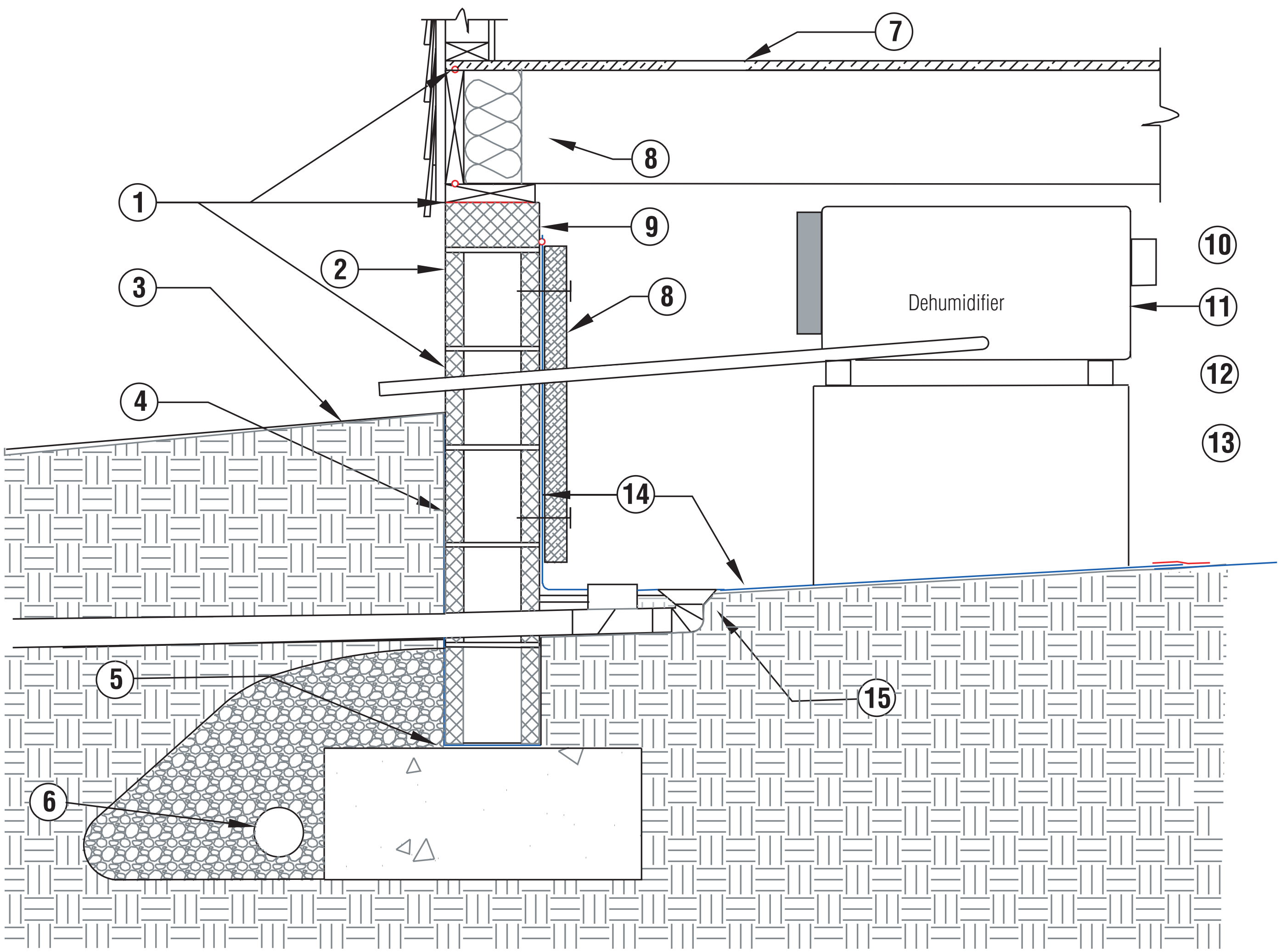
Advanced Energy Sample Design: A Closed Crawl Space With Dehumidifier and Wall Insulation



Drawing not to scale

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 routs 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.

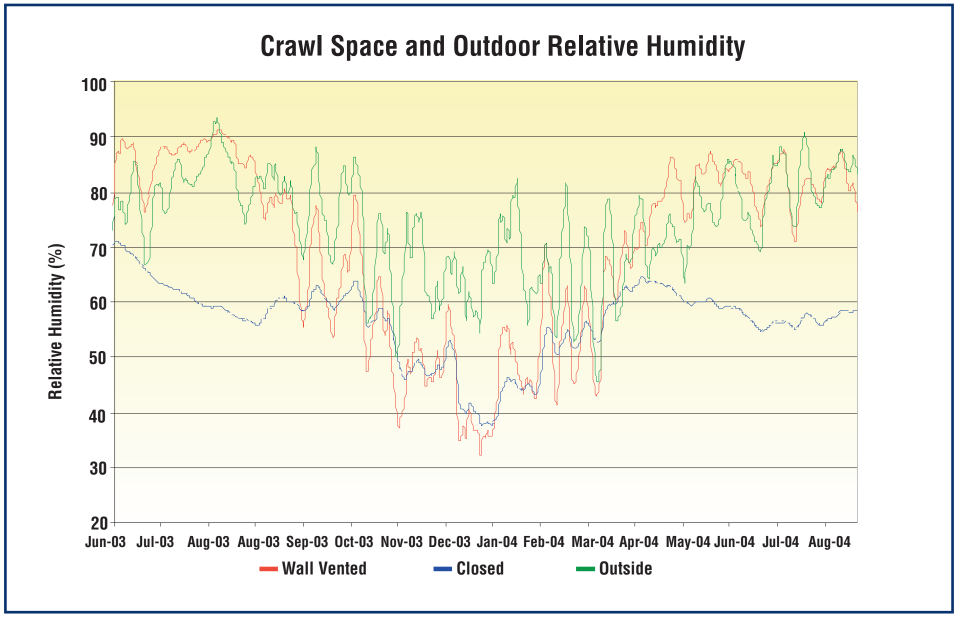
Moisture Performance

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 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.

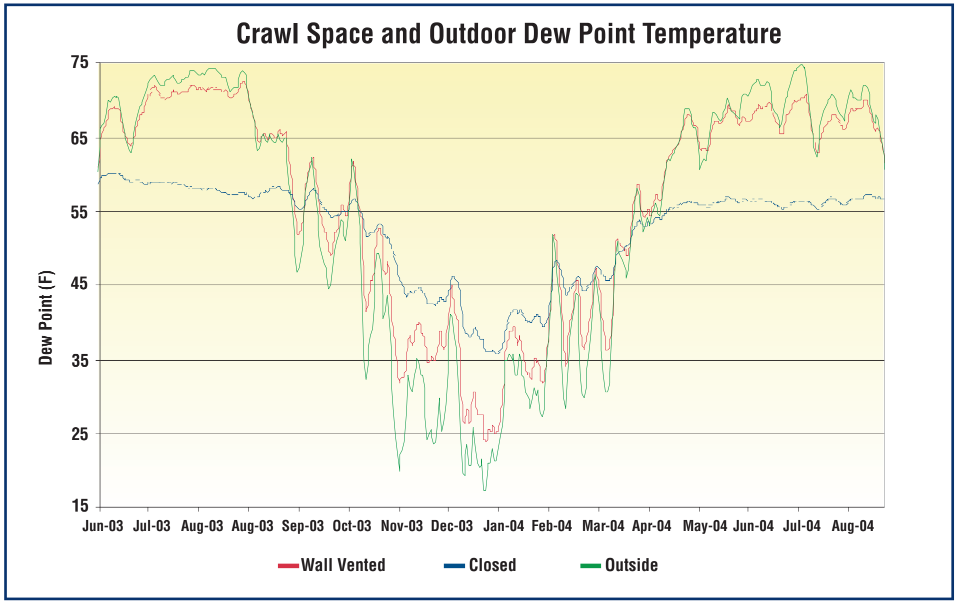


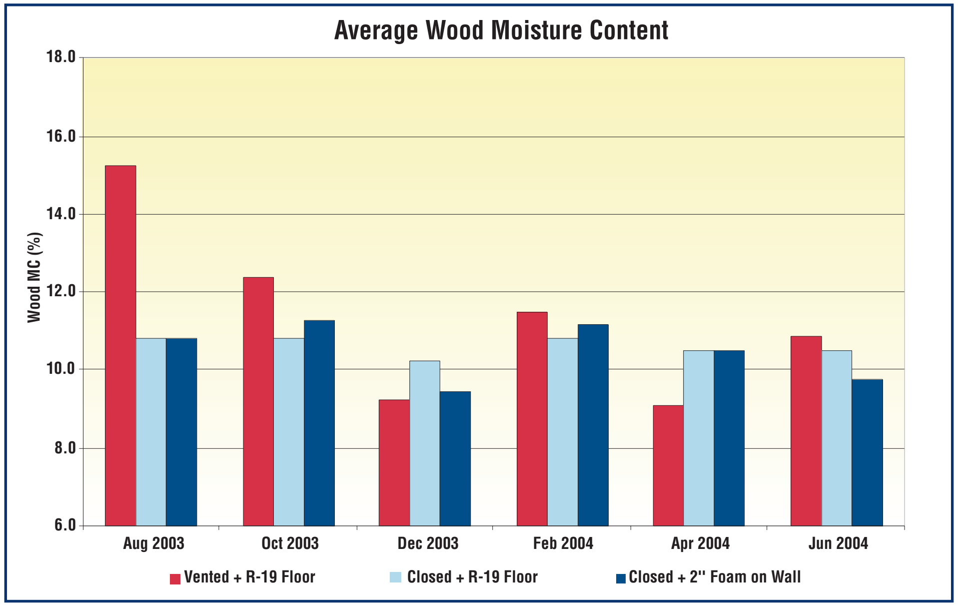
Summer (June-August) Relative Humidity Summary

	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%

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.





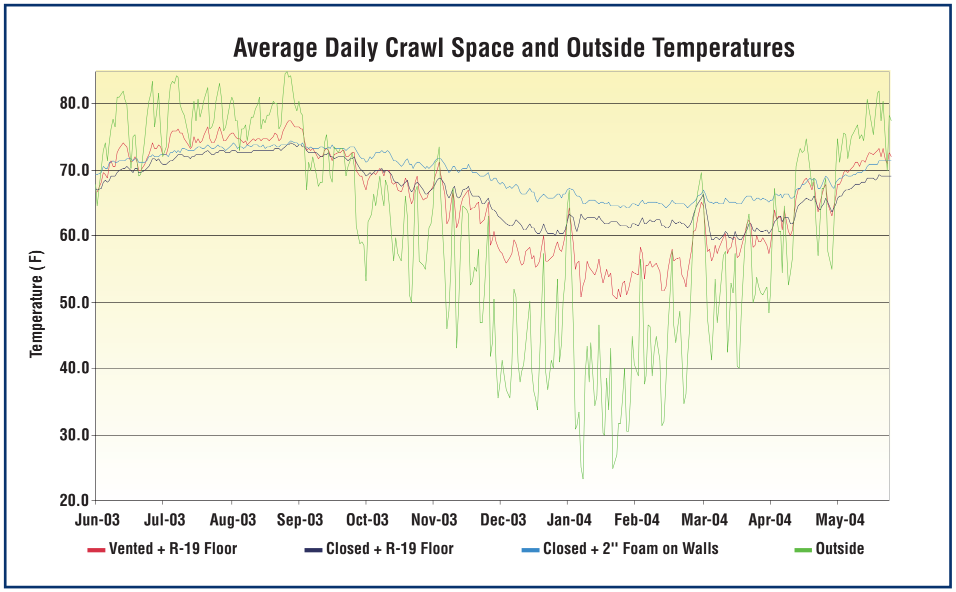
The average wood moisture content graph shows readings for the three types of crawl spaces. The fact that the average wood moisture content in the framing lumber in the closed crawl spaces stays below 12% is notable, not only because it reduces the likelihood of surface mold growth but also because wood 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.