring and summer months, the Princeville closed crawl space designs control relative

humidity below 65% during the same period. The research also shows that the homes built on closed crawl spaces save up to 15% on annual energy usage for heating and cooling when compared to the homes built on wall-vented crawl space foundations.

The Princeville project findings supported a 2004 revision of the North Carolina residential code that governs crawl space construction. The new code language is currently available for use and will be enforced with the next print

release of the North Carolina code in 2006. Design guidelines that are based on the requirements of this new code language are highlighted in the guide.

Visit www.crawlspaces.org for complete research reports, short videos on key concepts, article links, or to obtain an electronic copy of this document. When online versions of code language related to closed crawl spaces are available, they will also be linked.

Why is the new design called a “closed” crawl space?

This guide uses the term “closed” to describe the alternative to a wall-vented crawl space design, but several other terms are commonly used. The term “closed” is used in the North Carolina building code. Here is a brief background on why “closed” was chosen over other options:

“Unvented”

In fact, several closed crawl space designs are vented, just not with outside air. Two common techniques are ventilation with conditioned air from a duct system and ventilation with conditioned air from the living space.

“Sealed”

The North Carolina residential code does not define a closed crawl space as requiring a sealed vapor retarder, which Advanced Energy recommends. Installers can differentiate this improved design from other closed crawl space designs by calling it “closed with a sealed liner.” Furthermore, it is impractical to perfectly air-seal a crawl space. The term “sealed crawl space” suggests an extreme level of air sealing

and implies that any small, unsealed air leakage path provides grounds for failing an inspection. In Advanced Energy’s experience, it is inappropriate to require code officials to use such a stringent, yet vague, standard for enforcement.

“Conditioned”

Not all closed crawl spaces are conditioned. A closed crawl space that is truly conditioned must have insulation located at the perimeter wall and a thermal barrier covering any foam plastic insulation. Unless specifically designed to do so, closed crawl spaces generally will not maintain the minimum 68° F (20° C) winter temperature required to qualify as a “conditioned area” as defined in the North Carolina (and International) residential code.

The words “closed,” “sealed,” “unvented” or “conditioned” will likely continue to be used interchangeably to refer to a variety of crawl space designs that do not have ventilation with outside air. Designers, installers, and code officials will need to make sure that the chosen specifications and requirements are clearly understood, whichever name is used.

Background

Crawl space foundations are widely used in building construction throughout the United States, with approximately 250,000 new homes built on crawl spaces every year and an estimated 26 million such homes already in existence. They are especially common in the southeast, where they are found in over 9 million existing homes and around 70,000 new homes per year.

Crawl spaces are inexpensive to build, functional in terms of providing a level foundation for flooring on sloping sites, and convenient spaces in which to locate plumbing, electrical lines, and ductwork for heating and air conditioning systems. Unfortunately, traditional wall-vented crawl spaces can also host a variety of serious moisture and insulation problems.

It is an all too common experience in the building professions to enter a wall-vented crawl space in the spring or summer and find beads of moisture in floor insulation, high wood moisture content, visible mold growing on surfaces, condensation on truss plates, plumbing pipes, air conditioning equipment or ducts, and in some cases, rot in the wood framing. Homeowners complain of high humidity, musty odors, buckled hardwood floors, and mold damage in the home above. Builders, mechanical contractors and insulation contractors routinely bear the brunt of these complaints.

Since the 1940s, residential building codes and conventional wisdom have prescribed passive ventilation with outside air as the means for providing crawl space moisture control. However, in the humid southeastern U.S., this prescription typically contributes to the moisture problems listed above instead of preventing them.

The expense of moisture repairs and the increase in complaints and legal action related to mold growth in homes have made homeowners, property managers, tenants, and the construction industry much more aware of the need to control moisture in homes. This awareness is helping to drive demand from a growing number of consumers and builders to invest the additional effort to incorporate closed crawl space systems in both new and existing homes. The moisture control provided by a properly closed crawl space can dramatically reduce the risk and associated liability of mold and moisture damage in the southeastern climate.

As a performance goal, crawl space foundations should certainly be free of rot. Ideally they should also minimize the conditions that lead to condensation and mold growth. While well built wall-vented crawl spaces may be able to control rot in the southeast, they cannot maintain relative humidity below the 70% threshold that supports mold growth and they routinely experience condensation on a variety of surfaces in the crawl space. Closed crawl spaces can maintain relative humidity below

the 70% target and dramatically reduce the potential for condensation on surfaces in the crawl space.

The key components of a closed crawl space system work in tandem to control the variety of water sources that affect crawl spaces:

- Exterior water management prevents intrusion of liquid water
- Air sealed walls minimize the entry of humid outside air
- Vapor retarders minimize the evaporation of water from the ground or perimeter wall
- Mechanical drying systems provide ongoing, active removal of water vapor
- Drains or pumps remove water coming from plumbing leaks or floods

Audience

This guide is intended to provide useful information to a broad range of stakeholders in the residential construction industry.

For builders and closed crawl space installers, we hope this reference provides effective guidance towards good design and implementation of closed crawl spaces, with tips about pitfalls to avoid and available alternatives. The background information on code development and field research is offered to help you gain acceptance of your closed crawl space designs by code officials and sub-contractors.

For code officials, we hope that the discussion on the development and components of the North Carolina residential code provides a resource for understanding the newly available code language. Outside of North Carolina, we offer this information as a resource for the development and adoption of similar code language to meet the needs of other regions.

For property owners and private home inspectors, we hope that this guide provides knowledge for assessing existing wall-vented or closed crawl spaces as well as tools for specifying and purchasing new closed crawl spaces.

Using this Guide

The closed crawl space designs and processes presented in this guide are not the only ones that are acceptable. They are simply examples that have performed successfully in Advanced Energy field testing or in projects by professional installers in North Carolina. There are many other closed crawl space designs that can perform acceptably and that meet the requirements of the North Carolina residential building code. As we verify the performance of additional designs and techniques we hope to add them to this reference, along with updated information gained from long-term monitoring.

It is important to keep in mind that the designs and techniques presented in this guide are not definitive specifications. If you are a builder,

property owner, or other contractor planning to install closed crawl spaces, we invite you to adjust these designs and processes to your local site conditions, code requirements, home design, construction processes and occupant needs to ensure success. Remember that closed crawl spaces share the same vulnerability of other foundation types or residential water control components: Just like basements, slabs, window and roof flashings, foundation waterproofing or plumbing, a closed crawl space that is installed improperly can do more harm than good.

Please note that the sample designs and processes discussed here have been tested

primarily in low-volume construction of closed crawl spaces in small homes with simple foundation plans. Builders of the more complex homes typically found in mainstream residential construction will likely need to adjust the sample construction process, especially if they build in high volume. Future Advanced Energy research will focus specifically on the delivery of closed crawl spaces in the production builder environment.

We anticipate that the performance improvements seen in closed crawl spaces in the Princeville project will translate very well to similar homes throughout the southeastern U.S. Future Advanced Energy research will also



A view of the homes in the Princeville research project. Six homes are located on each side of the same street.

confirm whether closed crawl spaces deliver similar improvements for moisture control and energy use in homes of different geometry in different climates.

The Ventilation Myth

Why doesn't ventilation with outside summer air dry out a southeastern crawl space? The traditional method of controlling moisture in crawl spaces is to provide passive ventilation with outside air. However, wall-vented crawl spaces routinely experience moisture problems like condensation, surface mold growth, high wood moisture content, or wood rot. The typical "cure" for such problems has been to add more ventilation, either in the form of additional ventilation openings to the outside or by installing a fan or multiple fans to intentionally move more outside air through the crawl space. Advanced Energy research has confirmed over the long term what we and other building scientists have measured repeatedly in previous short-term investigations of crawl space failure: *the outside air contains more water vapor than the air in the crawl space during the warm seasons, and has no potential to dry the crawl space.* Instead, the outside air ends up contributing water vapor to the crawl space.

To understand why, first we need to define three properties of air: temperature, relative humidity, and dew point temperature. Temperature is the most familiar property, and

is simply a measure of the heat in the air. But what exactly is relative humidity?

At any moment, the air around you contains a certain amount of water vapor. At the current temperature, there is also a limit to how much water vapor that air can contain before the water vapor condenses into liquid water... better known to us as "condensation" or "rain". Relative humidity is the ratio of actual water vapor in the air to the maximum amount of water vapor that the air can possibly hold at the current temperature. So, the relative humidity changes if either the amount of water vapor in the air changes or the temperature of the air changes. If the relative humidity in one location is 90% and the relative humidity in another location is 40%, you can't tell which location has more water vapor unless you also know the air temperatures. Cold air can hold less water vapor than warm air, so if air gets cooler without losing water vapor, its relative humidity increases.

Dew point temperature, often just called "dew point," is a more direct indication of how much water vapor is in the air. If you change the temperature of air without adding or removing water vapor, the dew point stays the same. If you remove water vapor, the dew point goes down whether or not the air temperature changes. If you add water vapor, the dew point goes up whether or not the air temperature changes. As you might guess, the dew point measurement tells you the temperature at which the water vapor in the air will condense into liquid water, either because the air cools

down to the dew point temperature, or because the air comes into contact with a surface that is cooler than its dew point temperature.

Psychrometric charts and slide rules allow you to calculate the unknown third property of air if you know the other two, for example, calculating dew point when the air temperature and relative humidity are known. They can calculate the change in one property if another property is changed. You can generally obtain a psychrometric chart or slide rule from manufacturers of air conditioning or dehumidification equipment, and there are several on-line psychrometric calculators on the Internet. We have provided a simplified version of the ACCA (Air Conditioning Contractors of America) psychrometric chart in Appendix B.

As an example, let's look at the properties of air on a mild summer day in North Carolina. Let's say it's 85° F (29° C) outside and the relative humidity is 60%. Conventional wisdom tells us that this air is warm and dry, so it should be great for ventilating a crawl space. Using a slide rule or chart, we determine that the dew point of this air is 70° F (21° C), which is relatively dry compared to typical conditions. Now let's assume that air goes into the crawl space. A typical summertime temperature in a wall-vented crawl space is 73° F (23° C), so the outside air cools down. No water vapor has been removed, so the dew point stays at 70° F. The temperature has dropped, so we need to use the psychrometric chart to find the new relative humidity... and now it's a whopping 90%! Furthermore, the temperature of the ductwork, plumbing, and bottom side of the insulation are below 70° F, so

the water vapor will condense on those surfaces. It may even condense on the crawl space floor or on the wood framing! It turns out that ventilating with the outside air adds moisture to the crawl space, it does not dry it out.

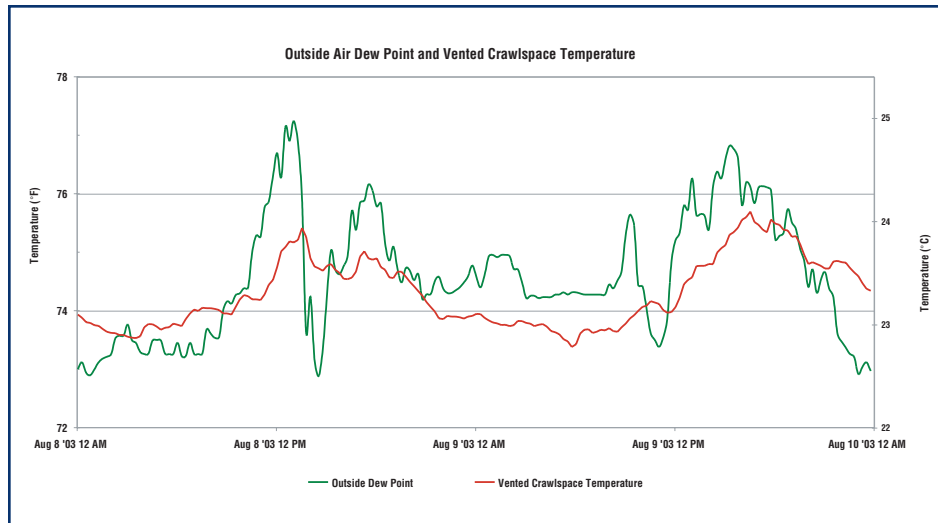
Summer moisture conditions in central and eastern North Carolina are often much wetter than the example. In the record-setting drought summer of 2002, the outside air dew point exceeded 70° F 44% of the time at Advanced Energy's Princeville research site. In the record-setting rainfall year of 2003, the outside air dew point exceeded 70° F 72% of the summer and was higher than the temperature inside the crawl space almost 20% of the summer.



After noticing light mold growth on floor joists in a wall-vented crawl space, a contractor recommended installation of a powered crawl space ventilation fan to “dry” the crawl space.



After installation of a powered crawl space ventilation fan, so much water condensed on the floor joists that rot set in and destroyed the lower portion of the joists.



This data from the Princeville site shows that for most of a very humid 48-hour period, the outside dew point exceeds 74° F (24° C) and is higher than the temperature inside the crawl space. If this outside air enters the crawl space, the water vapor will condense on surfaces inside. Note that this was not a period of very rainy weather; records indicate only 0.2 inches of rainfall over this entire 48-hour period.

Section 1

RECOMMENDED DESIGN COMPONENTS

Overview

This section presents a variety of design components that meet or exceed the minimum requirements for closed crawl spaces, as specified by the North Carolina residential code discussed in Section 4.

The recommended design components presented here are not the only ones that are acceptable. They are simply examples that performed successfully in the field testing detailed in Section 6, in other Advanced Energy research projects or by professional installers in a variety of locations in North Carolina. There are many other closed crawl space designs that can perform acceptably and that meet the requirements of the North Carolina residential building code.

The design components presented here are not definitive specifications. If you are a builder, property owner, or other contractor planning to install closed crawl spaces, you will need to adjust these design components to your local site conditions, code requirements, home design, construction processes and occupant needs to ensure success.

The dozens of individual components that make up a complete and effective closed crawl space system fall into six general categories of function:

- Moisture management
- Pest control
- Combustion safety
- Thermal insulation
- Fire safety
- Radon safety

This section discusses each category with background information and then specific components. The list of categories follows the order of requirements in the North Carolina residential code. Several specific items, like foundation drainage or foam plastic fire safety, are not in the crawl space code section but are included here in the interest of completeness.

This section uses three symbols to indicate different levels of components:

- ✓ A red check mark indicates a component that is required by the North Carolina residential code
- ✚ A green plus sign indicates a component that is recommended by Advanced Energy
- ★ A gold star indicates an optional component that will provide an extra level of performance or safety

Moisture Management

Moisture management of the finished crawl space is the primary goal of any closed crawl space system, and it involves components both outside and inside the crawl space. Moisture management, for both liquid water and water vapor, uses two basic strategies:

1. Blocking sources
2. Facilitating removal

Note that moisture management during the construction process involves several additional measures which are described in the sample construction sequence in Section 3. We have chosen not to present the components of moisture management in the order used by the North Carolina residential code. Instead, we present them in order of components located outside the crawl space to components located inside the crawl space, since this follows the model of first blocking sources and then facilitating removal.

Moisture Management: Blocking Sources

Roof runoff

- ✦ Use a system to direct roof runoff away from the house and prevent the runoff from entering the crawl space. This is often a gutter system, but could also be a system of foundation waterproofing, perimeter gravel bed and a drain. Another option is foundation “flashing,” for example, a layer of impermeable material like EPDM rubber that extends down and away from the foundation wall below grade for approximately 6 feet.
- ✓ If sub-surface drain pipes or gutter leaders are used to manage roof runoff, they must not be connected to the crawl space drain. This eliminates the chance that blockages or heavy rains will cause roof runoff to enter the crawl space.

Exterior ground and surface water

- ✓ Provide site grading around the perimeter of the house with a minimum of 6 inches (152 mm) of fall over 10 feet (3048 mm) of run to direct ground surface water away from the house. Swales or drains may be used if lot lines, slopes, walls, or other barriers prohibit the required grading.

- ✦ Ensure that landscapers or property owners do not install flower beds, tree mounds, mulch piles or other landscaping features that prevent drainage away from the house. In-ground irrigation systems or yard sprinklers require special attention because they can easily cause a water problem in an adjacent crawl space. Make sure these systems do not put water onto the crawl space walls.
- ✓ Provide a foundation drain system whenever the exterior grade is 12 inches (305 mm) or more above interior crawl space grade. Keep foundation drain systems separate from crawl space drain systems.
- ✓ Provide foundation damp-proofing or water-proofing when the exterior grade is

above the interior crawl space grade to prevent the flow of water through the wall by capillary action or “wicking.”

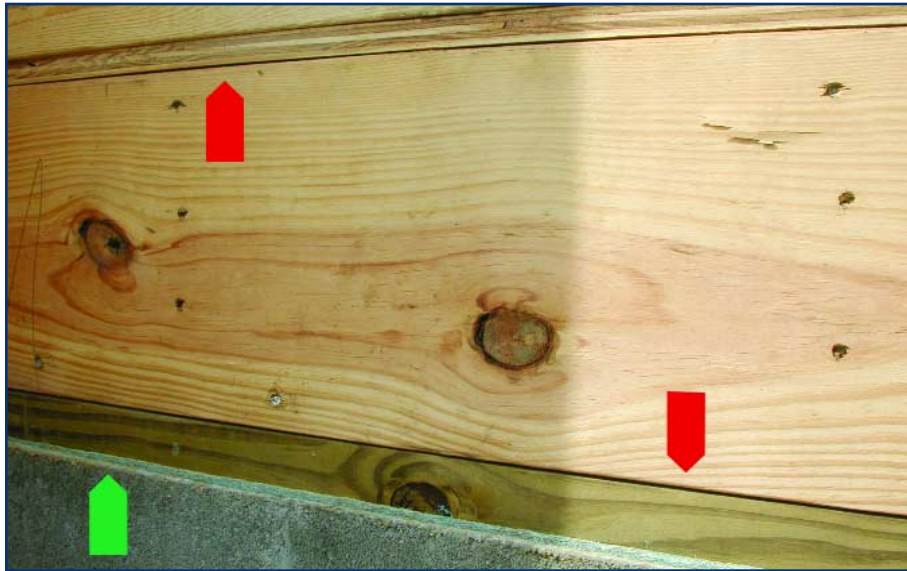
- ✦ Raise the crawl space grade above the exterior grade to eliminate the need for a foundation drain, damp-proofing or water-proofing.
- ✦ Protect exterior crawl space access door(s) from roof runoff. For example, if there is no roof runoff system, locate the access door on a gable end wall. Whenever possible, build the bottom of the access at least 4 inches (102 mm) higher than the exterior grade. If raised access is not possible, provide a dam or gravel drain to prevent water entry. Use non-corroding access doors, especially in coastal communities, to prevent deterioration.



The entrance to this closed crawl space is elevated well above exterior grade, reducing the likelihood of water entry in heavy rains or minor flooding. Photo credit: Indoor Environmental Systems.

Humid Air

- ✓ Seal all gaps between foundation wall and sill plate, sill plate and band joist, and band joist and subfloor. Seal penetrations through the crawl space wall for water service, electrical service, plumbing fixtures, ductwork, etc. Use solid blocking and sealants to seal gaps between the exterior wall opening and ductwork for outdoor packaged-unit heating and cooling equipment, if present.
- ✓ Seal connections from the crawl space to areas under attached porches or decks, which are common sites of liquid water intrusion or entry of humid outside air.
- ✓ Houses in an area prone to flooding or designated as a Special Flood Hazard Area (SFHA) by the Federal Emergency Management Agency (FEMA) or the National Flood Insurance Program (NFIP) must have FEMA/NFIP-compliant flood vents in the crawl space perimeter wall. See the "Flood Vents" sidebar for more information.



This foundation wall has an effective gasket between the sill and the masonry wall, but small gaps between the sill plate and the band joist or between the band joist and the subfloor add up to large leak areas. Close these joints with gaskets or sealants as well.

Photo credit: Building Performance Specialists.



When you see packaged unit equipment on the outside of the crawl space...

Photo credit: Healthy Home Environment.



... there are typically large gaps in the perimeter wall around and between the supply and return ducts. These gaps require solid backing materials and sealants for proper air-sealing. Remove any rubble underneath the opening to reduce the risk of damage to the ground vapor retarder.

Photo credit: Healthy Home Environment.



Seal all penetrations in the perimeter wall.

Photo credit: Indoor Environmental Systems.

- + When required, choose flood vents that minimize stand-by air leakage.
- + Build hollow-block masonry foundation walls with either a continuous top course

of solid masonry or the top course of masonry grouted solid to prevent passage of air from the interior of the wall into the crawl space.

Flood Vents

Flood vents are openings in a foundation wall that automatically allow the free passage of flood water into and out of a foundation in order to equalize hydrostatic forces on the foundation walls. When required in a closed crawl space, choose a flood vent model that reduces standby air leakage as much as possible.

The Federal Emergency Management Agency and the National Flood Insurance Program specify the design requirements for flood vents as well as the guidelines for where they must be implemented. The 2000 (and later) International Codes meet these requirements.

To determine if a property is located in a Special Flood Hazard Area (SFHA) and will be required to have flood vents installed, contact your local building inspections department or governing authority. A property survey and elevation certificate may be required before a final determination can be made.

Non-compliance with flood vent requirements can jeopardize a community's ability to

participate in the NFIP or to receive a wide range of federal funds for emergency assistance, construction, property loans, and more. For the individual homeowner, insurance premiums may go up significantly when insurance policies are renewed or when a house is sold if the house does not comply with flood vent requirements.

For additional information, refer to Technical Bulletin 1-93, Openings in Foundation Walls, available from FEMA (www.fema.gov, or 800-480-2520) or contact your state's division of emergency management or floodplain management.



This flood vent has a weather strip to reduce stand-by air infiltration and the central panel is insulated with foam.

Photo credit: Hazard Mitigation Contractors, Inc.

Evaporation from the ground and perimeter walls

- ✓ Cover all crawl space ground with a minimum 6-mil polyethylene vapor retarder. Lap seams at least 12 inches (305 mm).



Do not leave any exposed earth in the crawl space! Photo credit: Bill Warren.

- + Cover the masonry perimeter walls with minimum 6-mil polyethylene vapor retarder, leaving at least 3 inches (76 mm) of exposed masonry at the top of the wall. Mechanically attach the vapor retarder material and seal it to the wall with duct mastic. Common strategies for mechanical attachment include powder-driven nails, pins or masonry screws that hold the vapor retarder up behind a furring strip or wall insulation.



One way to mechanically attach a wall vapor retarder: secure it behind a preservative-treated plywood furring strip attached to the masonry with nails driven through washers. Photo credit: Bill Warren.

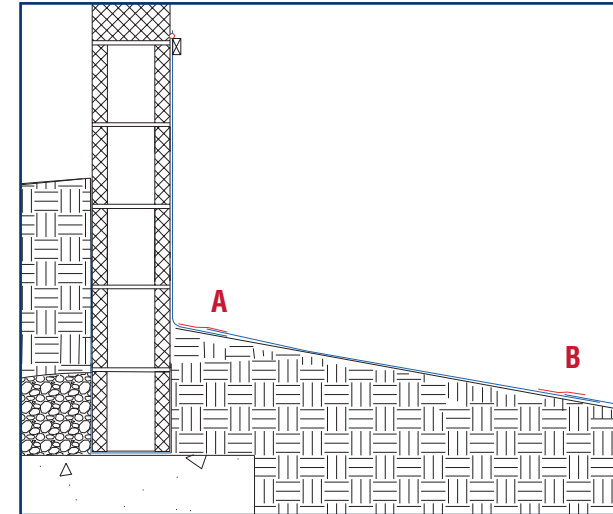


This heavy-duty vapor retarder material is mechanically supported by metal pins with cap washers and sealed to the masonry with fiberglass mesh tape and duct mastic. Photo credit: Indoor Environmental Systems.

- + Seal the ground vapor retarder to interior columns at least 4 inches (102 mm) above the crawl space floor.
- + Install the ground and wall vapor retarders as a sealed liner by sealing all seams and connections to masonry with fiberglass mesh tape embedded in duct mastic. If you choose to use a tape product to seal seams, ensure that all surfaces are clean before applying the tape and do not subject tape joints to mechanical stress. Both of these situations have caused tape joints to fail in Advanced Energy research houses.



Vapor retarder material is attached with a furring strip three inches (76 mm) below the top of the masonry wall and sealed to the wall with mastic. The wall vapor retarder material is sealed to the ground vapor retarder to form a continuous liner. Penetrations, like the dryer vent in the photo, are completely air sealed. The top of the masonry wall and the front edge of the sill plate have been painted white with mastic to improve inspectability by pest management professionals.



Overlap seams in the vapor retarder material to reduce the chance that liquid water running downhill from the wall or ground will collect against the underside of the sealed seams. Lap the ground vapor retarder on top of the wall vapor retarder (A) and lap downhill sections of vapor retarder over uphill sections of vapor retarder (B).

- + If you use unreinforced 6-mil polyethylene (the material most commonly available at home improvement retail stores), protect it with an additional layer of durable material (for example, artificial turf, vinyl runners, or other carpet material) in storage areas or traffic areas, like a service path to mechanical equipment. Consider using thicker, reinforced vapor retarder materials for improved durability and puncture resistance, and to eliminate the need for additional protective coverings.
- ✓ The ground vapor retarder must be secured to resist movement or tears.

Why does Advanced Energy recommend installing the vapor retarder as a sealed liner?

Advanced Energy recommends the use of a sealed vapor retarder covering the walls and ground because we have field tested this design as part of a system that provided effective crawl space moisture management. Sealing the seams of the vapor retarder material reduces the risk of damage when people move around in the crawl space, and makes it more likely that a water failure like a plumbing leak will be discovered. The sealed liner is not designed to prevent intrusion of liquid water from the ground, but it will make it less likely. Another unintended benefit may be improved resistance to the movement of soil gases into the crawl space.

Choosing to not use a vapor retarder on the perimeter walls will typically result in more moisture entering the crawl space during warm weather. Choosing not to seal the seams of the ground vapor retarder increases the chance that ground will be exposed. Such a system can still perform acceptably if the installed drying mechanism is capable of removing the resulting additional moisture load.

- ✚ Secure the ground vapor retarder material as necessary to resist movement due to anticipated traffic. Anchor 6-mil polyethylene with sod staples or

galvanized spikes through washers or nailing tins on approximately 12 foot (3658 mm) centers. Use additional staples or spikes to secure the vapor retarder in steeply sloped areas or in heavy traffic areas like the crawl space entrance or service paths. Heavier vapor retarder materials in small crawl spaces or in large crawl spaces with intermediate piers may not need any staples or spikes.

Moisture Management: Facilitating Removal

Please remember that moisture still gets into a properly closed crawl space. Ground moisture can wick up through masonry walls or support columns and evaporate into the crawl space. Rain can wick through the perimeter masonry wall or sill plate and evaporate into the crawl space. Wind, duct leakage or other building pressures will inevitably force some amount of humid air through the perimeter wall, since it's impossible to do a perfect air-sealing job. Plumbing failures or floods put liquid water in the crawl space.

For all these reasons, a closed crawl space needs components that remove both liquid water and water vapor. Duct leakage and diffusion of water vapor to the house above may provide some drying potential for a closed crawl space, but an intentional drying mechanism is required to ensure adequate moisture management.

Some installers and researchers have theorized that the moisture control improvements of closed crawl spaces allow the mechanical contractor to down-size the installed heating and cooling equipment. However, there are few commonly available tools at the time of this writing to calculate the impact of a closed crawl space on the sizing of mechanical equipment for the home.

- ✓ Grade the floor of the crawl space to one or more low points. Provide a drain or sump pump at each low point to remove liquid water from the crawl space in case of a plumbing leak or other flooding event.
- ✚ Use a backflow valve in crawl space drains and a check valve in sump pump out-flow pipes to prevent reverse flow of outside water into the crawl space and to reduce the chance of vermin entry. Floor drains with p-traps that connect to the whole-house plumbing waste drain or to a municipal sewer system may allow entry of sewer gases if (when) the trap dries out and pose a risk of sewage backup.



This crawl space drain and backflow valve assembly is ready for installation.

Photo credit: Indoor Environmental Systems.



The finished ground vapor retarder is sealed directly to the drain opening.

Photo credit: Indoor Environmental Systems.



Use sump pumps if desired or when gravity drains are not feasible. This model includes a cap for the housing and an optional liquid water alarm to detect a failure of the sump pump system.

Photo credit: Indoor Environmental Systems.

- + Terminate crawl space drains or sump pump discharges in ways that reduce the risk of damage or blockage. For example, surround the termination with gravel or shrubbery to reduce the risk of soil blockage or damage from lawn equipment.
- ✓ Provide a mechanical drying system to remove water vapor. Six methods are allowed under the NC residential code discussed in Section 4. See the next item for recommended strategies.
- + Use conditioned air from the supply-side ductwork or stand-alone dehumidifiers to meet the requirement for a mechanical drying system. Advanced Energy has field tested both of these methods. See Section 3, Sample Designs and Construction Process, for a detailed description of these two drying mechanisms and discussion of advantages and disadvantages for each.
- ✓ Terminate appliance water discharge pipes (for example, water heater temperature/pressure relief valves, air conditioner or dehumidifier condensate drains, or water softener discharges) to outside, to an interior pump, or to a crawl space drain.
- + Drain appliance discharge pipes directly to outside or to an interior pump, not to crawl space drains. If the backflow valve in the crawl space drain is installed out of level or if there is water in the drain pipe exerting pressure on the backflow valve, appliance discharges may build up significantly inside the crawl space before they can drain out.
- + Include relative humidity monitors or liquid water detectors in the design to inform occupants of the performance of the system.
- ★ Install auxiliary condensate drain pans with float kill-switches under air handlers or dehumidifiers in a closed crawl space for added security against overflows due to blockage in the condensate line.
- ✓ Terminate clothes dryer exhaust vents to outside.
- + Terminate all kitchen and bathroom exhaust vents to outside.

Pest Control

Two important goals of a closed crawl space design are to

1. Avoid increasing the risk of damage from subterranean termites or other insect pests
2. Provide the ability for pest management professionals to inspect the structure and provide treatment, when necessary.

Under North Carolina structural pest control regulations, pest management professionals are not liable for infestations or damage already present in hidden or obstructed areas

when they perform inspections for real estate transactions if the professional identifies such areas on the inspection report. The definition of “hidden or obstructed” includes areas of the building that would require disassembly with tools or removal of pieces or parts of the building to allow for inspection.

For properties under a service contract or warranty, the pest management contractor may be held responsible for any and all damage that occurs to the property after the date of their treatment. This discourages them from contracting on properties with hidden or obstructed areas. In new construction projects, pest management contractors may be reluctant to provide soil pre-treatment, wood pre-treatment, or an alternative pre-construction treatment unless they have sufficient information about the closed crawl space design to believe that they will have adequate access for the pre-treatment or for future inspections or treatments.

Closed crawl space designs must pay particular attention to materials applied on the perimeter walls, since this is a common path for wood-destroying insects from the ground to the structure. It is not acceptable to drape insulation or vapor retarder materials from the band joist or sill plate to the crawl space floor because this prevents inspection.

- ✓ Provide a termite inspection gap of at least 3 inches between the top of any wall vapor retarder material and/or perimeter wall insulation and the top of the perimeter masonry wall. Vapor retarder or insulation materials must not contact any wood framing.



This crawl space under construction has careful detailing at all beam pockets to maintain the termite inspection gap at every interface of masonry and wood.

Photo credit: Building Performance Specialists.

- ✓ Provide a clearance or wicking gap of at least 3 inches between the bottom of any perimeter wall insulation and the crawl space floor surface.

- ✓ When the perimeter wall of a closed crawl space is insulated, the band joist must also be insulated.

- The use of rigid foam on the band joist will seriously impair visual or physical inspection (“probing” or “sounding”) of the band by a pest management professional, because the foam may be damaged in the process or impossible to replace in its original condition. Foam insulations with low (< 1 perm) permeability to water vapor will reduce the ability of the band to dry to the crawl space, but would also reduce the potential for condensation on the band when the band is cold.
- Insulating the band joist with faced batt insulation, with the vapor retarder facing towards the inside of the crawl space, facilitates inspection or treatment by a pest management professional since it is more easily removed and replaced without damage. This strategy allows some drying of the band joist to the crawl space during the cooling season, but may increase the chance of condensation on the band when the band is cold. The facing material may need to be fire-rated for direct exposure.

Combustion Safety

Gas- or oil-fired appliances, such as furnaces, water heaters, or boilers, need combustion air. Without sufficient combustion air, the appliance can produce carbon monoxide or fail to draft properly. Advanced Energy has documented numerous cases in which combustion equipment in wall-vented crawl spaces

1. did not have sufficient combustion air volume or openings to the outside per mechanical code requirements,
2. generated unacceptably high levels of carbon monoxide, or
3. did not draft acceptably due to air pressures created by duct leakage or stack effect.

A properly air-sealed closed crawl space is much tighter than a wall vented crawl space and can even be tighter than the house above. As a result, Advanced Energy recommends that:

✦ **Atmospheric or “natural” draft appliances should not be installed in a closed crawl space.**



- ✓ Fuel-burning appliances located in a closed crawl space shall obtain combustion air from outdoors per the North Carolina Mechanical Code. Note that the use of passive combustion air

openings is not acceptable because it violates the air-sealing requirements for the perimeter wall around and the floor above the closed crawl space.

- ✦ Specify direct-vent (“two-pipe”) models to ensure adequate combustion air when fuel-fired appliances are used. All air for combustion should be piped directly from outside into the appliance and all combustion exhaust gases should be piped directly from the appliance to outside. Some manufacturers have separate cabinets or enclosures that can be used to convert non-direct-vent appliances to direct-vent operation.



The two large PVC pipes entering this direct-vent furnace bring combustion air from outside and take exhaust gases to outside to ensure that the furnace will not backdraft or burn inefficiently in the presence of negative building pressures.

Photo credit: Bill Warren.

General Combustion Safety

Regardless of whether or not a home has a closed crawl space foundation, combustion safety is a serious issue. Over 200 people die every year in the U.S. from carbon monoxide (CO) poisoning due to faulty combustion appliances in the home. Thousands of people require emergency room treatment for exposure to high levels of CO, and researchers are still working to understand the potentially serious effects of chronic low-level exposure to CO.

- ✦ Advanced Energy recommends the use of carbon monoxide low-level monitors or alarms in any home (including homes with slab or basement foundations) that has an attached garage or any fuel-fired cook stove, furnace, boiler, water heater, fireplace, or other appliance.
- ✦ For additional protection, consider using a fuel-gas alarm when there are gas-fired appliances or gas lines in a home. These alarms can detect leaks of propane or natural gas and alert occupants to the problem.

Thermal Insulation

The North Carolina residential code allows insulation in a closed crawl space to be located at the sub-floor or at the perimeter wall. This conflicts with the 2004 Supplement to the International Residential Code, which requires insulation in an “unvented” crawl space to be located at the perimeter wall only. The research results in Section 6 showed that closed crawl spaces with either floor or wall insulation similarly outperform wall-vented crawl spaces with floor insulation in central North Carolina.

- ✓ Perimeter wall insulation may be located on any combination of the interior surface, exterior surface or inside of the perimeter wall, or the perimeter wall itself may provide the required R-value.
- ✓ If the perimeter wall is insulated, then insulation must be installed on the band joist. See “Pest Control” above for notes on options for band joist insulation.
- ✓ Perimeter walls that are partially masonry and partially wood framed (the wood framed portion is commonly referred to as a “pony wall”) do not require insulation on masonry wall heights of 9 inches or less.
- ✚ Use non-porous insulation (for example, a closed-cell foam insulation) if the inside of the perimeter wall is insulated. This reduces the risk of contamination or other

damage to the insulation if there is a water leak or flood.

- ✚ Install insulation at the sub-floor without gaps or compression and in full contact with the sub-floor to achieve the nominal R-value. Insulating open-web floor truss systems with batt insulation is discouraged due to the difficulty in insulating the openings in the truss structure. Better options for insulating open-web floor truss systems include using spray foam or netting the bottom of the trusses and completely filling the cavity with blown insulation. These strategies would likely also improve insulation performance in wooden I-beam floor structures.

Fire Safety

A key element in residential fire safety is fireblocking between different levels in a home. Fireblocking requirements already exist in the residential building code, but allow the use of porous materials like fiberglass or rock wool insulation. North Carolina has improved these requirements to require the use of non-porous materials for fireblocking in crawl spaces.

Foam plastic insulation receives special scrutiny in residential building codes because some foam insulations have the potential to release toxic or flammable gases when heated, or they can accelerate the spread of a fire if

they ignite. To reduce these risks, most codes require a thermal barrier (typically 1/2 inch [13 mm] gypsum board or equivalent) or an ignition barrier (typically 3/8 inch [10 mm] gypsum board or equivalent) over foam insulation. However, several foam insulation products have been designed and tested to reduce or eliminate those risks. Such products can be installed without a thermal barrier or ignition barrier with the appropriate documentation.

- ✓ Seal all plumbing, electrical, duct, plenum, gas line and other wiring penetrations through the subfloor with non-porous materials. Rock wool or fiberglass insulation alone is not sufficient.
- ✓ Provide documentation of product fire-ratings (in the International Code Council National Evaluation Report (ICC NER) for the product) to allow installation of exposed foam insulation without a thermal barrier or an ignition barrier, if applicable
- ✓ Provide documentation of fire-rating to allow installation of exposed facing materials on batt insulation in the band joist or pony walls, if applicable
- ✚ Do not use a crawl space to store gasoline, solvents, or any tools or materials that present a fire hazard.

Radon Safety

Radon is an odorless, colorless gas that is the second most common cause of lung cancer in the United States, resulting in over 20,000 deaths per year. An estimated 1 in 15 U.S. homes has a high level of radon. For these reasons, the U.S. Surgeon General and the Environmental Protection Agency (EPA) recommend that all homes be tested for radon.

For jurisdictions where radon-resistant construction is required, radon control methods are specified in Appendix F of the International Residential Code. Table AF101(1) lists the counties identified by the Environmental Protection Agency (EPA) as High Radon Potential (Zone 1) counties. The High Radon Potential designation indicates areas with expected radon concentrations of 4 pCi/L (picocuries per liter) or greater, where it is likely that radon-resistant construction will be required.

The EPA recommends that all homes with radon concentrations of 4 pCi/L and greater be mitigated. The EPA also recommends that the county listing be supplemented with other available state and local data, for example, data from state radon offices, public health agencies or cooperative extension services, to further understand the radon potential of Zone 1 areas.

When radon mitigation is required, the requirements for floor sealing, duct sealing, ground vapor retarder, access door air sealing, and damp proofing of a closed crawl space

system are compatible with the requirements of Appendix F. Sub-slab or sub-membrane depressurization systems may be utilized in a closed crawl space in the same manner as in a slab, basement or wall-vented crawl space foundation. Local jurisdictions may require additional measures for the ground substrate, foundation wall, concrete joints, condensate drains, or sump pits in wall-vented or closed crawl spaces.

Summary

The dozens of individual components that make up a complete and effective closed crawl space system fall into six general categories of function:

- Moisture management
- Pest control
- Combustion safety
- Thermal insulation
- Fire safety
- Radon safety

You might be wondering “Do I really need to follow all of the recommendations in this section to have a closed crawl space that works?” The short answer is “no.” There are other designs that will perform successfully. The key for acceptable moisture management is that the rate of moisture removal from the crawl space must be at least as much as the

rate of moisture entry. So for example, if you choose not to install a wall vapor retarder, then you need to ensure that the drying mechanism you install is sufficient to provide the desired moisture management despite the extra moisture load of the exposed perimeter walls. This may require a trial and error approach since there are no readily available tools to accurately predict such moisture loads and size the drying mechanism.

Altogether, these recommendations represent closed crawl space components that have proven their performance in real-world field tests. They perform as a system, and although it's obvious that some components, like preventing water intrusion, are critical, we have not experimented to determine which of the other components could be sacrificed without compromising the system as a whole.

It is important to keep in mind that these sample design elements were tested in small homes with very simple foundation plans. To ensure success, builders of the more complex homes typically found in mainstream residential construction will likely need to adjust the designs to accommodate local site conditions, code requirements, home design, construction processes and occupant needs.

Section 2

IMPLEMENTING A CLOSED CRAWL SPACE

Overview

It would be wonderful if simply having a good design guaranteed a closed crawl space that controls moisture and saves energy. But in the real world the end result also depends on the materials, process and workmanship that put the good design into practice.

There is no trade association or industry-accepted set of standards for implementing closed crawl space systems beyond the requirements of the residential building code. The residential building code specifies minimum requirements for what must be done, not necessarily the process for how it must be done. Therefore, the implementation guidelines Advanced Energy recommends in this section are not legal requirements, but are likely to be critical to the successful implementation of a closed crawl space.

Property owners, general contractors, or others can adapt the design and implementation recommendations in this guide to their specific circumstances to create a closed crawl space or they can seek a professional installer to do

the work. In some regions, owners and builders may have to do the work themselves due to a lack of local experienced installers.

Advanced Energy divides implementation guidelines into six broad topics:

- Defining the design
- Working with code officials
- Overcoming conventional wisdom
- Managing labor
- Managing job site logistics
- Quality assurance

A seventh topic applies when you hire an installer:

- Establishing a clear contract and pricing.

Defining the Design

You or your installer may prefer one closed crawl space design to others, but should also be able to customize the choice of materials or drying mechanism to suit the needs of the house design or local residential code requirements. Factors like site conditions,

Finding a Quality Installer

More and more businesses are offering the service of closing crawl spaces. Currently, you could purchase a closed crawl space in central North Carolina from:

- Home performance contractors
- Pest management contractors
- General contractors
- Professional engineers
- Mechanical (HVAC) contractors
- Insulation contractors
- Foundation repair/waterproofing contractors

Although hiring an installer to provide a closed crawl space may be more expensive up front than doing it yourself, the knowledge and experience

of a quality installer can be well worth the additional expense.

Finding a quality installer typically requires identifying providers of closed crawl spaces in your area and then getting proposals from several providers for the specific job at hand to make an apples-to-apples comparison. Ideally you would look at previous work and talk with previous clients to assess the provider's performance. Assess the knowledge, experience and integrity of the provider with regard to the seven implementation topics described in this section. The potential benefits and risks of installing a closed crawl space demand that the work is performed the right way at the right time. Advanced Energy recommends that you think of the closed crawl space installer as a partner in moisture management, not as just another "sub" on the project.

occupant requirements, or cost will also influence the design. For example, a homeowner with severe allergies may choose a dehumidifier to dry the crawl space instead of a supply air strategy. A home on a steeply sloped site may require such a large amount of wall insulation that it is financially advantageous to use a floor-insulated design.

Working with Code Officials

You or your installer will need to work with your local code officials to ensure that your closed crawl space design is acceptable and either meets or exceeds all code requirements. Coming to agreement early and avoiding surprises during construction are key strategies for preventing any delay in the issuance of a certificate of occupancy at the end of construction. In some cases, local code officials may require or accept a stamped letter of approval from a registered professional engineer as an alternate path for permitting and inspection.

Note that software programs for energy analysis may not accurately predict the energy savings associated with a closed crawl space. If the home is required to meet a particular Model Energy Code or International Energy Conservation Code standard, the software might require additional efficiency measures in the house. Arguably, these measures are not

necessary and this may require negotiation to avoid installing the additional efficiency measures.

If you are hiring an installer, ask candidates how they ensure acceptance of their work by code officials.

Overcoming Conventional Wisdom

At some point in the process, you or your installer may need to overcome the conventional wisdom of construction professionals who still believe that crawl spaces need ventilation with outside air, or who do not recognize the potential risks of wall-vented crawl spaces. For example, a pest management professional may refuse to treat or provide a warranty on a home with a closed crawl space. In some cases you may be able to use the information in this guide or other resources to convince the professional of the acceptability and benefits of closed crawl spaces, but in other cases you may need to switch to another service provider to keep the project on schedule.

Managing Labor

You or your installer need to ensure that employees are trained in the use of the materials and processes required to install a

closed crawl space system. Naturally, crawl space work is difficult due to the confined nature of the space. It may also present respiratory hazards. Advanced Energy has not tested mold levels in new closed crawl spaces during construction, but given the high levels of airborne mold spores measured in our crawl space research projects whenever settled dust is disturbed in finished crawl spaces, Advanced Energy recommends that workers wear respiratory protection in both new and existing crawl spaces. We recommend combined High-Efficiency Particulate Arrestance (HEPA) and activated carbon filters at a minimum. Those with beards should consider using full-face powered air-purifying respirators. Workers may need to be tested for respirator fit and lung function according to applicable Occupational Safety and Health Administration (OSHA) regulations.

Managing Job-Site Logistics

You or your installer will need a process for coordinating with the other building trades to ensure proper scheduling and to reduce the risk of damage to the closed crawl space system during construction or after the house is turned over to a customer. Contractors you may need to coordinate with include the:

- Site grading and preparation contractor
- Foundation or masonry contractor

- Pest management company
- Framer
- Plumber
- Electrician
- Insulator
- Mechanical contractor
- Gutter installation contractor
- Landscaping and/or irrigation contractors
- Cable TV, security system, or computer network wiring contractors

In particular, you or your installer must coordinate as soon as possible with the pest management professional to ensure that the closed crawl space system does not interfere with their treatment or affect their warranty, if applicable. For properties under a service contract or warranty, the pest management contractor may be held responsible for any and all damage that occurs to the property after the date of their treatment. This discourages them from contracting on properties with hidden or obstructed areas. In new construction projects, pest management contractors may be reluctant to provide soil pre-treatment, wood pre-treatment, or an alternative pre-construction treatment unless they have sufficient information about the closed crawl space design to believe that they will have adequate access for the pre-treatment or for future inspections or treatments.

Managing moisture during the process of construction is critical, because all crawl spaces, including closed crawl spaces, can

become ideal environments for growing mold as soon as the sub-flooring is installed. Mold can grow on all surfaces in the crawl space, but it is most readily noticed when it grows on the wood framing or subfloor. When excess humidity drives up the wood moisture content to 19% or more, conditions are right for surface mold to appear. In some cases, dramatic mold blooms can grow in as little as 48 hours. Seeing surface mold on the crawl space wood in the past was seldom an issue with homebuyers, but now public concerns

about mold can slow or prevent a home sale. Mortgage providers may even require a mold test prior to a home purchase.

Often, the processing, transport and job-site storage of wood framing and subfloor materials exposes them to rain for long periods of time. The materials may arrive on the job site already contaminated with mold growth or wet enough to foster germination of the mold spores that they will inevitably be exposed to. Using wet moldy lumber defeats the purpose of any recommended moisture management practices.

Beware of Long Construction Schedules

Volunteer-built homes and large homes, particularly large custom homes, often have long construction periods before they are dried in. This makes it even more likely that the crawl space will be wet before the house is dried in. Building over long time periods requires a process that includes early rain water management, ground cover and dehumidification to successfully avoid mold contamination.

Another strategy could be to build such homes with a temporary ground vapor retarder and foundation vents and leave the vents open prior to dry-in, at which time you could begin the conversion to a closed crawl space. This approach might provide enough drying potential to avoid mold growth during the dry times of the year or in dry climates, but likely won't when construction occurs primarily in spring or summer.

In some cases, the only feasible strategy for implementing a closed crawl space may be to just build the house with a traditional wall-vented crawl space, and either perform some mold control or cleanup activities during construction, or to wait until the house is complete and then convert the wall-vented crawl space to a closed crawl space, with any desired cleanup. . In these cases, it may be possible to suppress mold growth in the floor structure prior to the crawl space being closed by using pre-treated wood products or applying fungicidal coatings to untreated wood products.

If feasible, provide a waterproof covering, secured to resist wind damage, to prevent rain from entering the crawl space when construction will stop for a prolonged period. In such cases, a dehumidifier may also be needed to prevent mold growth.

Even when you install dry materials, once the subfloor is installed the crawl space becomes an enclosed space that can trap moisture. The subfloor prevents excess water from drying with sunlight, and there is much less potential for liquid water or water vapor to leave the space. The crawl space is vulnerable to major rain or snow entry until the house is dried-in by installing the roof, wall sheathing, windows, and exterior doors.

The sample implementation process listed in Section 3 includes steps designed to prevent moisture problems during the construction process.

Providing Quality Assurance

Quality builders and installers care about the long-term performance of their closed crawl space system and will usually offer one or more of the following quality assurance options:

- A monitoring system to inform the homeowner of relative humidity levels in the crawl space
- A water alarm to inform the homeowner of a buildup of liquid water in the crawl space
- A posted sign or signs identifying the different components of the system and informing anyone entering the crawl space of the importance of maintaining the integrity of the system.

- A repair kit for fixing small areas of damage to the liner after the house is occupied
- An annual monitoring service to replace batteries in monitoring systems and check that the crawl space system is in good working order. This may include measurements of wood moisture content or air tightness, or a download and analysis of

data logging equipment

- A guarantee or warranty that relative humidity will be maintained below an agreed-upon target (for example, a guarantee for relative humidity not to exceed 70% at a specified monitoring point for more than 7 consecutive days) with exceptions for water leaks or intrusion outside the installer's control

Basic Maintenance for Crawl Spaces

Most people don't like to go into crawl spaces, but periodic inspection of any crawl space helps to ensure that any problems are caught before they cause damage. Property owners can perform these inspections and basic maintenance checks themselves or hire a private home inspector or other contractor to do it for them.

Property owners should:

- Ensure that access doors are closed, especially during warm weather.
- Ensure that drains or sump pumps are functioning properly
- Ensure that dehumidifiers are maintained per the manufacturer's instructions and are in proper working order
- Ensure that there are no solvents, gasoline or other potentially hazardous materials in the crawl space.
- Inspect the crawl space regularly to:

- Identify vapor retarder damage or water problems. Note that small water leaks in a crawl space may not be indicated by relative humidity sensors.
- Ensure that no damage occurs when any contractors work in the crawl space.
- Check and replace batteries as needed in sensors or alarms.
- Ensure that any water intrusion, especially flooding, is quickly drained or pumped out of the crawl space.



One of these items doesn't belong in a crawl space...

Photo credit: Indoor Environmental Systems.

- A guarantee or warranty against growth of visible mold for a specified period of time, with exceptions for water leaks or intrusion outside the installer's control
- References for quality assurance inspections by independent third parties
- Guidelines for basic maintenance of the crawl space system (see sidebar on page 22)

Establishing a Contract and Pricing

If you choose to hire an installer to implement a closed crawl space, the installer should have a contract or plan that clearly spells out what they are responsible for, and what the builder or other contractors are responsible for. Responsibilities for other contractors might include foundation waterproofing, foundation drains, grading, and/or installation of the drying mechanism if it requires a licensed electrician or mechanical contractor and the crawl space installer is not licensed.

Contracts may also specify financial incentives or penalties geared towards ensuring an efficient installation. For example, there may be a trip charge assessed when the builder calls the installer to the site but has not completed the work necessary for the installer to proceed, or a back charge assessed if the builder or other trades damage the crawl space system to the point that it requires repair or replacement of any component.

Currently in North Carolina, pricing from contractors providing closed crawl space systems to general contractors for new construction ranges from \$1.00 to \$3.50 per square foot of crawl space floor area for a variety of installations. Some factors that affect pricing are the number of piers in a crawl space, height above or below grade, height of perimeter walls, or the complexity of the foundation footprint. These sample installation costs do not take into account the cost reductions that the builder may realize from not having to install features like insulation or drainage, since they may be included in the pricing of the closed crawl space system.

Initial costs associated with building closed crawl spaces will generally be more than for traditional wall vented construction. As new construction methods are evaluated both by builders and researchers, it will be important to factor in the value of reduced callbacks due to moisture and mold issues, the perception of enhanced value by the consumer, and potential for increased sales price and reduced legal exposure. Reduced maintenance, a reduction in costly, long-term repairs, and significant energy savings enhance the value of closed crawl space construction to the consumer, appraisers and realtors. The future might even include insurance premium reductions for houses built on closed crawl spaces.

Summary

Successful implementation, whether by a property owner, builder, or professional closed crawl space installer, must address six main topics:

- Defining the design of the closed crawl space
- Working with code officials to ensure acceptance of the design
- Overcoming the conventional wisdom that favors venting with outside air
- Managing labor, including training and safety
- Managing job site logistics, especially moisture management and coordination with other trades
- Providing quality assurance

Finally, if you hire a professional installer, make sure to establish a well-defined plan and a contract that clearly specifies responsibilities and pricing.

Section 3

SAMPLE DESIGNS AND CONSTRUCTION PROCESS

Overview

Advanced Energy has field tested several closed crawl space designs. This section contains drawings for the designs that proved effective for moisture control and that meet the minimum requirements of the North Carolina residential building code described in Section 4. The numbered callouts refer to notes for each of the specific components in the drawing. This section also includes background information, advantages and disadvantages for the two humidity control strategies used in the sample designs, as well as a sample construction sequence based on processes Advanced Energy uses to have closed crawl spaces built in occupied homes for field research projects.

The designs presented here are not the only closed crawl space designs that are acceptable. They are simply examples that performed successfully in the field testing detailed in Section 6. These designs have been utilized in

other Advanced Energy research projects and by professional installers in a variety of locations in North Carolina. There are many other designs that can perform acceptably and that meet the requirements of the North Carolina residential building code.

The sample designs and process presented here are not definitive specifications. If you are a builder, property owner, or other contractor planning to install closed crawl spaces, you will need to adjust these designs and processes to your local site conditions, code requirements, home design, construction processes and occupant needs to ensure success.

Recommended Humidity Control Methods

Some installers and researchers have theorized that the moisture control improvements of closed crawl spaces allow the mechanical contractor to down-size heating and cooling equipment. However, there are few commonly available tools at the time of this writing to calculate the impact of a closed crawl space on the sizing of mechanical equipment for the home, and Advanced Energy research projects have not investigated this aspect of performance.

Recommendation 1

Control humidity in the closed crawl space with dry air from the supply-side ductwork of the house air-conditioning system. Provide a

backflow damper (for example, a gravity-operated butterfly damper) and either a balancing damper or constant airflow regulator to provide nominal airflow of 1 cubic foot per minute (0.5 liters per second) per 30 square feet (4.6 square meters). Traditional balancing dampers are adjustable over a range of flows. Constant airflow regulators provide a calibrated amount of flow without any need for adjustment. Multiple supply vents may be used to achieve the desired airflow and/or desired distribution of air. If necessary, adjust the airflow to control relative humidity in the crawl space to the desired level, typically 70% relative humidity or lower. Flow can be measured with a simple bag-fill method (for an example, see the Resources and References section under Canada Mortgage and Housing Corporation) an anemometer/digital air flow meter, a powered flow hood, or a passive flow hood. No return air vent is allowed with this method.



Metal strapping holds this 4 inch (102 mm) diameter supply duct horizontal to ensure proper operation of the butterfly backdraft damper. The balancing damper is visible behind the butterfly damper. The connection to the supply trunk duct is sealed with mastic.



This 4 inch (102 mm) diameter constant airflow regulator (CAR) uses a pressure-modulated, flexible bladder to deliver a constant rate of airflow over a wide range of duct system pressures. The model shown delivers 30 cubic feet per minute (15 liters per second). Operation is completely passive, with no electronic controls.

Advantages

This system is inexpensive, simple to install, fully adjustable, and has no need for maintenance beyond a periodic inspection. It is unlikely to be affected by the operation of other exhaust fans in the house, including large exhausts like clothes dryers. If the central air conditioner fails, the homeowner is likely to repair it, thus guaranteeing operation of the drying mechanism for the closed crawl space. The lack of return duct or passive transfer grill from the crawl space to the house reduces the chance that the crawl space will affect the indoor air quality of the living space above.

Disadvantages

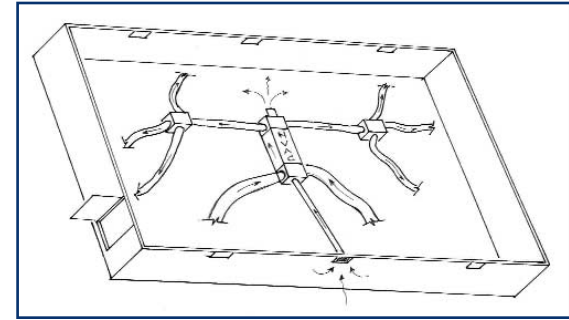
Relative humidity control appears to be less effective in the spring and fall when air-

conditioner use is lower. If the air conditioner is not providing adequate dehumidification for the living space, then it may not provide adequate dehumidification for the crawl space. Oversizing the air conditioner or setting the system fan to run after the air conditioner compressor has stopped are bad strategies because they can reduce the air conditioner's ability to dehumidify. Occupants can prevent the air conditioner from controlling humidity by generating excessive humidity in the house, choosing not to run the air conditioner, running the air handler fan continuously, and/or keeping windows and doors open to outside during humid weather. The lack of return duct or passive transfer grill from the crawl space to the house does not meet the requirements for an "unvented" crawl space specified in the 2004 Supplement to the International Codes. See Section 4 for more details.

What about Pressure Effects?

Theoretically, in a very tightly air-sealed house, operating the supply duct to the closed crawl space with no return to the house could create a small negative pressure in the house with reference to outside or to the crawl space. Some of the air supplied to the crawl space might then return to the living space. In Advanced Energy field tests, the small crawl space airflow causes a negligible pressure effect that is far exceeded by the effects of duct leakage, stack pressure or wind-induced pressures in the building. Sealing floor penetrations reduces the risk of crawl space air entering the living space. To help eliminate the

possibility of negative pressure, an outside air intake can be properly sized and installed in the return side of the HVAC duct system. In such a system, the ventilation air slightly pressurizes the living space and then exits through the building envelope. The crawl space supply makes use of some of the exiting



Schematic representation of crawl space duct system with integrated outside air intake and crawl space supply duct. Drawing provided by Indoor Environmental Systems, ©2005.



This outside air intake replaces a standard-size concrete masonry unit (CMU) block or foundation vent and houses a washable filter.

Photo credit: Indoor Environmental Systems.

ventilation air by using it to dry the crawl space before it leaves the building. Section 6 has details on how this system was implemented in Advanced Energy's Princeville research project.

Recommendation 2

Control water vapor in the crawl space with one or more permanently installed dehumidifiers, each with a minimum 15 pint-per-day capacity. Adjust as needed to control relative humidity in the crawl space to desired level, typically 70% or lower. Pipe condensate per local code requirement to outdoors or to an interior pump that discharges to outdoors. Provide a dedicated, non-switched, GFCI-protected electrical outlet for the dehumidifier.

Advantages

Dehumidifiers are capable of rapidly removing large amounts of water vapor and are independent of the house conditioning system. They can maintain lower relative humidity levels than air conditioning equipment. Low-profile or horizontal-mount units are available to accommodate short crawl spaces.

Disadvantages

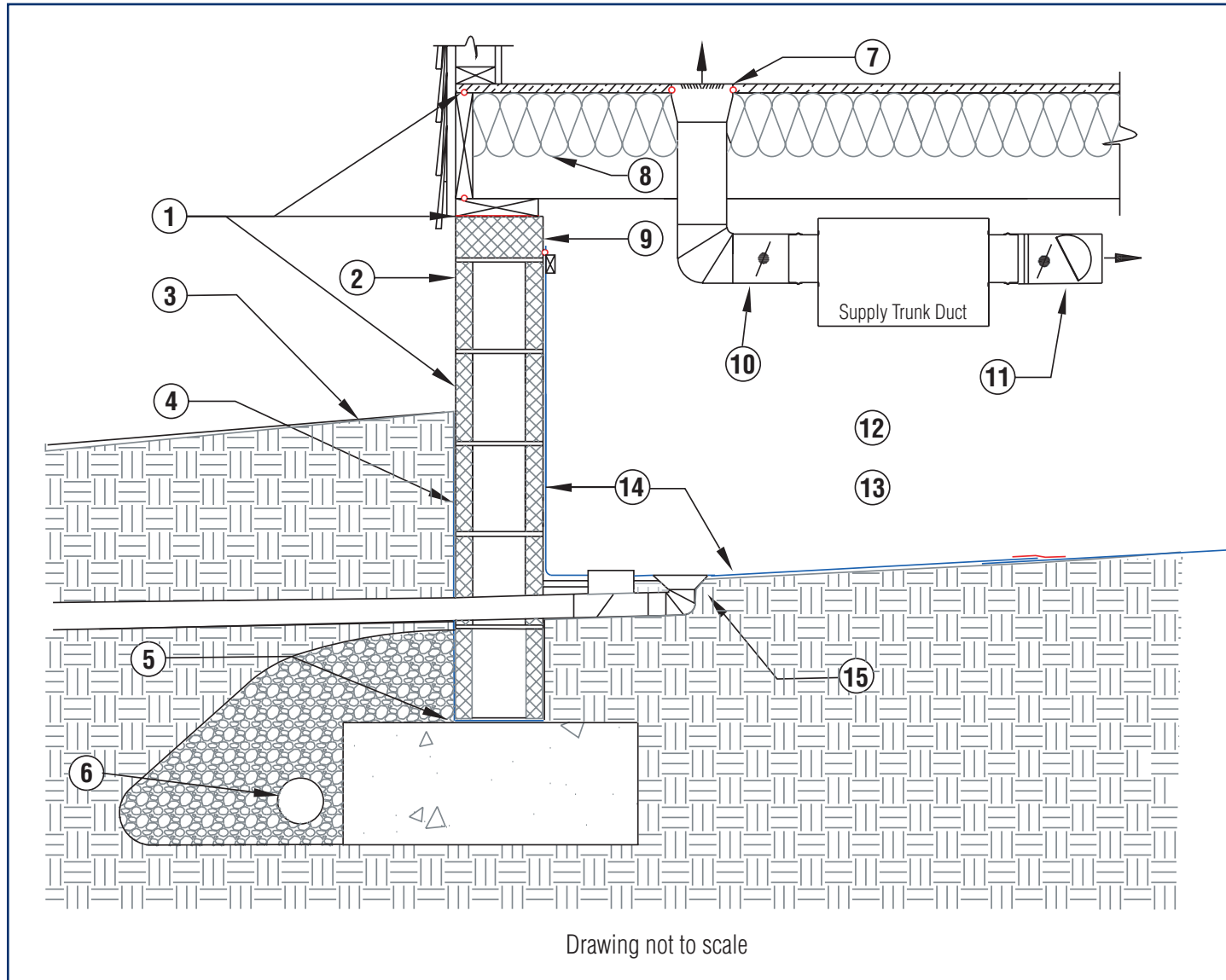
Dehumidifiers require periodic maintenance and may not be noticed when they fail. Some units must be re-activated manually after power outages. High-quality models can be

expensive. Condensate drains require periodic inspection and, if they fail, can allow liquid water in the crawl space. There is currently no standard protocol for calculating the required dehumidifier capacity; manufacturers provide general sizing guidelines. Dehumidifier capacity decreases as ambient temperature decreases, so performance must be verified if dehumidification is needed in the winter months.

Sample Design: Supply Air and Floor Insulation

1. Seal exterior wall penetrations and mating surfaces at top and bottom of sill plate and at top and bottom of band joist. Crawl space access panel(s) or door(s) must be air-sealed.
2. No open foundation vents are allowed in exterior walls. Openings to ventilated porch foundations must be air-sealed with an access panel or permanent materials. Install flood vents per local residential code where required.
3. Slope finished grade away from building per local residential code or for 6 in. drop over 10 ft. Provide a method to transport roof runoff away from the house. Gutters and downspouts are one such method.
4. Dampproof or waterproof the exterior wall surface when the crawl space floor is below exterior grade.
5. It is not necessary to provide a capillary break (mortar admixture or physical barrier) between the footings and foundation walls or interior columns, but this may provide additional moisture control.
6. Provide foundation drain to daylight per local residential code requirements.
7. Seal all plumbing, electrical, duct, cable, and other penetrations through the sub-floor with fire-stop materials and sealants. Fiberglass or rock wool insulation alone are not sufficient.
8. Insulate floor joist cavities. Place insulation in full contact with the sub-floor and ensure that it is secured in place. Use R-value required by local residential code.
9. Leave a minimum 3" termite inspection gap between the top of the wall vapor retarder and the top of the masonry wall. Seal the top of the vapor retarder to the wall with duct mastic or equivalent sealant. Optionally, apply a light colored paint or coating over the inspection gap to improve inspectability by pest control professionals.
10. Air seal all heating and cooling ductwork with a duct mastic system. Install all ductwork located in the crawl space with R-value per local code requirement.
11. Control moisture vapor in the crawl space with supply air from the house air-conditioning system. Set supply air volume per local residential code requirement. Adjust as needed to control relative humidity in crawl space to desired level. Provide a backflow damper and either a balancing damper or constant airflow regulator to control airflow. Multiple supply vents may be used to achieve the desired airflow and/or desired distribution of air. No return air vent is allowed in the crawl space.
12. Terminate water heater drains, temperature/pressure relief pipes, and A/C condensate drains to outdoors or to an interior pump that discharges to outdoors. Terminate all kitchen, bathroom and clothes dryer vents to outdoors.
13. Any fuel-fired furnaces, water heaters, or other appliance in a closed crawl space should be of a "direct vent" or "two-pipe" design, meaning that all air for combustion is piped directly from outside to the appliance and all combustion exhaust gases are piped directly from the appliance to outside.
14. Cover 100% of the crawl space floor with a minimum 6-mil vapor retarder. Mechanically fasten and seal the vapor retarder material to the inside wall surfaces, leaving the required termite inspection gap at the top of the wall. Extend the vapor retarder up the interior columns at least 4 inches above the crawl space floor. Seal all seams and edges with fiberglass mesh tape and duct mastic or equivalent. Mechanically secure the ground vapor retarder as necessary.
15. Grade the crawl space floor to one or more low points. Provide crawl space drain(s) or sump pump(s) at lowest point(s). Slope drains to daylight and include an accessible backflow valve and 1/4-inch rodent screening. Gutter drains and foundation drains (interior or exterior) must not be connected to the crawl space drain.

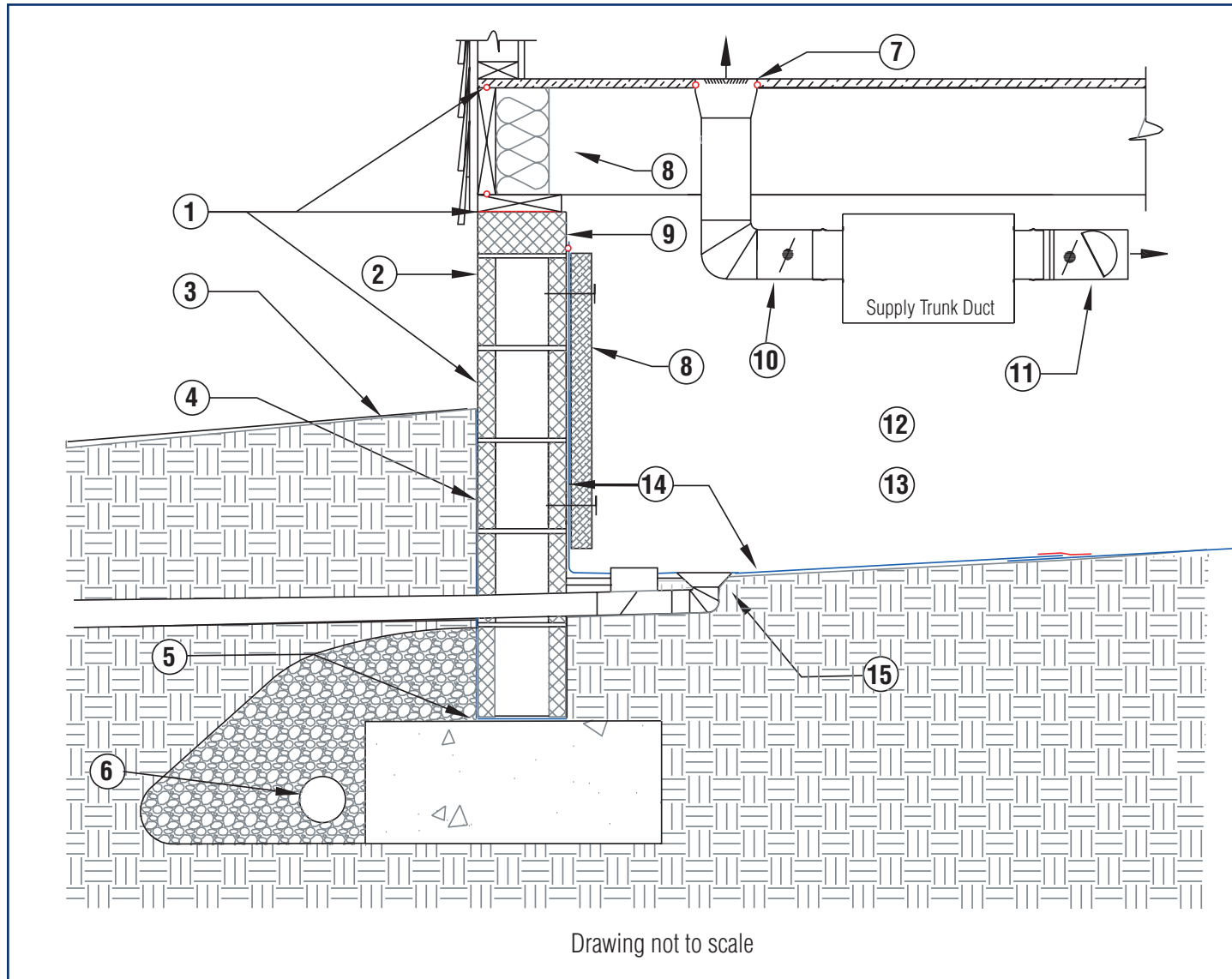
Advanced Energy Sample Design: A Closed Crawl Space With Supply Air and Floor Insulation



Sample Design: Supply Air and Wall Insulation

1. Seal exterior wall penetrations and mating surfaces at top and bottom of sill plate and at top and bottom of band joist. Crawl space access panel(s) or door(s) must be air-sealed.
2. No open foundation vents are allowed in exterior walls. Openings to ventilated porch foundations must be air-sealed with an access panel or permanent materials. Install flood vents per local residential code where required.
3. Slope finished grade away from building per local residential code or for 6 in. drop over 10 ft. Provide a method to transport roof runoff away from the house. Gutters and downspouts are one such method.
4. Dampproof or waterproof the exterior wall surface when the crawl space floor is below exterior grade.
5. It is not necessary to provide a capillary break (mortar admixture or physical barrier) between the footings and foundation walls or interior columns, but this may provide additional moisture control.
6. Provide foundation drain to daylight per local residential code requirements.
7. Seal all plumbing, electrical, duct, cable, and other penetrations through the sub-floor with fire-stop materials and sealants. Fiberglass or rock wool insulation alone are not sufficient.
8. Insulate the crawl space wall over the wall vapor retarder material with rigid foam or other non-porous insulation material. Leave a minimum 3" termite inspection gap between the top of the wall insulation and the top of the masonry wall. Leave a minimum 3" wicking gap between the bottom of the wall insulation and the crawl space floor surface. Obtain R-value from local residential code. Ensure that the insulation complies with local residential code requirements for installation without a thermal barrier or ignition barrier. Insulate the band joist with batt insulation to facilitate removal and reinsertion during pest control inspections. Ensure that batt facings comply with local fire requirements.
9. Leave a minimum 3" termite inspection gap between the top of the wall vapor retarder and the top of the masonry wall. Seal the top of the vapor retarder to the wall with duct mastic or equivalent sealant. Optionally, apply a light colored paint or coating over the inspection gap to improve inspectability by pest control professionals.
10. Air seal all heating and cooling ductwork with a duct mastic system. Install all ductwork located in the crawl space with R-value per local code requirement.
11. Control moisture vapor in the crawl space with supply air from the house air-conditioning system. Set supply air volume per local residential code requirement. Adjust as needed to control relative humidity in crawl space to desired level. Provide a backflow damper and either a balancing damper or constant airflow regulator to control airflow. Multiple supply vents may be used to achieve the desired airflow and/or desired distribution of air. No return air vent is allowed in the crawl space.
12. Terminate water heater drains, temperature/pressure relief pipes, and A/C condensate drains to outdoors, or to an interior pump that discharges to outdoors. Terminate all kitchen, bathroom and clothes dryer vents to outdoors.
13. Any fuel-fired furnaces, water heaters, or other appliance in a closed crawl space should be of a "direct vent" or "two-pipe" design, meaning that all air for combustion is piped directly from outside to the appliance and all combustion exhaust gases are piped directly from the appliance to outside.
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15. Grade the crawl space floor to one or more low points. Provide crawl space drain(s) or sump pump(s) at lowest point(s). Slope drains to daylight and include an accessible backflow valve and 1/4-inch rodent screening. Gutter drains and foundation drains (interior or exterior) must not be connected to the crawl space drain.

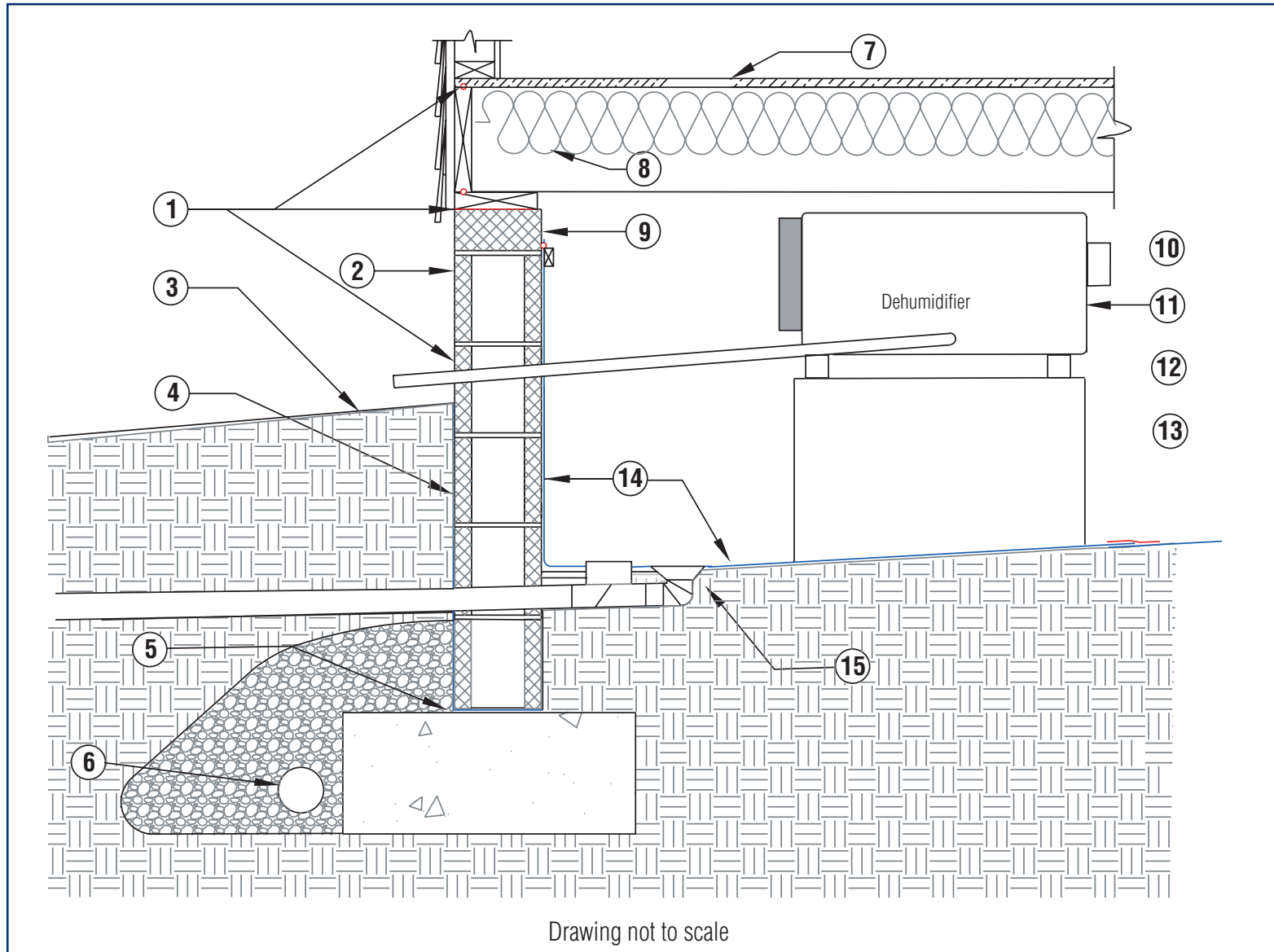
Advanced Energy Sample Design: A Closed Crawl Space With Supply Air and Wall Insulation



Sample Design: Dehumidifier and Floor Insulation

1. Seal exterior wall penetrations and mating surfaces at top and bottom of sill plate and at top and bottom of band joist. Crawl space access panel(s) or door(s) must be air-sealed.
2. No open foundation vents are allowed in exterior walls. Openings to ventilated porch foundations must be air-sealed with an access panel or permanent materials. Install flood vents per local residential code where required.
3. Slope finished grade away from building per local residential code or for 6 in. drop over 10 ft. Provide a method to transport roof runoff away from the house. Gutters and downspouts are one such method.
4. Dampproof or waterproof the exterior wall surface when the crawl space floor is below exterior grade.
5. It is not necessary to provide a capillary break (mortar admixture or physical barrier) between the footings and foundation walls or interior columns, but this may provide additional moisture control.
6. Provide foundation drain to daylight per local residential code requirements.
7. Seal all plumbing, electrical, duct, cable, and other penetrations through the sub-floor with fire-stop materials and sealants. Fiberglass or rock wool insulation alone are not sufficient.
8. Insulate floor joist cavities. Place insulation in full contact with the sub-floor and ensure that it is secured in place. Use R-value required by local residential code.
9. Leave a minimum 3" termite inspection gap between the top of the wall vapor retarder and the top of the masonry wall. Seal the top of the vapor retarder to the wall with duct mastic or equivalent sealant. Optionally, apply a light colored paint or coating over the inspection gap to improve inspectability by pest control professionals.
10. Air seal all heating and cooling ductwork with a duct mastic system. Install all ductwork located in the crawl space with R-value per local code requirement.
11. Control humidity in the crawl space with one or more permanently installed dehumidifiers, each with a minimum 15 pint-per-day capacity. Adjust as needed to control relative humidity in the crawl space to desired level. Pipe condensate per local code requirement to outdoors or to an interior pump that discharges to a drain or outdoors. Provide a dedicated, non-switched, GFCI-protected electrical outlet for the dehumidifier.
12. Terminate water heater drains, temperature/pressure relief pipes, and A/C condensate drains to outdoors or to an interior pump that discharges to outdoors. Terminate all kitchen, bathroom and clothes dryer vents to outdoors.
13. Any fuel-fired furnaces, water heaters, or other appliance in a closed crawl space should be of a "direct vent" or "two-pipe" design, meaning that all air for combustion is piped directly from outside to the appliance and all combustion exhaust gases are piped directly from the appliance to outside.
14. Cover 100% of the crawl space floor with a minimum 6-mil vapor retarder. Mechanically fasten and seal the vapor retarder material to the inside wall surfaces, leaving the required termite inspection gap at the top of the wall. Extend the vapor retarder up the interior columns at least 4 inches above the crawl space floor. Seal all seams and edges with fiberglass mesh tape and duct mastic or equivalent. Mechanically secure the ground vapor retarder as necessary.
15. Grade the crawl space floor to one or more low points. Provide crawl space drain(s) or sump pump(s) at lowest point(s). Slope drains to daylight and include an accessible backflow valve and 1/4-inch rodent screening. Gutter drains and foundation drains (interior or exterior) must not be connected to the crawl space drain.

Advanced Energy Sample Design: A Closed Crawl Space With Dehumidifier and Floor Insulation



Sample Design: Dehumidifier and Wall Insulation

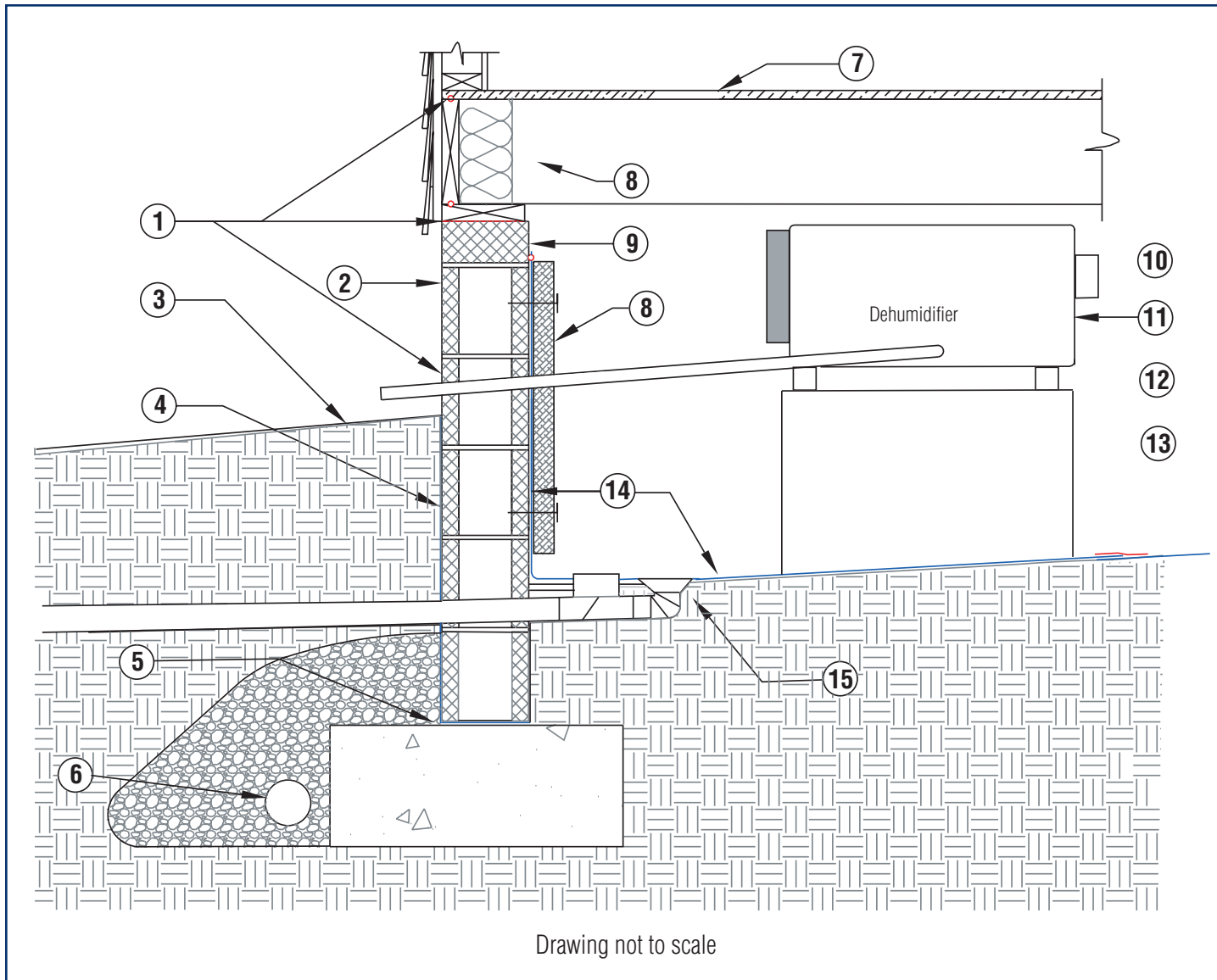
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3. Slope finished grade away from building per local residential code or for 6 in. drop over 10 ft. Provide a method to transport roof runoff away from the house. Gutters and downspouts are one such method.
4. Dampproof or waterproof the exterior wall surface when the crawl space floor is below exterior grade.
5. It is not necessary to provide a capillary break (mortar admixture or physical barrier) between the footings and foundation walls or interior columns, but this may provide additional moisture control.
6. Provide foundation drain to daylight per local residential code requirements.
7. Seal all plumbing, electrical, duct, cable, and other penetrations through the sub-floor with fire-stop materials and sealants. Fiberglass or rock wool insulation alone are not sufficient.
8. Insulate the crawl space wall over the wall vapor retarder material with rigid foam or other non-porous insulation material. Leave a minimum 3"

termite inspection gap between the top of the wall insulation and the top of the masonry wall. Leave a minimum 3" wicking gap between the bottom of the wall insulation and the crawl space floor surface. Obtain R-value from local residential code. Ensure that the insulation complies with local residential code requirements for installation without a thermal barrier or ignition barrier. Insulate the band joist with batt insulation to facilitate removal and reinsertion during pest control inspections. Ensure that batt facings comply with local fire requirements.

9. Leave a minimum 3" termite inspection gap between the top of the wall vapor retarder and the top of the masonry wall. Seal the top of the vapor retarder to the wall with duct mastic or equivalent sealant. Optionally, apply a light colored paint or coating over the inspection gap to improve inspectability by pest control professionals.
10. Air seal all heating and cooling ductwork with a duct mastic system. Install all ductwork located in the crawl space with R-value per local code requirement.
11. Control humidity in the crawl space with one or more permanently installed dehumidifiers, each with a minimum 15 pint-per-day capacity. Adjust as needed to control relative humidity in the crawl space to desired level. Pipe condensate per local code requirement to outdoors or to an interior pump that discharges to a drain or outdoors. Provide a dedicated, non-switched, GFCI-protected electrical outlet for the dehumidifier.

12. Terminate water heater drains, temperature/pressure relief pipes, and A/C condensate drains to outdoors or to an interior pump that discharges to outdoors. Terminate all kitchen, bathroom and clothes dryer vents to outdoors.
13. Any fuel-fired furnaces, water heaters, or other appliance in a closed crawl space should be of a "direct vent" or "two-pipe" design, meaning that all air for combustion is piped directly from outside to the appliance and all combustion exhaust gases are piped directly from the appliance to outside.
14. Cover 100% of the crawl space floor with a minimum 6-mil vapor retarder. Mechanically fasten and seal the vapor retarder material to the inside wall surfaces, leaving the required termite inspection gap at the top of the wall. Extend the vapor retarder up the interior columns at least 4 inches above the crawl space floor. Seal all seams and edges with fiberglass mesh tape and duct mastic or equivalent. Mechanically secure the ground vapor retarder as necessary.
15. Grade the crawl space floor to one or more low points. Provide crawl space drain(s) or sump pump(s) at lowest point(s). Slope drains to daylight and include an accessible backflow valve and 1/4-inch rodent screening. Gutter drains and foundation drains (interior or exterior) must not be connected to the crawl space drain.

Advanced Energy Sample Design: A Closed Crawl Space With Dehumidifier and Wall Insulation



Sample Closed Crawl Space Construction Sequence

The sample process presented here is not a definitive specification; it is based on recommendations from professional installers as well as processes used by Advanced Energy to have installers construct effective closed crawl spaces for several research projects. If you are a builder, property owner, or other contractor planning to install closed crawl spaces, you will need to adjust these designs and processes to your local site conditions, code requirements, home design, construction processes and occupant needs to ensure success. More specifically, this sample process is geared towards low-volume construction of closed crawl spaces in small homes with simple foundation plans. Builders of the more complex homes typically found in mainstream residential construction will likely need to make significant changes to this process, especially if they build in high volume.

Remember that long construction schedules make it much more difficult to manage moisture prior to the crawl space and house being dried in. Refer to the sidebar on long construction schedules in Section 2 for alternative strategies to implement a closed crawl space in such cases.

This process covers steps directly related to the crawl space installation. It does not attempt to cover other requirements like foundation reinforcement, framing anchors, or masonry specifications.



💧 Steps that are designed specifically to provide moisture management during the construction process are indicated by the blue water drop.

Foundation Phase





1. Locate footings.
2. Locate crawl space drain(s) or sump pump(s).
3. Locate crawl space access(es).
4. Pour footings and build foundation wall, installing crawl space drain pipe(s) through wall.
5. For hollow masonry walls, either fill the cores of the top course of block with mortar or use solid cap block for the top course.
6. Whenever possible, make the interior finished grade equal to or higher than the exterior finished grade.
7. Grade the crawl space ground to slope to drain(s) or sump(s) location.
 - When using drain(s),
 - a. Install crawl space floor drain and backflow valve.
 - b. Extend exterior portion of crawl space floor drain pipe to daylight and terminate with 1/4" rodent screening.
 - When using sump pump(s),
 - a. Excavate sump locations and protect from collapse.
8. Install exterior foundation drain system, separate from crawl space drain system. Extend foundation drain pipe to daylight.
9. Ensure that all penetrations in the foundation wall are water tight. Apply damp-proofing or water-proofing on exterior of foundation wall, if applicable.
10. 💧 Place backfill against the foundation wall and grade to slope away from the foundation as soon as possible.
11. Air seal all penetrations in the foundation perimeter wall.
12. Attach and seal wall vapor retarder material to the perimeter wall with required termite inspection gap. Extend the wall vapor retarder material approximately 12 inches horizontally onto the ground. (Alternately, wall vapor retarder can be installed when the finished ground vapor retarder material is installed.)

13. Attach and seal vapor retarder material around each of the interior piers, extending up at least 4 inches above the crawl space floor. Extend the pier vapor retarder material at least 12 inches horizontally onto the ground. (Alternately, this could be done when the finished ground vapor retarder material is installed.)
14. Install wall insulation, if applicable, with required termite inspection gap at top and wicking gap at bottom.
15. Ensure that the top of the foundation wall is solid or can be air sealed.

Floor Platform Phase

16. Apply gasket or sealant between sill plate and top of foundation wall.
17. Build first floor platform. Apply sealant or gasket between band joist and sill plate. Apply sealant or gasket between band joist and subfloor.
18.  Cover holes in subfloor that can leak water into the crawl space.
19.  Install temporary layer of minimum 4-mil polyethylene on crawl space ground as soon as possible. Puncture holes in this temporary ground vapor retarder to allow standing water to drain into the ground. Note that it may not be feasible to install the temporary ground cover until after the home is dried-in.

Main Construction Phase

20.  Install and close the crawl space access door(s). Spring-loaded hinges and/or a locked latch can help to ensure that the door stays closed. Ensure that someone on site is responsible for keeping the door closed as much as possible during the day and for locking the door at the end of every day.
21.  Ensure that roof runoff does not enter the crawl space.
22.  If drains are installed, ensure that drains remain clear. If sump pits are installed, remove water with temporary pumps if needed.
23.  Install and run a temporary dehumidifier to maintain targets of <70% relative humidity or <15% wood moisture content. The dehumidifier condensate must be drained or pumped to outside. Ensure that someone on site is responsible for providing power to the dehumidifier and making sure the dehumidifier is safe from theft.
24. Finish all plumbing work in the crawl space, including sump pumps and dehumidifier drain, if applicable.
25. Finish all electrical work in the crawl space, including at least one permanently wired, non-switched GFCI-protected outlet to accommodate at least one permanent or temporary dehumidifier.
26. Install crawl space supply air duct, if applicable.
27. Finish all other mechanical work in the crawl space, including duct sealing and installation of outside air intake, if applicable. Ensure that vapor retarder material is installed under the air handler unit(s) if the unit is to be installed in the crawl space.
28. Ensure that clothes dryer vent, kitchen exhaust, bathroom exhaust, condensate drains, and water heater temperature/pressure relief all terminate outside the crawl space.
29. Air seal all penetrations in the subfloor and band joist.
30. Install insulation in subfloor, if applicable.

After ALL Crawl Space Work Is Complete

31. Remove temporary ground vapor retarder and all construction debris, wood forms, or organic matter from the crawl space.
32. Install permanent ground vapor retarder material, overlapping the horizontal flap of the wall vapor retarder and any other seams by at least 12 inches.
33. Secure the ground vapor retarder as desired.

34. Seal all seams in the vapor retarder material with fiberglass mesh tape and duct mastic.
35. Confirm proper installation and operation of the crawl space drain.
36. Attach the permanent ground vapor retarder material to the crawl space drain(s) or sump pump(s).
37. If 6-mil unreinforced polyethylene is used for the ground vapor retarder, provide reinforcing material along the paths to the air handler unit and any other equipment that will be serviced.
38. Install permanent dehumidifier, if applicable.
39. Confirm that the access door is weather-stripped, fits well, and can be latched.
40. Install a laminated sign inside the crawl space access door to remind people to keep the crawl space access door closed and maintain the integrity of the vapor retarder. The sign should also list the components of the closed crawl space system, any maintenance the components need, and a phone number for questions.
41. Obtain Certificate of Occupancy and permanent power connection.
42. Remove temporary dehumidifier, if applicable.
43. Activate permanent dehumidifier(s), if applicable.
44. Activate sump pump(s), if applicable.
45. Activate HVAC system, then set supply air flow rate, if applicable.

Post-Occupancy

Provide documentation of the intended level of relative humidity control to the property owners and provide crawl space maintenance guidelines as desired. See Section 2 for a sample list of maintenance guidelines. If a relative humidity and/or liquid water monitoring system is installed in the crawl space, specify the conditions under which the property owner should contact the crawl space installer or builder for service or inspection.

At a later date, verify proper performance of all system components and adjust the supply air flow rate or dehumidifier setting, if necessary, to maintain the intended relative humidity in the crawl space. Some installers may want to re-inspect the system within a few weeks of activation. This inspection (or an additional inspection) may be scheduled several months after activation to verify performance in the humid spring or summer months. The inspection could occur as part of a contract installer's quality assurance program, part of a builder's warranty inspection processes, or as a response to the property owner's monitoring of the system.

Section 4

BUILDING CODES

Historic Origins

Construction guidelines from agencies like the National Bureau of Standards (1923) and the Federal Housing Administration (1935) contain the earliest known recommendations that crawl spaces be ventilated with outside air. Despite documented failure in such crawl spaces in the 1930s and a lack of technical justification, the FHA turned these guidelines into requirements in the early 1940s. Since then, building regulations across the United States have required ventilation of crawl spaces with outside air. This history is documented by William Rose (Davis, Warren and Rose, 2002) and shows that there is no scientific basis for current crawl space ventilation requirements.

Building research from the 1970s onward has documented that this ventilation may cause or contribute to moisture problems instead of preventing them, and more recent building codes like the 2000 and 2003 versions of the International Residential Code (IRC) have included language to allow the construction of crawl spaces without ventilation openings to the outside. Unfortunately, these more recent codes still require ventilation with outside air as the default, and allow crawl spaces to be approved without any ground vapor retarder.

The exceptions that allow closed crawl spaces are vague or incomplete and as a result are nearly impossible to follow or enforce consistently. For example, IRC Section R408.2 Exception 5 allows a closed crawl space if there is a ground vapor retarder, perimeter wall insulation, and conditioned air, but it gives no guidance on how much conditioned air should be supplied or acceptable methods for injecting the air.

Other sections of the code are problematic for technical reasons. Exception 5 requires that the perimeter wall insulation be installed in accordance with Section N1102.1.7. Section N1102.1.7 requires the perimeter wall insulation to extend downward from the subfloor to the finished grade level and then vertically and/or horizontally for at least an additional 24 inches (61 cm). This is often referred to as the “L-shaped” method of installing insulation. This method is not viable in the Southeast for two reasons:

- First, the risk of insect pest damage is too high in the Southeast to deprive the pest management industry of an inspection gap at the top of the masonry foundation wall and convenient access to the sill plate for inspection or treatment whenever possible. Insulation in ground contact can increase the risk of termite infestation.
- Second, the “L-shaped” installation method is extremely impractical in terms of real life construction sequences, access, inspections, and potential pest treatments given currently available insulation materials.

The 2004 Supplement to the International Codes retains the problematic insulation requirement in the IRC (now section N1102.2.8) and in the International Energy Conservation Code (Section 402.2.8). However, the Supplement has significantly changed Section R408 Under Floor Spaces in the IRC. The exceptions noted above in Section R408.2 have been deleted. A new section, R408.3 Unvented Crawl Space, has been added. This new section allows construction of a crawl space with no ventilation openings to the outside if (1) there is a sealed ground vapor retarder, (2) the perimeter walls are insulated in accordance with Section N1102.2.8, and (3) the crawl space is designed as a plenum or it is designed with either an exhaust ventilation system with an air pathway to the common area or a conditioned air supply with a return air pathway to the common area. There is no apparent compliance pathway for a closed crawl space that is isolated from the living space or that utilizes only floor insulation.

Revising the North Carolina Residential Code

The inconsistencies and omissions of the current code demanded a substantial revision in order to create a compliance path that can be consistently followed and enforced for a variety of acceptable closed crawl spaces. A broad group of stakeholders including code

officials, pest management professionals, builders, building scientists, installers of closed crawl spaces, and product manufacturers, worked with the North Carolina Building Code Council and the code enforcement staff at the North Carolina Department of Insurance for over two years to craft this sorely-needed code revision. The end result was an updated Section 408 that governs wall-vented crawl spaces, and a completely new Section 409 that governs closed crawl spaces. Requirements or options were added to the code when research or field data indicated that they perform as intended, and existing requirements were left in place unless there was research or field data that showed they do not perform as intended.

The North Carolina Building Code Council adopted the new crawl space code language in September 2004 and the state of North Carolina approved it in November of 2004. This new code was made available for reference as of December 1, 2004 as an alternate to the existing printed code, and the new code will be enforced in 2006 with the release of the updated North Carolina Residential Code in print. In some cases, local code officials may require or accept a stamped letter of approval from a registered professional engineer as an alternate path for permitting and inspection.

Requirements of the New North Carolina Residential Code

This section provides a general overview of the requirements of the new code language for both wall-vented and closed crawl spaces. This section is not a direct copy of the official code language, and compliance with the items listed here does not guarantee compliance with the residential building code. Where there is any difference between the items listed here and the residential building code, the code language takes precedence. For links to online North Carolina code information, refer to www.crawlspaces.org.

All Crawl Spaces

- ✓ Water drains (e.g. pressure relief, condensate lines, drain pans, etc.) shall terminate outdoors, to a crawl space floor drain, or to an interior pump and shall not intentionally discharge in the crawl space.
- ✓ Dryer vents shall terminate outdoors.
- ✓ The crawl space shall be separated from adjoining basements, porches, and garages by permanent walls. All utility penetrations shall be sealed.
- ✓ Latched and weather-stripped doors or access panels shall provide access between the crawl space and adjoining basements, porches, and garages.
- ✓ A minimum 6-mil polyethylene vapor retarder or equivalent shall cover 100% of exposed earth in the crawl space, with joints lapped at least 12 inches (305 mm).
- ✓ The floor of the crawl space shall be graded to one or more low spots, and a drain to daylight or a sump pump installed at each low spot.
- ✓ Crawl space drains shall be separate from roof gutter drain systems and foundation perimeter drains.
- ✓ Where the outside grade is higher than the inside grade, the exterior walls shall be dampproofed from the top of the footing to the finished grade as per section R406.1.
- ✓ The building site shall be graded to drain water away from the foundation per section R401.3.
- ✓ All penetrations through the subfloor shall be sealed with non-porous materials, caulks or sealants. The use of rock wool or fiberglass insulation is prohibited as an air sealant.
- ✓ All heating and cooling ductwork in the crawl space shall be sealed with duct mastic or other industry approved duct closure systems.
- ✓ All organic material, vegetation, wood forms for placing concrete and other construction materials shall be removed before the building is occupied or used for any purpose.
- ✓ Buildings in flood-prone areas shall be provided with flood openings in the crawl space perimeter wall per section R327.2.2.

Wall-vented Crawl Spaces

- ✓ Minimum net area of ventilation openings shall be 1 sq. foot (0.0929 sq. meter) per 150 sq. feet (13.9 sq. meters) of crawl space floor area. Minimum net area may be reduced to 1/1,500 of the crawl space ground area where the openings are placed so as to provide cross-ventilation.
- ✓ One vent shall be within 3 feet (914 mm) of each corner of the building. When the crawl space is on a sloped site, the uphill foundation walls may be constructed without wall vent openings to prevent entry of rainwater.
- ✓ Vent dams, to prevent entry of ground surface water, shall be provided whenever the bottom of the foundation vent opening is less than 4 inches (102 mm) above the finished exterior grade.
- ✓ Insulation must be installed in the floor structure.

Closed Crawl Spaces

- ✓ The crawl space perimeter wall shall be air-sealed.
- ✓ Access panels or doors shall be tight-fitting, have a latch mechanism, and be insulated to at least R-2
- ✓ The minimum 6-mil polyethylene ground

vapor retarder may optionally be installed as a full interior liner by sealing the edges to the walls and beam columns and sealing the seams. The top edge of such a liner shall terminate at least 3 inches below the top edge of the masonry foundation wall. The top edge of the liner shall be brought up the interior columns a minimum of 4 inches above the crawl space floor.

- ✓ The ground vapor retarder may optionally be protected against ripping and displacement by pouring a minimum 2 inch thick, unreinforced concrete surface over the vapor retarder. Floor grading and drain or sump pump requirements still apply.
- ✓ At least one of the following methods of space moisture vapor control shall be provided, and combinations of multiple methods are allowed:

Dehumidifier. A permanently installed dehumidifier shall be provided in the crawl space. The minimum rated capacity per day is 15 pints (7.1 Liters). Condensate discharge shall be drained to daylight or interior condensate pump. Permanently installed dehumidifier shall be provided with an electrical outlet.

Supply air. Supply air from the dwelling air conditioning system shall be ducted into the crawl space at the rate of 1 cubic foot per minute (0.5 L/s) per 30 square feet (4.6 sq. meters) of crawl space floor

area. No return air duct from the crawl space to the dwelling air conditioning system is allowed. The crawl space supply air duct shall be fitted with a backflow damper to prevent the entry of crawl space air into the supply duct system when the system fan is not operating. An air relief vent to the outdoors may be installed. Crawl spaces with moisture vapor control installed in accordance with this section are not to be considered plenums.

House air. House air shall be blown into the crawl space with a fan at the rate of 1 cubic foot per minute (0.5 L/s) per 50 sq. feet (4.6 sq. meters) of crawl space floor area. The fan motor shall be rated for continuous duty. No return air duct from the crawl space back to the dwelling air conditioning system is allowed. An air relief vent to the outdoors may be installed. Crawl spaces with moisture vapor control installed in accordance with this section are not to be considered plenums.

Exhaust fan. Crawl space air shall be exhausted to outside with a fan at the rate of 1 cubic foot per minute (0.5 L/s) per 50 square feet (4.6 m²) of crawl space floor area. The fan motor shall be rated for continuous duty. There is no requirement for make-up air.

Conditioned space. The crawl space shall be designed as a heated and/or cooled, conditioned space with insulation on the perimeter wall. Intentionally

returning air from the crawl space to space conditioning equipment that serves the dwelling shall be allowed. Foam plastic insulation located in a conditioned crawl space shall be protected against ignition by an approved thermal barrier.

- ✓ Closed crawl spaces used as supply or return air plenums for distribution of heated or cooled air shall comply with the requirements of the N.C. Mechanical Code. Crawl space plenums shall not contain plumbing cleanouts, gas lines or other prohibited components. Foam plastic insulation located in a crawl space plenum shall be protected against ignition by an approved thermal barrier.
- ✓ Fuel burning appliances located in the crawl space such as furnaces and water heaters shall obtain combustion air from outdoors as per the N.C. Mechanical Code.
- ✓ The thermal insulation in a closed crawl space may be located in the floor system or at the exterior walls, with the exception that insulation shall be placed at the walls when the closed crawl space is designed to be an intentionally heated or cooled, conditioned space.
- ✓ Where the floor above a closed crawl space is not insulated, the walls shall be insulated. Wall insulation can be located on any combination of the exterior and interior surfaces and within the structural cavities or materials of the exterior crawl space walls. Wall insulation systems require that the band joist area of the floor

frame be insulated. Wall insulation shall begin 3 inches below the top of the masonry foundation wall and shall extend down to 3 inches above the top of the footing or concrete floor, 3 inches above the interior ground surface or 24-inches below the outside finished ground level, whichever is less. No insulation shall be required on masonry walls of 9 inches height or less.

Other North Carolina Residential Code Issues

Unregulated Specifications

The new code language does not specify requirements for every crawl space design element. Such items will need to be specified by the designer.

Some examples are:

- Pitch of grade for the crawl space ground
- Size of crawl space drains
- Mechanical fastener schedules for wall vapor retarder or wall insulation
- Sump pump ratings
- Maximum air flow for the supply air drying method
- Methods of securing the ground vapor retarder

Fire Ratings for Foam Plastic Insulation

Changes awaiting adoption by the N.C. Building Code Council at the time of this writing will remove ASTM E84 as a stand-alone test to allow installation of foam plastic insulation in crawl spaces without a thermal barrier or ignition barrier. The following methods of compliance will still be accepted: FM 4880, UL 1040, ASTM E 152, UL 1715, or other tests related to actual end use configurations.

Pressure relief

The code language allows an air relief vent to the outdoors when either house air or conditioned supply air is utilized to meet the moisture control requirement. Installing such a relief vent is not recommended by Advanced Energy, but if one is installed it should incorporate a backdraft damper to prevent outside air from flowing into the crawl space.

Exhaust Fan Strategies Require Careful Design

The N.C. residential code allows the use of an exhaust fan to take air from the crawl space and reject it to the outside as an accepted method for providing the required water vapor control, with the assumption that the makeup air comes from the conditioned volume of the house above.

This method presents some risks. First, to avoid the risk of backdrafting any combustion appliances, don't consider using exhaust fans in the crawl space unless all combustion appliances in the crawl space are direct vent ("two-pipe") models, with all combustion air piped directly from outside to the appliance and all combustion gases piped directly from the appliance to outside.

Second, there is no guarantee that the make-up air for the fan will come from the house as opposed to outside. The floor air sealing (which the code also requires) reduces the flow of makeup air from the house. House exhaust fans and "stack effect" – the natural action of warm air rising up and out of a home – can reduce air pressure in the house such that air will not flow to the crawl space. When this happens, the air removed from the crawl space by the exhaust fan is more likely be replaced by air from outside – exactly the situation the closed crawl space is designed to avoid.

There are several scenarios which may require you to exhaust air from the crawl space, especially in existing homes. For example, you may need to remove radon or other harmful soil gases, ensure isolation of crawl space air from the living space when there are environmental hazards like mold or asbestos present, or simply prevent objectionable crawl space odors from entering the home. In these cases, provide a designed source of makeup air (one example could be a second fan that injects house air into the crawl space) to ensure that the crawl space exhaust fan won't create a combustion hazard or water vapor load.

Section 5**IMPROVING
WALL-VENTED
CRAWL SPACES****Overview**

Improving a wall vented crawl space or converting it to a closed crawl space can present choices and challenges that are not found in new construction. This section focuses on those challenges and does not repeat the general design information discussed in Section 1.

Converting a crawl space is much more than just closing the vents!

Cutting off the flow of outside air into the crawl space is one of the key components of a properly closed crawl space, but all the design elements from Section 1 are needed for success. Simply closing the vents in an existing crawl space will likely cause moisture levels to increase and cause damage, particularly if there is exposed ground without a vapor retarder. Just closing the vents can be downright hazardous if there is combustion equipment located in the crawl space. Does that mean there's no middle ground between a wall-vented crawl space and a fully closed crawl space with a sealed vapor retarder? No.

In existing homes, it can be acceptable to improve the crawl space in steps. Besides moisture control and combustion safety, another reason to proceed carefully with a conversion is to avoid cosmetic damage in the living area that can occur if the house is dried too quickly or if lack of attention during the drying process results in more drying than is necessary. For example, it is unlikely that wood framing ever needs to be dried below 12% moisture content, but unattended dehumidifiers could dry the wood well below this level and cause damage. However, if the home has experienced wet conditions for a long time, the materials in the home will have stabilized at a high moisture content and some damage may be unavoidable. As the crawl space is dried down to acceptable levels, gaps may open in hardwood floors, wood trim carpentry, drywall surfaces, or cabinetry in the living area. On the other hand, swollen or cupped wooden flooring may flatten out again. Once installed, closed crawl spaces stay drier than wall-vented crawl spaces in the summer and more humid in the winter (see the Research Results for details), which will tend to reduce the range of shrinkage and expansion of those materials over time.

**Steps for Improving a
Wall-vented Crawl Space****Step 1: Protect the crawl space
from water sources**

At a minimum, wall vented crawl spaces need a ground vapor retarder on 100% of the crawl space ground, including steep-sloped earthen walls. There should be no plumbing leaks, no intrusion of ground water, and no intrusion of water from outside. This may require:

- Adding a system to manage rain water,
- fixing leaking irrigation or sprinkler systems,
- blocking off low crawl space vents that allow rainwater to enter,
- reducing flooding potential by altering the exterior grade,
- sealing off below-grade holes,
- adding or repairing a foundation drainage system,
- adding or repairing foundation waterproofing,
- fixing plumbing leaks,
- draining standing water, or
- adding an internal drain system or sump pump.

Replace damaged or dirty, incomplete ground vapor retarders with a new vapor retarder that covers all soil and is secured to prevent future movement or damage. All kitchen, bathroom, and clothes dryer vents must terminate outside the crawl space. All air conditioner or dehumidifier condensate drain lines and water heater drains must terminate outside the crawl space.

Step 2: Repair structural damage or rot

Eliminating all the sources of water listed in Step 1 will help to prevent rot from occurring in the future. If rot has occurred in the past or is ongoing, you may need to replace or repair structurally damaged framing or flooring in conjunction with completion of Step 1. In either case, Step 1 must be completed to eliminate all the sources of liquid water that caused the rot in the first place.

At this point, cleaning up surface mold in the crawl space is not worthwhile, since the air entering through the crawl space vents in spring and summer will make it possible for mold to grow. If you continue to Step 5 and convert the wall-vented crawl space to a closed design, then cleanup of surface mold growth can be effective. See “Should I clean up the mold?” in Section 7 for more details.

Step 3: Monitor for water intrusion

Periodically inspect the improved wall-vented crawl space to ensure that all liquid water problems were successfully repaired in Step 1 and to ensure that no new problems have occurred.

Even if all the water problems were properly repaired, you may still encounter small puddles of liquid water on the top of the new vapor retarder. Where ground water is not present, the ground vapor retarder can be punctured to allow small puddles to drain into the soil. This is acceptable because a small hole lets liquid water drain out but only lets a negligible amount of water vapor diffuse into the crawl space.

You might be wondering, “Where would these small puddles come from after all the water intrusion was fixed?” At this point, the foundation vents that remain open will allow outdoor air to enter the crawl space in the spring and summer, and the water vapor in that air will condense on ductwork, water pipes, or other cool surfaces, drip down, and collect in pockets or low areas in the ground vapor retarder. (Refer to the Introduction for an explanation of why this condensation happens.) Note that operating the house at low indoor temperatures in the summer accelerates this problem, especially when the ductwork is in the crawl space, by creating more cold surfaces where condensation can occur. “Low indoor temperatures” means thermostat

settings of less than 72° F/22° C in central North Carolina, but could include warmer settings in extremely humid conditions like those found in coastal environments.

Step 4: Isolate the crawl space from the house

To reduce the chance that a damp crawl space will impact the living space above, seal penetrations in the subfloor with fire-blocking materials and seal ductwork in conjunction with an overall assessment of air leakage and combustion safety in the home by a qualified building performance contractor. Sealing ductwork also reduces the leakage of cold air into the crawl space during air-conditioning periods, which reduces the amount of cold surface area that may experience condensation. For reference, see the appendix on duct sealing.

Step 5: Convert the wall-vented crawl space to a closed design

Once steps 1 and 2 are addressed, the crawl space can be closed using the design and implementation guidelines from Sections 1 and 2, with these additional steps:

- Clean out debris. Remove any materials (e.g. cardboard, paper, etc.) that provide a food source for mold. Ensure that you remove any

existing vapor retarder before new material is installed to avoid trapping water and debris that will allow obnoxious molds or other organisms to grow. Remove rubble to provide a smoother surface that is less likely to damage the new vapor retarder material. Ensure that any hazardous contents (e.g. asbestos, gasoline, household chemicals, etc.) are properly handled and removed. Remove any other objects that will interfere with installation of the ground vapor retarder. Abandoned heating equipment and ductwork are common finds, but everything from old tires and other trash to broken lawn equipment and children's toys are found in crawl spaces.

- Replace damaged or contaminated insulation. Porous insulation that has been wetted will likely not recover its rated R-value, even after it dries thoroughly. Support sagging batt insulation in the floor structure with tension wires (sometimes referred to as "tiger teeth") so that the batts are in continuous contact with the subfloor but is not overly compressed. If there is so much damage that you want to replace all the insulation, use either floor or perimeter wall insulation as desired. If you choose perimeter wall insulation, consult with your pest management contractor to ensure that treatments can continue and that the new insulation will not void your insect pest warranty or bond, if applicable.

- Provide a mechanism to control or detect liquid water problems. It may not be feasible to correct interior grading or install gravity drains in retrofit situations, like when the crawl space or exterior grade is flat or in a low spot. In these situations, sump pumps or liquid water alarm systems are alternatives.
- Provide adequate combustion air for gas- or oil-fired furnaces, water heaters or boilers. Without sufficient combustion air, the appliance can produce carbon monoxide or back draft.

A crawl space with atmospheric or "natural" draft equipment should not be closed.



Ideally, any fuel-fired furnaces or water heaters in a closed crawl space should be of a "direct vent" (often called "two-pipe") design, meaning that all air for combustion is piped directly from outside into the appliance and all combustion exhaust gases are piped directly from the appliance to outside. Induced-draft combustion systems may be able to operate safely in a closed crawl space with the installation of a combustion air injection system by a professional mechanical contractor. The system must ensure adequate combustion air for the appliance, and installation should include pressure testing to verify proper draft in the combustion vent pipe and proper pressure in the combustion appliance zone with reference to outside.

- Be aware that objectionable odors may develop. Advanced Energy has received five reports of strong ammonia-like odors associated with the drying-out of existing crawl spaces in North Carolina, which may be caused by the mold slowly dying or going dormant. The odors persisted for weeks or months without dissipating. Application of a fungicide in conjunction with reducing moisture levels has been reported to eliminate this problem.
- Install a temperature and relative humidity monitor in the repaired or converted crawl space to verify that the improvements are effective or to indicate the need for adjustments to the drying mechanism. Wireless sensors that display the crawl space temperature and relative humidity on a receiving unit inside the house make it very easy for the homeowner or occupant to monitor those conditions. Some of these sensors include a user-adjustable alarm that will indicate when conditions exceed the desired levels. See Section 8 for a manufacturer of such monitors.
- Decide whether or not to clean mold contamination. Once the crawl space is properly closed, cleaning up surface mold in the crawl space can be effective since the improved crawl space conditions should prevent mold growth from recurring. In general, it is not necessary to clean up mold, but there are a variety of reasons why you may want to do so. See "Should I clean up the mold?" in Section 7 for more details.

Basic Maintenance for Crawl Spaces

Most people don't like to go into crawl spaces, but periodic inspection of any crawl space helps to ensure that any problems are caught before they cause damage. Property owners can perform these inspections and basic maintenance checks themselves or hire a private home inspector or other contractor to do it for them.

Property owners should:

- Ensure that access doors are closed, especially during warm weather.
- Ensure that there are no solvents, gasoline or other potentially hazardous materials in the crawl space.
- Inspect the crawl space regularly to:
 - Identify vapor retarder damage or water problems. Note that small water leaks in a crawl space may not be caught by relative humidity sensors.
 - Ensure that no damage occurs when any contractors work in the crawl space.
 - Check and replace batteries as needed in sensors or alarms.
- Ensure that any water intrusion, especially flooding, is quickly drained or pumped out of the crawl space.

Section 6

RESEARCH RESULTS

Overview

By the late 1990s, concern over wall-vented crawl space moisture failures across the southeast had grown significantly among homeowners, builders, and building code officials. The need to quantify existing problems and then compare and document the performance of viable alternatives led Advanced Energy to conduct a study of existing homes and a controlled field study of improved homes. This crawl space project was a multi-year effort to document how various crawl space ventilation and insulation strategies affect moisture levels, energy use, and indoor air quality in real-world, occupied houses (Davis and Warren 2002). Another primary goal of the research was to demonstrate practical, understandable closed crawl space construction techniques that can be transferred to mainstream construction practice.

Co-funded by the U.S. Department of Energy and Advanced Energy, the project was directed by Bruce Davis of Advanced Energy and managed by Cyrus Dastur of Advanced Energy and Bill Warren of Bill Warren Energy Services.

The project advisory team includes Dr. Achilles Karagiozis, Oak Ridge National Laboratory; Dr. Wayne Thomann, Duke University; Dr. John Straube, University of Waterloo, Canada; Architect Bill Rose, University of Illinois at Urbana-Champaign; Dr. Joe Lstiburek, Building Science Corp.; Physicist Anton TenWolde, U.S. Forest Products Laboratory; and Environmental Scientist Terry Brennan, Camroden Associates. Vital support has been provided by the N.C. Solar Center, in Raleigh, N.C. and Southface North Carolina in Boone, N.C.

Advanced Energy is by no means the first group to investigate the moisture performance of wall vented crawl spaces. Rose (1994) wrote a review of crawl space investigation and regulation through history. Rose and TenWolde (1994) wrote a symposium summary paper to review many of the issues associated with wall vented crawl space construction. The above material, along with that of several others, is included in Recommended Practices for Controlling Moisture in Crawl Spaces, ASHRAE Technical Data Bulletin, volume 10, number 3. Additionally, during the first year of the study Rose contributed an update of the historical review of crawl space regulation as part of a technology assessment report (Davis et al. 2002). These articles reference a wide range of the authors and activities over the years that built the understanding of wall vented crawl space moisture problems and solutions.

The field study has operated since the summer of 2001, but here we are reporting findings from the experimental setup used from the summer of 2003 through the summer of 2004, which is the basis for the design samples in Section 3. The complete technical reports that are the basis for this section are available online at www.crawlspaces.org.

Quantifying Existing Crawl Spaces

The characterization study examined ten houses, from 2 to 9 years old, with wall-vented crawl spaces in the Piedmont (central) region of North Carolina. A variety of instrumentation and first hand observation techniques were used to describe the moisture, thermal, and indoor air quality performance of each house. These techniques included:

- homeowner interviews,
- detailed measurements of the home, crawl space and surrounding property,
- surveys of moisture content, mechanical equipment, insulation quality, and moisture problems in the crawl space,
- bioaerosol sampling and analysis of total and viable spore counts, and
- detailed air leakage testing to quantify leakage through the supply ductwork, return

ductwork, floor plane, and wall-ceiling planes; and detailed logging of mechanical system pressure effects.

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.

Only two houses had a complete ground vapor retarder, and these homes suffered from rainwater intrusion and condensation on the ductwork, with visible mold covering most of the wood framing. Three homes had no ground vapor retarder at all.

These findings confirmed the theory that wall vented crawl spaces as they are currently designed and built are not sufficient to control moisture acceptably in the North Carolina climate. Furthermore, all ten houses had significant air leakage pathways measured across the floor system that separates the crawl space air from the house air. Leakage from the crawl space represented almost 19% of the total leakage of the house. Of that 19%, 44% was leakage through the duct system. This showed that the crawl spaces are not well isolated from the living space above, so contaminants from the crawl space are likely to affect the living space.

Field Study Experimental Setup

In addition to the 10-house characterization study, this project studied 12 homes with improved crawl spaces to identify solutions to the moisture problems. These 12 homes, located in Princeville, North Carolina, are all located in the same development. Six houses are built side-by-side on each side of one street. All are the same size at 1,040 square feet, with the same floor plan and window schedule. The development was built on several feet of controlled fill soil to elevate it and reduce the potential for future flood damage. This added to the uniformity of the site soil conditions, and the site was graded to provide proper drainage.

The study homes are broken into three groups of four homes each: one control group and two experimental groups. We reduced duct leakage and house leakage to comparable levels across all the groups. Average duct leakage varies from 51 to 68 CFM25 for these groups, which represents rates of 5% to 7% of floor area. Dividing the duct leakage by the conditioned floor area lets us use a consistent target across many different sizes of home. Typical duct leakage for homes in North Carolina is upwards of 15%. Ideally, duct leakage would be 3% or less. Average envelope leakage for the study houses varies from 0.22 to 0.27 CFM50 per square foot of envelope area. Typical house leakage for homes in North Carolina is roughly 0.35 CFM50 per square

foot envelope area, which is the same as Advanced Energy's standard house leakage target.

Floor and ceiling insulation deficiencies were corrected in all houses, and all 12 homes have the same make and model of packaged-unit heat pump. The ARI rated capacity of the heat pump is 22,000 BTU/hr. with efficiencies of 10.0 SEER and 6.8 HSPF. Heat pump refrigerant charge and system airflow were measured and corrected as needed in all houses. All the houses have an outside air ventilation intake integrated with the HVAC ductwork. A six-inch insulated flex duct from outside routes air through a one-inch pleated media filter and then connects directly to the return plenum. Whenever the HVAC system is operating, 40 cfm of filtered outside air is mixed into the return air stream, conditioned, and then distributed to the house. No fan-timing or fan-cycling controls are used in the mechanical system.

The four control houses have conventionally vented crawl spaces, with eleven 8" x 16" foundation vents. Each house has a six-mil polyethylene ground cover that is mechanically secured to the soil with turf staples. The seams are lapped approximately six inches but are not sealed. The ground cover extends completely to the foundation wall and intermediate piers, covering 100% of the soil. Although the building code allows a reduction in the amount of wall venting when a ground vapor retarder is present, all 11 foundation vents were retained. (Note that the North Carolina code in place at

the time of construction (the 2000 International Residential Code) does not require the ground vapor retarder since these vents provide the net free area to meet the 1:150 ventilation-area to crawl-space-area requirement). The floors of the control houses are insulated with well-installed R-19 Kraft-faced fiberglass batts.

The crawl space vents of the experiment homes were sealed with rigid polystyrene foam and duct mastic or spray foam. Each of these closed crawl spaces has a sealed, six-mil polyethylene liner covering the floor and extending up the foundation wall, stopping three inches from the top of the masonry to provide a termite inspection gap. The seams of the liner are sealed with fiberglass mesh tape and duct mastic, and the edges are sealed with duct mastic and mesh tape to the foundation wall or intermediate piers. The liner is mechanically secured to the soil with turf staples and to the foundation wall with a furring strip.

Mechanical drying in the closed crawl spaces is provided by a 4-inch duct that provides 35 cfm of conditioned air to the crawl space from the supply plenum whenever the air handler is running. As designed, the extra air simply exfiltrates through the crawl space perimeter wall. No fan-timing or fan-cycling controls are used in the mechanical system, and no stand-alone dehumidifiers are used for moisture control. A balancing damper permits adjustment of the flow, and a back-flow butterfly gravity damper with a non-metallic

hinge prevents movement of air from the crawl space into the supply plenum when the system is off.

Four of the closed crawl spaces are insulated with R-19 Kraft-faced fiberglass batts in the floor, with the Kraft facing in contact with the subfloor, and the other four are insulated with 2 inches of R-13 foil-faced polyisocyanurate foam on the perimeter wall and on the band joist. This closed-cell foam was installed with a three-inch gap between the top of the foam and the bottom of the sill plate to allow for monitoring of termite activity, and there is a second gap at the bottom of the foam insulation to prevent ground contact and wicking of moisture into the foam insulation. This foam meets the ASTM E84 and Factory Mutual FM 4880 requirements of the 2000 International Residential Code for installation without a thermal barrier.

The ground vapor retarder is attached to the inside surface of the foam insulation with tape or fiberglass mesh tape and duct mastic. We specifically did not install the wall insulation in the IECC-required form, which specifies wall insulation down to 24 inches below outside grade or horizontally on top of the soil in from the foundation wall for 24 inches. Instead, the bottom edge of the crawl space wall insulation was only 3 to 6 inches below outside soil grade level.

Instrumentation and Data Collection

We recorded outside air temperature and moisture content using three battery-operated data loggers distributed across the development in locations shielded from rain and direct sun. We used the same type of logger to record conditions inside each house and inside each crawl space. Measurements were recorded at 15-minute intervals. The house data logger was placed at the center of the house in the HVAC return closet and two loggers (one extra for redundancy) were located together in the center of the crawl space on the support beam for the floor joists.

We measured wood moisture content on a 60-day interval at ten locations in each crawl space, including sill plate, band joist, floor joist, center beam, and subfloor readings.

After seeing the potential for energy savings during a billing analysis in early 2003, we outfitted all 12 houses with electricity sub-meters to record exact energy consumption by each home's package-unit heat pump system. The whole-house meter and sub-meters are read monthly.

The crawl space experiment has been monitored for more than three years at the time of this writing. Ongoing measurements clearly indicate that the closed crawl spaces consistently outperform the wall-vented crawl spaces in terms of both moisture control and

energy use, and here we'll present a cross-section of findings from a one-year period ranging from the summer of 2003 through the summer of 2004.

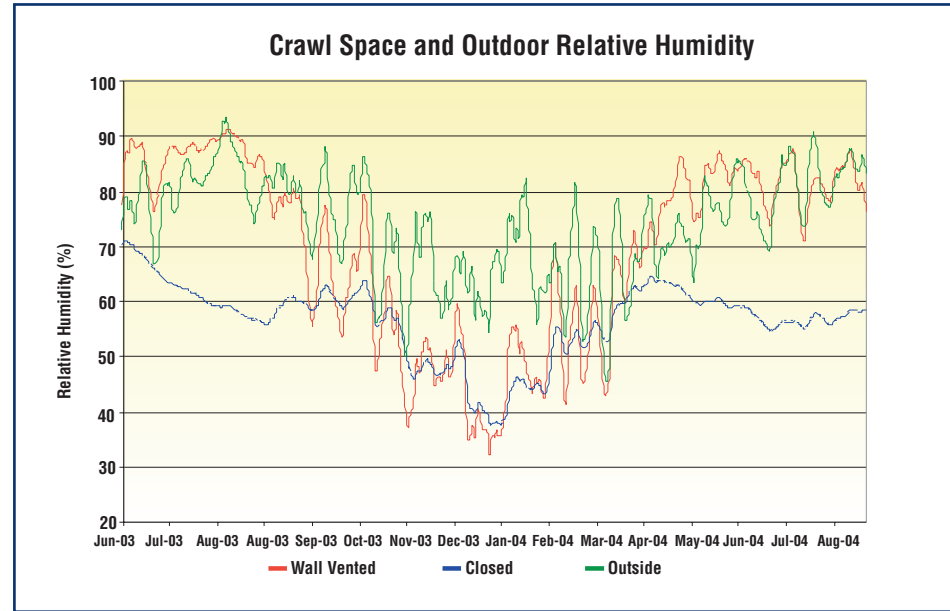
Moisture Performance

The closed crawl spaces in this project perform notably better than the vented crawl spaces with regard to relative humidity, absolute moisture (presented for convenience as dew point temperature), and wood moisture content, which are summarized in the figures below.

Daily average relative humidity in the closed crawl spaces began a steady decline through the humid 2003 summer season as soon as the crawl space supply duct was opened and the access door closed.

As fate would have it, 2003 was the wettest year in recorded history in this part of North Carolina, while 2002 was a record-setting drought year. The table below compares the percent of time in each summer that the different crawl spaces had a daily average relative humidity above the given thresholds:

The closed crawl spaces provided far better performance under the harshest conditions than the vented crawl spaces did under even the mildest conditions. *These results highlight the fact that even a carefully installed and maintained ground vapor retarder covering 100% of the soil is not sufficient to control*



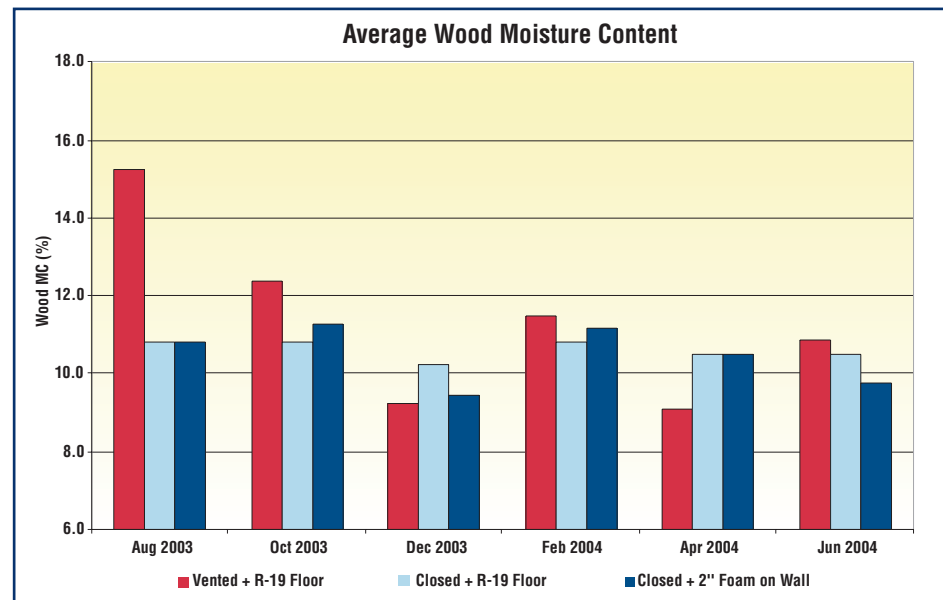
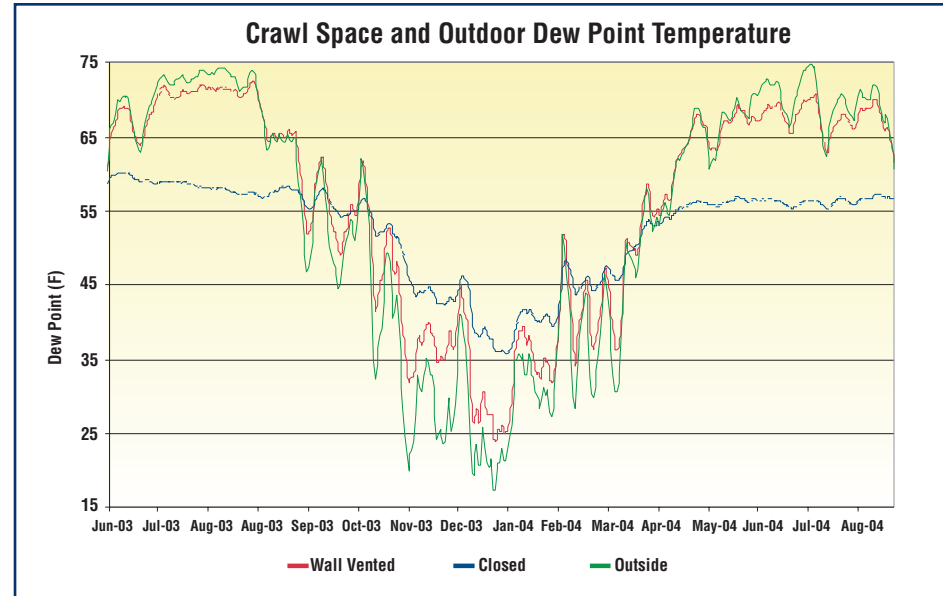
	2002		2003		2004	
RH Threshold	Vented	Closed	Vented	Closed	Vented	Closed
Above 90 %	0%	0%	23%	0%	7%	0%
Above 80 %	39%	0%	86%	0%	70%	0%
Above 70 %	79%	0%	98%	5%	92%	0%
Above 60 %	94%	0%	100%	64%	100%	13%
Above 50 %	100%	100%	100%	100%	100%	100%

relative humidity levels in a wall-vented crawl space, even with excellent exterior drainage. Well-constructed, extensively wall-vented crawl spaces without water intrusion and with a 100% ground vapor retarder may prevent wood rot in

crawl spaces, but water vapor control would be even worse in typical vented crawl spaces given the usual poor quality of ground vapor retarder installation and maintenance in general construction.

The dew point temperature graph shows that the outside air contains more water vapor than the air in the wall-vented crawl spaces during the warm season, actually adding water vapor instead of providing drying potential. Consider this: the average dew point of the outside air at Princeville during the summer of 2003 was 73° F (23° C). This corresponds to conditions of 88° F (31° C) and 60% relative humidity. When that air goes into the crawl space and encounters anything cooler than 73° F, the relative humidity peaks at 100% and the water vapor in the air can condense on that object. Supply ducts (55-65° F, 13-18° C), water pipes and tanks (55-65° F), and even the floor of the crawl space (65-70° F, 18-21° C) and the wood framing above (70-78° F, 21-26° C) can experience this condensation, especially if the homeowners condition their house to temperatures below 72° F (22° C). Even if conditions aren't bad enough for condensation, the relative humidity of the air entering the crawl space will still easily reach levels of 90% or higher for prolonged periods of time.

The dew point measurements also highlight the fact that the closed crawl spaces stay more humid than the wall-vented crawl spaces in winter, further reducing the moisture swing seen by the house over the course of the year. This can in turn reduce the likelihood of common cosmetic problems like shrinking and swelling of hardwood floors and wood trim, or cracking and "nail pops" in drywall.



The average wood moisture content graph shows readings for the three types of crawl spaces. The fact that the average wood moisture content in the framing lumber in the closed crawl spaces stays below 12% is notable, not only because it reduces the likelihood of surface mold growth but also because wood this dry is less attractive to termites and very inhospitable to Southeastern species of wood-boring beetle pests. Wood moisture content in the wall vented crawl spaces is much lower than is found in typical existing crawl spaces, showing the beneficial impact of the 100% ground vapor retarder and proper site water management.

Temperature Conditions

Warmer temperatures in closed crawl spaces during the winter months and the absence of open vents reduce the risk of intermittent freeze damage to pipes or appliances in the closed crawl space during sub-freezing weather, especially in windy conditions.

Energy Performance

Going beyond initial expectations, the closed crawl space homes exhibited clear and significant energy savings over the control houses. This is true even for the four closed

crawl space houses with wall insulation that included a termite inspection gap and did not have insulation installed down 24" below grade or 24" horizontally onto the crawl space floor, as is required by energy codes.

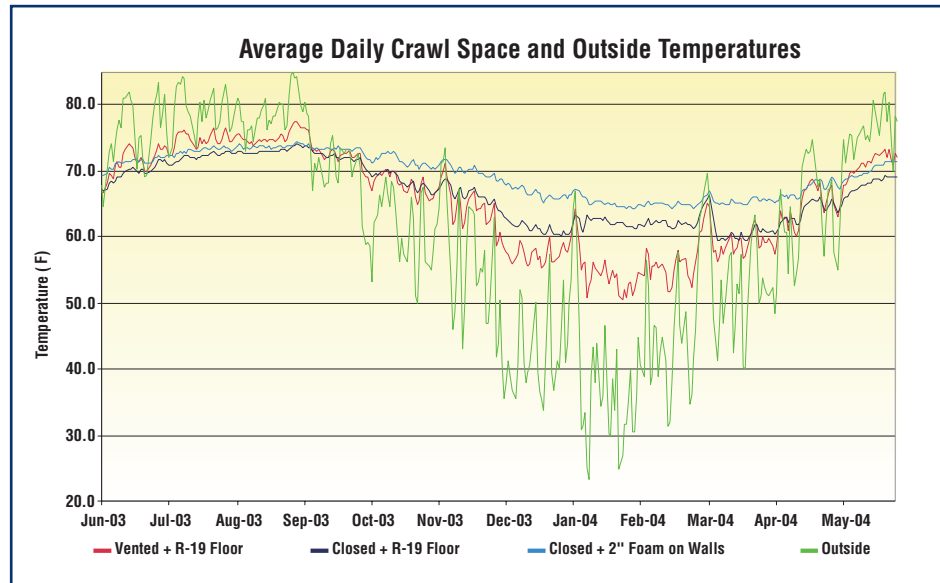
Energy used for heating and/or cooling for the average house in each group is shown in the "Average Seasonal HVAC Use per House" chart. The percentage of savings as compared to the control houses is reported in the inset table.

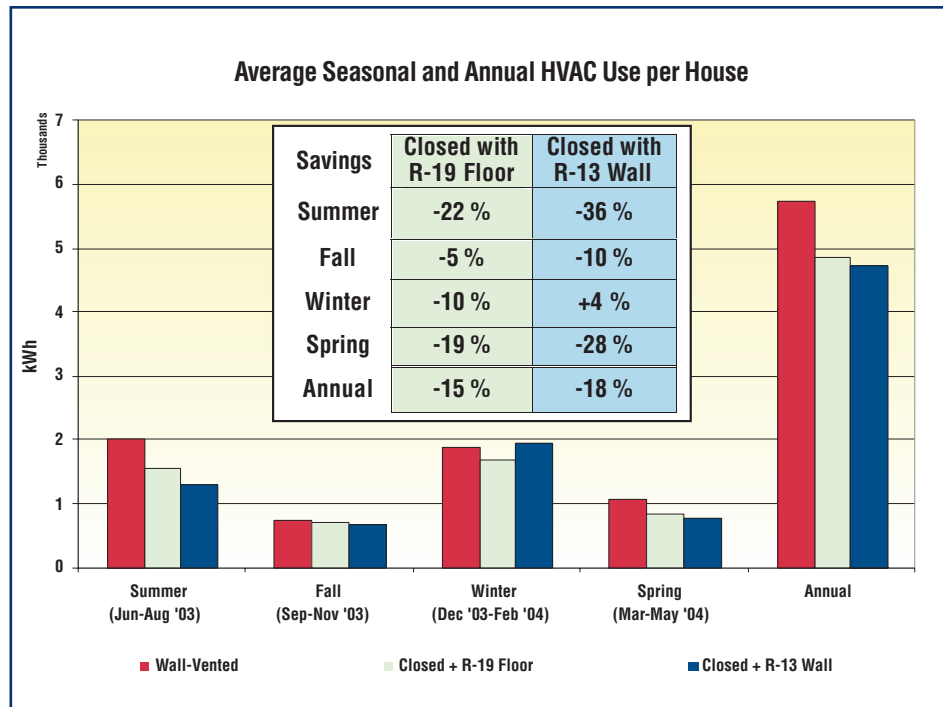
For the 12 months analyzed, the floor-insulated closed crawl space houses used an average of 15% less energy for space conditioning than the control houses, which represents a savings of approximately 870 kWh (or roughly \$87) per year for each household.

The wall-insulated closed crawl space houses used on average 18% less energy than the control houses over the same 12-month period, which represents a savings of approximately 1025 kWh (or roughly \$103) per year for each household.

Factors Affecting Energy Use

While we controlled the variables of climate, site drainage, architecture, insulation, shell leakage, duct leakage, and mechanical equipment performance, there remain variations in base load consumption and occupant thermostat settings among the groups that may be significant due to the small sample size.





We did not sub-meter the appliance, lighting, water heating or exhaust fan loads, but noted that the total base load use in the control homes was significantly higher (10-20% in any given month) than that of the experiment homes over the entire year. By luck of the draw, the control homes had higher occupancy numbers and greater numbers of children relative to the experiment houses. The extra occupant and base load in the controls would theoretically increase the need for cooling in the summer and decrease the need for heating in the winter. The difference in base load usage between the controls and the floor-insulated

experiment houses is about the same in both summer and winter, which suggests that the surpluses offset each other in terms of heat pump energy used/saved in the control houses to compensate for the difference. However, there is a greater difference in base load consumption between the control houses and the wall-insulated experiment houses in the summer than there is in the winter, which makes the summertime wall-insulated house performance look better.

Impact of Moisture Load on Comfort and Energy Use

A review of the interior house data indicated that the control houses were operated 1° to 2° F cooler than the experiment houses in the summer of 2003 and 1° to 2° F warmer than the experiment houses in the winter of 2003-04. This behavior could account for a portion of the energy savings we recorded, or it could be another indicator of the moisture benefits of the closed crawl spaces, since humidity levels play a large role in occupant comfort and the data shows that the dew point temperatures in all the homes were very consistent.

We have not administered a formal survey of occupant comfort, but had an experience that indicated the impact of crawl space performance on occupant thermostat settings: in June of 2004 we upgraded three of the four wall-vented control crawl spaces to test a new version of closed crawl space. We installed a crawl space supply duct to provide supplemental drying, as was done in the other closed crawl spaces. When we returned to the site four days later, one resident (who rarely adjusts her thermostat) excitedly let us know that the night after we closed her crawl space, she turned up her thermostat because she felt too cold in the house. This anecdotal evidence suggested that the difference in indoor set point temperatures may not be a simple matter of homeowner preference that reduces the measured energy savings, but instead be a result of the improved performance of the closed crawl spaces which deserves more

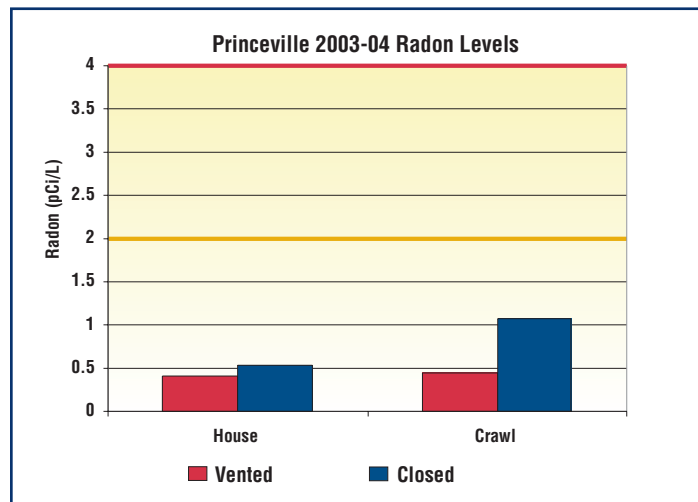
detailed investigation. Subsequently, in July and August of 2004, the occupants of the three upgraded crawl space homes operated their homes within an average of 0.5 degrees of the temperatures in the other closed crawl space homes, while the occupants of the last remaining wall-vented crawl space home continued to operate their house an average of 2 degrees cooler than the occupants in the closed crawl space homes.

Radon Measurements

To ensure that these closed crawl space designs were not negatively impacting the health of the homeowners with regard to radon exposure, we conducted radon monitoring in the crawl spaces and the living areas from the summer of 2003 to the summer of 2004.

According to the EPA's "A Citizen's Guide to Radon" homes should be remediated when radon levels are above 4 pCi/L. One should consider fixing the home when levels are between 2 and 4 pCi/L. Reducing radon levels below 2 pCi/L is difficult.

The measured 2003-04 long-term results indicate slightly higher average concentrations in the closed crawl spaces, with measurements averaging 0.5 pCi/l in the vented crawl spaces and 1.1 pCi/l in the closed crawl spaces. The radon measurements in the living space do not show a difference correlated with foundation type; all houses average approximately 0.5 pCi/l with a maximum reading of 0.7 pCi/l in any house. The three highest crawl space measurements all occurred in closed crawl spaces, with values of 2.0, 1.5 and 1.4 pCi/L. All other measurements were below 1.0 pCi/L.



While the crawl space levels were all below the EPA action threshold, the higher measured radon levels do appear to correlate to the closed crawl spaces. Advanced Energy recommends treating closed crawl spaces like a short basement with regard to radon testing and mitigation. If the closed crawl space is being built in a radon risk area, the same measures used for radon assessment and control with a basement or slab foundation are applicable.

Mold Sampling Results

Anderson samplers were used to measure viable spores in the crawl spaces, outside, and in the living spaces in 2001 and 2002. Measurements in the living spaces were significantly lower than the outside measurements, but measurements in the living space above two of the wall-vented crawl spaces were the highest of the group.

Total spore counts, measured with Burkard samplers, were significantly higher in the wall-vented crawl spaces than in the closed crawl spaces, but large numbers of mold spores were measured in all the crawl spaces during the first round of sampling in 2001. Generally, viable and total spore counts as high as were measured in this project are found only in the presence of very large sources – e.g. harvesting fields, contaminated rooms, or composting facilities.

In the case of these crawl spaces, there were two contributing factors. First, the surrounding area was deluged by heavy rains shortly before the samples were made. This is reflected in both the crawl space and outdoor air data. Second, the sampling procedure required the technician to enter the crawl space, stirring up settled dust, and this likely contributed to the sampled levels being as strikingly high as they were.

In subsequent testing, we inserted the sampler into the crawl spaces on a long cantilever so that the technician would not have to enter and stir up settled dust. These readings were in fact much lower than the initial samples. After the cantilever sample was complete, we verified the impact of entering the crawl space by having a technician crawl inside the crawl space and take a followup sample. These followup samples, whether in the closed or wall-vented crawl spaces, showed a large increase in airborne spores. Most importantly, these findings point to the need to wear respiratory protection in all crawl spaces, even if there is no visible mold.

See Section 7 for background information on molds and health impacts of mold exposure.

Research Implications

The Princeville field demonstration project is scheduled to conclude in April of 2005. During the winter of 2004-05 Advanced Energy will test a new crawl space configuration to assess the energy impact of a 24-inch wide strip of R-10 foam insulation installed horizontally on the ground of the wall-insulated, closed crawl space houses. Final results and additional analysis will be posted on the project website, www.crawlspaces.org.

The performance improvement shown by the closed crawl spaces is impressive, especially considering that the control houses likely represent the best possible performance of wall-vented crawl spaces. The vast majority of newly built wall-vented crawl spaces are not installed or maintained to the standards used for this project.

We believe the findings of this study will transfer well to houses of similar geometry and geography to the study homes. However, additional consideration and study are required for houses in other locations and with different geometry. The energy results seem to indicate that wall-insulated closed crawl spaces will perform best in cooling-biased climates while floor-insulated closed crawl spaces will perform best in heating-biased climates. Of course, these homes have shallow foundations, and we have not tested crawl space foundations with deeper footing depths such as may be found farther north. A wall insulation strategy may also prove to perform best in such houses.

We won't know with any certainty how well the improvements in moisture and energy performance will transfer to houses in other climates until a number are actually constructed and monitored. Advanced Energy has begun a new project to gather that data in multiple climate zones while demonstrating the ability of the production housing market to incorporate closed crawl space technology into its construction processes.

Currently we find that the energy benefits of closed crawl spaces are not accurately predicted by popular energy analysis software, so it may be some time before closed crawl spaces get their due respect when builders are choosing house specifications aimed at achieving a certified minimum energy rating. Future research will include a detailed analysis of a variety of software tools, with the goal of identifying improvements needed in the tools and to reinforce the finding that consumers can improve the efficiency of their homes by building or retrofitting a properly closed crawl space.

Two of the field study homes were highly instrumented and monitored by Oak Ridge National Laboratory (ORNL) throughout the duration of the field study. The data collected from these houses has been used to calibrate and validate a computer-based hygrothermal modeling software tool. This software tool can now predict the hygrothermal performance of different crawl space designs when given basic thermal and moisture characteristics of the materials to be used in the design, along with environmental conditions.

Section 7

COMMON QUESTIONS ABOUT MOLD

This section summarizes detailed mold information that is presented in several of the technical references, specifically ACGIH, 1999; Davis, 2002; Burge, 2004; Fallah, 2004 and Brennan, 2005. In addition, we offer recommendations based on Advanced Energy research findings and building investigations.

What is Mold?

Mold, together with mushrooms, bracket fungi, and puffballs are classified as fungi. These organisms consist of a mat of hair-like strands called hyphae that form both the main body and fruiting bodies that make spores. Spores are essentially baby fungi with a lunch box. Mushrooms, puffballs, and bracket fungi have large, easily seen fruiting bodies, while molds have tiny fruiting bodies that are visible as a surface discoloration only when there are many of them. Mold coverage ranges from light spotting to thick blooms that cover large areas. They can range in color from black to green to white, yellow and red and be present as discrete speckles or large fuzzy masses.

Mold reproduces by sending microscopic spores sailing on the air or floating on water. Mold spores are typically in the range of 3 to 40 microns in size; for reference, a human hair is typically 100 to 150 microns in diameter. A small colony may release millions of spores. When it is above freezing, a sample of outdoor air almost anywhere in the United States is likely to contain hundreds or thousands of mold spores per cubic meter. Consequently, almost all environmental surfaces have spores attached – it is virtually impossible to avoid them.

In order to sprout and grow into a colony, most spores need to be in a location that provides oxygen, liquid water and/or relative humidity greater than 70%, a source of carbon, and temperatures between 45° F (7.2° C) and 100° F (37.8° C). Once most molds have germinated, they do not need liquid water to continue growing. Unfortunately, these conditions are found in nearly every wall-vented crawl space in the southeast for much of the year. Because crawl spaces have numerous air path connections to the house via plumbing penetrations, electrical penetrations, leaky ductwork, and more, we could say that the crawl space is “MADD” – a Mold Amplification and Delivery Device.

Because spores, carbon sources, warmth, and dark spaces are found in all houses, the only realistic strategy for controlling mold growth is to control moisture levels. Eliminating liquid water is the first step. Controlling relative humidity is the second step and fortunately, most people are more comfortable at relative

humidity levels below the 70% threshold required by most molds.

Hyphae exude enzymes that may decompose organic materials so the nutrient can be absorbed into the hyphal mat. That, in fact, is their ecological job – to decompose dead plants and animals. Molds are essential to the proper workings of the natural world.

Most molds are not good at digesting cellulose. Wood decaying fungi (soft rot, white rot, or brown rot) are the organisms that actually decompose solid wood, and they generally require very wet wood with a moisture content of 30% or more. Soft rot requires the continual presence of liquid water. Brown rot usually occurs on wood in contact with damp soil or a continuous water source, but can also be caused by molds that transport moisture from some other location (this latter type is typically referred to as “dry rot”). Crawl spaces with long-term condensation, standing water, or exposed soil are vulnerable to any of these molds, especially at low temperatures caused by air conditioning below 72° F (23° C) or in colder climates with low soil temperatures.

Sap stain or blue stain fungi may cause discoloration of cut lumber but are not reported to lead to rot or structural damage and probably do not present an air quality concern. Sap stain fungi can be mistaken for *Stachybotrys* species due to their dark coloration, but scientists note that the growth of *Stachybotrys* species on wood is extremely

poor and rarely occurs. *Stachybotrys* species (e.g. *S. atra* or *S. chartarum*) typically occur on fiberboard, gypsum board, paper, dust or lint. These molds are associated with constant high levels of moisture resulting from flooding, un-repaired plumbing leaks or standing water. They are not often found in crawl spaces.

Growth of other fungi on solid wood in drier conditions (19-30% wood moisture content or ambient relative humidity above 70%) is generally limited to the surface and does not cause structural damage. Composite materials like engineered wood products consisting of bits of wood and adhesives can be structurally degraded by molds because the mold can often digest the adhesives. Composite materials must be dried and cleaned very quickly to prevent damage.

Should I Test for Mold?

Advanced Energy does not recommend mold testing unless there is a specific need to identify samples by species. As detailed below, it is generally expensive and time-consuming to get reliable mold sampling and analysis. Visible mold, regardless of species, indicates a moisture problem that requires attention. In some cases, molds are located in hidden areas or are simply not visible to the naked eye. Whether visible or not, the key to suppressing mold growth is to remove the mold's moisture source.

The generally accepted practice for bioaerosol sampling, as laid out by the American Conference of Governmental Industrial Hygienists (ACGIH), is to compare indoor samples with outdoor samples taken at the same time. If the spore concentrations are significantly higher indoors than outdoors or the species mix is significantly different indoors than outdoors, it is evidence that mold is growing inside the building.

Unfortunately, interpreting the results of bioaerosol sampling is fraught with sources of uncertainty:

- In sample sets taken at a few locations over an interval of hours or days, false positives and false negatives are common. To reduce the chances that something important has been missed, numerous samples must be made over extended time periods.
- Bioaerosol sampling requires trained technicians with specialized equipment, and even then, measurements vary significantly over short time frames. In controlled air sampling during the field research described in Section 6, outdoor viable spore count samples taken within hours of each other varied by a factor of five.

Ideally, mold samples should be "speciated," or counted and categorized by individual species of mold present in the sample. Speciation provides better evidence for distinguishing whether there is independent mold growth in a building (or part of the

building) or whether the mold in the building simply reflects the mold present in the surroundings. "Viable" spore counts are easier to speciate than total spore counts, but viable spore samplers may be biased towards smaller species, and growth conditions can vary depending on the lab doing the analysis.

Tape lifts and direct microscopic examination of surfaces are other techniques to identify the presence of mold and, to some extent, identify the mold. These techniques also require trained specialists and do not generally allow for speciation.

Finally, even if sampling is detailed and comprehensive enough to provide confidence in the measured results, there is no consensus on numerical standards to which test results can be compared to indicate a dangerous condition. Human reaction to mold varies greatly from individual to individual.

Should I Clean Up Existing Mold in My Crawl Space?

Mold does not necessarily have to be cleaned up as part of a strategy to improve a crawl space. Molds go dormant as their environment dries out. However, dormant mold can still trigger allergies, asthma events, or other symptoms in susceptible individuals. Potential health impacts and the reporting of mold by

private home inspectors prior to home purchases is causing more and more homeowners to consider removing or “remediating” mold from their crawl space. The homeowner’s choice of whether or not to clean up mold depends on their level of concern about the potential health impacts of leaving the mold in place or the impact on the value of their home. One specific benefit is that cleaning out existing mold will make it easier to detect a recurrence in the future.

Of course, there is no point in cleaning up surface mold without improving the moisture conditions that allowed the mold to grow in the first place. The mold would simply grow back. Any activity to clean up surface mold should be part of an overall plan to close the crawl space permanently.

Mold-contaminated ductwork also presents the question of whether to leave the mold in place, clean the ductwork, or replace the ductwork. Flexible duct and fiberglass-lined ductwork is very difficult, if not impossible, to thoroughly clean. Other options include leaving the duct as is, replacing the ductwork or spraying fungicides or encapsulating materials to isolate the mold in the duct from the air stream. Sheet metal ductwork is generally more feasible to clean and reuse without encapsulation.

Advanced Energy recommends that you seal ductwork and seal holes between the house and the crawl space whether or not the mold is cleaned up. This air-sealing work reduces the chance that mold, mold byproducts or other

contaminants in the crawl space can enter the living area of the home by air transport. It is also critical to help prevent new or cleaned ducts from becoming recontaminated. For additional protection, the homeowner can upgrade air filtration in the house with stand-alone HEPA units or HEPA air handler/duct system filters, and/or apply a fungicide over the existing mold to provide short-term anti-fungal activity and some level of continued suppression.

Advanced Energy has received several reports of strong ammonia-like odors associated with the drying-out of existing crawl spaces in North Carolina, which may be the result of the mold slowly dying or going dormant. The odors persisted for weeks or months without dissipating. Application of a fungicide in conjunction with reducing moisture levels has been reported to eliminate or prevent this problem.

If a property owner does decide to clean up existing mold, work can range from spot cleaning of affected areas to comprehensive cleaning of most, if not all surfaces. Large jobs are likely too labor-intensive and time consuming to do as a home project. In these cases, property owners can contract for professional cleanup services from water damage or mold remediation companies. Building performance or other contractors may also offer this service.

This guide is by no means a complete reference for doing safe and effective mold

remediation, but simple advice is provided below. See the Resources and References section for several published sources of mold cleanup procedures.

During any cleanup, Advanced Energy recommends the following steps to help reduce the chance of cleaning materials, mold toxins, mold spores, mold fragments, or other contaminants moving from the crawl space to the living space:

- Turn off any heating and cooling system that utilizes ductwork in the crawl space.
- Reduce or stop the use of exhaust fans and clothes dryers in the living space.
- Pressurize the living area with HEPA-filtered air and/or depressurize the crawl space.

Additional notes on cleaning mold:

- Remove as much contaminated material as possible before beginning cleanup.
- Remove contaminated or damaged insulation. Porous insulation that has been wetted should be replaced, since it will likely never recover its designed R-value, even when thoroughly dried.
- Not all fungicides are effective on all materials. Follow all manufacturers’ recommendations for application and safe handling. Swimming goggles can provide eye protection when working overhead.

- Chlorine bleach is not a long-term fungicide. If you use chlorine bleach, never mix it with ammonia because toxic gas can be produced in fatal levels.
- Liquid cleaning or dry scraping may not remove all staining caused by surface molds.
- HEPA vacuums can be used to collect surface mold removed by scraping, and are recommended instead of sweeping to clean up debris on surfaces or the crawl space floor.
- Pressure washing, sanding or blasting with baking soda or dry ice are cleaning options that may remove staining. Residual materials should be removed afterwards.
- Application of sealants, primers, and paint topcoats may be required to completely cover stains and resist bleed-through.
- Replace the ground vapor retarder after a cleanup operation.
- Air-sealing and subfloor repairs are easier while insulation is removed.
- Fungicides can be applied after cleaning to encapsulate mold spores that were not removed and to provide some level of continued mold suppression.
- Monitor and control relative humidity below 70% after cleanup to reduce the risk of mold growth recurring.

Does Mold Make People Sick?

At the time of this writing, the scientific and medical research communities have not documented a causal relationship between mold growth in residences and human illness. There is an association between damp home environments and occupant medical conditions like allergic rhinitis and asthma, however it is unclear whether mold or some other substance or organism (for example, bacteria) that exists in the same conditions is responsible for the symptoms.

The bottom line is that it is clearly less healthy for humans to live in homes with moisture problems, and strategies that eliminate the potential for such problems are beneficial.

Health effects generally attributed to mold exposure are of four types: allergy, irritation, infection, and toxicity. The most common health effects are allergic reactions and asthma events. The symptoms can include runny nose, eye irritation, sinusitis, and difficulty breathing. A tiny fraction of allergy sufferers may develop more serious, chronic lung disease from chronic exposures. Most molds release alcohols and sulfur compounds, which can irritate mucous membranes and the trigeminal nerve ending in the back of the throat, which reacts to pungency and irritation. People are sometimes infected by molds, but generally, people become colonized by molds only if their immune system is not functioning well.

Some molds produce toxins called mycotoxins. Mycotoxins are not produced as part of the act of living, as are the compounds from respiration and nutrient decomposition. They are produced only occasionally by some mold species. It is thought that molds are most likely to produce toxins when in competition with other molds or bacteria for habitat. In this case, people are collateral damage in chemical warfare between microscopic creatures. The best-documented cases of mycotoxin poisoning are from veterinary medicine when livestock eat mold-contaminated material. There is not much human data to help us understand the risks from mycotoxin exposure, however, the toxins do exist and some of them are similar in toxicity to nerve gases.

Section 8**RESOURCES AND REFERENCES****Online Resources**

American Conference of Governmental Industrial Hygienists
www.acgih.org

American Red Cross
www.redcross.org

“Repairing Your Flooded Home”
www.redcross.org/services/disaster/afterdis/reptoc.html

Canada Mortgage and Housing Corporation

www.cmhc-schl.gc.ca/en/index.cfm

Measuring air flow with plastic bags: Search for “garbage bag”

Centers for Disease Control and Prevention (CDC)

www.cdc.gov

Mold information

www.cdc.gov/nceh/airpollution/mold

Products and Services

The following is a list of the manufacturers or providers of products and services used in Advanced Energy projects discussed in this guide.

Product/Service

Anemometer/air flow meter
 Backflow dampers
 Carbon monoxide monitors
 Constant airflow regulators
 Duct mastic
 Flood vents (FEMA/NFIP-compliant)
 Fire-rated foam insulation
 Fuel gas leak detectors
 High performance vapor retarder
 Liquid water alarms
 Mold sample analysis
 Outside air intake and filter housing
 Radon test kits and analysis
 Sump pumps
 Wireless Temperature/RH meters
 Wood moisture meters

Manufacturer/Provider

TIF
 Famco
 CO-Experts
 American Aldes
 RCD Corp.
 Smartvent, Inc.
 Dow Chemical (Thermax brand)
 S-Tech
 Raven Industries
 Basement Systems
 Environmental Microbiology Lab
 Indoor Environmental Systems
 AccuStar Labs
 Basement Systems
 Oregon Scientific
 Wagner, Delmhorst

Federal Emergency Management Agency (FEMA)

www.fema.gov

“Technical Bulletin 1-93, Openings in Foundation Walls”

Florida Solar Energy Center (FSEC)

www.fsec.ucf.edu

“Florida Home Mold & Mildew Guide for Consumers”

www.fsec.ucf.edu/bldg/science/mold

National Association of Home Builders (NAHB) Research Center – ToolBase Services

“Mold in Residential Buildings”

<http://toolbase.org/index-toolbase.asp>

(search for “mold” if necessary)

U.S. Forest Products Laboratory

www.fpl.fs.fed.us

(search for “wood handbook”)

U.S. Environmental Protection**Agency****www.epa.gov**

"A Brief Guide to Mold, Moisture and Your Home"

www.epa.gov/iaq/molds/moldguide.html

"Mold Remediation in Schools and Commercial Buildings"

www.epa.gov/iaq/molds/mold_remediation.html

Indoor air quality

www.epa.gov/iaq/pubs/index.html#homes

Radon information

www.epa.gov/radon/**Technical References**

ACGIH, 1999: "Bioaerosols – Assessment and control." American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio.

Brennan, Terry and Harriet Burge. 2005. "Assessing Mold in Buildings". ASHRAE Journal, January 2005. American Society of Heating, Refrigeration and Air-conditioning Engineers. Atlanta, GA.

Burge. 2004. "Wood Decaying Fungi – An Insight on Types and Roles in Wood Decay." The Environmental Reporter Volume 2, Issue 5. Environmental Microbiology Laboratory, Inc.

Davis, Bruce and William E. Warren. 2002. Field Study Pilot Report: *A field study*

comparison of the energy and moisture performance characteristics of ventilated versus sealed crawl spaces in the south. Raleigh, N.C.: Advanced Energy.

Davis, Bruce, William E. Warren and William B. Rose. 2002. *Technology Assessment Report: A field study comparison of the energy and moisture performance characteristics of ventilated versus sealed crawl spaces in the south.* Raleigh, N.C.: Advanced Energy.

Fallah, Payam and Kamash Ramanathan. 2004. "Fungi of the Month (II): Lumberyard molds – Ceratocystis/Ophiostoma (C/O) group." The Environmental Reporter Volume 2, Issue 5. Environmental Microbiology Laboratory, Inc.

Hill, William W. 1998. "Measured Energy Penalties from Crawl Space Ventilation." In *Proceedings of the 1998 Summer Study on Energy Efficiency in Buildings*, Vol. 1. Washington, D.C. American Council for an Energy Efficient Economy.

Rose, W. B. 1994. "A Review of the Regulatory and Technical Literature Related to Crawl Space Moisture Control." In *ASHRAE Transactions*, Vol. 100 Pt. 1. Atlanta, Ga. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Rose, W. B. and A. TenWolde. 1994. Issues in crawl space design and construction – a

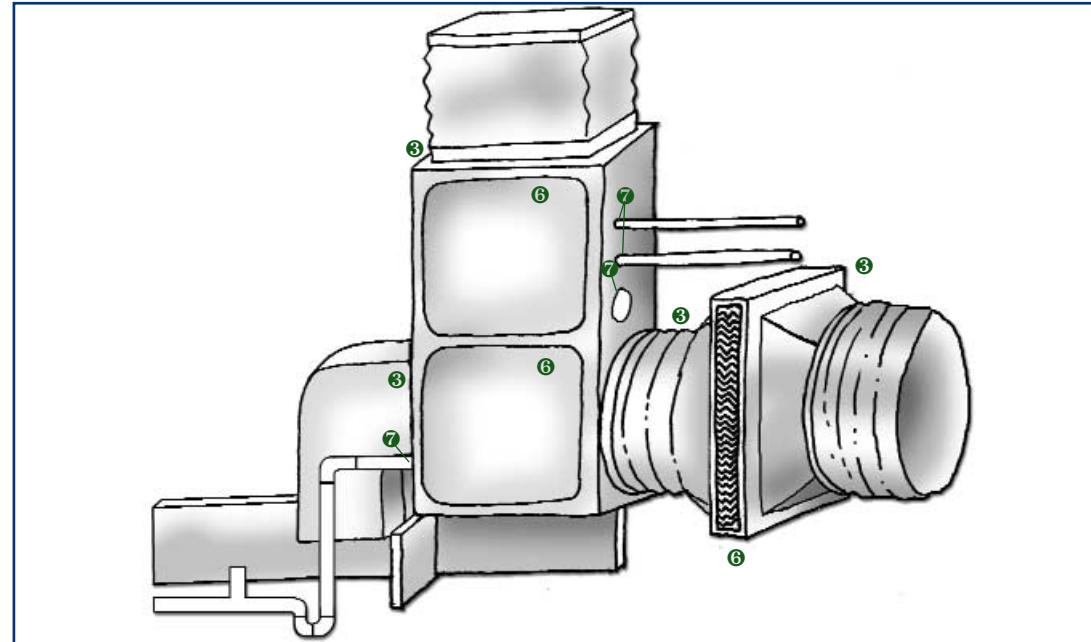
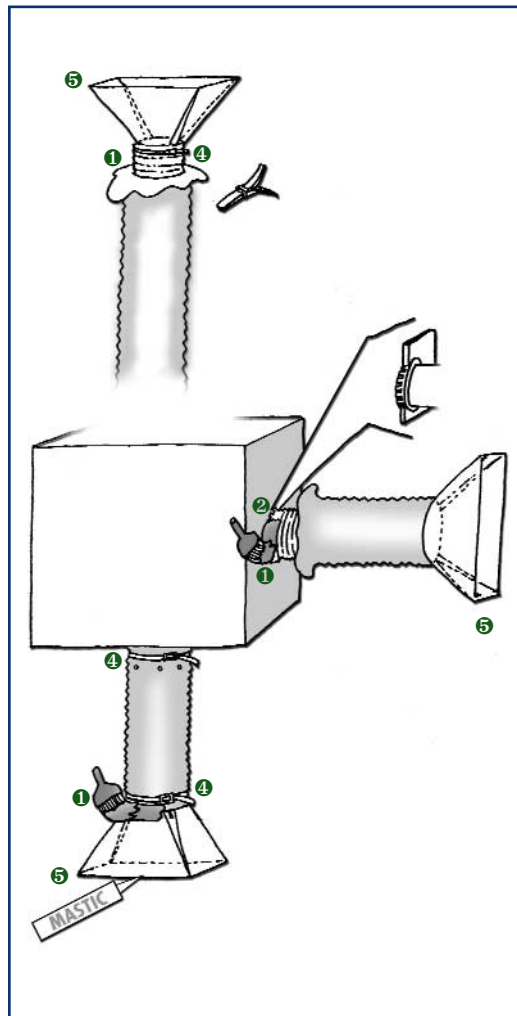
symposium summary. *Recommended Practices for Controlling Moisture in Crawl Spaces*, ASHRAE Technical Data Bulletin volume 10, number 3. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Ga.

Other Resources

IICRC. 2003. *Standard and Reference Guide for Professional Mold Remediation S520*. Institute of Inspection, Cleaning and Restoration Certification, Vancouver, Wash.

Institute of Medicine, 2004. *Damp Indoor Spaces and Health*. Committee on Damp Indoor Spaces and Health; Institute of Medicine, National Academies Press.

NYCDOH, 2000. *Guidelines on Assessment and Remediation of Fungi in Indoor Environments*. New York City Department of Health.

Appendix A**A QUICK OVERVIEW OF DUCT SEALING**

Sealing ductwork for forced-air heating and cooling systems is one of the most effective ways to improve energy efficiency and indoor air quality in a home. If you have any gas-fired or other fuel-burning appliances in the home, you should contact a building performance professional to assess whether duct sealing will cause a combustion safety problem. It is ideal to contact a building performance professional in any case, so that any necessary changes to the duct system can be implemented before sealing, and so that the duct tightness improvement and combustion safety can be verified after the sealing work is complete. Sealing ducts involves the following steps:

1. Seal all permanent connections or seams in the duct system with duct mastic
2. Embed fiberglass mesh tape in the mastic at connections or seams with gaps larger than 1/8 inch.

3. Embed fiberglass mesh tape in the mastic at connections or seams within ten feet of an air handler unit.
4. Mechanically fasten the inner liners of flexible ducts to register boots and seal the joint with mastic. Mechanically fasten the outer liner to the register boot. Zip-tie connectors are typically used for the mechanical attachments.
5. Seal duct register boots with mastic to the subfloor, drywall or other paneling they penetrate. Seal joints or gaps in the boot itself with mastic.
6. Gasket or tape access panels for the air handler or filtering systems.
7. Seal permanent panels, electrical, refrigerant and condensate line penetrations, and any unused holes in the air handler permanently.

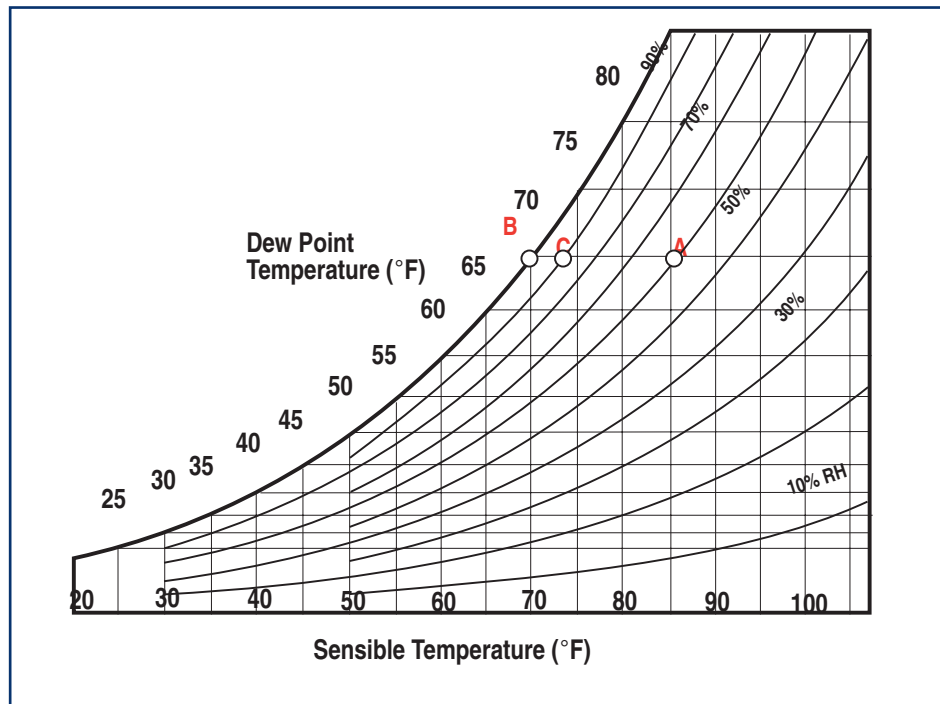
Appendix B**SIMPLIFIED
PSYCHROMETRIC
CHART**

This chart is a simplified version of the complex psychrometric charts typically used in the refrigeration and air-conditioning industries. It is included as a tool for calculating the dew point temperature of air

when temperature and relative humidity are known, and for predicting changes to dew point temperature or relative humidity when the air temperature changes.

Sensible temperature (also referred to as “dry bulb” temperature) is read on the bottom scale of the chart and is the temperature reading you would get from a standard thermometer. Relative humidity is plotted on the curved lines in the center of the chart. Dew point temperature is read along the curved left side of the chart.

As a quick example, say that you have air conditions of 85° F and 60% relative humidity. Find 85° F on the sensible temperature scale at the bottom of the chart, then go up vertically until you reach the intersection with the 60% relative humidity curve, at point A. To determine the corresponding dew point temperature, go left horizontally until you reach the dew point temperature scale on the left side of the chart at point B, which indicates that the dew point temperature is 70° F. To find out the relative humidity of this air at different temperatures, go right horizontally until you line up vertically with the desired sensible temperature. For example, going right to point C indicates that at 73° F sensible temperature, the relative humidity of this air would be 90%.



Appendix C**WOOD MOISTURE
CONTENT AT
DIFFERENT
TEMPERATURES AND
RELATIVE
HUMIDITIES**

Taking a single-point measurement of either wood moisture content or relative humidity in a crawl space may not provide a complete picture of the long-term moisture conditions inside the crawl space. Relative humidity can vary much more quickly than wood moisture content, and wood moisture content readings can be dramatically increased by the presence of intermittent condensation on the surface of the wood.

The table below relates wood moisture content and ambient temperature to long-term conditions of relative humidity. If you can measure wood moisture content and ambient temperature, you can use this table to then estimate the long-term relative humidity that the wood has been exposed to. Note that wood moisture content varies only slightly (0.5% to 1.2%) at a particular relative humidity over the range of temperature from 40° F to 90° F.

For example, if you were to measure wood moisture content of 18% in a 70° F crawl space, then you can estimate that the wood has been exposed to relative humidity of approximately 85% over recent days or weeks, even if the relative humidity at the time of your measurement is much lower due to drier outside conditions.

Note that when the crawl space is vented with outside air, relative humidity inside the crawl space can change significantly over short periods of time. In some situations, measurements of relative humidity and wood moisture content may still appear to be contradictory even when using the equilibrium data from the table. The more controlled conditions in a closed crawl space generally make it easier to interpret measurements.

Moisture content of wood in equilibrium with stated temperature and relative humidity

(Source: U.S. Forest Products Laboratory, Wood Handbook, Table 3-4.)

Temperature		Moisture content (%) at various relative humidity values											
°C	°F	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
4.4	40	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21	24.3
10	50	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3
15.6	60	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1
21.1	70	7.7	8.5	9.2	10.1	11	12	13.1	14.4	16	17.9	20.5	23.9
26.7	80	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6
32.2	90	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3

*Appendix D***GLOSSARY OF ACRONYMS AND ABBREVIATIONS**

ACCA – Air Conditioning Contractors of America

ACGIH – American Conference of Governmental Industrial Hygienists

AE – Advanced Energy

ARI – Air Conditioning and Refrigeration Institute

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers

ASTM – American Society for Testing and Materials

BTU – British thermal unit

CAR – constant airflow regulator

CDC – Centers for Disease Control and Prevention

CMU – concrete masonry unit

CO – carbon monoxide

DOE – U.S. Department of Energy

EPA – U.S. Environmental Protection Agency

EPDM – Ethylene propylene diene terpolymer

FEMA – Federal Emergency Management Agency

FHA – Federal Housing Administration

FSEC – Florida Solar Energy Center

HEPA – High-Efficiency Particulate Arrestance

HSPF – Heating System Performance Factor

HVAC – Heating, Ventilation and Air Conditioning

ICC NER – International Code Council National Evaluation Report

IECC – International Energy Conservation Code

IRC – International Residential Code

MADD – Mold Amplification and Delivery Device

NAHB – National Association of Home Builders

NBS – National Bureau of Standards

NFIP – National Flood Insurance Program

ORNL – Oak Ridge National Laboratory

OSHA – Occupational Safety and Health Administration

SEER – Seasonal Energy Efficiency Ratio

SFHA – Special Flood Hazard Area

TIF – Thermal Industries of Florida, Inc.

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