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***Field Study Final Report***

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

Instrument # DE-FC26-00NT40995

June 22, 2005

Submitted to:
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**DISCLAIMER**



**ACKNOWLEDGEMENT STATEMENT**

This report was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-00NT40995. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE.

**ABSTRACT**

This study compared the performance of closed crawl spaces, which had sealed foundation wall vents, a sealed polyethylene film liner and various insulation and drying strategies, to traditional wall-vented crawl spaces with perimeter wall vents and polyethylene film covering 100% of the ground surface. The study was conducted at 12 owner-occupied, all electric, single-family detached houses with the same floor plan located on one cul-de-sac in the southeastern United States. Using the matched pairs approach, the houses were divided into three study groups of four houses each. Comparative data was recorded for each house to evaluate sub-metered heat pump energy consumption, relative humidity, wood moisture content, duct infiltration, house infiltration, temperature, radon, and bioaerosol levels. Findings indicated that in the humid conditions of the southeastern United States, a properly closed crawl space is a robust construction measure that produces a substantially drier crawl space and significantly reduces occupied space conditioning energy use on an annual basis.

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# ACKNOWLEDGEMENTS

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**U.S. Department of Energy Project Manager:** Parrish Galusky, **National Energy Technology Laboratory** served as the project manager from May 2002 through the conclusion of the project in 2005. Jenny B. Tennant, also of NETL, served as the inaugural project manager from October 2000 through April 2002.

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

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**Oak Ridge National Laboratory**, Oak Ridge, Tennessee, conducted the moisture engineering analysis for the Hygrothermal Performance Study. The key team member is **Achilles Karagiozis**, Ph.D., Senior Research Engineer, Building Thermal Envelope Systems and Materials Program.

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

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

**John Straube**, Ph. D., professor of Building Envelope Science at the University of Waterloo in Canada, provided the system design and fabrication of the Hygrothermal Study data acquisition system. Dr. Straube is deeply involved in the areas of building envelope design, moisture physics, and whole building performance as a consultant, researcher, and educator.

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

## 1. Executive Summary

This study investigates the characteristics and performance of "sealed" (hereafter referred to as "closed") crawl spaces in the Southeastern United States. Closed crawl spaces have sealed or unsealed vapor barrier treatments and no foundation wall vents to the outside, in contrast to the traditional wall vented design commonly used in residential construction (and required by construction codes in many jurisdictions).

The study involves twelve new homes that were divided into groups to compare the wall vented design (control group) with closed crawl spaces (experiment groups). The performance evaluation is based on thermal and moisture monitoring, wood moisture content readings, and air leakage characteristics determined from pressure testing.

Field data monitoring began in June 2001. Full comparative performance data became available starting in August of 2001, after the crawl spaces were setup and initial drying of the closed crawl spaces was conducted.

Phase I operated from June of 2001 through May of 2003. The control group crawl spaces were wall-vented, with R-19 fiberglass batt insulation in the framed floor above the crawl space and a vapor retarder covering the entire earth floor, with seams lapped at least six inches. The first experiment group had a sealed vapor retarder covering the crawl space floor and walls, and no insulation on the walls or in the framed floor. The second experiment group had a sealed vapor retarder covering the crawl space floor and walls, and approximately R-3 blown rock wool insulation installed on the crawl space walls and the band joist. After initial dry-down with dehumidifiers, known quantities of duct leakage were the only drying mechanisms present in the Phase I experimental crawl spaces. All homes had an outside-air intake system installed to provide 40 cubic feet per minute (CFM) (20 Liters per second) of outside air to the conditioned space whenever the heat pump air handler was in operation.

Phase II operated from June of 2003 through May of 2004. The control group was still wall vented with a complete, lapped-seam ground vapor retarder, and an R-19 framed floor. The first experiment group had the same sealed vapor retarder covering the crawl space floor and walls, and now had R-19 fiberglass batts installed in the framed floor above the crawl space. The second experiment group had the same sealed vapor retarder, but the rock wool insulation was replaced with R-13 rigid foam board insulation on the perimeter walls and band joist. At the beginning of Phase II, the crawl space ductwork and subfloor penetrations were sealed in all control and experimental houses to measured levels. A small duct was installed in the supply trunk of the experimental crawl space homes to provide a known quantity of conditioned air (35 CFM) to the crawl space for the purpose of providing a drying mechanism.

Phase III operated from June of 2004 through mid-December 2004. Three of the four control crawl spaces were converted to a new variant of closed crawl space design, which we refer to as experiment group 3. In these three crawl spaces, all vent openings to the outside were plugged and sealed, but the ground vapor retarder seams were left lapped by at least six inches (not sealed) and there was no vapor retarder installed on the crawl space walls. The R-19 fiberglass batt insulation was retained in the framed floor and a supply duct identical to those used in the experimental homes was installed. The other experimental crawl spaces were not modified. 110 Lowe's Ct. was required to be left as a vented control crawl space due to its involvement in the ORNL hygrothermal study.

Phase IV operated from mid-December, 2004 through mid-March, 2005. The four wall-insulated closed crawl spaces in experiment group 2 were modified by adding 2 feet of R-10 foam insulation, placed horizontally on the ground around the perimeter of the crawl spaces. 110 Lowe's Ct., the last remaining wall-vented crawl space home, was converted to the experiment group 3 configuration established in Phase III. All other crawl spaces remained in their existing configurations.

Overall results indicate that the experiment designs may save significantly on energy used for heating and cooling. A comparison of the sub-metered heat pump energy use of the experiment houses to that of the control houses shows savings in excess of 15% on energy used for space conditioning, with the majority of the savings being realized during the cooling seasons.

Furthermore, the experiment groups maintained much lower relative and absolute humidities during the humid summer seasons than the control group. The wood moisture content in the closed crawl spaces was also significantly lower than the wood moisture content in the wall-vented crawl spaces. The moisture conditions in the closed crawl spaces tend to track the conditions inside the houses while the wall vented crawl spaces tend to track the conditions of the outside climate.

This study has produced data on fungal counts that is unavailable from other sources. Wall vented crawl spaces appear to be more vulnerable to fungal colonization than the experiment crawl spaces. Researchers have noted the need for evaluation of air leakage between the house and the crawl space and the effects of pressures acting on the crawl space with respect to indoor air quality. A series of pressure diagnostics on the house, ducts, and crawl space for houses in this study contributes to characterizing the air leakage paths in houses with wall vented versus closed crawl spaces, but does not provide definitive analysis of these phenomena.

The measured data from this practical, applied investigation indicates the importance of following improved guidelines for wall vented crawl space construction and also documents the major improvements that result from following guidelines for closed and thermally improved crawl spaces. The authors hope these findings will prompt the home construction industry to increasingly employ construction techniques that improve the performance of crawl space foundations. Project results and resources are compiled and available online at www.crawlspaces.org.

## 2. Introduction

The purpose of this project was to conduct a field study over a multi-year period that compared the performance of closed crawl spaces, which have detailed vapor barrier treatments and no foundation wall vents to the outside, to traditional, wall vented crawl spaces in residential homes in the Southeastern United States, while demonstrating practical implementations in a field setting. The study utilized twelve new homes that have been divided into three groups of four homes each to compare the traditional wall vented design (control group) with dry construction technology crawl spaces (experiment groups). The performance evaluations are based on energy consumption monitoring, thermal and moisture air monitoring, wood moisture content readings, indoor air quality assessments and air leakage characteristics determined from pressure testing.

This report describes the protocol development, experiment design, home recruitment, initial characterization and instrumentation of the field test site. The report also summarizes performance data that has been collected on site. The authors hope these findings will prompt the home construction industry to increasingly employ construction techniques that improve the performance of crawl space systems.

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

Preliminary reports on the pilot phases of all three studies and the technology assessment were submitted to DOE/NETL in December 2001. This project utilized the findings and technology assessment to deploy improved guidelines and to help the state of North Carolina implement new building code provisions for wall vented and closed crawl spaces.

## 3. Energy Performance Overview

This field study tested the hypothesis that the closed crawl space construction systems used in the experiment houses have improved thermal performance over the standard wall vented crawl space systems found in the control houses during Phases I and II. During Phase III we examined the relative performance of a closed crawl space system that did not incorporate a fully sealed vapor retarder on the crawl space floor and walls. During Phase IV we assessed the impact of additional horizontal perimeter insulation installed on the floor, which is the recommended method in existing residential and energy codes.

Energy performance was assessed in Phase I using a base-load subtraction method to estimate heating and cooling energy use based on utility bill data. When this analysis indicated the potential for significant savings in the closed crawl space homes, all the homes in the project were equipped with sub-meters to accurately record energy used by the heat pump system. The sub-meter data was used for all energy analysis from Phase II forward.

The key thermal performance difference between the closed and wall vented designs is that the closed designs extend the air/pressure boundary down and out from the framed floor structure to the crawl space ground surface and walls. Depending on the choice of insulation configuration, the closed crawl space design may either retain the thermal boundary at the framed floor structure, or marry the thermal boundary with the new air/pressure boundary at the crawl space perimeter wall.

In the control houses, outdoor air readily exchanges with the crawl space air through intentional holes represented by the 11 wall vents, as well as the unintentional holes represented by the duct penetration hole through the crawl space wall to the outdoor packaged heat pump, plus framing cracks and miscellaneous wall penetrations. The combined hole size of intentional holes is in excess of 7 square feet per house for the control group. This large hole size allows for large amounts of crawl space and outdoor air mixing. Consequently the control crawl spaces represent tempered outdoor air zones. Temperatures within the crawl space are expected to approach outdoor temperatures, with tempering effects provided by heat loss/gains from the ductwork, ground surface and framed floor structure.

The construction techniques utilized in the experiment homes require intentional and unintentional holes to be sealed to minimize the entry of unconditioned outdoor air into the crawl space. Sealing work in the experiment groups extends the ground moisture barrier (in this study, 6-mil polyethylene sheets) to cover the interior of the crawl space wall. Once sealed to control air and moisture transport, the crawl space walls and floor become significant thermal boundaries. This converts the experiment crawl spaces from tempered outdoor air zones into semi-conditioned (moisture-managed) zones. The generic thermal and pressure boundaries for various designs are illustrated in Figure 1.

Some energy savings were expected to result from the fact that the study homes have duct distribution systems located in the crawl spaces. In the control houses, duct heat and air leakage losses and gains are to the outside, whereas in the experiment houses these gains and losses are to the tempered closed crawl space.

The experiment crawl spaces were not heated and cooled to the same design conditions as the conditioned space by providing large supply air vents and/or air transfer grilles across the floor. Instead, (from Phase II onward) they received only a small amount of heating and cooling by virtue of the small supply air flow provided as a drying mechanism for the crawl spaces. It was expected that temperatures within the crawl spaces would depend on the following additional variables:

- Effectiveness of the wall or floor insulation, where applicable
- Duct insulation heat loss and gain
- Supply and return duct air leakage
- Air leakage between the outdoors and the crawl space
- Air leakage between the conditioned space and the crawl space
- Ground heat transfer relationship

**Figure 1: Conceptual Thermal Diagrams of Wall Vented and Closed Crawl Spaces**

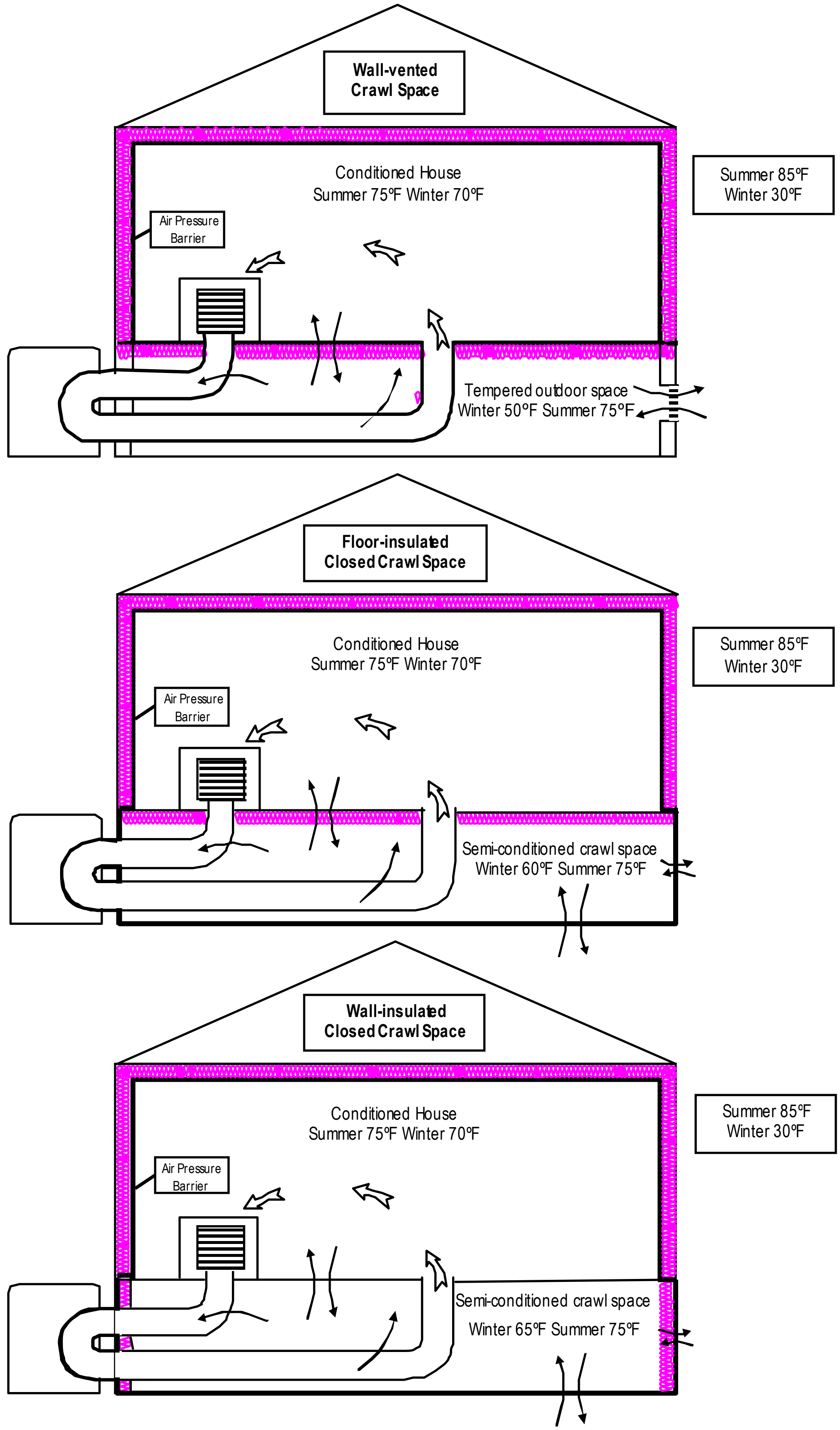

**Table 1: Comparison of thermal characteristics of Control and Experiment groups.**

| Thermal pathways | Wall vented crawl space | Floor-insulated closed crawl space | Wall-insulated closed crawl space |
|---|---|---|---|
| **Convective flows (air leakage)** | | | |
| Primary air/pressure boundary | Subfloor | Crawl space walls | Crawl space walls |
| Secondary air/pressure boundary | None | Subfloor | Subfloor |
| Crawl space duct air leakage | To tempered outside air in crawl space | To semi-conditioned crawl space | To semi-conditioned crawl space |
| **Conductive/radiant flows** | | | |
| Primary thermal barrier | Finish flooring, subfloor, cavity insulation, and joists | Finish flooring, subfloor, cavity insulation, and joists | Crawl space walls and band joist insulation, masonry block, wood sills and band joists; plus earth floor of crawl space |
| Secondary thermal barrier | None | Masonry block, wood sills and band joists; plus earth floor of crawl space | Finish flooring, subfloor, batt insulation, and joists |
| Crawl space duct heat loss and gain | To tempered outside air in crawl space | To semi-conditioned crawl space | To semi-conditioned crawl space |

The two convective flows in the experiment groups are air leakage through the air barrier and air leakage in and out of the ductwork located in the crawl space. In the control group the air leakage pathway is represented by seam gaps in the subflooring and the gaps left in floor penetrations. The primary floor penetrations found in the field study homes are listed below.

- Ten 4” by 10” floor supply registers
- One 8” by 16” return plenum
- Twenty-seven plumbing holes for waste and supply water piping for sinks, toilets, bathtubs, and the washing machine.
- One 4” dryer vent hole
- Minimal electric wire penetrations (virtually all house wiring is run in the walls and attic)
- Newly installed penetrations by Homeowners for cable and satellite TV connections and added phone lines.

The average number of floor penetrations in these houses exceeds 45. Of this hole inventory, by far the largest gaps found are associated with the floor holes cut for the plumbing waste pipes. These holes are often two to three times larger than the pipe exterior diameter of the waste pipe.

In the experiment groups, intentional and unintentional crawl space wall and ground holes have been sealed to minimize air moisture intrusion and thermal air leakage. No attempt was made to seal any of the floor hole gaps listed above during Phase I. Since sealing of these holes could be expected to improve the thermal efficiency of both the control and experiment groups, the holes were sealed before beginning Phase II.

Labor-intensive sealing work was required to seal off the wall and ground leakage holes, even though the sealing work took place immediately after the experiment houses had been built. The combined sealing effort significantly exceeded the study estimates for time and expense. These cost and time overruns strengthen the argument that crawl spaces can be best air- and moisture-sealed during initial home construction.

The other significant air leakage pathway at the field site was duct air leakage. Duct leakage was measured in all 12 houses to identify outlier homes. Eleven of twelve homes had typical pretreatment duct leakage rates ranging from 153 to 193 cubic feet per minute at a test pressure of 50 Pascals (CFM50), with house twelve, F100, being the clear outlier at 445 CFM50. F100 was the only house where a panned, floor joist return system was installed. It took three different contractors to reduce the air leakage of this return to similar levels found in the other eleven houses.

Two other duct repairs were made. First, F108 had two supply flex and the main flex return replaced because these ducts flooded during a major plumbing leak that occurred in the house when the new owners were moving in. Second, the exterior duct joints to the outdoor packaged heat pumps were all reinforced with mastic sealants after initial inspection work revealed that the air leakage durability of these joints was questionable given the length of the study.

Prior to the beginning of Phase II, additional duct and envelope sealing was carried out in order to reduce leakage and to further reduce any variation between the study groups. Average duct leakage varies from 5% to 7% $CFM_{25}$ per square foot of floor area (average control home has 68 $CFM_{25}$, average group 1 home has 51 $CFM_{25}$, average group 2 home has 59 $CFM_{25}$). Average house leakage varies from 0.22 to 0.27 $CFM_{50}$ per square foot of envelope area (average control home has 749 $CFM_{50}$, average group 1 home has 838 $CFM_{50}$, average group 2 home has 695 $CFM_{50}$).

In the control group crawl spaces, the conductive and radiant flows take place in the floor plane assembly. Calculating an actual heat transmission U-value for this thermal assembly is greatly compromised because of the variability of how the floor batt insulation is typically installed, as well as how it was actually installed in the 12 field site houses. Following is a listing of the factors that degrade floor insulation performance in wall vented crawl spaces and in particular the control group crawl spaces.

- Floors above crawl spaces are difficult to insulate. Generally, the floor thermal plane has the most thermal envelope penetrations for ductwork, plumbing, electrical, telephone and cable runs.

- With regards to the twelve field houses, the R-19 faced batt insulation had to be installed around the 45 or so ducts, pipes and wires that run through the floor. This resulted in numerous small gaps, voids and compression problems around these items.

- Because of the low headroom, it was also difficult work to install the floor insulation batts, particularly in the center of the floor area over the main joist beam, and supply and return ducts. It was not uncommon to find no insulation installed in some of these difficult locations.

- By design, the insulation wires that are commonly used to hold insulation batts in place, compress floor batts reducing the effective batt R-value. All twelve field houses had insulation compression due to the use of insulation wires. The opposite also occurred. Some batts sag down and are not in contact with the subfloor surface.

- Insulation performance degrades over time as batts settle and poorly installed batts fall down. Despite the fact that the floor batts had been installed less than one month, most of the field houses were found to have one or more partially fallen or fully fallen batts. Note that in the control group, fallen batts and missing insulation batt problems were corrected during the experiment setup phase.

- Insulation performance is degraded by moisture accumulation. Preliminary moisture readings indicate that the floor insulation in the control houses absorbed air moisture during the summer.

The insulation defects found in the field houses were typical of new floor insulation installations. The combined effect of the above variables in the control group is significant, but difficult to quantify. What is clear however is that the actual thermal performance is significantly less than the rated insulation performance, likely within the range of one to two thirds less.

In closed crawl spaces, insulation is often installed on the crawl space walls and band joist surfaces. This aligns the insulation in contact with the primary air/pressure boundary and theoretically maximizes the thermal boundary performance. Generally in the southeast no insulation layer is applied to the crawl space earth floor, but this application was tested in Phase IV. In the summer time when the house is being cooled the earth temperature is expected to be less than the cooling space temperatures maintained in the experiment houses. All study homeowners air conditioned their homes during the summer. Thus, the cool ground surface in the experiment groups did not produce any additional indirect cooling load on the house heat pump system, and may in fact have acted as a heat sink to reduce the cooling load on the heat pump. A potential energy penalty was expected during the winter when we anticipated heat loss from the semi-conditioned crawl space air and floor surfaces to the tempered ground surface temperatures or to the outside through exposed masonry areas required for termite inspection.

When the air/pressure boundary was moved to the crawl space walls and ground in the experiment groups, a secondary air/pressure and thermal boundary was established at the subfloor. The pressure testing data reveals this effect. The Phase I zone pressure results show a marked difference between the control group and experiment groups. When the houses were depressurized to 50 Pascals with reference to outside, the crawl space to house pressure differences averaged 49 Pascals in the control group and 22 Pascals in the experiment groups. The averaged 22 Pascal reading found in the experiment group demonstrate that the crawl space wall is acting as a primary air/pressure boundary. The subfloor acts as a secondary air/pressure boundary. The thermal consequence of this condition is that the floor continues to reduce house air leakage, and in addition, the large area floor components, carpet and padding, wood subfloor and joists provide some measure of heat flow resistance, or in other words some added floor insulation effect.

The second major category of conductive losses takes place through the duct insulation. The field homes have internally lined trunk ducts and flex supply run outs, as well as a flex return mainline. The R-value of the internally lined ducts is estimated to be R-3, whereas the rated insulation on the flex ducts is R-4.2. In the control group heat loss and gains from the ducts is to the tempered outdoor air conditions found in the crawl space. In the experiment groups heat loss is to the semi-conditioned environment of the crawl space. The major reduction in temperature difference occurred during cold weather. Radiant losses and gains from the ductwork are minimized by the foil outer liners of the flex ducts, and also by the galvanized metal exterior surfaces of the trunk ducts.

The sub-metered heating and cooling energy use data collected from June of 2003 through the end of the study indicated that the closed crawl space homes delivered significant energy savings when compared to the control houses. This was true even for the four closed crawl space houses with wall insulation where we provided a termite inspection gap of exposed masonry and did not install the insulation either down 24" below grade or 24" horizontally onto the perimeter of the crawl space floor, as is typically recommended in energy codes and published design guidelines. In fact, limited analysis of the impact of installed perimeter insulation in the final winter season of the study does not indicate any positive impact of this strategy. The least-controlled variable in the energy analysis is the base load use of the occupants in the different study homes. Normalizing for base load may reduce the delivered energy improvements of the closed crawl space homes from the documented 15-18% annual savings for space conditioning energy use based on sub-meter data alone.

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. The homes in this study have shallow foundations, and

Advanced Energy has not tested crawl space foundations with deeper footing depths such as may be found farther north. A wall insulation strategy may prove to perform best in such houses, where foundation depth and colder temperatures will be significant differences from the study described here. 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, and Advanced Energy has now begun a 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 their construction processes.

## 4. Experiment Design

### 4.1 Site Description/Background

The field study is located in Princeville, a small town in eastern North Carolina that was devastated by Hurricane Floyd in 1999. The site consists of twelve houses that were built by Habitat for Humanity as a part of the relief effort and rebuilding of this community. A description of this sub-development is presented in the appendices. These homes are all located on a new cul-de-sac street, which runs north to south. There are six homes on each side of the street: the even numbered homes are located on the east side of the street and the odd numbered homes are located on the west side of the street. A simplified site plan is presented in Figure 2. Each house is identified with a code that indicates whether it was a Phase I control house (C) or experiment house (E1 or E2).

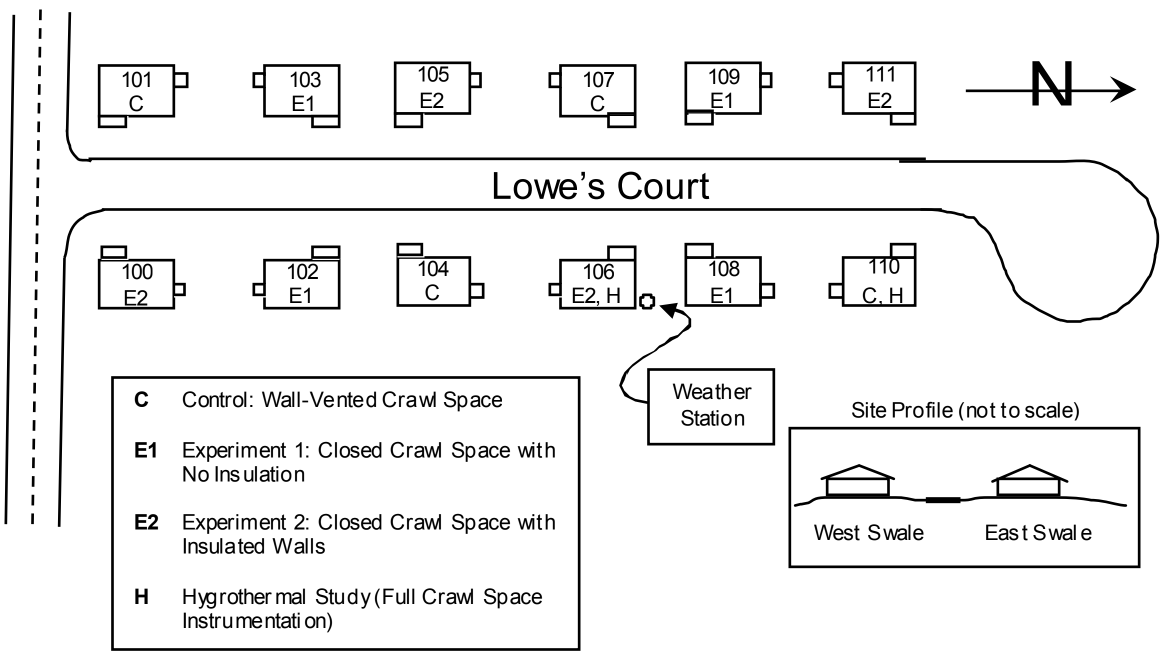


**Figure 2: Princeville Site – Experiment Plan**

The houses have three bedrooms and two bathrooms and the floor plan designs are mirror images of one another. The outside dimensions are 40' x 26' and they have standard eight foot ceilings. Each home has a full crawl space that is about 28" high or just over three concrete blocks high. The façade of the block foundation wall is fiber-reinforced stucco and the houses have vinyl siding. The houses do not have gutters and the crawl space doors are about 1" above ground level. A typical floor plan is presented in Figure 3.

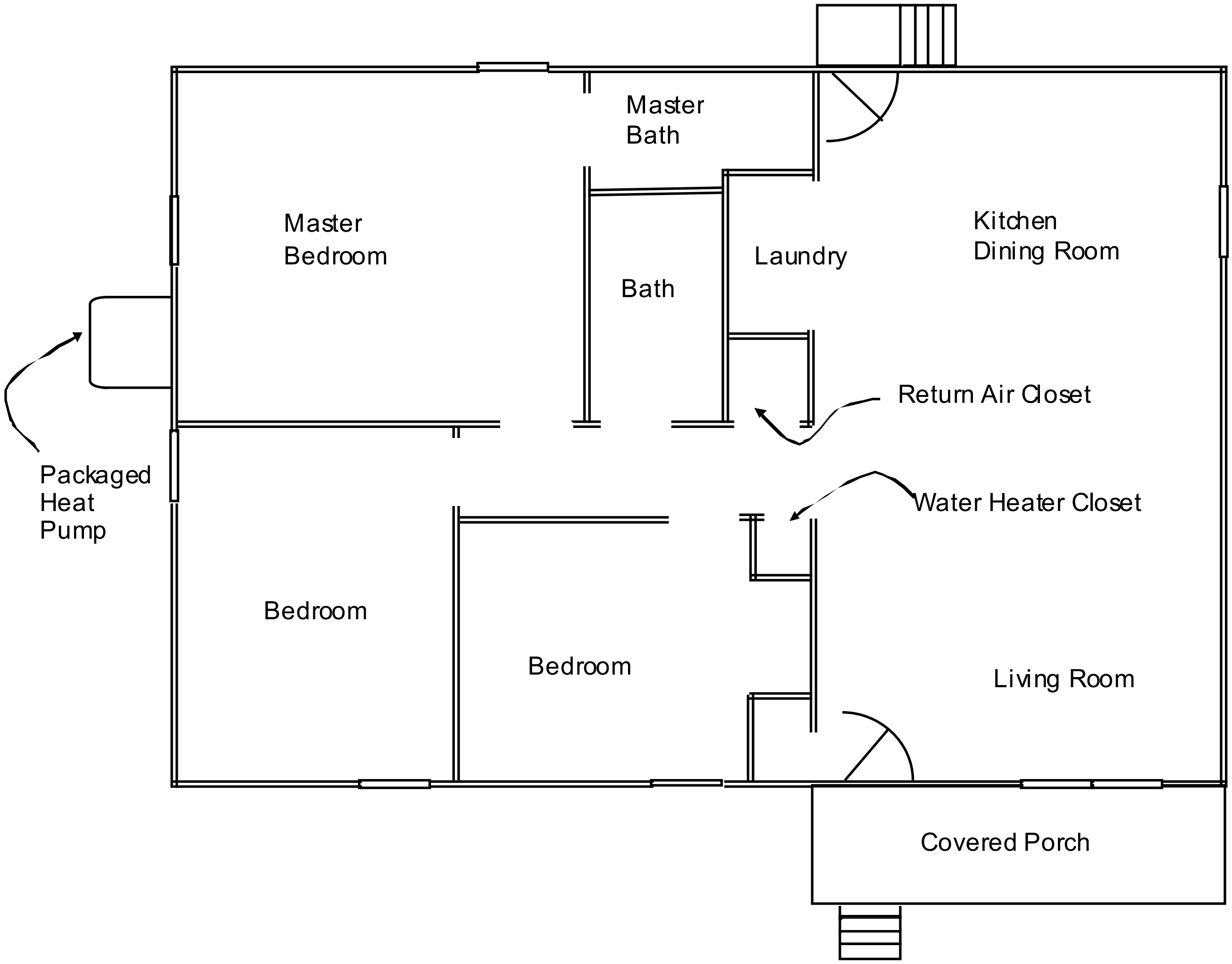


**Figure 3: Typical Lowe's Court Floor Plan**

A key reason why this site was chosen for the study is the site grading. Prior to building the homes, the site was built up with approximately three feet of sandy soil to reduce future flood damage. This infill results in all homes having uniform soil characteristics under and adjacent to the crawl spaces.

The twelve homes are divided into three groups with four homes in each group.

Phase I operated from July 1, 2001 through May 31 of 2003. During this period, the first group is the control group, which represents the standard house construction with a wall vented crawl space, 100% vapor barrier coverage on the ground, and R-19 Kraft-faced fiberglass batt insulation mounted in the floor system using tension wires (Figure 4).

The second group is referred to as Experiment 1 (Figure 5). This group has a closed crawl space and no floor or crawl space wall insulation. The R-19 floor insulation installed during construction was removed in June 2001. The primary thermal barrier is the low-performing masonry wall, with an R-value of approximately R2. This approach was conceived as a closed crawl space design that meets local termite control restrictions, because in North Carolina and other southern states it can be difficult to get termite control companies and building code officials to accept the use of any foundation wall insulation. This design was also intended to assess the impact of just providing a closed crawl space with a sealed liner and no thermal insulation.

The third group is called Experiment 2 (Figure 6). The R-19 floor insulation installed during construction was removed in June 2001. During the July-October 2001 pilot study data period, this group had identical thermal characteristics to experiment group 1. The installation of wall insulation was deferred because the researchers wanted to collect as much comparative summer performance data as possible. Adding wall insulation would have shortened the pilot-phase summer comparative period by several weeks. In mid-October 2001 damp-sprayed rock wool insulation was applied to the crawl space perimeter walls and band joist. The rock wool was damp sprayed using a cement binder on to the interior walls and band joist surfaces of experiment group 2. A minimum of two inches of rock wool was installed but there is significantly more insulation thickness at the bottom of the walls. Since the insulation was sprayed on, coverage was very complete. There were no unintentional gaps or seams. However this insulation system is intentionally compromised by a continuous, horizontal inspection gap was left at the top of the masonry wall. The two to three inch gap is a termite inspection strip. Because of documented cases of termite tunneling, the North Carolina State building code as well as the ICC code limits the installation of foundation wall insulation systems. In this case a 2-inch inspection gap was left at the top of the masonry wall to allow for inspections of termite mud tunnels.

Phase II operated from June of 2003 through May of 2004. At the beginning of Phase II, the crawl space ductwork and subfloor penetrations were sealed in all control and experimental houses to measured levels. The control group was still wall vented with an R-19 framed floor structure. In both experiment groups (but not in the control group), researchers installed a 4" diameter duct outlet with a balancing damper and a backflow damper in the supply trunk of the experimental crawl space homes. This duct was installed to initially provide 25 cubic feet per minute (CFM) whenever the air handler fan was in operation. After two weeks of operation, the humidity levels in the experimental crawl spaces were examined and determined to be higher than observed during Phase I, so researchers subsequently increased the supply air flow to 35 CFM in mid-July of 2003. To set the flow, researchers entered one crawl space and installed a temporary plenum box over the duct. They used a Minneapolis Duct Blaster as a powered flow hood to precisely measure the airflow from the duct as the researcher adjusted the flow to the desired level with the balancing damper. Then, a TIF anemometer was centered in the air stream and the air velocity recorded. In subsequent houses, the anemometer was centered in the crawl space supply duct air stream and the balancing damper was adjusted until the air velocity matched the reading determined in the first house.

Experiment group 1 (Figure 7) retained the same sealed vapor retarder on the crawl space floor and walls, but now had R-19 fiberglass batts installed in the framed floor structure above the crawl space. The second experiment group (Figure 8) retained the same sealed vapor retarder, but the rock wool insulation was removed and replaced with R-13 rigid foam board insulation (2" Dow Thermax foil-faced polyisocyanurate) on the perimeter walls and band joist. Note that at this time, house 108 was switched from experiment group 1 to experiment group 2 and house 111 was switched from experiment group 2 to experiment group 1. This was done to avoid installing insulation in the floor structure of 108, which during site startup had experienced a large mold bloom.

Phase III operated from June of 2004 through mid-December 2004. Three of the control crawl spaces were converted to a new variant of closed crawl space design, called experiment group 3 (Figure 9). Experiment group 3 had all vent openings to the outside plugged with rigid foam board (2" Dow Thermax foil-faced polyisocyanurate insulation) and sealed with caulk or mastic. The ground vapor retarder was left un-sealed (joints remained overlapped by 6-12 inches) and there was no vapor retarder installed on the crawl space perimeter walls. The R-19 fiberglass batt insulation was retained in the framed floor structure, and a supply duct identical to those used in the experimental homes was installed and set to deliver the same 35 cubic feet per minute of conditioned air as in the other experiment group crawl spaces. 110 Lowe's Ct. was left as a vented crawl space control home due to its involvement in the ORNL hygrothermal study. The experiment group 1 and experiment group 2 crawl spaces were not modified at this time.

Phase IV operated from mid-December, 2004 through mid-March, 2005. The experiment 2 wall-insulated closed crawl spaces were modified by adding 2 feet of R-10 foam insulation (1 ½" Dow Thermax foil-faced polyisocyanurate), placed horizontally on the ground around the perimeter of the crawl spaces (Figure 10). 110 Lowe's Ct. was converted to the experiment group 3 configuration. All other crawl spaces remained in their existing configurations.

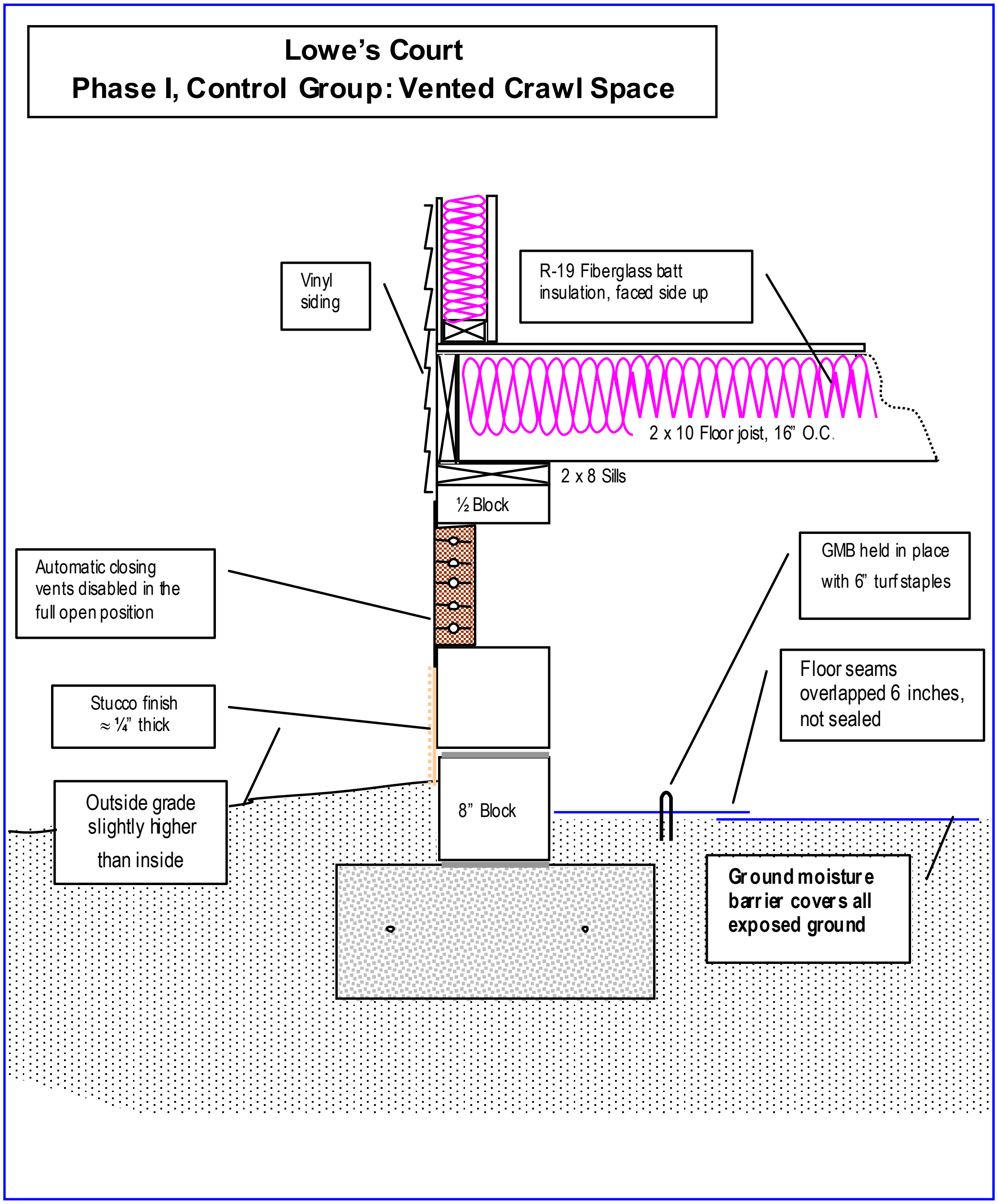


**Figure 4: Field Study Crawl Space Setup – Phase I, Control Group**

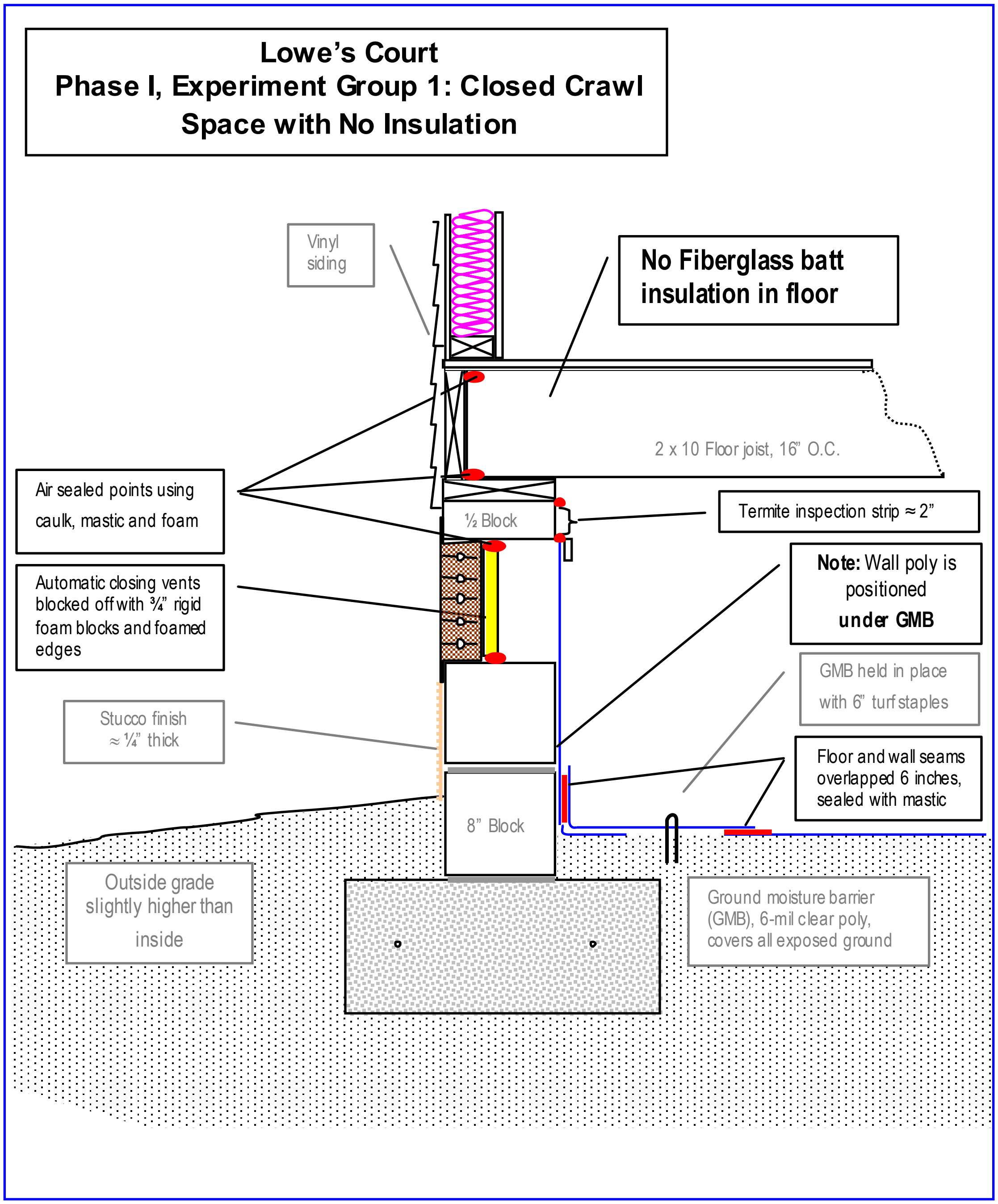


**Figure 5: Field Study Crawl Space Setup – Phase I, Experiment Group 1**

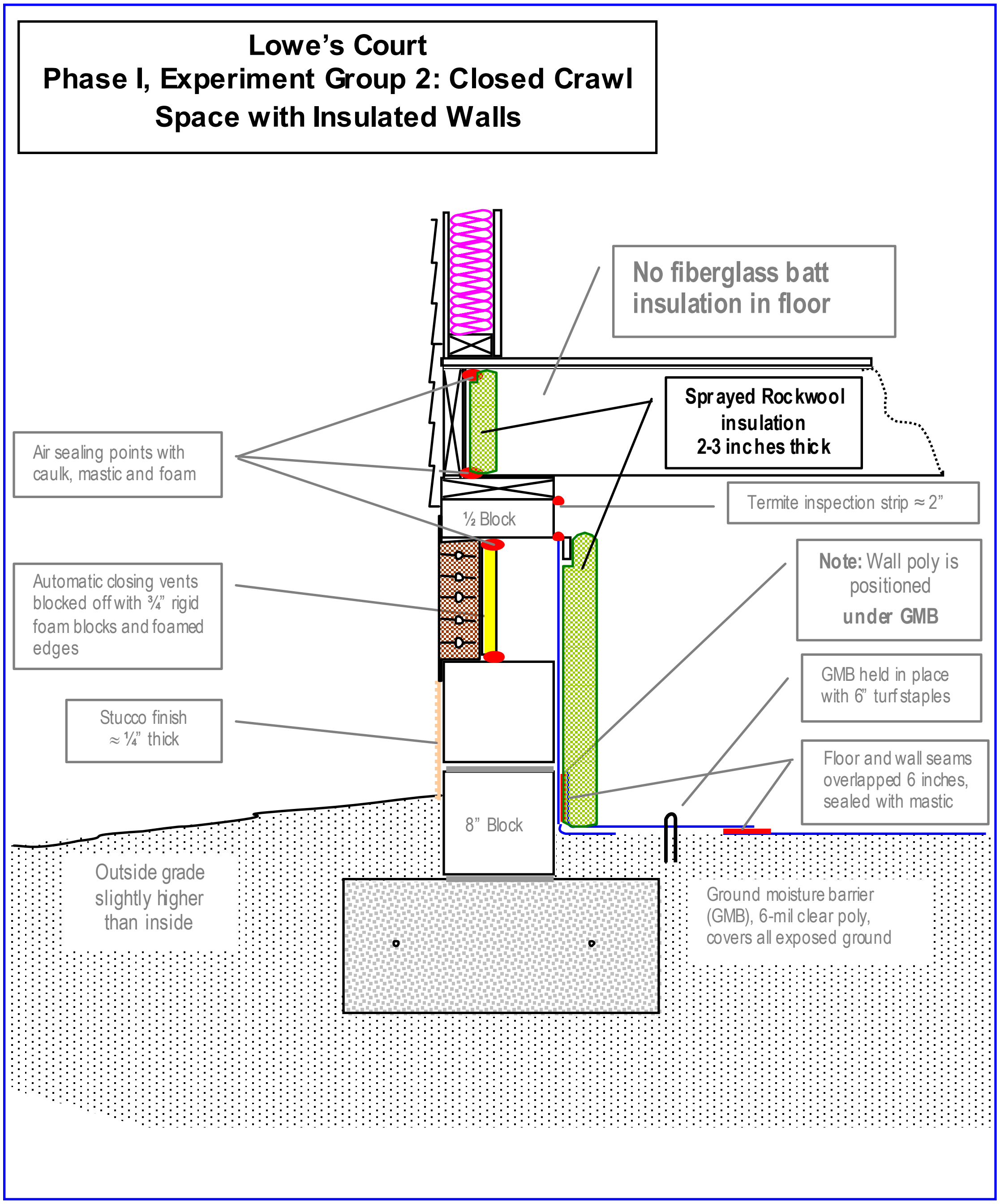


**Figure 6: Field Study Crawl Space Setup – Phase I, Experiment Group 2 (Note that wall insulation was not installed until mid-October 2001)**

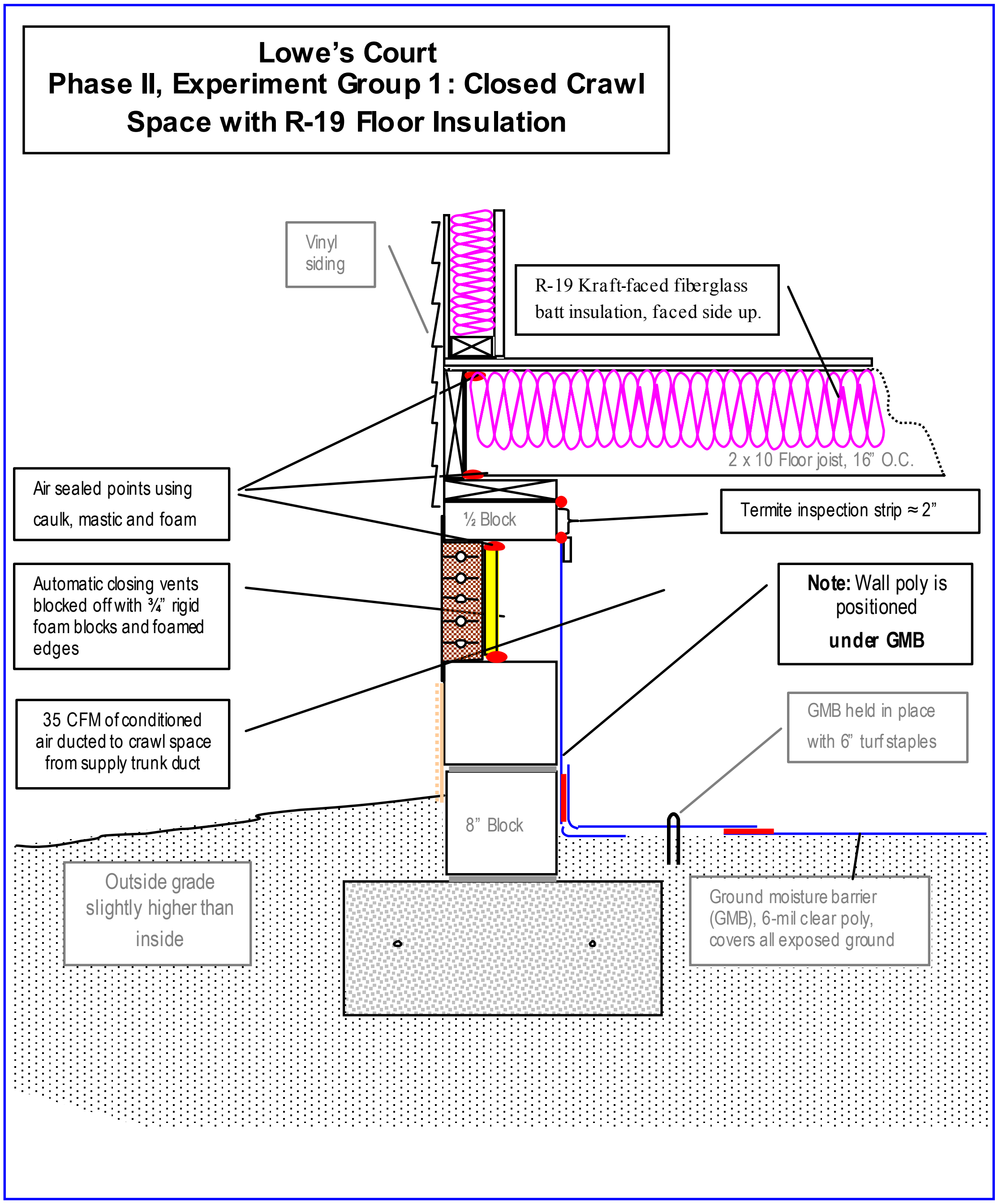


**Figure 7: Field Study Crawl Space Setup – Phase II, Experiment Group 1**

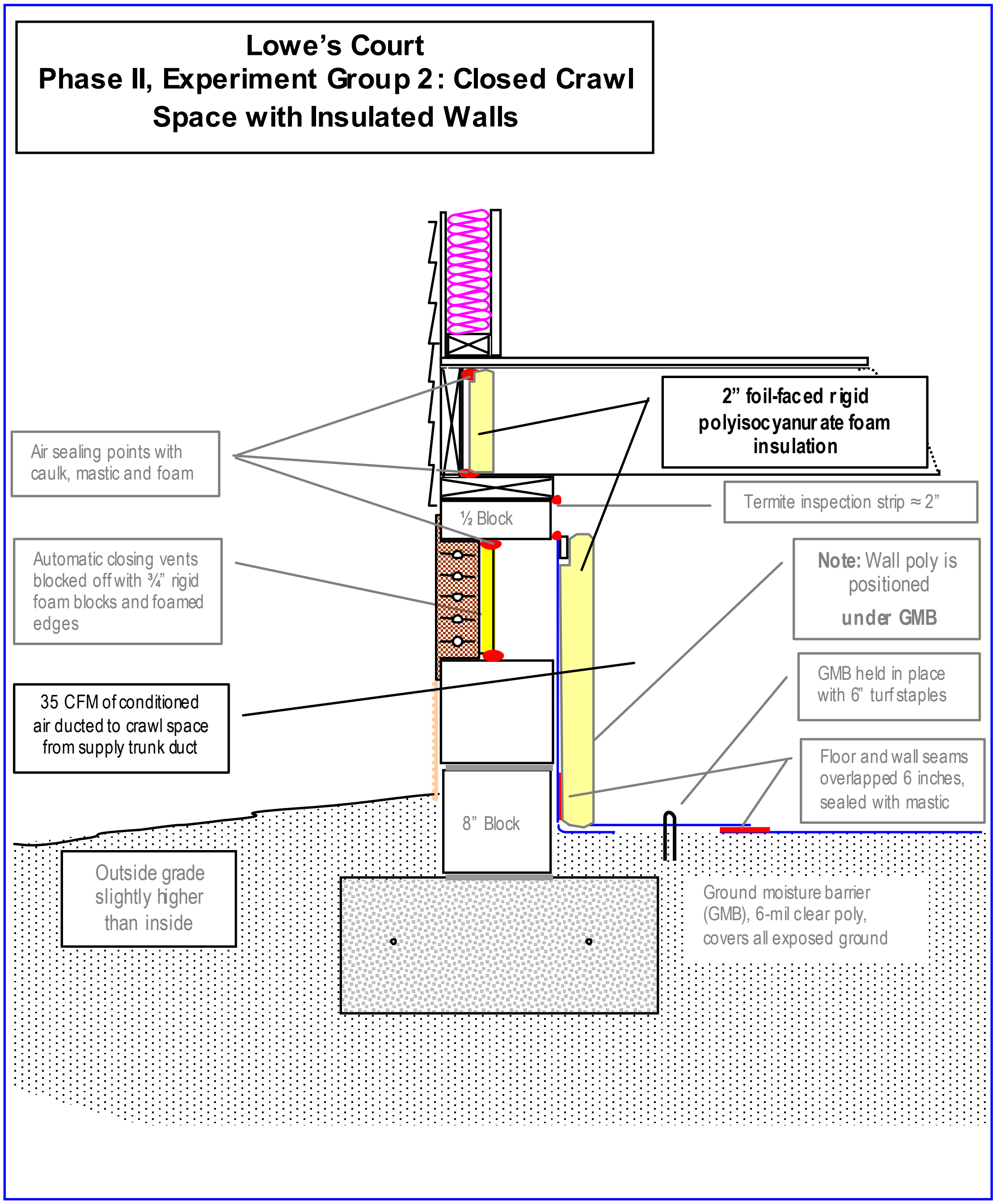


**Figure 8: Field Study Crawl Space Setup – Phase II, Experiment Group 2**

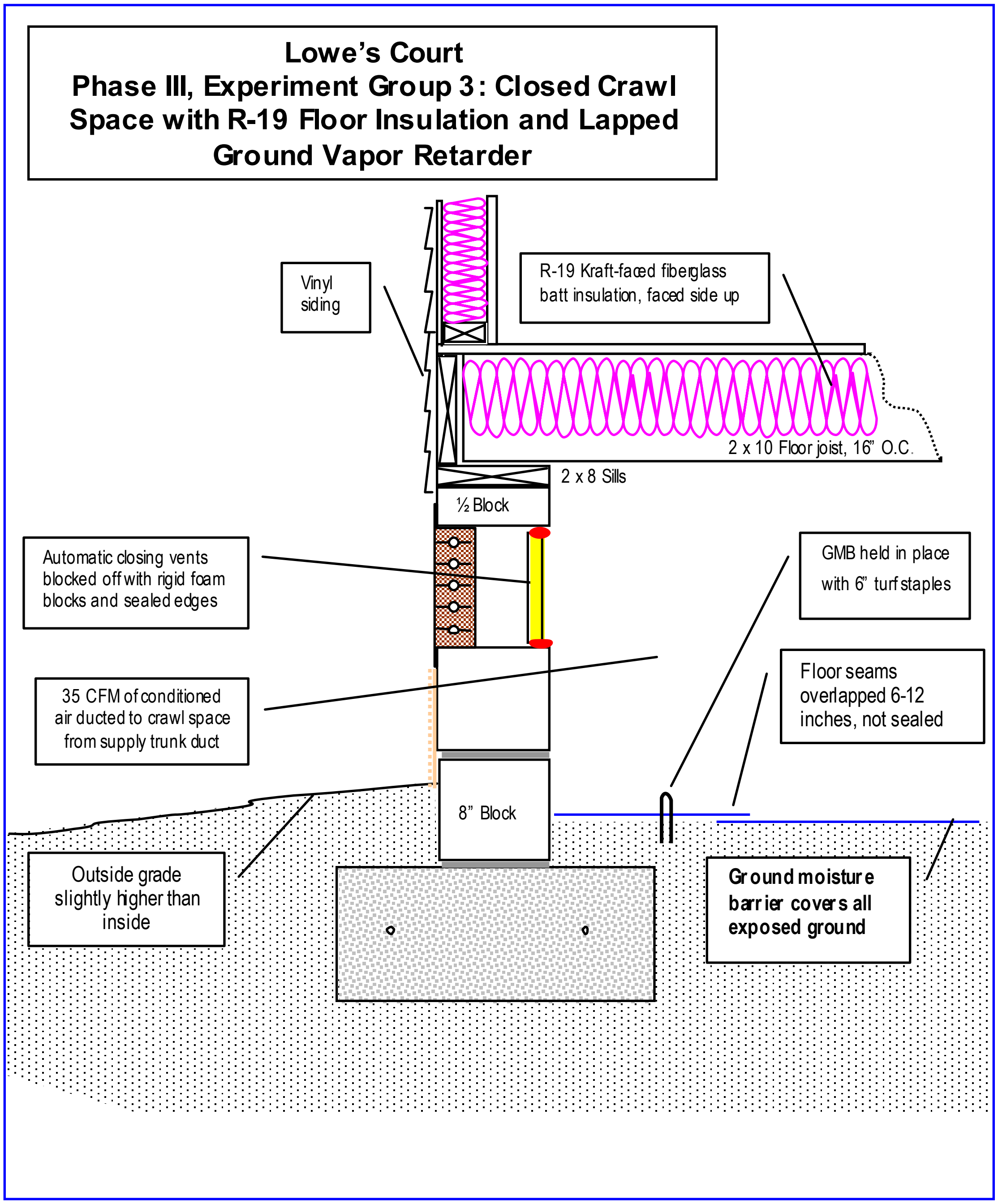


**Figure 9: Field Study Crawl Space Setup – Phase III, Experiment Group 3 (Original Control Group)**

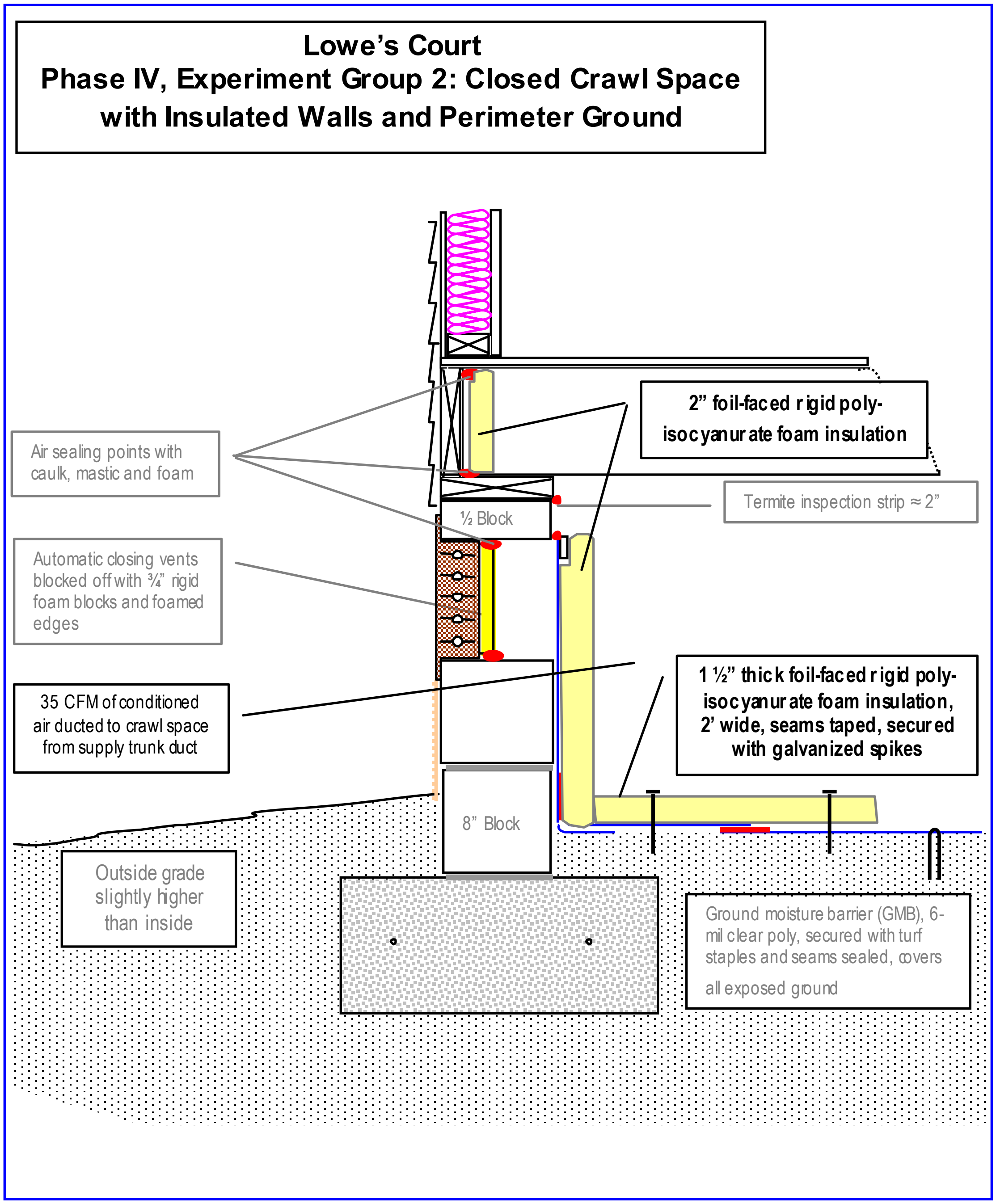


**Figure 10: Field Study Crawl Space Setup – Phase IV, Experiment Group 2**

### 4.2 Initial Field Observations

| Group | House No. | % Vapor Barrier | Moisture Control Problem Comments |
|---|---|---|---|
| Control | F101 | 40 | Condensation on supply ducts |
| | F104 | 70 | Water on vapor barrier from water heater overflow drain; mold or fungus on ground |
| | F107 | 40 | Plumbing leak from cracked bathtub |
| | F110 | 80 | Land slopes toward house |
| Experiment 1 | F102 | 75 | Puddles on vapor barrier from ducts; visible mold |
| | F103 | 60 | Soil moist where vapor barrier missing |
| | F108 | 80 | Water dripping from supply; land slopes towards house |
| | F109 | 75 | None noted |
| Experiment 2 | F100 | 45 | Puddles on vapor barrier from suspected plumbing leak, visible mold |
| | F105 | 30 | Land slopes toward house |
| | F106 | 80 | Plumbing leak from washer |
| | F111 | 100 | Plumbing leak from disconnected bathtub drain |

**Table 2: Initial vapor barrier and moisture control problems in crawl spaces.**

It is important to note some initial observations on the test houses. Initial conditions of the crawl spaces are presented in Table 2. All twelve homes were completed in 2001 and had a 6-mil polyethylene of vapor barrier. However, the vapor barrier in most cases did not cover 100% of the ground. In fact, complete sections of vapor barrier were missing in several homes. There were basic site grading issues such as land sloping toward the house. The initial visit also revealed that several houses had plumbing problems. The plumbing leaks were fixed in house F106, F108, and F111 in early June 2001. Minor intermittent plumbing leaks continued throughout the study in houses F103, F105, F107, and F110. As stated earlier, site grading deficiencies were corrected in October 2001.

### 4.3 Site Work

A detailed description of the set up work is presented here to relate the intensive efforts required to establish a well-controlled study site. The site work began in May 2001 with a trial set-up of house F106 as a closed crawl space. In early June 2001, work began on all field homes to set-up the homes with either wall vented or closed crawl spaces. First, due to the poor layout and condition of the original vapor barriers, they were removed from the crawl spaces. The original condition and percent coverage of the vapor barrier was noted. The floor insulation was removed from the experiment homes (100, 102, 103, 105, 106, 108, 109, and 111) but was left intact in the control crawl spaces.

Under houses F100, F103, F104, F107, F108, and F111, a ditch was excavated under the return ductwork to elevate and decompress the main return flex ducts. Plumbing drainage trenches were also dug in houses F103 and F108. Since none of the twelve homes have gutters, a drainage ditch was also made just inside the access of each crawl space to deter and drain water from heavy rains. Drainage away from the crawl space access was made behind F103, F105, F107, F108, F109, and F111 during a heavy rain to keep water from going into crawl space. These houses in particular had poor grading in the back yard so that water did not drain away from the house. The grading behind F110 made it impossible for water to drain away from the house even with a ditch. To remove the poor site drainage and the potential of surface water entering the crawl spaces, a landscaping contractor was hired during October 2001 to properly grade the site.

Masonry chiseling and metal shaping work was done to crawl space access panels to get panels to close and latch. To insure that no one could tamper with the crawl spaces, locks were installed on every crawl door.

A vapor barrier of 6-mil polyethylene was installed in every crawl space and secured with six-inch sod staples. Adjoining sheets and pieces of polyethylene have about a six-inch overlap. Along with the drainage ditches, the vapor barrier is the only form of moisture control in the wall vented crawl spaces. The vents of the experiment crawl spaces were permanently sealed with rigid expanded polystyrene. Also, the 6-mil polyethylene was extended up the walls almost to the top of the block wall in these crawl spaces. All seams and edges were covered with either duct tape or fiberglass mesh tape and then secured with duct mastic. Gaps from any penetration through the wall were also sealed. A masonry patching compound was used to seal the plumbing hole through the crawl space wall in all homes. Caulk and spray foam insulation were used to fill gaps along the sill plate and block wall in the sealed homes.

Outdoor air ventilation systems were added to all 12 homes. The systems consisted of a six inch flex duct and boot connecting one crawl space vent to the return air plenum. A six-inch balancing damper and a 12” by 12” pleated, in-line filter with housing were installed in the flex duct. The damper was adjusted using an Exhaust Fan Flow Meter from the Energy Conservatory and a digital manometer. The flow pan was placed over the crawl space vent that was used to provide ventilation while the air handler was running. The flow pan’s position E2 was used so equation 2.1 below is the corresponding flow equation.

$$\text{Flow (CFM)} = 20.72 * (\text{Metering Box Pressure in Pascals})^{0.5} \qquad (2.1)$$

From this formula, it was determined that the metering box pressure differential to outside should be 3.8 Pa to provide approximately 40 CFM while the air handler was running. This adjustment procedure must be done while outside wind conditions are calm. With metering box in place and air handler off, fluctuations in digital pressure reading should be less than ±0.5 Pa.

Loose fitting crawl space vents were repaired, secured and sealed on all homes, particularly F101, F104, F106, F107, and F110. Water soaked ducts (two 6" supply and one 14" return flex ducts) were replaced in F108. These ducts were soaked during an overnight plumbing leak in the house when the family was moving into the home. Maintenance and repair to the heating and air conditioning system was also performed. First, durability sealing and support repairs in 12 homes were made to all main supply and return ductwork located under the exterior package unit cowling. Faulty thermostats were replaced in F101 and F110. On all 12 homes, rock-filled drainage pits were made for the heat pump condensate discharge pipes, which terminate at or partially below finished ground level outside the crawl space. Air filters for the houses were replaced or distributed during several site visits. Homeowners had not changed filters by the end of June and many replaced filters were clogged.

Because sealing of the homes was finished after the humid season began, permanent crawl space dehumidifiers with outside drainage were added for the 8 experiment homes. These units were installed for multiple purposes. First, they provided an initial dry down of the closed crawl spaces. Second, because these homes are occupied, they would provide backup moisture control for ongoing site drainage and plumbing problems, if necessary. Third, researchers assessed the capability of small, retail dehumidifiers as an option for the crawl space drying mechanism.

On October 23, 2001, rockwool insulation was sprayed on the walls of Experiment 2 homes (F100, F105, F106, and F111). The dehumidifiers were used at this time to remove excess moisture from the wet spray that is used to install this type of insulation. A summary of sealing work and experiment setup for Phase I is shown in Table 3.

| House | Ground Vapor Retarder | Sealed Ground and Wall Vapor Retarder | Wall Vents Plugged and Sealed | Rock Wool Insulation on Walls | R-19 Kraft-faced Fiber-glass Insulation in Floor | Designation |
|---|---|---|---|---|---|---|
| F100 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F101 | ✓ | × | × | × | ✓ | Control |
| F102 | ✓ | ✓ | ✓ | × | × | Experiment 1 |
| F103 | ✓ | ✓ | ✓ | × | × | Experiment 1 |
| F104 | ✓ | × | × | × | ✓ | Control |
| F105 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F106 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F107 | ✓ | × | × | × | ✓ | Control |
| F108 | ✓ | ✓ | ✓ | × | × | Experiment 1 |
| F109 | ✓ | ✓ | ✓ | × | × | Experiment 1 |
| F110 | ✓ | × | × | × | ✓ | Control |
| F111 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |

**Table 3: Summary of Phase I crawl space setups.**

On June 30 and July 1, 2001, equipment for the Hygrothermal Performance Study was set up in F106 (Experiment 2) and F110 (Control). Achilles Karagiozis, Ph.D from Oak Ridge National Laboratory conducted the moisture engineering analysis for this concurrent study. Because of poor drainage behind F110, a sump pump system next to the access panel of the crawl space was installed. The sump pump was designed to keep water out in case of heavy rain so that equipment would not be damaged. Fortunately, it was not needed.

Figure 11 presents a timeline of the significant events in the experiment site start up.

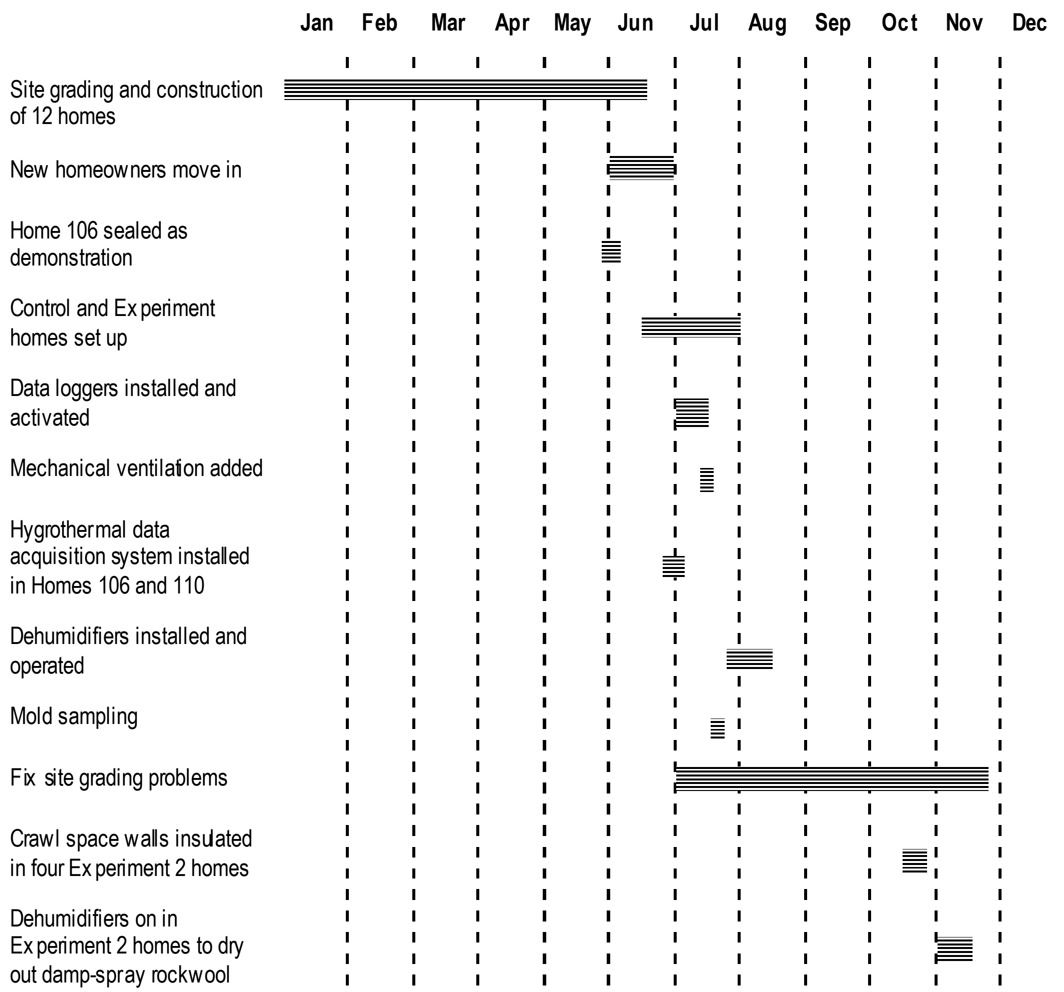


**Figure 11: Experiment site timeline, 2001**

The study was routinely monitored during a contract hiatus in 2002, and after the contract was reinstated, additional data logging, experiment configurations and preventive maintenance were implemented per Figure 12:

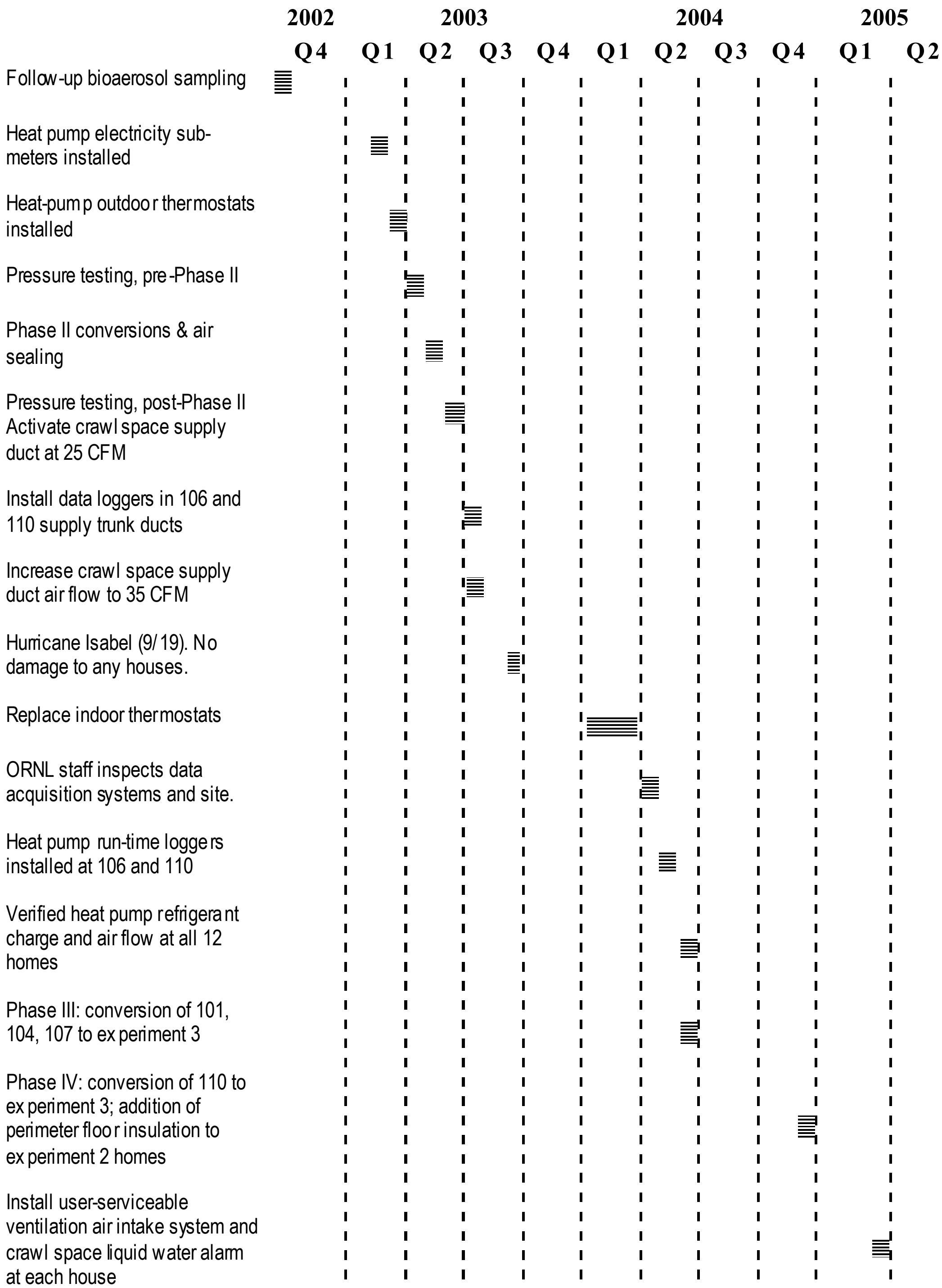


**Figure 13: Lowe's Court Experiment Site Timeline, 2002-05**

Tables 4-6 summarize the crawl space configurations for phases II-IV.

| House | Ground Vapor Retarder | Sealed Ground and Wall Vapor Retarder | Wall Vents Plugged and Sealed | R-13 Foam Insulation on Walls | R-19 Kraft-faced Fiber-glass Insulation in Floor | Designation |
|---|---|---|---|---|---|---|
| F100 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F101 | ✓ | × | × | × | ✓ | Control |
| F102 | ✓ | ✓ | ✓ | × | ✓ | Experiment 1 |
| F103 | ✓ | ✓ | ✓ | × | ✓ | Experiment 1 |
| F104 | ✓ | × | × | × | ✓ | Control |
| F105 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F106 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F107 | ✓ | × | × | × | ✓ | Control |
| F108 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F109 | ✓ | ✓ | ✓ | × | ✓ | Experiment 1 |
| F110 | ✓ | × | × | × | ✓ | Control |
| F111 | ✓ | ✓ | ✓ | × | ✓ | Experiment 1 |

**Table 4: Experiment configurations, Phase II**

| House | Ground Vapor Retarder | Sealed Ground and Wall Vapor Retarder | Wall Vents Plugged and Sealed | R-13 Foam Insulation on Walls | R-19 Kraft-faced Fiber-glass Insulation in Floor | Designation |
|---|---|---|---|---|---|---|
| F100 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F101 | ✓ | × | ✓ | × | ✓ | Experiment 3 |
| F102 | ✓ | ✓ | ✓ | × | ✓ | Experiment 1 |
| F103 | ✓ | ✓ | ✓ | × | ✓ | Experiment 1 |
| F104 | ✓ | × | ✓ | × | ✓ | Experiment 3 |
| F105 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F106 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F107 | ✓ | × | ✓ | × | ✓ | Experiment 3 |
| F108 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F109 | ✓ | ✓ | ✓ | × | ✓ | Experiment 1 |
| F110 | ✓ | × | × | × | ✓ | Experiment 3 |
| F111 | ✓ | ✓ | ✓ | × | ✓ | Experiment 1 |

**Table 5: Experiment configurations, Phase III**

| House | Sealed Ground and Wall Vapor Retarder | Wall Vents Plugged and Sealed | R-13 Foam Insulation on Walls | 2' R-10 Foam Insulation on Ground Perimeter | R-19 Kraft-faced Fiber-glass Insulation in Floor | Designation |
|---|---|---|---|---|---|---|
| F100 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F101 | × | ✓ | × | × | ✓ | Experiment 3 |
| F102 | ✓ | ✓ | × | × | ✓ | Experiment 1 |
| F103 | ✓ | ✓ | × | × | ✓ | Experiment 1 |
| F104 | × | ✓ | × | × | ✓ | Experiment 3 |
| F105 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F106 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F107 | × | ✓ | × | × | ✓ | Experiment 3 |
| F108 | ✓ | ✓ | ✓ | ✓ | × | Experiment 2 |
| F109 | ✓ | ✓ | × | × | ✓ | Experiment 1 |
| F110 | × | ✓ | × | × | ✓ | Experiment 3 |
| F111 | ✓ | ✓ | × | × | ✓ | Experiment 1 |

**Table 6: Experiment configurations, Phase IV**

### 4.4 Heat Pump Performance Verification

Performance measurements were applied to the heat pumps for all twelve houses. Adjustments were made as needed to confirm that all twelve systems had the correct air flow across the coil and that they had the correct refrigerant charge. Proper operation of equipment controls was also examined and confirmed. These activities were carried out at the beginning of the study and again at the conclusion of Phase II.

### 4.5 Routine Maintenance

Several maintenance items were addressed by field technicians throughout the study. The filters in the outside air intake system were replaced intermittently during Phase I and then regularly (once every three months) during Phase II and onward. Heat pump condensate drains were checked for blockages during cooling-season site visits. The crawl-spaces were checked for water intrusions or plumbing leaks during data collections. Most homeowners were surveyed for comfort complaints or any other concerns during site visits. Dryer vents were checked to ensure they were discharging outside the crawl space and they were repaired when disconnections were found.

## 5. Procedures and Methods

There are five main types of data that were collected during this study: pressure diagnostics and air leakage data, electrical energy consumption data, air temperature and humidity data, wood moisture data, and indoor air quality (radon and mold) data.

### 5.1 Energy: Pressure Testing for Air Leakage

Before site work was performed, standard Blower Door (CFM50) and Duct Leakage (CFM25) tests were done on all homes. These tests were conducted using a Minneapolis Blower Door ™ System and a Minneapolis Duct Blaster ™ System from the Energy Conservatory with a DG3 digital manometer to measure pressure differences and flow. The primary goal of the pressure testing procedures was to ensure that the performance of all the study houses was comparable, so that differences in moisture and energy performance could be attributed to crawl space design and not to some other envelope variable. Also, the tests were used to see if the homes were tight enough to require mechanical ventilation. Although the results from these procedures could give an indication of the level of "connectedness" of the living spaces to the crawl spaces in the various homes, these procedures were not intended to quantify rate of exchange of air between the crawl space and living space, nor calculate the rate of spread of contaminants from the crawl space to the living space.

After sealing with polyethylene was finished on the experiment crawl spaces, the houses were tested with a detailed pressure testing protocol in October 2001. The detailed pressure testing protocol was performed again both prior to and just after the experiment transitions of April-May 2003. The goal of the detailed pressure testing protocol was to quantify the "holes" characterized by CFM50 flow between the crawl space and house, house and outside and duct to crawl space that might lead to moisture transport, and to measure the driving forces (pressures) that are created by the HVAC equipment. This information was needed to ensure comparable performance between houses, and also provided some insight into the functional effects of different crawl space designs.

To obtain air leakage flows with the most precision, the detailed pressure testing setup utilized an 8-channel Energy Conservatory Automated Performance Testing (APT) System with two Minneapolis Blower Door ™ systems (one for the house and another for the crawl space) and a Minneapolis Duct Blaster ™ system for the duct system. The APT is a multi-channel data acquisition system that transfers data directly to a laptop running Energy Conservatory's TECLog software. For the purposes of this study, only the eight pressure sensors on the APT were utilized. The detailed pressure testing protocol was conducted using TECLOG ver 1.04 with the pressure tap configuration shown in Table 7.

In October 2001, ten of the twelve houses were tested using the following pressure testing procedure (Houses 100, 101, 103, 104, 106, 107, 108, 109, 110, and 111). Houses 102 and 105 were tested using a similar procedure, but only Tests #1 and 2 were run. Any conclusions from Tests #3 and #4 do not include data from these two homes.

Indoor and outdoor temperatures were recorded to account for variation in air density due to temperature. First, the standard House CFM50 test [Test #0] was run using TECTITE Ver. 2 (Win 95/98) Airtightness Testing Software. This test is conducted with the air handler off, all windows closed, and the crawl space access closed. TECTITE measures building leakage by taking 100 data points at 50 Pa, 45 Pa, 40 Pa, 35 Pa, 30 Pa, 25 Pa, 20 Pa, and 15 Pa. The purpose of taking the measurements at several pressures is to allow a flow equation exponent to be determined. TECTITE uses this test data to determine the CFM50 leakage. In addition, in ten of the houses the hoses were set up as shown in Table 7 to obtain zone pressures for the crawl space, the supply and the return during the TECTite CFM50 test.

First, all pressures were logged for one minute with the exterior windows and doors closed and without the HVAC system running. The logged pressures are the baseline pressures. Then, the air handler fan was turned on and pressures were logged for at least one minute. During this time, each zone was again monitored for reaction to the operation of the HVAC system. During windy or inclement weather, each test period was increased to two or three minutes. Because houses 102, 105, and 111 were tested first before some modifications to the pressure testing protocol, pressure changes from the HVAC system were measured using a hose connected to a digital manometer.

| Pressure Tap # | Tap Location | Input Tap Hose Color | Reference Hose Color |
|---|---|---|---|
| 1 | house | n/c | green (outside) |
| 2 | house blower door | red (fan pressure) | n/c |
| 3 | crawl space | purple | n/c |
| 4 | crawl blower door | orange (fan pressure) | purple |
| 5 | closest supply duct to air handler (#1) | blue | n/c |
| 6 | duct blaster | red2 (fan pressure) | clear (fan reference) |
| 7 | return duct | yellow | n/c |
| 8 | furthest supply duct from air handler (#2) | green | n/c |

**Table 7: Hose configuration for the APT System.**

As the duct blaster and the second blower door for the crawl space were set up, the floor registers were sealed before conducting the first test. For the wall vented crawl spaces, it was necessary to close most of the crawl space vents in order to reach a 50 Pascal pressure difference. To run through all the tests as described below, start time and ring configuration for both blower doors and the duct blaster of each test was recorded. An Excel spreadsheet was created to automatically convert binary TECLOG data to text, import the data, and calculate flows based upon fan pressure. The manual for the APT system was consulted in the design and creation of this spreadsheet (TEC 1998). The spreadsheet converts pressure measurements across either the blower door fan or duct blaster fan into flow using the calibration formulas provided in the operation manual by the Energy Conservatory as shown in Table 8.

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

**Table 8: Calibration formulas for flow across the blower door and duct blaster.**

The following figures step through and illustrate the testing procedure and theory of how each flow was calculated. Leakage paths between the house, outside, ducts, and crawl space are illustrated in Figure 14. These leakage paths are based upon relations between flow measurements that are defined in Figures 15 through 18.

The hole sizes (characterized by CFM50 flow) can be quantified as follows:

| | | |
|---|---|---|
| Outside to Crawl Space | = | **B** |
| Outside to House | = | **A** |
| Crawl Space to House | = | **E** |
| Crawl Space to Ducts | = | **C** + **D** |
| Ducts to Outside | = | **G** + **F** |
| Crawl Space to Return Duct | = | **C** |
| Crawl Space to Supply Duct | = | **D** |

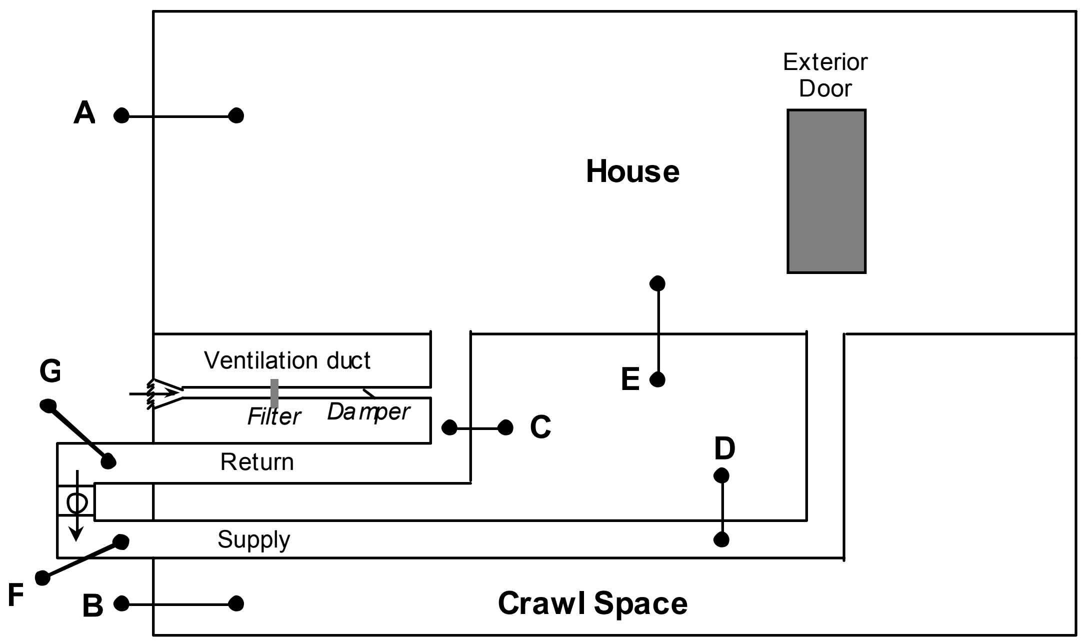


**Figure 14: Leakage paths determined from series of pressure tests conducted on homes**

Test #1 was conducted with registers sealed and the house door closed. The house, crawl space and ducts were depressurized to 50 Pa with respect to outside. Because there was no pressure difference between the house, crawl space, and ducts, the outside to duct flow (G+F), outside to crawl flow (B), and outside to house flow (A) could be calculated from this configuration.

Flow 1 = **B**

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

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

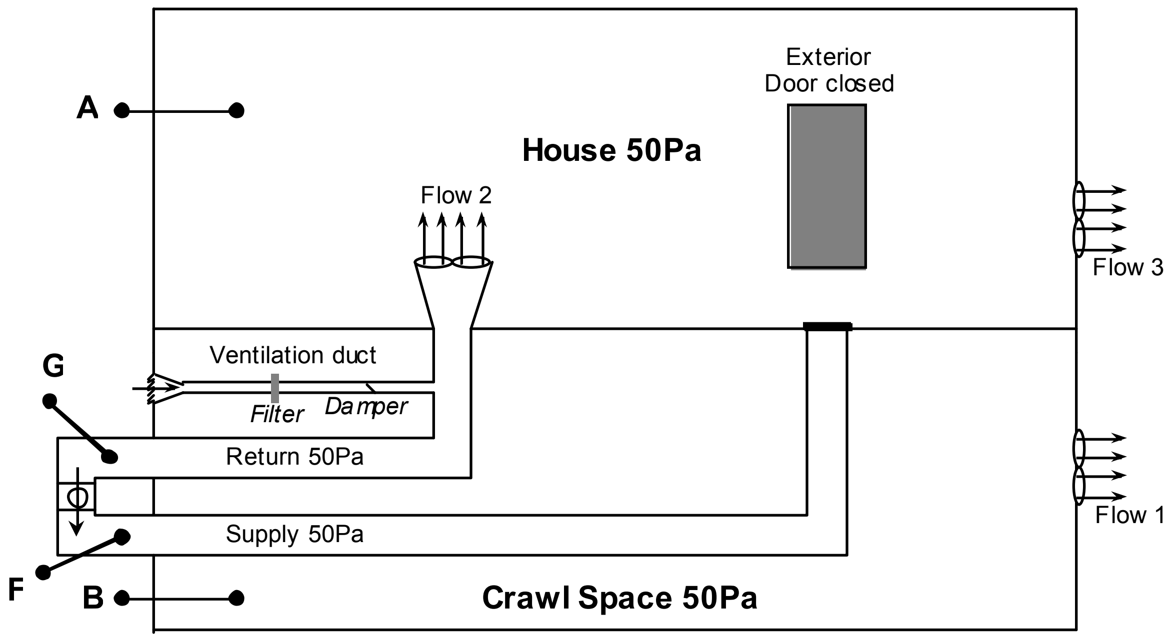


**Figure 15: Illustration of flow and air leakage paths definitions used during Test 1**

Test # 2 was conducted to quantify floor system leakage (E) and crawl space to duct leakage (C+D) as shown in Figure 16. The ducts and house were both depressurized to 50 Pa with respect to outside. The crawl space access door was left open allowing it to have the same pressure as outside. Flow 4 in this test represents duct leakage. The outside to duct leakage determined in Test 1 can now be subtracted from duct leakage to quantify crawl to duct leakage. Similarly, the floor leakage is determined by looking at the flow across the blower door fan in this test and subtracting outside to house leakage (Test 1) and duct leakage.

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

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

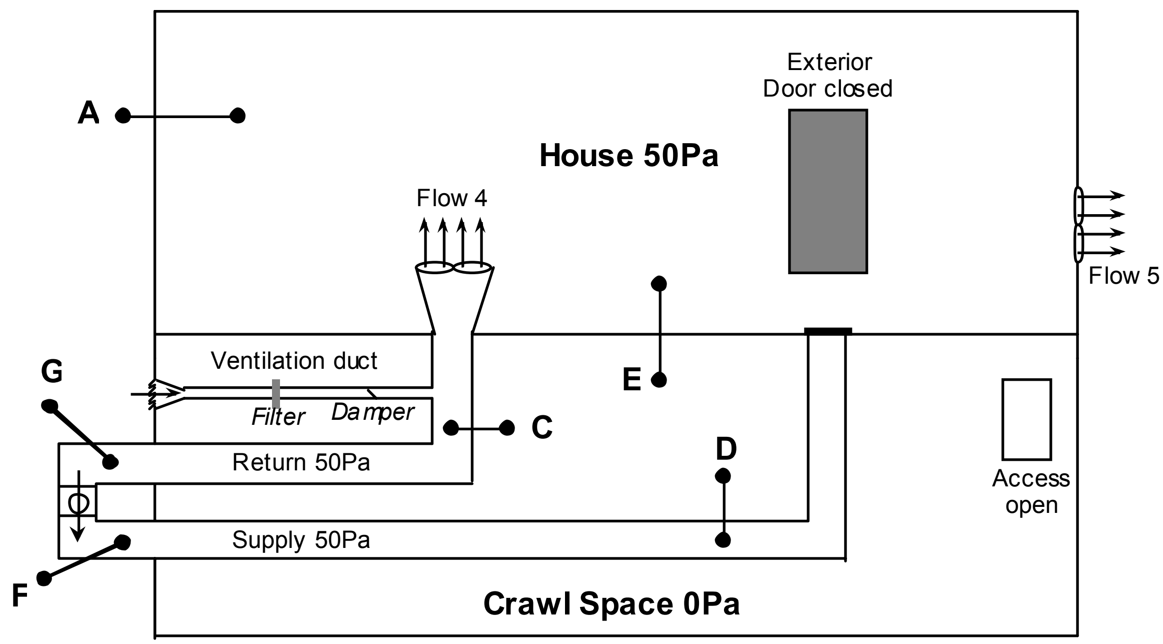


**Figure 16: Illustration of flow and air leakage path definitions used in Test 2**

The purpose of Test #3 is to quantify the return leakage from the outside and crawl space. For this test, the supply ducts are not taped and house door and crawl space access are opened. The supply is separated from the return. The return ducts are depressurized to 50Pa with reference to outside, while the supply, house, and crawl space are also at the same pressure as outside. The flow across the duct blaster now represents return leakage from outside and crawl space.

Flow 6 = **G** + **C**

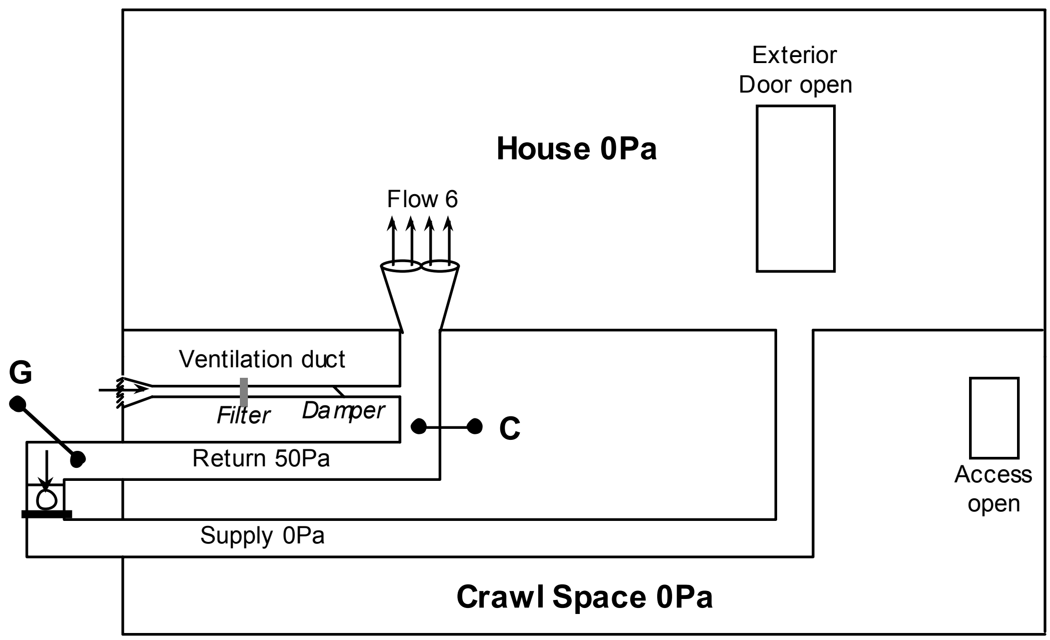


**Figure 17: Illustration of flows and air leakage path definitions used in Test 3**

The purpose of Test #4 was to isolate the outside to return leakage as shown in Figure 18. For this test, the house door was open, the supply was sealed from the return, and the supply registers were not taped. The crawl space and return ducts were depressurized to 50 Pa with reference to outside while the house remained at the same pressure as outside.

Flow 7 = **G**

Flow 8 = **B** + **D** + **E**

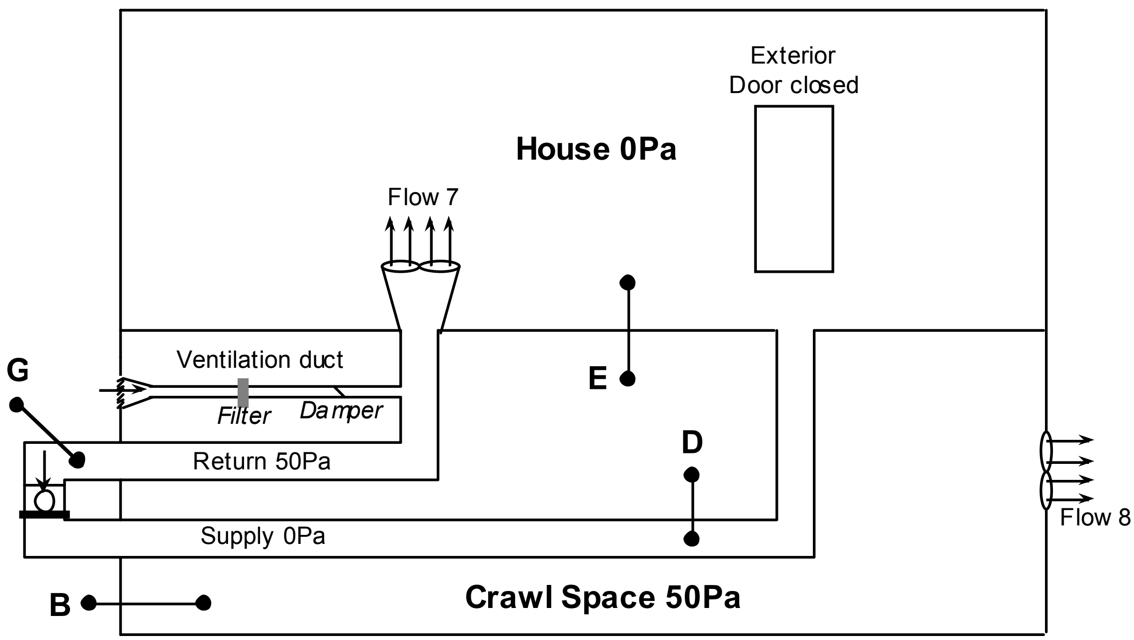


**Figure 18: Illustration of flow and air leakage path definitions used in Test 4**

The final component of the pressure testing was to record baseline pressures again. For the final baseline pressures, the house was returned to normal operating conditions. All exterior doors were closed, the tape on return and duct blaster, and the air filter was returned. The seal separating the supply ducts from the return duct was removed.

Before and after the crawl space reconfigurations in May of 2003 we performed a slightly simplified version of the detailed pressure testing protocol to (1) assure consistency of performance across the study groups, (2) assess the impact of the sub-floor and duct-sealing measures applied during the transition, and (3) assess the impact of the installation of the crawl space supply duct on baseline operation and HVAC-induced pressures in the house and crawl space.

The figures above that describe the testing setup and design also applied to the 2003 testing, with the exception that we omitted tests 3 and 4, and added a test to assess crawl space air flow at a depressurization of 50 Pa. As a result, duct leakage was not segmented into supply leakage and return leakage. Prior to beginning the testing process, researchers installed new filters in the HVAC return grill and in the ventilation air intake duct.

The crawl space supply duct was then set to provide 25 CFM of air flow whenever the air handler unit was turned on, using the following method: Researchers set the crawl space supply duct air flow very precisely in one house, by installing a temporary plenum box over the duct and using a Minneapolis Duct Blaster as a powered flow hood to measure the airflow from the duct as the researcher adjust the flow to the desired level with the balancing damper. Then, a TIF anemometer was centered in the air stream and the air velocity recorded. In subsequent houses, the anemometer was centered in the crawl space supply duct air stream and the balancing damper was adjusted until the air velocity matched the reading determined in the first house.

The ventilation intake and crawl space supply ducts were then plugged, and the crawl space access door was closed.

Indoor, outdoor, and crawl space temperatures were measured while the data logging and Blower Door equipment was set up in the home and crawl space. TECTite was then used to perform the multi-point CFM50 house leakage test. Then, TECLog was initiated to log a one-minute interval of readings from all pressure taps during each of the following configurations:

- All systems off
- HVAC air handler on
- Crawl space depressurized to 50 Pa with reference (WRT) outside (which was not always attainable in wall-vented crawl spaces)
- Crawl space depressurized to 50 Pa WRT house

Next, the wall-vent openings in the vented crawl spaces were plugged, the HVAC return filter was removed, the Duct Blaster was installed on the HVAC return grill, and all supply registers were taped with duct mask. Pressures were then logged for one minute while the fans were operated in the Test 1 configuration.

Next, the crawl space door was opened and pressures were logged for one minute while the fans were operated in the Test 2 configuration.

Then, the supply registers were untaped, the Duct Blaster was removed from the return grill, the ventilation air intake was unplugged, and crawl space wall vents were unplugged (wall-vented homes only). The crawl space door was closed and pressures were logged for one minute.

Next the air handler fan was turned on and pressures were logged for another minute. The crawl space supply duct was then unplugged and pressures logged for another minute. Finally, the air handler fan was turned off and pressures logged for another minute.

## 5.2 Energy: Electrical Consumption Data

In February of 2003, each heat pump was sub-metered with a General Electric Type I-70-S watt-hour meter to measure total heat pump energy consumption in kWh. The total house energy consumption (kWh) was recorded from the utility customer account (whole-house) meter. Readings were taken from both meters at each house once per month. The sub-meters are calibrated to ±0.2% accuracy under both light and full load conditions, and readings were rounded to units of whole kWh.

## 5.3 Temperature and Humidity Data

Outside, crawl space, and house psychrometric conditions were monitored with Onset Hobo Pro data loggers (Model H08-032-08). These loggers record sensible temperature, relative humidity, dew point temperature, and absolute moisture and are designed to operate from $-22^0$ to $122^0$F ($-30^0$ to $50^0$C) and from zero to 100% relative humidity (RH). The RH sensor is designed to withstand intermittent condensing environments up to $86^0$F ($30^0$C) and non-condensing environments above $86^0$F ($30^0$C). In the high resolution temperature mode used in this study, the sensible temperature accuracy of these loggers is $\pm 0.33^0$ @ $70^0$F ($\pm 0.2^0$ @ $21^0$C). RH accuracy is ±3% from $32^0$ to $122^0$F ($0^0$ to $50^0$C) and ±4% in condensing environments.

Throughout the study, crawl space conditions were recorded by two loggers (for redundancy only) attached to the side of the center support beam on the side of the beam opposite from the heat pump duct work. House conditions were recorded by one logger installed inside the central closet of each house that houses the heat pump central return. Outside conditions were recorded at three locations distributed across the site. The outside loggers were placed under the back porch and were protected from rain by a weather shield supplied by Onset Computer Corp.

The data loggers were set to record psychrometric conditions every fifteen minutes. The house logger was installed with an extension cable inserted into its data port that allowed field technicians to download its data from the crawl space. Recorded data was downloaded either directly onto a laptop computer using Onset Computer BoxCar Pro software or via a Palm Pilot (model M100 or M130) and then transferred to the laptop using Onset Computer HandCar EX and BoxCar Pro software packages. All logger data (typically collected at two-month intervals) was reviewed on site at the time of collection to assess the need for any logger repair or replacement or to identify and correct anomalous behavior in any of the study homes. Later, the data was exported from BoxCar Pro into Microsoft Excel for analysis and plotting.

In September 2003, one additional logger was installed in each of the crawl spaces of houses 100, 101, and 102 Lowe's Court to informally assess the level of variation of psychrometric conditions between the standard logging location on the center beam versus a position on a floor joist either halfway between the center joist and the perimeter wall (September 2003 – November 2003) or approximately 18 inches from the perimeter wall (November 2003 – March 2005).

At the request of Achilles Karagiozis of Oak Ridge National Laboratory (the principal investigator of the hygrothermal assessment and modeling study portion of this project) four additional data loggers were installed at the homes being monitored for the hygrothermal study (106 and 110 Lowe's Court). An Onset Computer alternating current (AC) field state logger was installed on the heat pump control electronics to record heat pump compressor run-time, and a Hobo Pro logger was mounted inside the supply plenum to measure (at an interval of once every 1 minute and 36 seconds) the psychrometric properties of the conditioned air supplied during operation of the heat pump. Data was downloaded from these loggers monthly and then sent in batches to Dr. Karagiozis for inclusion in the hygrothermal analysis and modeling.

**5.4 Wood Moisture**

Crawl space wood moisture readings were taken at ten locations in each crawl space. The moisture reading locations were the sill plate next to the crawl access door, band joist next to the access door, sill plate at worst location, band joist at worst location, center beam in the middle, floor joist next to access below insulation, floor joist next to access above insulation, floor joist at worst location, below insulation, floor joist at worst location above insulation, and subflooring in the center. Sill plates, band joists, floor joists, and center beams were all southern yellow pine. Sill plates and band joists were pressure-treated. Measurements made next to access were made 2' either to the right or left of the access door. Sill plate measurements were made on top of the plate about halfway between band joist and edge of sill plate. Band joist measurements were made approximately 1" from the bottom of the plate below insulation. Center beam measurements were made in the middle of the house, generally next to the data loggers. These sampling locations were marked and numbered with a black permanent marker.

The worst location is assumed to be the lowest clearance. For this study, for consistency, all worst location readings were taken at the front of the crawl space in the middle above where the plumbing soil line exits the house. In general, the floor for these crawl spaces was fairly even and therefore the height did not vary considerably. For the houses, which the insulation was removed, the above insulation readings were taken at the top of the floor joist near the subfloor.

Wood moisture readings were taken using a Delmhorst J-4 moisture meter with uninsulated pins. This meter has an accuracy of ±0.5% for the 6 - 12% range, ±1.0% for the 12 - 20% range and ±2% for the 20 - 30% range. The Delmhorst moisture meter is calibrated for measuring wood moisture content in Douglas Fir at 70ºF, therefore, the pin readings had to be adjusted according to the temperature and wood species correction tables provided with the Delmhorst meter (Delmhorst 1999).

First, the readings were adjusted for temperature. Temperature (at the location of each individual wood moisture measurement) was measured using a Ray-tek ST20 Pro™ non-contact infrared temperature meter. This meter has an accuracy of ±1% of reading or ±$2^0$F (±$1^0$C), whichever is greater, for ambient operating temperature from $73^0$ to $77^0$F ($23^0$ to $25^0$C). For ambient temperatures between $0^0$ to $73^0$F (-$18^0$ to $23^0$C) the accuracy was rated at ±$3^0$F (±$2^0$C).

An equation was determined using Microsoft Excel Solver to model the correction for temperature. To determine this equation, only corrections for 40°F to 100° were used in the meter reading range of 6-30%. The temperature correction equation is as follows:

$$MR_{corr}=A1+A2*T+A3*MR+A4*MR*T \quad (5.1)$$

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

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

$$M_{SYP} = 1.1407*M_{DF} + 0.4085 \quad (5.2)$$

$M_{SYP}$ = Moisture content for Southern Yellow Pine
$M_{DF}$ = Moisture content for Douglas Fir

A Delmhorst technician indicated that OSB had the same correction as Basswood. The equation obtained and applied was as follows:

$$M_{OSB}=0.925*M_{DF} + 0.0907 \quad (5.3)$$

$M_{OSB}$ = Moisture content of OSB
$M_{DF}$= Moisture content of Southern Yellow Pine

Some reference readings of warehouse OSB were taken and found to range from 8.5 to 9.5. All field subfloor readings can be compared to this reference range. No conversion numbers are available for this variable man-made wood product.

Readings were taken on August 31, 2001 with a Protimeter due to a broken pin on the Delmhorst. The Protimeter instrument is calibrated for wood at 68°F (20°C). Temperature compensation is approximated by the following corrections. For every 9°F (5°C) above 68°F, ½ % is subtracted from the meter readings. For every 9°F below 68°F, ½ % is added to the meter reading (Protimeter 2000). Protimeter had a direct reading for our species, therefore, these readings do not reflect any adjustment for Yellow Pine. Both procedures of meter correction were applied to all readings except those from the subfloor.

Average overall wood moisture was used to compare study groups. For the average wood moisture, the OSB subflooring reading was not included since its composition is different from the framing lumber. The Delmhorst technician also confirmed that the correction for pressure-treated Southern Yellow Pine is similar to untreated Southern Yellow Pine. As long as the readings seem reasonable, the same correction was used for both of these woods. However, it is possible that the sill plate reading may be slightly in error because the sill is pressure-treated wood, so these readings are also excluded from the results presented in section 6.

**5.5 Indoor Air Quality: Bioaerosol Data**

To establish a baseline of bioaerosol presence in the homes, airborne fungal samples were made at each home in the crawl space, on the first floor, and outdoors. Both viable and total spore counts were measured. Viable spores (those able to reproduce) were measured using an Anderson sampler. Anderson samplers consist of an inlet orifice, a perforated aluminum disk (200 holes) suspended just above the surface of nutrient in a petri dish, and an air pump. Air is drawn through the inlet, through the filters, and out through the pump (28.3 lpm). The sampler is designed so that particles in the size range of fungal spores are collected on the sticky surface of the nutrient. Smaller particles largely pass out through the pump. The plate is incubated and the resulting colonies can be counted and identified by microscopic examination. The fraction of the 200 holes that grow a colony combined with the amount of air sampled forms the basis for calculating the number of culturable spores present in each cubic meter of air. If there are high concentrations of fungal spores or the sampling time is too long, colonies will grow at each pinhole location, so only an upper bound can be calculated.

In this study, a total of 84.9 liters of air was sampled for each sample taken. The samples were then sent to Aerobiology Laboratory Associates, Inc. for incubation and identification. The total spore count (those able to reproduce and those not) was established using a Burkard sampler. The Burkard sampler draws particles through a slit and deposits particles by inertia onto a greased glass slide at a flow rate of 10 lpm for a period of nine minutes. The Burkard samples were also sent to Aerobiology Laboratory Associates, Inc., where microscopic counting and identification of fungal matter was performed.

Protocol for making samples:

- Crawl space or house may have been done first
- Crawl space sample taken at center of crawl space, near Hobos
- Sample taken about 12” off ground
- Double samples taken simultaneously on Burkard and sequentially with Anderson
- Took tape and wipe samples at same time as air samples
  - Tapes and wipes of visible growth chosen to reflect variation
  - Where not much mold visible in crawl space, sampled in suspicious looking places
  - Marked locations
- Upstairs near return with air handler running; no tape or wipe samples upstairs
- Outdoor air samples taken over the day at different locations (AM, PM, next AM and from south to north, double samples) 12” off ground
- Tape lifts and swab samples of active fungal growth in crawl spaces were made and analyzed.

**5.6 Indoor Air Quality: Radon Data**

Short-term radon levels were measured in the pilot phase of the study. Long-term levels were measured from July 2003 to July 2004. Long-term readings were recorded with alpha-track monitors from AccuStar Labs.

# 6. Results

## 6.1 Energy: Pressure Testing for Air Leakage

This section summarizes the pressure testing protocol results. As was pointed out in the Energy Overview chapter the experiment group houses have complex pressure relationships due to the introduction of the secondary pressure plane at the first floor level. Consequently the comparison of results between the control and experiment groups is significantly more involved than comparing standard blower door tests between the two groups. The reader whose interest is limited to "bottom line" comparative results is directed to Tables 17 and 18 at the end of this section, which provide a component breakdown of the air leakage pathways.

The primary goal of the pressure testing procedures was to ensure that the performance of all the study houses was comparable, so that differences in moisture and energy performance could be attributed to crawl space design and not to some other envelope variable. Although the results of these procedures give an indication of the level of "connectedness" of the living spaces to the crawl spaces in the various homes, these procedures were not intended to quantify rate of exchange of air between the crawl space and living space, nor calculate the rate of spread of contaminants from the crawl space to the living space.

### 6.1.1 CFM50 House Leakage Testing Results

A standard CFM50 depressurization house leakage test was conducted on each of the twelve field study homes, using a Minneapolis Blower Door™ system with an Energy Conservatory APT-2 automated pressure testing system and TECTITE airtightness testing software. Table 9 shows the results of the house leakage test for all twelve homes during Phase I and table 10 shows the results of the house leakage testing for phase II. Where indicated, the units are in CFM50, or air flow in units of cubic feet per minute at a test pressure of -50 Pa in the house with reference to outside. Note that the results for Phase I were measured with the ventilation intake open and the results for Phase II were measured with the ventilation intake and the crawl space supply duct plugged.

To allow investigators to compare the results of the homes in this field study with homes of other sizes and configurations, it is useful to present the CFM50 results in several alternative forms such as CFM50 per square foot of living space, CFM50 per square foot of envelope surface area, and estimated natural air changes per hour (ACH). The CFM50 value is converted to air changes per hour (ACH) due to natural infiltration with the following formula:

$$ACH_{nat} = CFM50/(Volume)*60/21.5 \qquad (6.1)$$

The number 60 in this formula converts minutes to hours. The 21.5 is the LBL correlation factor used for all of these houses. The LBL correlation factor takes into account number of stories in the house and exposure to wind or other outside forces (Home Energy 1993). These houses are one story and have normal exposure. All twelve homes were identical with 1040 square feet of living space, 3136 square feet of envelope surface area and 8320 cubic feet of living space volume. Each of the forms of the results of the CFM50 tests are presented in Tables 9 and 10. The estimated natural ACH is the amount of air leakage the house would experience as a result of wind and temperature differentials between inside and outside. ACH is estimated on an annual average basis.

Because no crawl space wall insulation had yet been installed at the time of testing during Phase I, the two experiment groups are treated as the same and the data is simply presented as the wall-vented group and the closed group.

| | House CFM50 | CFM50/ft$^2$ living space | CFM50/ft$^2$ envelope | ACH natural infiltration |
|---|---|---|---|---|
| F101 | 1107 | 1.06 | 0.35 | 0.37 |
| F104 | 965 | 0.93 | 0.31 | 0.32 |
| F107 | 1113 | 1.07 | 0.35 | 0.37 |
| F110 | 1024 | 0.98 | 0.33 | 0.34 |
| **Wall-Vented Average** | **1052** | **1.01** | **0.34** | **0.35** |
| | | | | |
| F102 | 810 | 0.78 | 0.26 | 0.27 |
| F103 | 1100 | 1.06 | 0.35 | 0.37 |
| F109 | 1197 | 1.15 | 0.38 | 0.40 |
| F111 | 901 | 0.87 | 0.29 | 0.30 |
| | | | | |
| F100 | 763 | 0.73 | 0.24 | 0.26 |
| F105 | 935 | 0.90 | 0.30 | 0.31 |
| F106 | 741 | 0.71 | 0.24 | 0.25 |
| F108 | 914 | 0.88 | 0.29 | 0.31 |
| **Closed Average** | **920** | **0.88** | **0.29** | **0.31** |

**Table 9: Phase I TECTite blower door CFM50 results.**
**(Measurements include leakage through ventilation system intake)**

| | House CFM50 | CFM50/ft$^2$ living space | CFM50/ft$^2$ envelope | ACH natural infiltration |
|---|---|---|---|---|
| F101 | 876 | 0.84 | 0.28 | 0.29 |
| F104 | 731 | 0.70 | 0.23 | 0.25 |
| F107 | 752 | 0.72 | 0.24 | 0.25 |
| F110 | 637 | 0.61 | 0.20 | 0.21 |
| **Wall-Vented Average** | **749** | **0.72** | **0.24** | **0.25** |
| | | | | |
| F102 | 636 | 0.61 | 0.20 | 0.21 |
| F103 | 978 | 0.94 | 0.31 | 0.33 |
| F109 | 953 | 0.92 | 0.30 | 0.32 |
| F111 | 784 | 0.75 | 0.25 | 0.26 |
| **Closed with Floor Insulation Average** | **838** | **0.81** | **0.27** | **0.28** |
| | | | | |
| F100 | 669 | 0.64 | 0.21 | 0.22 |
| F105 | 776 | 0.75 | 0.25 | 0.26 |
| F106 | 619 | 0.60 | 0.20 | 0.21 |
| F108 | 714 | 0.69 | 0.23 | 0.24 |
| **Closed with Wall Insulation Average** | **695** | **0.67** | **0.22** | **0.23** |

**Table 10: Phase II TECTite blower door CFM50 results.**
**(Measurements were taken with ventilation intake and crawl space supply ducts plugged.)**

### 6.1.2 Duct Leakage Pressure Testing

There are two conventional ways of reporting duct leakage, total duct leakage and outside duct leakage. In this study, only outside duct leakage is considered. Outside duct leakage is a measure of the leakage from the outside to the ducts when the ducts are depressurized with respect to outside. Generally, most of that leakage comes from the crawl space to the ducts. In a wall vented crawl space, the crawl space is at about the same pressure as outside and thus the crawl space is essentially outside. In a closed crawl space, there may be a considerable pressure difference between the outside and the crawl space when the duct leakage test is being conducted. For closed crawl spaces, it is not a good assumption to consider the crawl space as outside.

In this study what is commonly referred to as outside duct leakage is simply referred to as duct leakage. However, it is broken down into crawl space duct leakage and outside duct leakage. For this testing procedure, crawl space duct leakage is the leakage that occurs directly between the ducts and the crawl space. Outside duct leakage is the leakage that occurs directly between the ducts and outside. Examples of outside duct leakage in this study are the leakage across joints within the outdoor mounted air handler/heat pump package unit, duct connections under the cowling and the return side ventilation system duct for outside air.

Duct leakage is typically measured at 25Pa. The pressure testing protocol for the field study homes dictated that the duct leakage testing pressure differential be 50 Pa instead of the usual 25 Pa in order to be consistent with the rest of the testing protocol. In Table 11, the duct leakage testing results for Phase I at 50 Pa were translated to the usual 25 Pa results using the flow equation with a pressure exponent of 0.56, the average pre-treatment measured value for eight of the homes. Table 12 presents the duct leakage values for the homes in Phase II.

| | Duct Leakage CFM25 | Duct Leakage % | Crawl Space Duct Leakage CFM25 | Crawl Space Supply Leakage CFM25 | Crawl Space Return Leakage CFM25 | Outside Duct Leakage CFM25 |
|---|---|---|---|---|---|---|
| F110 | 160 | 15.4% | 110 | 100 | 10 | 50 |
| F101 | 155 | 14.9% | 107 | 91 | 16 | 47 |
| F104 | 130 | 12.5% | 83 | 68 | 15 | 47 |
| F107 | 123 | 11.8% | 62 | 56 | 7 | 61 |
| **Wall-vented Average** | **142** | **13.7%** | **91** | **79** | **12** | **51** |
| | | | | | | |
| F100 | 176 | 16.9% | 125 | 85 | 40 | 51 |
| F108 | 165 | 15.9% | 76 | 73 | 3 | 89 |
| F105 | 150 | 14.4% | 83 | n/a | n/a | 67 |
| F109 | 143 | 13.8% | 81 | 62 | 18 | 62 |
| F103 | 130 | 12.5% | 91 | 75 | 15 | 39 |
| F111 | 125 | 12.0% | 63 | 29 | 33 | 62 |
| F102 | 124 | 11.9% | 69 | n/a | n/a | 55 |
| F106 | 106 | 10.2% | 57 | 44 | 13 | 48 |
| **Closed Average** | **140** | **13.4%** | **81** | **62** | **20** | **59** |
| **Overall Average** | **141** | **13.5%** | **84** | **68** | **17** | **57** |

**Table 11: Phase I duct leakage testing results.**
**(These measurements include leakage through the ventilation system intake.)**

The key finding from Table 11 is that duct leakage was, on average, almost identical between control and experiment groups during Phase I. The average duct leakage for all twelve homes was 141 CFM. The average duct leakage for the four control homes was 142 CFM while it was 140 CFM for the eight experiment homes. The fact that these values are essentially the same is intentional. During initial field work, all duct systems were tested and outlying homes were tightened to bring them into line with the other duct systems. Also, all systems had the same measured ventilation system duct air flow added. Table 11 also presents the alternate forms of the duct leakage testing results and results of more specialized tests explained in the following paragraphs.

The values of duct leakage are also presented in an alternate form of $CFM_{25}$ per square foot of living space served by the duct system. In this form, the average duct leakage for all of the homes is 0.135 CFM/ft$^2$. It is usual practice to present duct leakage per square foot of living space in percentage form. Thus the average duct leakage for all homes was 13.5%. The tightest duct system of these homes was 10.2%. Initial inspection of these percentages leads to the conclusion that the duct leakage is high. However, these percentages include the added intentional ventilation system outside duct air flow, which is a substantial portion of the outside duct leakage. Investigation revealed that the ventilation system contribution is in the range of 50% to 55% of the average outside duct leakage.

The pressure testing protocol presented in section 5.1 called for a series of tests that allowed the duct leakage to be found along with its components. The duct leakage was broken down into the crawl space duct leakage and the outside duct leakage. In addition, for all homes except 102 and 105, the crawl space to duct leakage was broken down into its crawl space return leakage and crawl space supply leakage components. The portion of the protocol that allowed the return leakage to be separated from the supply was not added until after houses 102 and 105 were pressure tested. Consequently these values are not available in Table 11.

This approach to separating return leakage from supply leakage has not been investigated thoroughly. There are no standards for the percent of leakage for return or supply. It is important to determine the amount of leakage in the return duct. When the air handler is turned on, the return becomes depressurized with respect to the crawl space. It is expected that air should flow from the crawl space into the return duct. The supply on the other hand becomes pressurized and leaks from the ducts to the crawl space. The effect of turning on the air handler is presented in section 6.1.6. On average, the crawl space duct leakage made up 60% of the duct leakage and the outside duct leakage made up 40% of the duct leakage. Of the average crawl space duct leakage, 80% was crawl space supply leakage and 20% was crawl space return leakage. The leakage from the supply should be greater because it has run-outs and more transitions.

Phase II duct leakage results are presented in Table 12. Segmented supply and return leakage was not assessed in this round of measurements, but leakage to the crawl space and leakage to outside are presented separately. Conversions from $CFM_{50}$ to $CFM_{25}$ were calculated by dividing by 1.6, the corresponding Minneapolis Duct Blaster flow conversion factor.

The total amount of duct leakage reported is significantly lower than in phase I. This is heavily influenced by the different measuring techniques: the phase II results were measured with the ventilation intake duct plugged. There is not quite as much consistency between the different groups. The wall-vented homes have slightly higher leakage than the experiment groups.

| | Duct Leakage CFM25 | Duct Leakage % | Crawl Space Duct Leakage CFM50 | Crawl Space Duct Leakage CFM25 | Outside Duct Leakage CFM50 | Outside Duct Leakage CFM25 |
|---|---|---|---|---|---|---|
| F101 | 103 | 9.9% | 119 | 74 | 46 | 29 |
| F104 | 66 | 6.4% | 76 | 48 | 29 | 18 |
| F107 | 54 | 5.2% | 74 | 46 | 13 | 8 |
| F110 | 50 | 4.8% | 61 | 38 | 19 | 12 |
| **Wall-vented Average** | **68** | **6.6%** | **83** | **52** | **27** | **17** |
| | | | | | | |
| F102 | 46 | 4.4% | 54 | 34 | 19 | 12 |
| F103 | 52 | 5.0% | 63 | 39 | 20 | 13 |
| F109 | 64 | 6.1% | 75 | 47 | 27 | 17 |
| F111 | 43 | 4.1% | 50 | 31 | 19 | 12 |
| **Closed with Floor Insulation Average** | **51** | **4.9%** | **61** | **38** | **21** | **13** |
| | | | | | | |
| F100 | 69 | 6.6% | 74 | 46 | 36 | 23 |
| F105 | 59 | 5.7% | 78 | 49 | 16 | 10 |
| F106 | 55 | 5.2% | 64 | 40 | 23 | 15 |
| F108 | 55 | 5.3% | 66 | 41 | 22 | 14 |
| **Closed with Wall Insulation Average** | **59** | **5.7%** | **71** | **44** | **24** | **15** |
| **Overall Average** | **60** | **5.7%** | **71** | **45** | **24** | **15** |

**Table 12: Phase II duct leakage testing results.**
**(These measurements do not include leakage through the ventilation system intake.)**

### 6.1.3 Sequential Testing Protocol Data

A summary of the measured flow results from Phase I is presented in Table 13. The protocol separates air flow rates into four envelope components: wall/ceiling, floor, crawl space ducts and outside ducts. The reported values, which should not be confused with standard blower door test results, are the flows across the specified leakage path when there is a 50 Pa pressure differential imposed across the path.

At first glance a number of the individual results for the experiment group appear counter intuitive, in that they are larger than the control group. The explanation is that the values are measured under an artificial condition; that is when the crawl space is being mechanically depressurized to 50 Pa by a second blower door fan.

The key information presented in this table is that, as was the case with duct leakage, the component hole sizes between control group and experiment groups were relatively similar in Phase I. The total flow for all components in the control group was 1037 CFM50 and in the experiment groups was 1090 CFM50. Even though the flow rates for the experiment groups are higher in this table, the actual air leakage rates are lower. This is because the experiment group crawl spaces operate at reduced pressure differences to the house, ducts and outdoors due to the presence of the secondary air/pressure boundary at the floor plane.

Leakage through the ventilation system is included in the outside duct leakage. The ventilation system contributed approximately 50% to 55% of the average outside duct flow. The series of tests was conducted to determine the leakage coefficients for each of the leakage paths.

| | Total Flow (CFM50) | Wall/Ceiling Flow (CFM50) | Floor Flow (CFM50) | Crawl Space Duct Flow (CFM50) | Outside Duct Flow (CFM50) |
|---|---|---|---|---|---|
| F107 | 1114 | 550 | 382 | 92 | 90 |
| F104 | 967 | 464 | 312 | 122 | 69 |
| F101 | 1107 | 452 | 428 | 158 | 69 |
| F110 | 961 | 396 | 329 | 162 | 74 |
| **Wall-vented Average** | **1037** | **465** | **363** | **133** | **76** |
| | | | | | |
| F109 | 1406 | 713 | 482 | 119 | 92 |
| F103 | 1333 | 669 | 472 | 134 | 58 |
| F105 | 1050 | 522 | 308 | 122 | 98 |
| F108 | 1066 | 483 | 341 | 112 | 130 |
| F111 | 988 | 454 | 351 | 92 | 91 |
| F102 | 876 | 427 | 266 | 102 | 81 |
| F100 | 1121 | 407 | 455 | 184 | 75 |
| F106 | 876 | 369 | 352 | 84 | 71 |
| **Experiment Average** | **1090** | **506** | **378** | **119** | **87** |

**Table 13: Phase I air flow across leakage paths.**
**(These are not standard CFM50 house leakage test results)**

Table 14 presents the Phase II measured air flows. As with the duct leakage results, all the houses are tighter due to the envelope and duct sealing measures that were implemented. The wall-vented control houses perform similarly to the wall-insulated closed crawl space houses, and both perform slightly better than the floor-insulated closed crawl space houses.

| | Total Flow (CFM50) | Wall/Ceiling Flow (CFM50) | Floor Flow (CFM50) | Crawl Space Duct Flow (CFM50) | Outside Duct Flow (CFM50) |
|---|---|---|---|---|---|
| F101 | 870 | 428 | 277 | 119 | 46 |
| F104 | 717 | 451 | 161 | 76 | 29 |
| F107 | 722 | 436 | 199 | 74 | 13 |
| F110 | 623 | 356 | 187 | 61 | 19 |
| **Wall-vented Average** | **733** | **418** | **206** | **83** | **27** |
| | | | | | |
| F102 | 664 | 480 | 111 | 54 | 19 |
| F103 | 996 | 657 | 256 | 63 | 20 |
| F109 | 953 | 732 | 119 | 75 | 27 |
| F111 | 833 | 618 | 146 | 50 | 19 |
| **Closed with Floor Insulation Average** | **862** | **622** | **158** | **61** | **21** |
| | | | | | |
| F100 | 725 | 476 | 139 | 74 | 36 |
| F105 | 838 | 542 | 201 | 78 | 16 |
| F106 | 628 | 470 | 71 | 64 | 23 |
| F108 | 721 | 530 | 103 | 66 | 22 |
| **Closed with Wall Insulation Average** | **728** | **505** | **128** | **71** | **24** |

**Table 14: Phase II air flow across leakage paths.**
**(These are not standard CFM50 house leakage test results)**

### 6.1.4 CFM50 Leakage Locations

The general relationship between flow and pressure across a surface is of the form

$$Q = C(\Delta P)^n$$

Where Q is the flow, C is the flow coefficient, ΔP is the pressure difference across both sides of the plane, and n is the flow exponent. The TECTite house leakage protocol presented in section 5.1 provided flow coefficients, flow exponents, and zonal pressures for the floor, wall/ceiling, crawl space duct, and outside duct surfaces. The leakage coefficients calculated for the Phase 1 pressure testing are presented in Table 15. Zone pressures were not recorded during the blower door testing step of the Phase II pressure testing, so the analysis below pertains only to the Phase I configurations.

| | Wall/Ceiling Flow Coefficient | Floor Flow Coefficient | Crawl Space Duct Flow Coefficient | Outside Duct Flow Coefficient |
|---|---|---|---|---|
| F107 | 43.26 | 30.08 | 10.32 | 10.11 |
| F104 | 36.51 | 24.51 | 13.69 | 7.78 |
| F101 | 35.52 | 33.65 | 17.77 | 7.79 |
| F110 | 31.14 | 25.87 | 18.15 | 8.31 |
| **Control Average** | **36.61** | **28.53** | **14.98** | **8.50** |
| | | | | |
| F109 | 56.11 | 37.88 | 13.35 | 10.28 |
| F103 | 52.62 | 37.15 | 15.01 | 6.52 |
| F105 | 41.06 | 24.20 | 13.75 | 11.00 |
| F108 | 37.97 | 26.84 | 12.60 | 14.65 |
| F111 | 35.68 | 27.62 | 10.37 | 10.27 |
| F102 | 33.60 | 20.89 | 11.44 | 9.14 |
| F100 | 32.00 | 35.77 | 20.62 | 8.42 |
| F106 | 29.04 | 27.69 | 9.46 | 8.01 |
| **Experiment Average** | **39.76** | **29.76** | **13.32** | **9.79** |

**Table 15: House and duct leakage coefficients**

With the leakage coefficients of Table 15 and the zonal pressure differentials measured during the CFM50 TECTite test, the individual flows that contribute to the total CFM50 house leakage flow rate can be calculated. Table 16 shows the pressures of zones while the TECTITE CFM50 house leakage was being conducted. Zone pressures were logged during the house leakage test for all homes except 102 and 107. Zone pressure logging was mistakenly not set active in the software program during the test of these two homes. Supply #1 is the register closest to the air handler. Supply #2 is the register furthest from the air handler.

| | Outside to House (P1) | Crawl Space to House (P3) | Supply #1 to House (P5) | Return to House (P7) | Supply #2 to House (P8) |
|---|---|---|---|---|---|
| F101 | 50.0 | 48.7 | 0.7 | 1.2 | 1.0 |
| F104 | 50.0 | 48.7 | 0.9 | 0.9 | 0.4 |
| F107 | 50.0 | n/a | n/a | n/a | n/a |
| F110 | 50.0 | 49.0 | 0.6 | 0.7 | 1.1 |
| **Control Average** | **50.0** | **48.8** | **0.7** | **1.0** | **0.8** |
| | | | | | |
| F100 | 50.0 | 14.2 | 0.2 | 1.1 | 0.2 |
| F102 | 50.0 | n/a | n/a | n/a | n/a |
| F103 | 50.0 | 23.8 | 0.5 | 0.8 | 0.6 |
| F105 | 50.0 | 20.6 | 0.5 | 0.0 | 0.4 |
| F106 | 50.0 | 20.0 | 0.2 | 0.3 | 0.0 |
| F108 | 50.0 | 21.2 | 0.2 | 0.3 | 0.3 |
| F109 | 50.0 | 22.9 | 0.4 | 0.8 | 0.4 |
| F111 | 50.0 | 30.9 | 0.6 | 0.0 | 0.4 |
| **Experiment Average** | **50.0** | **21.9** | **0.4** | **0.5** | **0.3** |

**Table 16: Zone pressures during Phase I TECTite testing.**

The zone pressure results show a marked difference between the control group and experiment groups. When the houses were depressurized to 50 Pa with reference to outside, the crawl space to house pressure differences averaged 49 Pa in the control group and 22 Pascals in the experiment groups. The averaged 22 Pa reading found in the experiment groups demonstrate that the crawl space wall is acting as a primary air/pressure boundary. The subfloor acts as a secondary air/pressure boundary.

### 6.1.5 Component air leakage summary

Tables 17 and 18 summarize the pressure testing results between the Phase I control and experiment groups, with component air leakage amounts presented in Table 17 and corresponding percentages presented in Table 18. There are notable differences between the control and experiment houses. Zone pressures were not recorded during the blower door testing step of the Phase II pressure testing, so the analysis below pertains only to the phase I configurations.

- For the control houses, the average percentage of CFM50 leakage through the floor and crawl space duct systems is 49% (35%+14%) while it is only 33% (25%+8%) for the experiment houses.

- Although both house groups had similar size holes through their floors and crawl space ducts (see Table 13), the averaged leakage rate of these two components was 496 CFM50 (351+145) for the control group and 298 CFM50 (229+69) for the experiment groups. In other words the control group had 66% more air leakage than the experiment groups through the floor and crawl space ducts, even though the actual leakage areas were similar.
- Sealing the crawl space greatly reduced the amount of leakage into the house through the floor and duct system. The experiment homes have a higher percentage of wall and ceiling and actual air leakage during the blower door test. However, the control houses have 16% more component air leakage when all air paths are considered.

The reader is advised that the total house leakage numbers presented in Table 17 are derived numbers that approximate but do not equal the house leakage values presented in Table 9. This analysis was completed to further investigate the impacts on envelope air leakage performance due to the variation in crawl space design and evaluate need for adjustment to the houses to ensure comparable envelope performance to reduce experimental uncertainty.

| | Total House Leakage CFM50 | Wall and Ceiling Leakage CFM50 | Floor Leakage CFM50 | Crawl Space Duct Leakage CFM50 | Outside Duct Leakage CFM50 |
|---|---|---|---|---|---|
| F101 | 1098 | 452 | 421 | 156 | 69 |
| F104 | 959 | 464 | 306 | 120 | 69 |
| F107 | n/a | 550 | n/a | n/a | 90 |
| F110 | 953 | 396 | 325 | 159 | 73 |
| **Control Average** | **1036** | **465** | **351** | **145** | **75** |
| | | | | | |
| F102 | n/a | 427 | n/a | n/a | 81 |
| F103 | 1102 | 669 | 292 | 83 | 58 |
| F109 | 1166 | 713 | 290 | 72 | 91 |
| F111 | 870 | 454 | 257 | 68 | 91 |
| | | | | | |
| F100 | 763 | 407 | 200 | 81 | 75 |
| F105 | 862 | 522 | 173 | 69 | 98 |
| F106 | 680 | 369 | 194 | 46 | 71 |
| F108 | 872 | 483 | 195 | 64 | 130 |
| **Experiment Average** | **891** | **506** | **229** | **69** | **87** |

**Table 17: Summary of Phase I component air leakage in CFM50.**

| | % Wall and Ceiling Leakage | % Floor Leakage | % Crawl Space Duct Leakage | % Outside Duct Leakage |
|---|---|---|---|---|
| F101 | 41% | 38% | 14% | 6% |
| F104 | 48% | 32% | 13% | 7% |
| F107 | 49% | n/a | n/a | 8% |
| F110 | 42% | 34% | 17% | 8% |
| **Control Average** | **45%** | **35%** | **14%** | **7%** |
| | | | | |
| F102 | 53% | n/a | n/a | 10% |
| F103 | 60% | 26% | 8% | 5% |
| F109 | 61% | 25% | 7% | 8% |
| F111 | 52% | 29% | 8% | 10% |
| | | | | |
| F100 | 53% | 26% | 12% | 10% |
| F105 | 60% | 20% | 9% | 11% |
| F106 | 54% | 28% | 7% | 10% |
| F108 | 55% | 22% | 8% | 15% |
| **Experiment Average** | **56%** | **25%** | **8%** | **10%** |

*Rounded numbers approximate 100%*

**Table 18: Phase I component air leakages (Table 17 values) as percentages of the total house leakage for each individual house.**

### 6.1.6 HVAC System Test

Several steps in the pressure testing procedure were designed to examine how operating the HVAC fan affected pressures in the house and crawl space. While this data can indicate the potential for air transfer between the crawl space and the house, the primary goal of this analysis was again to examine and ensure the consistency of performance of the study homes.

The small magnitudes of the pressures recorded and the relatively large variability in the readings and in results from one house to another seem to indicate that there are several significant variables in play. Further study would be required to adequately document this aspect of performance as it relates to the crawl space design and mechanical system, which was outside the scope of this project.

Using the TECLOG software with the APT system, researchers monitored the pressures of house with reference to outside, crawl space with reference to the house, and the crawl space with reference to outside for one minute with the HVAC system fan off (the "baseline" measurement) and for one minute with the HVAC fan on. Table 19 shows the average pressure changes (pressure with fan on minus baseline pressure with fan off) between various zones caused by turning the HVAC fan on in Phase I. Complete data for 102 and 105 are not available.

The tests show that HVAC system operation caused all of the houses to have the living space be slightly positive in pressure with reference to the crawl space. Most of the living spaces also became positive with reference to the outside. This is likely due to the ventilation system air duct installed between outside and the return plenum adding outside air into the house.

All but one of the experiment crawl spaces for which we have data became positive with reference to outside, as did two of the wall vented crawl spaces. For these houses, the general direction of air flow through the whole structure when the heat pump is on improves their indoor air quality. Outside air enters the house through the ventilation system and pushes conditioned air to the crawl space. From there the air moves through minor holes to the outside.

| | | House to Outside Change (Pa) | House to Crawl Change (Pa) | Crawl to Outside Change (Pa) |
|---|---|---|---|---|
| **Control Houses** | F101 | 1.19 | 0.96 | 0.23 |
| | F104 | -0.16 | 1.61 | -1.76 |
| | F107 | 2.82 | 2.59 | 0.23 |
| | F110 | -0.16 | 0.24 | -0.40 |
| | | | | |
| **Experiment Houses** | F102 | 0.80 | n/a | n/a |
| | F103 | 1.41 | 1.15 | 0.26 |
| | F109 | 2.19 | 0.20 | 1.99 |
| | F111 | 0.20 | 0.80 | -0.60 |
| | F100 | 3.52 | 2.54 | 0.98 |
| | F105 | 0.40 | n/a | n/a |
| | F106 | 3.08 | 1.74 | 1.33 |
| | F108 | 3.94 | 0.24 | 3.7 |

**Table 19: Phase I pressure changes from baseline due to HVAC fan operation.**

The Phase II tests reported in Table 20, which take into account the effect of the crawl space supply duct, show the pressure results of HVAC system operation (including the ventilation intake) before and after the crawl space supply duct was opened in the closed crawl space houses. Please note that these results reflect the performance of the system with the crawl space supply air flow set at its original value of 25 CFM during the post-conversion testing in June of 2003. The flow was subsequently increased to 35 CFM in July to achieve more robust moisture management.

Intermittently breezy conditions during testing contributed to uncertainty in interpreting the results for some houses. The shaded rows contain the most reliable results. The pressure readings (sampled over a one-minute duration) in those rows were known to be taken during a period of calm wind conditions and have a standard deviation less than 0.4 Pa for the readings taken with both the ventilation intake and crawl space supply ducts open. Samples with high uncertainty were not repeated since the measurements did not indicate a significant effect on the overall performance of the study, and since this analysis was not an objective of the study.

All but one of the homes (house 103) were slightly positive in pressure with reference to outside during HVAC operation with both ventilation intake and crawl space supply ducts open. However, seven of the eight experiment homes have a slightly negative house pressure with reference to the crawl space after the crawl space supply duct is opened (compared to only four of eight prior to the supply duct being opened.) This suggests that the addition of the crawl space supply duct increases pressure in the crawl space enough to create, in some houses, pressure values that could cause crawl space air to enter the home if a path for air flow is available. Note that actual air flow from the crawl space to the house was not measured in this testing. The extensive floor air sealing performed on these houses is intended to block such transfer of air between the crawl space and house.

The fact that four of the closed crawl space homes (prior to the crawl space supply duct being opened) and one of the vented crawl space homes had house pressures that were negative with reference to the crawl space suggests that other variables, such as duct leakage magnitude, duct leakage distribution, house tightness, and/or wind, have significant impact. Finally, the increase of crawl space supply air flow from 25 CFM to 35 CFM could be expected to increase the crawl space to outside pressure and decrease the house to crawl space pressure from the levels presented here.

| | | Ventilation with crawl supply duct plugged | | | Ventilation with crawl supply duct open | | | |
|---|---|---|---|---|---|---|---|---|
| | | House to Outside Pressure (Pa) | Crawl Space to Outside Pressure (Pa) | House to Crawl Space Pressure (Pa) | House to Outside Pressure (Pa) | Crawl Space to Outside Pressure (Pa) | House to Crawl Space Pressure (Pa) | Standard Deviation of House to Crawl Pressure[1] |
| Wall Vented | F101 | 2.2 | 0.4 | 1.8 | N/A | N/A | N/A | 1.6 |
| | F104 | 0.4 | -0.2 | 0.6 | N/A | N/A | N/A | 0.3 |
| | F107 | 1.2 | 2 | -0.8 | N/A | N/A | N/A | 0.9 |
| | F110 | 1.8 | 0.1 | 1.7 | N/A | N/A | N/A | 0.3 |
| | | | | | | | | |
| Closed with Floor Insulation | F102 | 1.6 | 2.0 | -0.4 | 0.4 | 2.1 | -1.7 | 0.6 |
| | F103 | 0.6 | -0.2 | 0.8 | -0.5 | 0.5 | -1 | 0.8 |
| | F109 | 1.8 | 2.1 | -0.3 | 1.8 | 3.3 | -1.5 | 0.4[2] |
| | F111 | 1.2 | 1.1 | 0.1 | 0.8 | 1.9 | -1.1 | 0.2 |
| | | | | | | | | |
| Closed with Wall Insulation | F100 | 4.0 | 4.5 | -0.5 | 4.4 | 4.5 | -0.1 | 0.4 |
| | F105 | 1.6 | 1.3 | 0.3 | 1.4 | 2.1 | -0.7 | 0.3 |
| | F106 | 2.2 | 0.3 | 1.9 | 1 | 0.5 | 0.5 | 0.1 |
| | F108 | 0.5 | 2.1 | -1.6 | 0 | 3.2 | -3.2 | 0.2[2] |

[1] Values for the wall vented crawl spaces are for ventilation with no crawl space supply duct. Values for all closed crawl spaces are for ventilation with crawl space supply duct in operation
[2] Windy conditions during monitoring

**Table 20: Phase II pressure measurements during HVAC fan operation.**

## 6.2 Energy: Electrical Energy Consumption Data

We had been advised when we were beginning this study that we should not expect to measure any space conditioning energy savings during the summer season from our experiment modifications. However, when we analyzed utility billing records for phase I, we realized that there could be notable energy savings. As a result, we installed sub-meters on all twelve heat pump systems in early 2003, and found significant energy savings in the closed crawl space houses, as illustrated by the sub-meter data presented below. Readings from individual houses are not presented in the bar graphs, due to the inability to present the large number of data points clearly in that format. Instead, the monthly data includes error bars indicating standard error for each bar to reflect the variability across the four homes in each group by month.

Figure 19 represents the average monthly energy used for space conditioning for one house in each of the three study groups during Phase II, June 2003 through May 2004.

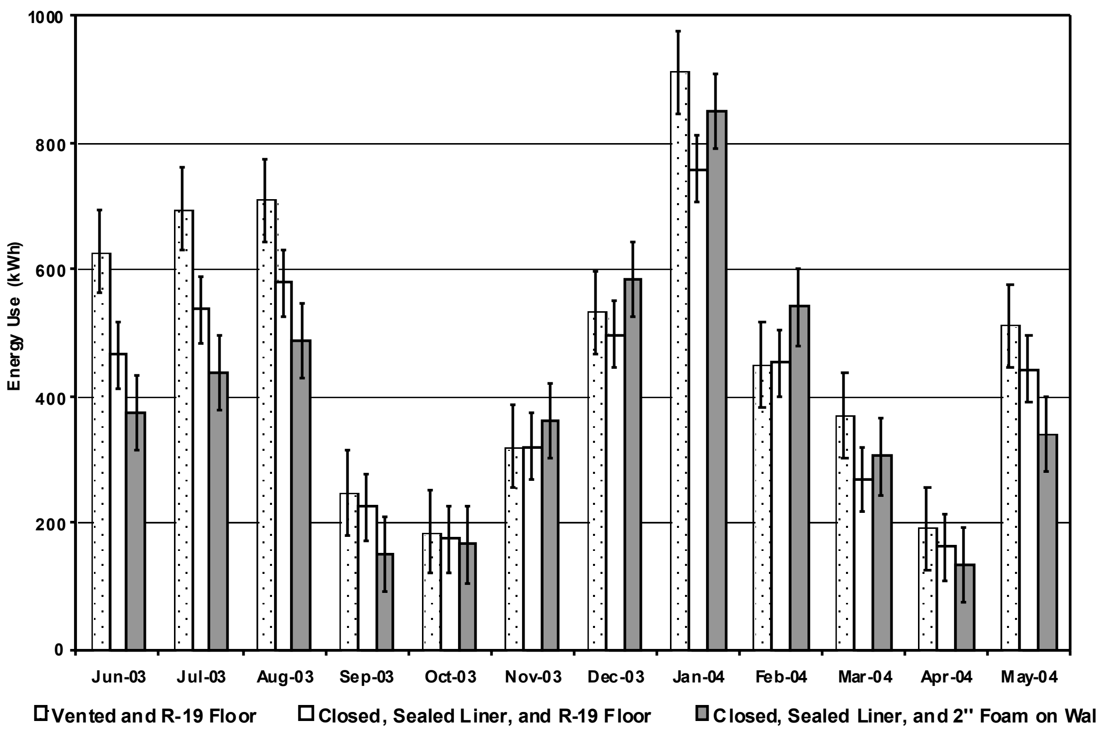


**Figure 19: Average monthly space conditioning energy use per house by group.**
**Error bars indicate the standard error calculated for the four house measurements that are averaged to create each bar.**

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. These same homes provided a cooling season, June through September, reduction of 473 kWh ($47), a 21% savings. It provided a heating season, November through March, reduction of 287 kWh ($29), an 11% savings.

The wall-insulated closed crawl space have 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. These same homes provided a cooling season, June through September, reduction of 831 kWh ($83), a 36% savings. It provided a heating season, November through March, increase of 56 kWh ($6) a 2% increase.

Figure 20 shows a seasonal grouping with an annual total of the same results displayed in Figure 19. Table 21 indicates percent savings by season for the different experiment types, as compared to the wall-vented control homes.

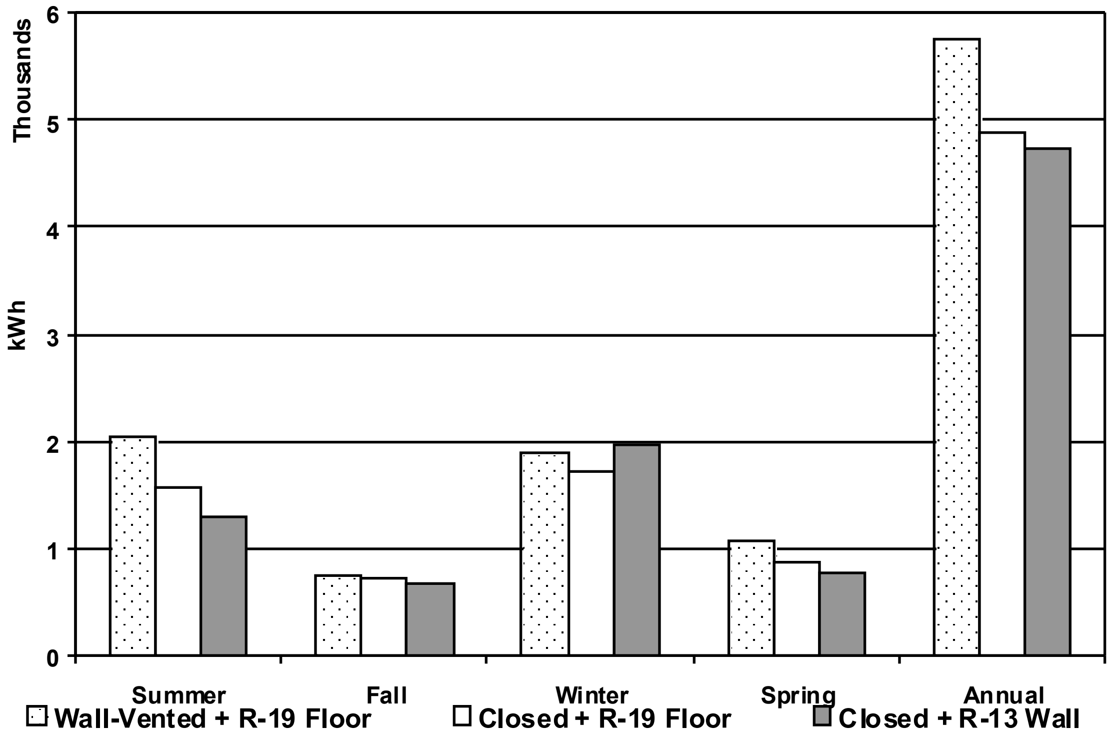


**Figure 20: Seasonal and annual space conditioning energy use per house by group**

| 2003-04 Savings over control homes | Closed with R-19 Floor | Closed with R-13 Wall |
|---|---|---|
| Summer (Jun-Aug) | -22 % | -36 % |
| Fall (Sep-Nov) | -5 % | -10 % |
| Winter (Dec-Feb) | -10 % | +4 % |
| Spring (Mar-May) | -19 % | -28 % |
| Annual | -15 % | -18 % |

**Table 21: Seasonal energy savings by experiment group during Phase II.**

The experiment one houses did not save as much as the experiment two houses during the summer but they did out perform them during the winter. However, both experiment groups used less energy for space conditioning than the wall vented crawl space group.

While we have 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. Base load usage during Phase II is illustrated below in Figures 21(a) and 21(b). By luck of the draw, the control homes had ended up with higher occupancy numbers and a higher proportion of occupied time (e.g. residents at home during the day) relative to the experiment houses. Researchers did not do a formal occupancy survey, but general observation during site work indicated general occupancy in the control group homes of eight adults and seven children, in experiment group 1 homes of six adults and two children, and in experiment group 2 homes of eight adults and three children. All four control group homes were observed to have residents in the home during the day, while only two experiment 1 and 1 experiment 2 homes were typically observed to have residents at home during the day.

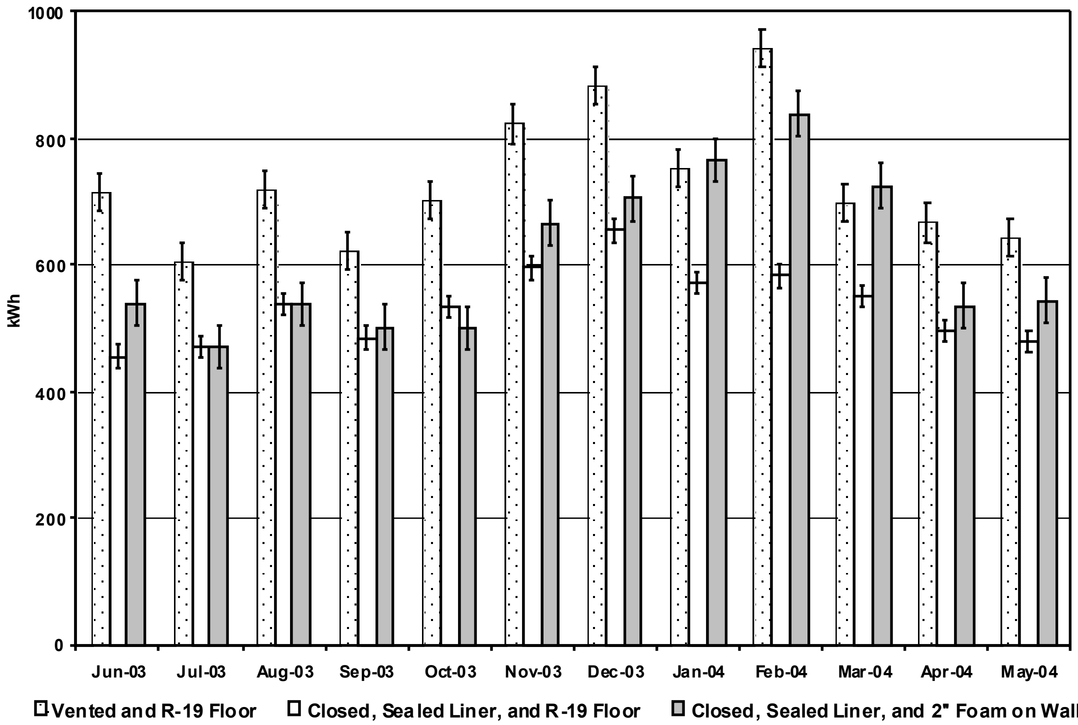


**Figure 21(a): Monthly average base-load energy use per house by group**

Error bars indicate the standard error calculated for the four house measurements that are averaged to create each bar.

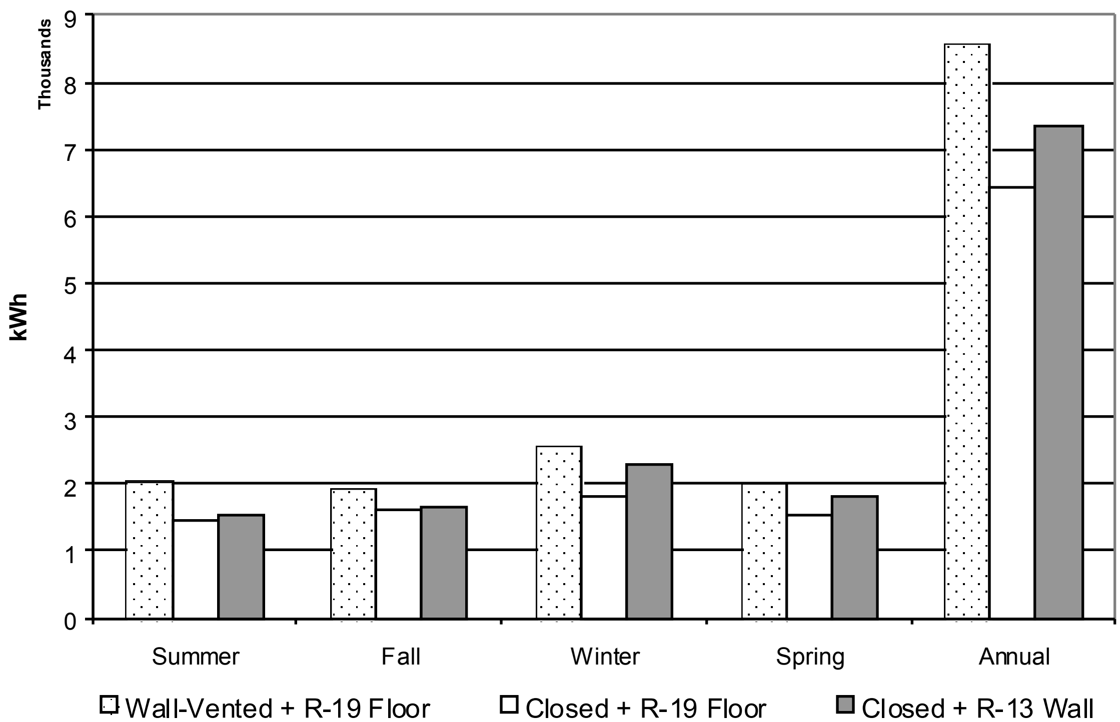


**Figure 21(b): Seasonal and annual base-load energy use per house by group**

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 more of a difference in base load consumption between the controls and the wall-insulated experiment houses in the summer than there is in the winter, which makes the summertime wall-experiment house performance look better.

A review of the interior house data indicates that the control houses were operated one- to two-degrees F cooler than the experiment houses in the summer (Figure 22) and one- to two-degrees F warmer than the experiment houses in the winter (Figure 23). To normalize the heat pump energy consumption with regard to these differences in thermostat set-point, we graphed average temperature difference between outside and inside for each house in each month and plotted that against the kWh consumption for space conditioning for that house in the same month (Figure 24). The trend lines (3$^{rd}$-order polynomial) for each group of houses indicate the same seasonal patterns of performance that we observed in the raw sub-meter data. Integration of the trend line equations over the general range of delta-T (-45° F to +10° F) actually predicts greater savings by the experiment groups than has been shown by the field data.

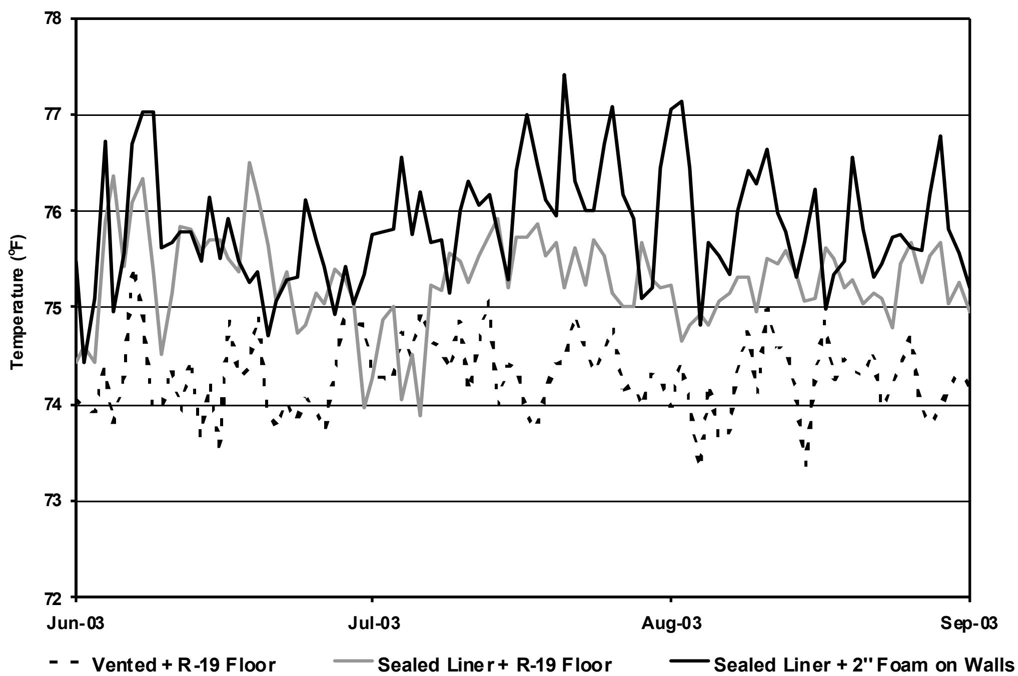


**Figure 22: Summer 2003 indoor temperatures (daily average by group)**

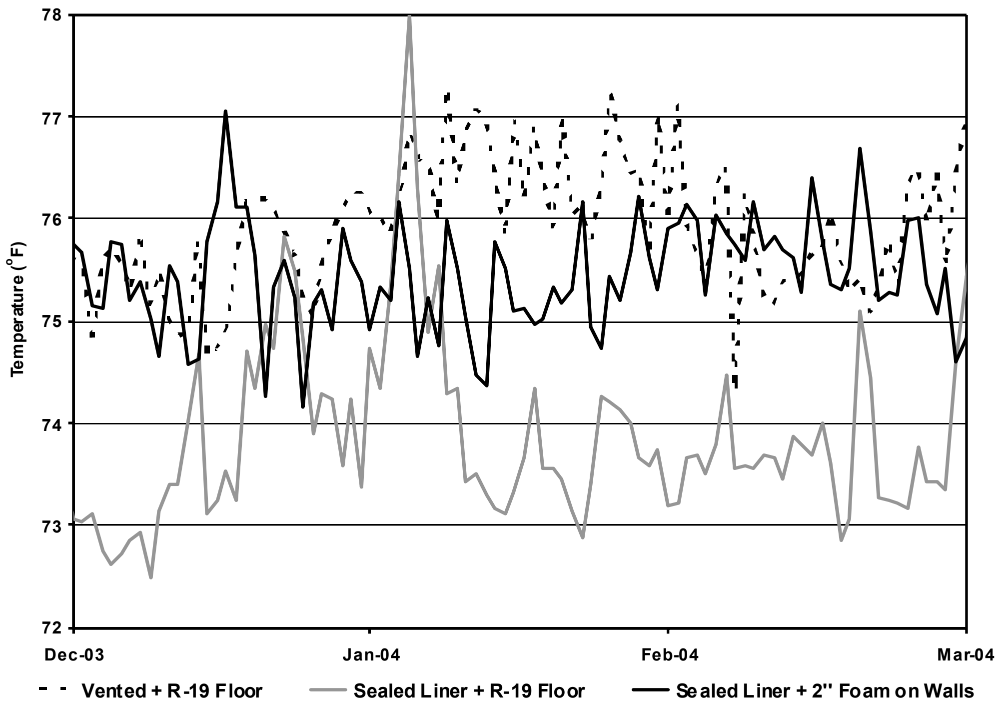


**Figure 23: Winter 2003-04 indoor temperatures (daily average by group)**

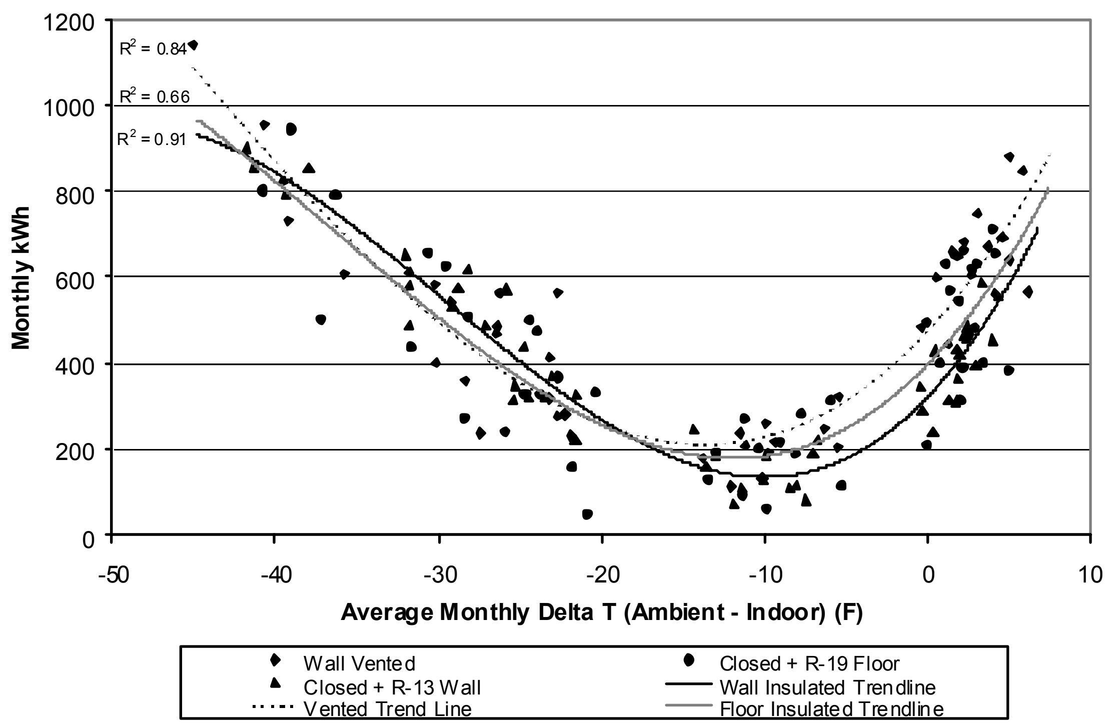


**Figure 24: Monthly space conditioning energy use (June 2003 through May 2004) versus average monthly temperature difference, by group.**

Phase III operated from June of 2004 to December of 2004. The key experimental change during this period was the conversion of three wall-vented crawl spaces to closed crawl spaces (now called experiment group 3). These three crawl spaces had their perimeter walls air-sealed and a supply air duct installed, but had no vapor retarder material installed on the perimeter walls, and no seams sealed in the ground vapor retarder. Monthly sub-meter results are plotted in Figure 25 and indicate that the retrofitted experiment group 3 homes now perform more similarly to the other experimental groups. We have omitted the sub-meter data for house 110, the last remaining vented crawl space home during this period, because its energy use has been historically at the high end of the control group. To present its data alone would artificially increase the perceived improvement of the experimental groups.

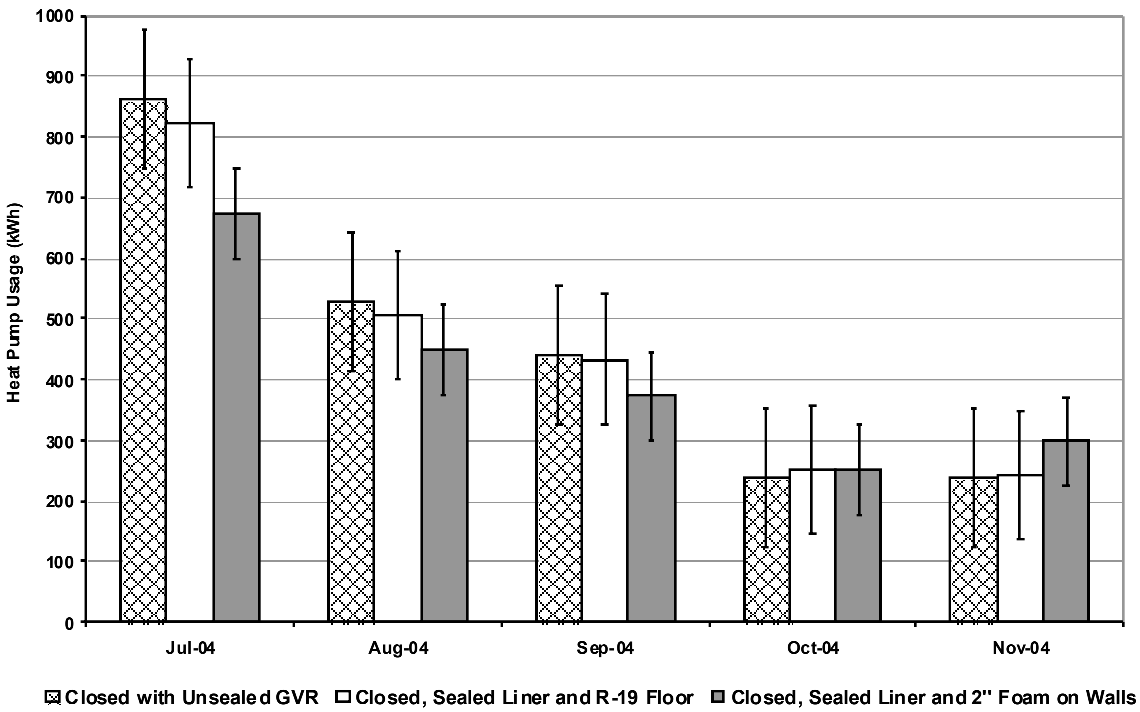


**Figure 25: Monthly space-conditioning energy use during Phase III.**
**Error bars indicate the standard error calculated for the four house measurements that are averaged to create each bar.**

We hoped to plot monthly average energy consumption per house versus temperature difference (outside - indoor) for the three control houses that were converted to create experiment group 3 over two periods: summer 2003 and summer 2004. This would perhaps better indicate the energy benefit illustrated in the monthly sub-meter data. However, the energy data was unsuitable for this type of analysis for two reasons: first, the three-month summer monitoring ranges did not coincide (June 5-September 9, 2003 versus June 24-October 13, 2004). Second, the sampling intervals for comparison were not the same (32 days, 32 days, and 32 days for the three samples in 2003 and 39 days, 31 days, and 41 days in 2004).

Figure 26 plots average daily indoor temperatures during the summer of 2004 in the three experiment groups as well as the last remaining wall-vented crawl space house (110 Lowe's Ct.). After crawl space closure, it first seemed that the residents of the previously vented crawl space homes chose to operate their homes at temperatures more consistent with the other experiment groups. However, when comparing the 2004 data with the indoor temperature data from the summer of 2003 (and separating house 110 to see its individual performance) shown in Figure 27 it appears that the control/experiment 3 houses performed relatively consistently from one year to the next, while the occupants of the other experiment groups operated their homes at a cooler temperature than the previous summer.

We have not administered a formal survey of occupant comfort, but had an anecdotal experience that supported our hypothesis that the moisture performance of the crawl spaces may also affect the occupant's thermostat settings, even though the broader data doesn't appear to support it. When we returned to the site four days after converting the three vented crawl spaces to closed crawl spaces, one resident (who rarely adjusts her thermostat) excitedly let us know that within a day of our improvement to her crawl space, she had to turn up her thermostat because she felt too cold in the house!

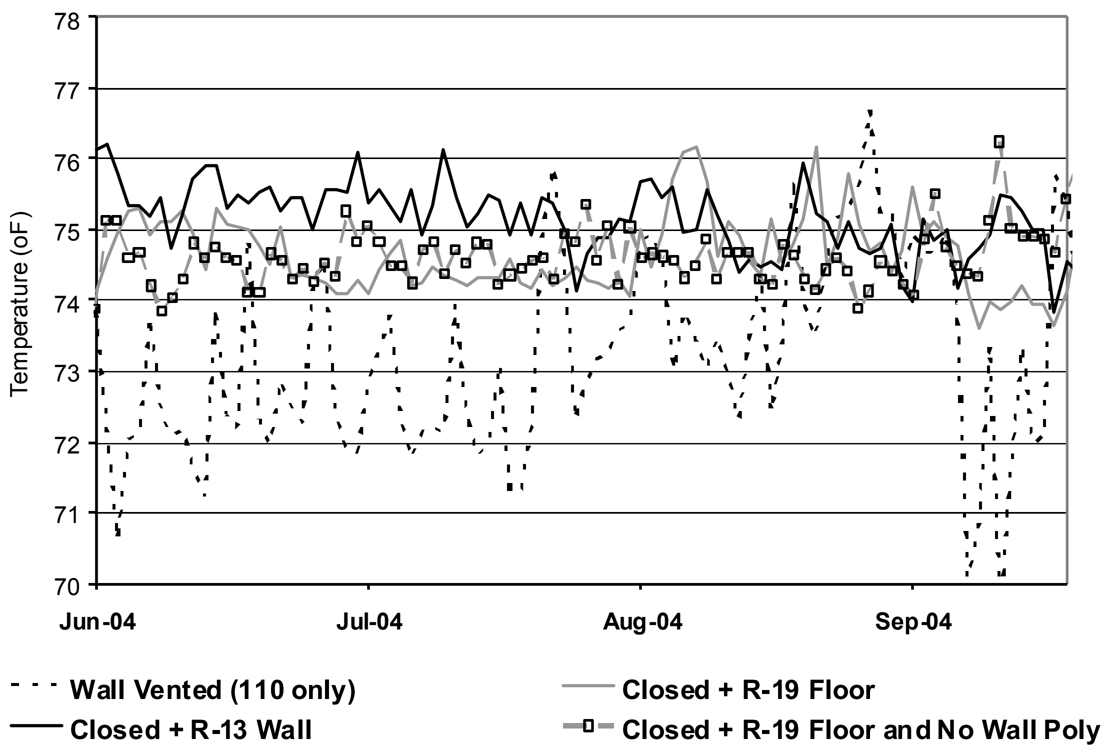


**Figure 26: Summer 2004 indoor temperatures**

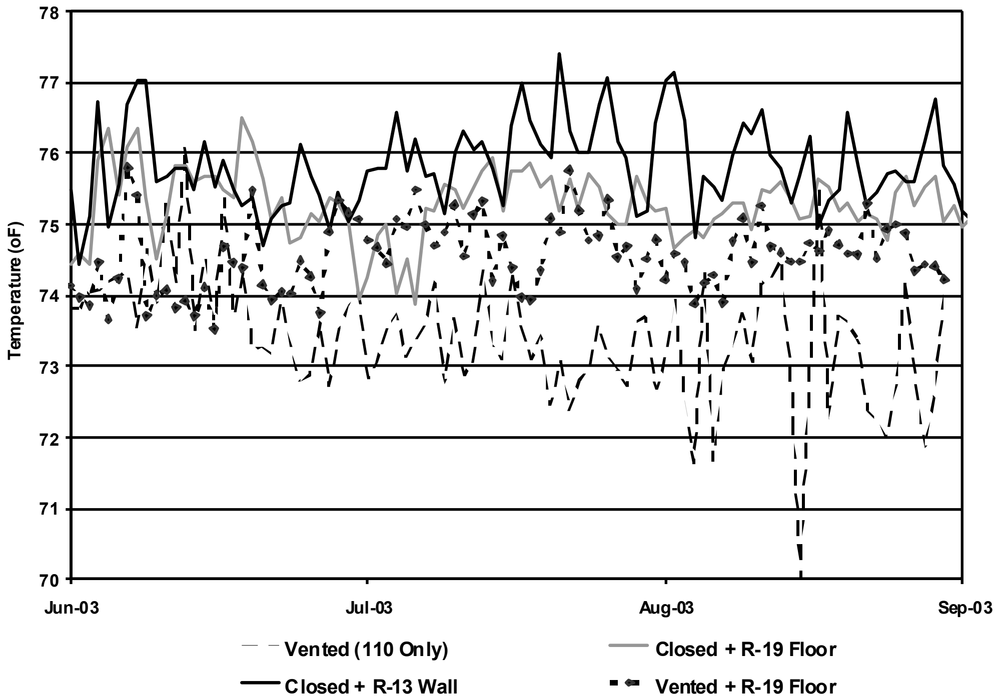


**Figure 27: Summer 2003 indoor temperatures with 110 Lowe's Ct. shown separately**

When Phase IV began in December 2004, the last vented crawl space house (110 Lowe's Ct.) was converted to the experiment group 3 configuration. No changes were made to the three existing experiment group 3 homes. Again we hoped to compare these homes' performance pre- and post-modification, this time for the winter of 2003-04 versus winter of 2004-05. The result is plotted in Figure 28, which appears to indicate that the energy performance decreased after closure. This contradicts the more general picture presented by the monthly sub-meter data alone (Figure 30), where these homes' performance improved relative to the other experiment homes when compared to the previous winter's performance. The relatively poor correlation of data points to the trend lines indicates the need for the collection of more precise energy monitoring data to be able to compare performance at this level of detail.

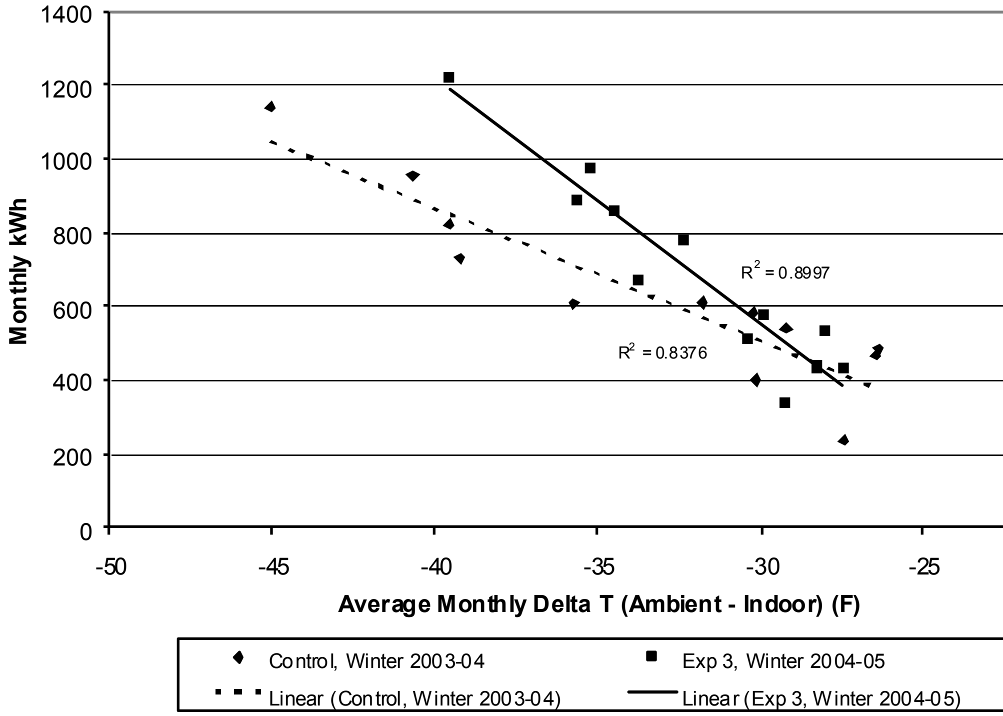


**Figure 28: Wintertime energy performance of four homes before (2003-04) and after (2004-05) their crawl spaces were closed**

Indoor set points (Figure 29) were very consistent across all groups in the winter of 2004-05. The experiment 1 group (closed with R-19 floor) operated their homes warmer than in the winter of 2003-04, and the experiment 3 (formerly control group) operated their homes slightly cooler. As with the summer data, this improvement in consistency does not seem to be attributable solely to the reconfiguration of the control homes with closed crawl spaces.

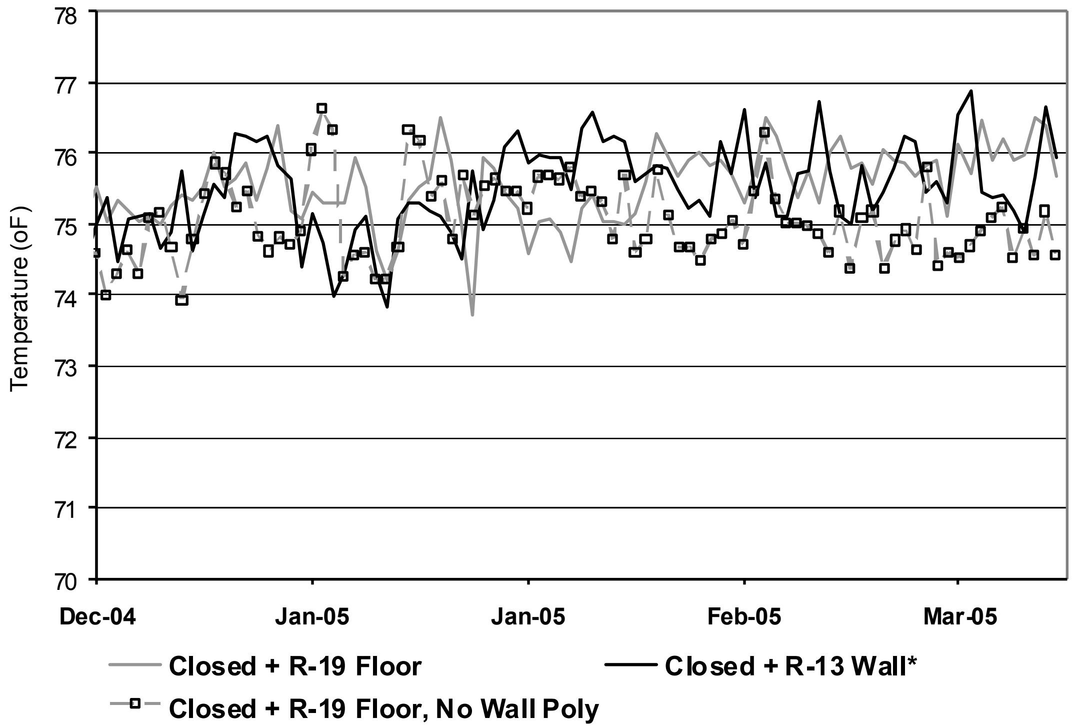


**Figure 29: Winter 2004-05 indoor temperatures**

The key experimental change for Phase IV was the addition of 2' of foam insulation horizontally around the perimeter of the crawl space floor. Figure 30 plots monthly space conditioning energy use during this period.

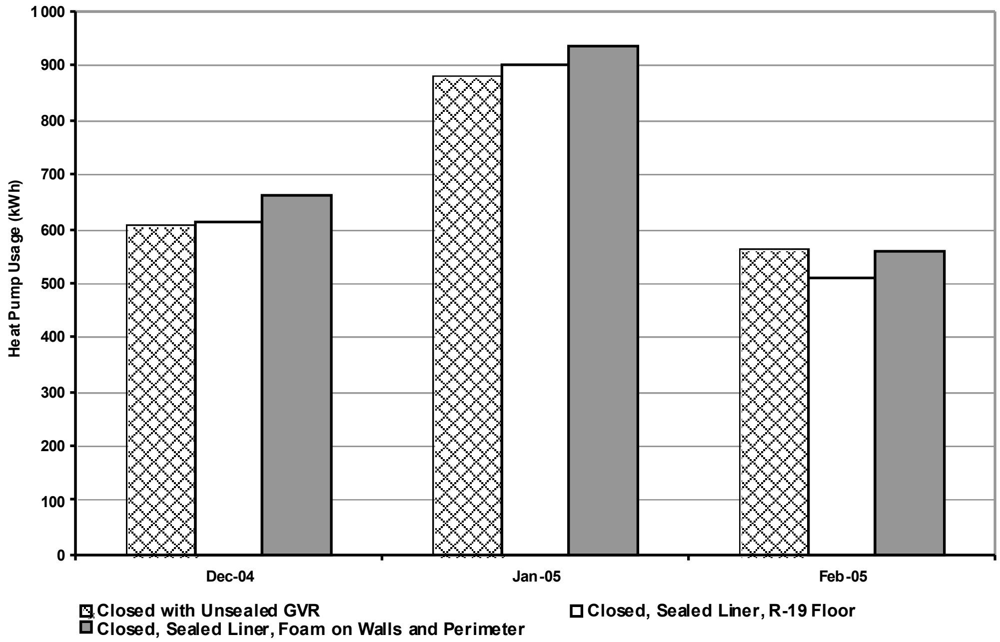


**Figure 30: Phase IV space conditioning energy use by group.**

Figure 31 plots monthly average energy consumption per house versus temperature difference (outside - indoor) for the four houses in experiment group 2. The first series represents the data points from the winter of 2003-04 (no perimeter floor insulation) and the second data series represents the data points from the winter of 2004-05 (perimeter floor insulation installed). Unfortunately, there is a high degree of variability in the data and the trend lines actually indicate that the addition of perimeter insulation has increased energy consumption for a given temperature condition, which puts the validity of this evaluation in doubt. It appears that more frequent energy measurement intervals would be required to generate a valid data set for comparison.

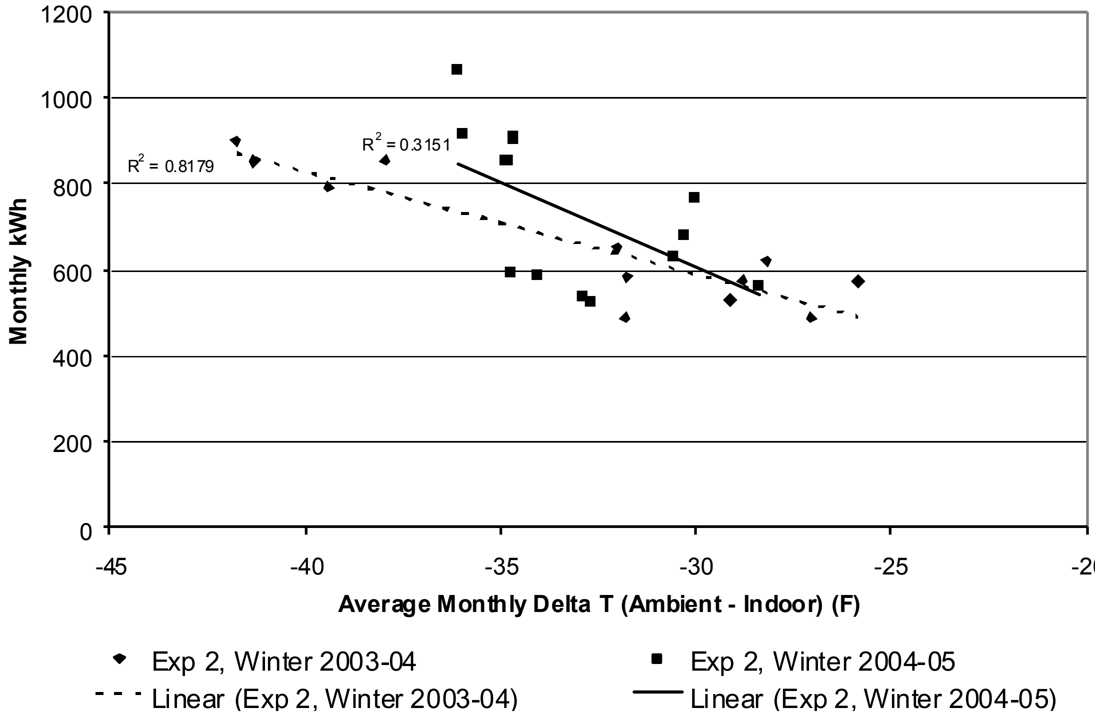


**Figure 31: Wintertime energy performance of wall-insulated closed crawl spaces with (2004-05) and without (2003-04) perimeter floor insulation**

### 6.3 Temperature and Relative Humidity Data

The Hobo Pro data loggers monitored ambient temperature and relative humidity at fifteen-minute intervals. Dew point temperature was then calculated by the data logger. This data was reviewed for inconsistencies, fluctuations, and logger problems. Because this study is examining long-term performance, researchers calculated daily average values from the measurements. Unless otherwise noted, the figures and analysis in this section are based on daily averages of the fifteen-minute interval measurements taken in the conditioned spaces, crawl spaces, and outside.

#### 6.3.1 Group Relative Humidity Comparison

A comparison of average daily relative humidity in the wall vented and closed crawl spaces is presented in Figures 32-35. Data collection for all crawl spaces began June 1, 2001 and retrofit work began June 11, 2001 on most crawl spaces. For the first two weeks in June, the groups seemed to perform closely. However, as sealing work was completed, the relative humidity in the experiment groups began to decline. After a mold bloom occurred in house 108 due to plumbing problems, heavy rains, and poor site grading, dehumidifiers were installed in all eight closed crawl spaces to test the use of small dehumidifiers to provide supplemental drying. The sharp decrease at the beginning of July reflects this dehumidification of the closed crawl spaces. All dehumidifiers were turned off by July 31, 2001 except in house 108, which was turned off on August 8, 2001. After researchers turned off the dehumidifiers the average relative humidity climbed from 40% and leveled off at 55-60% within two or three weeks, with only the measured duct air leakage as the supplemental drying mechanism in the crawl space.

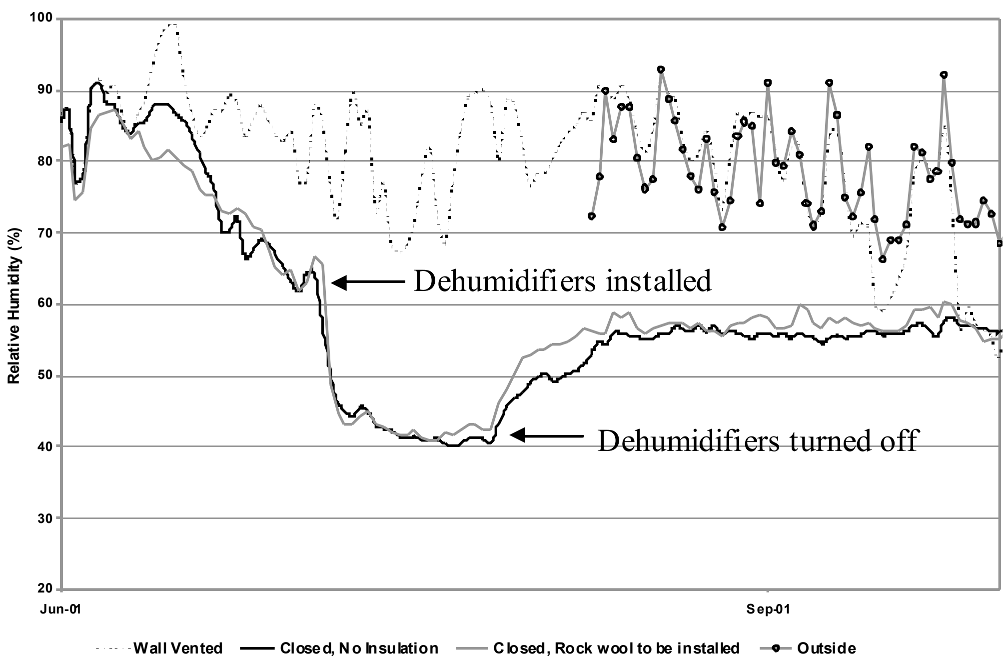


**Figure 32: Average daily relative humidity during startup**

Figure 33 shows a larger span of readings from Phase I (calculated as rolling weekly averages for clarity) from March, 2002 through May, 2003. Because of the small variation in performance between the two types of closed crawl space, the data for those two groups of houses is presented as one series "Closed". The transition of the crawl spaces from Phase I to Phase II took place during April and May 2003, and required that the closed crawl spaces were open for an extended period of time. The transition during that time period is reflected in the rise in relative humidity in April and May, 2003. In the Phase II results shown in Figure 34 (again using rolling weekly averages) it can be seen that the transition work was completed in June 2003 and the experimental crawl spaces were again closed and began to dry. With the opening and adjustment of the HVAC supply air duct the necessary supplemental drying mechanism was achieved [1 $ft^3$/min (0.5 L/s) of supply air per 30 $ft^2$ (2.8 $m^2$) of crawl space ground surface]. In both figures, the relative humidity in the wall-vented crawl spaces drops between November and March due to the dry winter conditions outside.

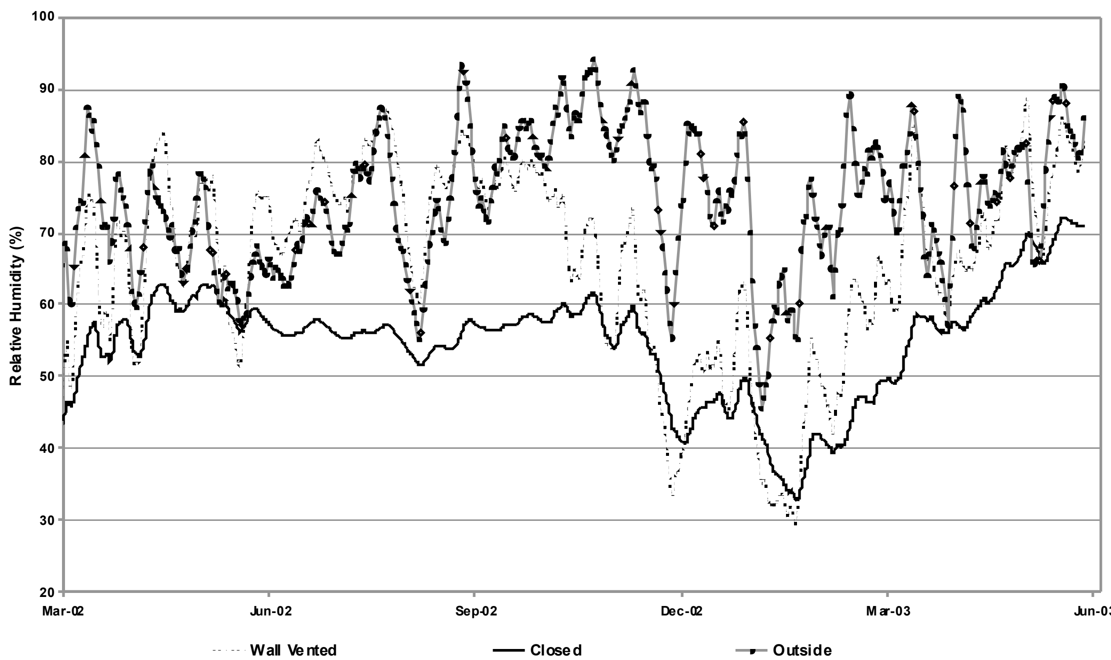


**Figure 33: Phase I relative humidity (rolling weekly average)**

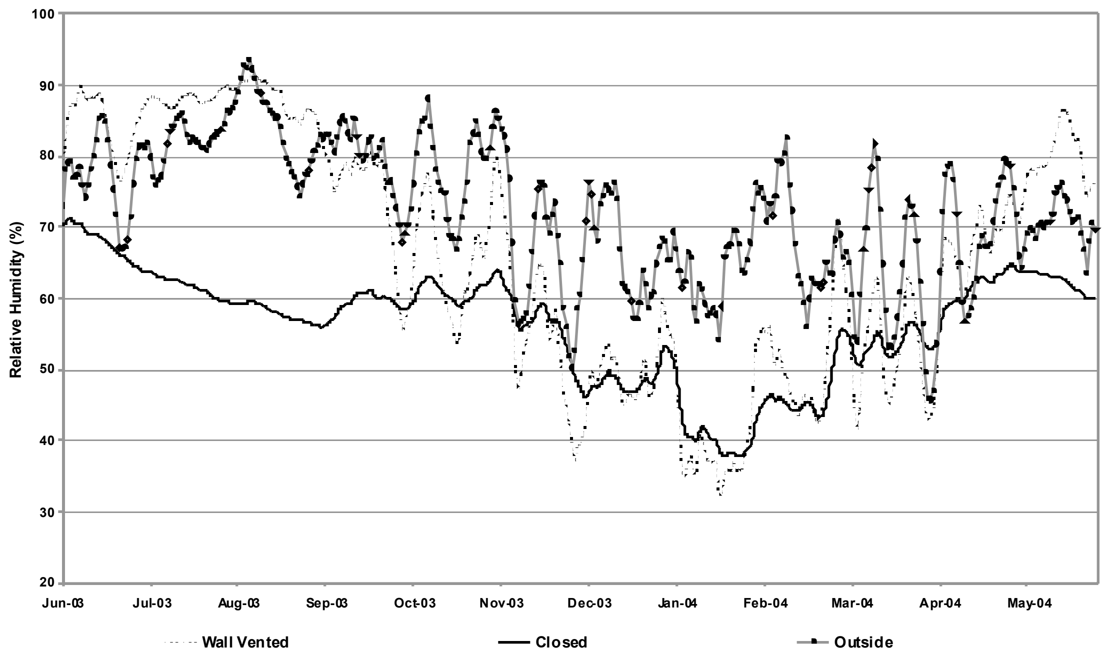


**Figure 34: Phase II relative humidity (rolling weekly average)**

Figure 35 presents results from Phase III, which ran from late June 2004 to mid-December 2004. Three of the wall-vented control crawl spaces were converted to a new variant of closed crawl space that had vents sealed and the same supply air duct providing the same volume of conditioned air to the crawl space as in the other eight closed crawl spaces. However, unlike the other eight closed crawl spaces, these three new closed crawl spaces did not have any vapor retarder installed on the perimeter wall of the crawl space and they did not have the seams sealed in the ground vapor retarder. The new crawl spaces did not show the same level of moisture control as was measured in the closed crawl spaces with the fully sealed vapor retarder with wall coverage, but their performance did show significant improvement over the last remaining wall-vented crawl space in house 110, and it appears that this performance was achieved within approximately four weeks of the change to the closed configuration.

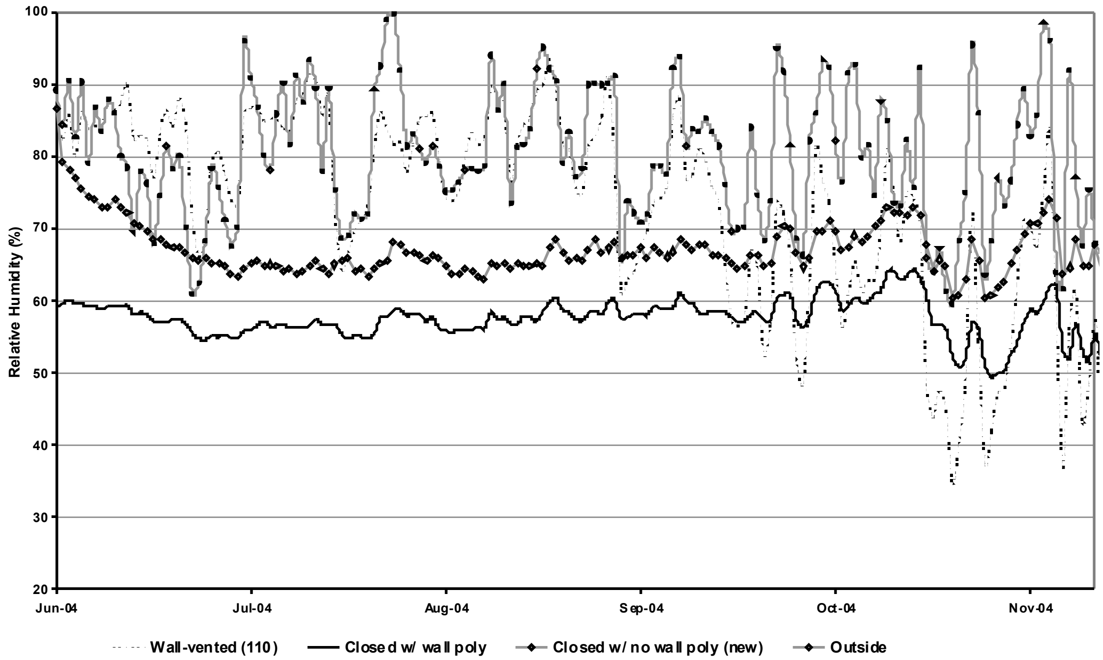


**Figure 35: Phase III relative humidity (rolling weekly average)**

Table 22 compares the percent of time in each summer that the different crawl spaces had a daily average relative humidity above the given thresholds. Note that in central and eastern North Carolina, 2002 was a record-setting drought year and 2003 was a record-setting rainfall year.

**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% |

**Table 22: Percentage of time above summer RH thresholds**

In summary, the relative humidity figures show that for the critical summer months the relative humidity in the closed crawl spaces remained substantially lower than in the wall vented crawl spaces. This is especially significant for Figure 34, the Phase II graph, because the summer of 2003 was one of the wettest on record for the test location and the closed crawl spaces still remained dry. For the summer seasons, air in the closed crawl spaces was generally below 60% relative humidity and air in the wall vented crawl spaces was often above 80 % relative humidity.

### 6.3.2 Group Dew Point Comparison

Dew point temperatures for control and experiment crawl spaces and outside during Phase I are shown in Figure 36. Through most of the summer, the dew point in the control crawl spaces stayed between 65 and 75°F. It followed a very similar pattern to the outside dew point. The dew point is not as consistent between outside and the experiment groups. The summers of 2001 and 2002 were drier than normal, with several dry periods that can be seen reflected in the wall vented crawl space data. The data for the closed crawl spaces show the drier characteristic when the summer seasons are examined.

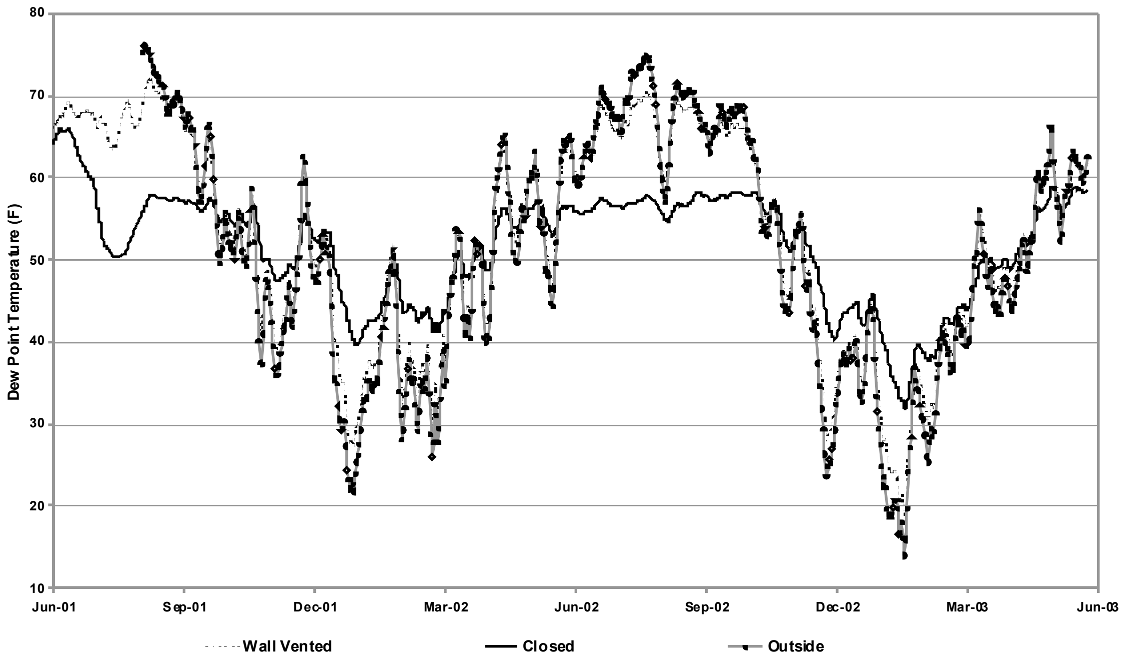


**Figure 36: Phase I dew point temperatures (rolling weekly averages)**

Phase II and III dew point readings are shown in Figures 37 and 38 and show the same trends performance seen in the relative humidity data.

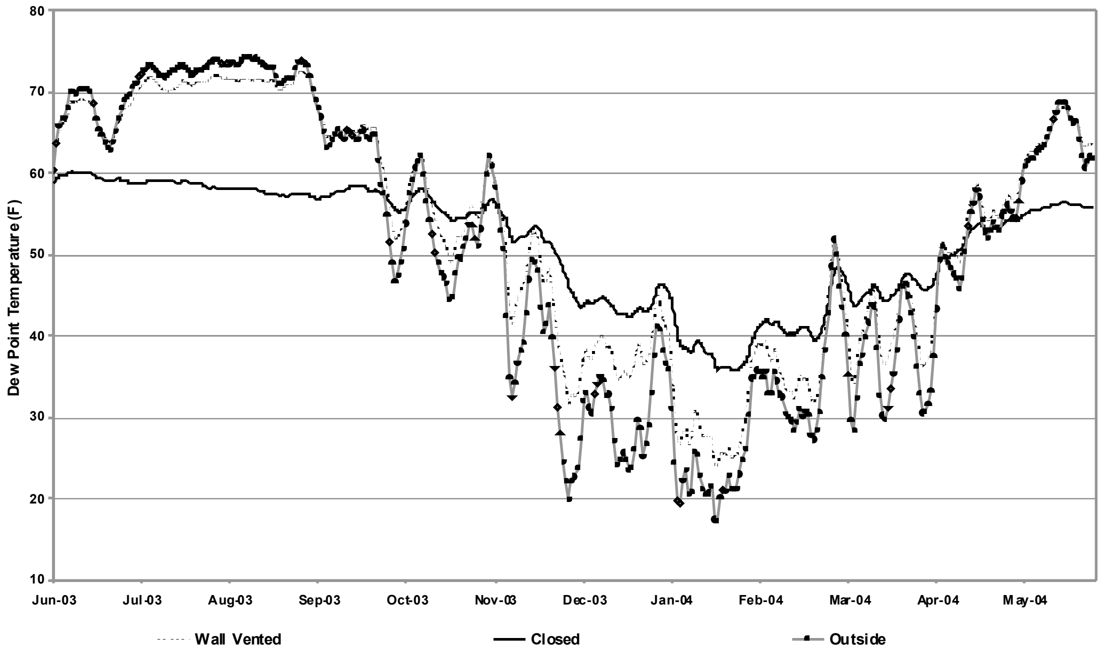


**Figure 37: Phase II dew point temperatures (rolling weekly averages)**

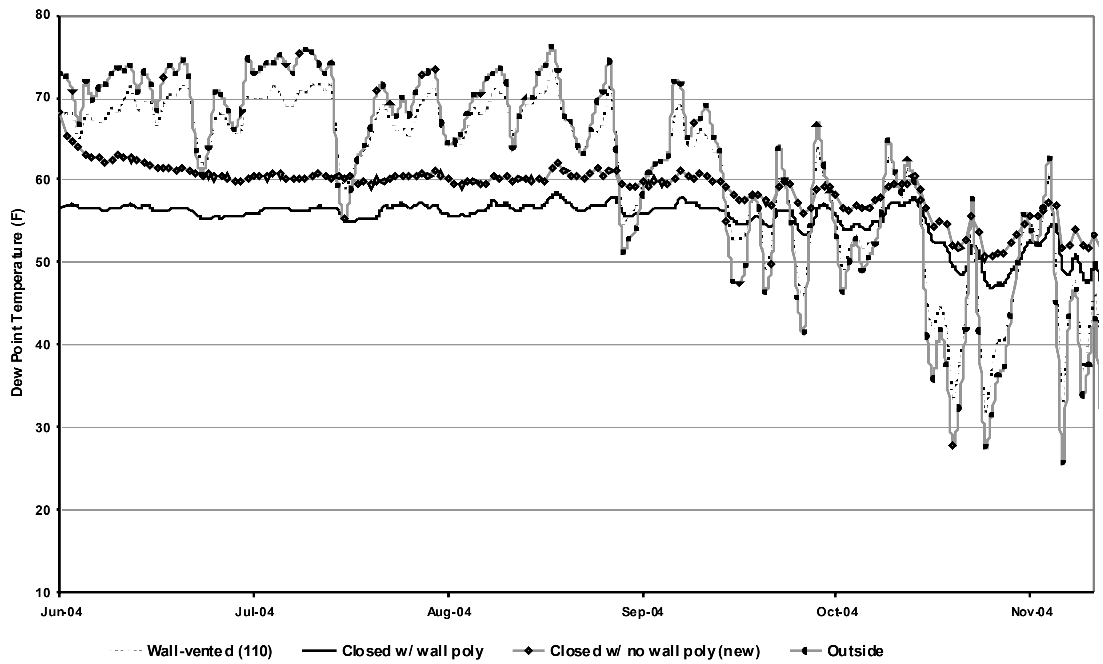


**Figure 38: Phase III dew point temperatures**

The dew point temperature data consistently show that the outside air contains more water vapor than the air in the wall-vented crawl spaces during the warm seasons, actually adding water vapor to the crawl space instead of providing drying potential. 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.

### 6.3.3 Relative Humidity Comparisons In the Conditioned Space

The relative humidity inside the conditioned spaces is shown in Figures 39-41. The relative humidity in the conditioned space is controlled by the air conditioning system and is similar in all houses, supporting the observations that the heat pump systems were functioning consistently and adequately. The houses with closed crawl spaces appear to have a slightly lower relative humidity in the conditioned space during the cooling seasons.

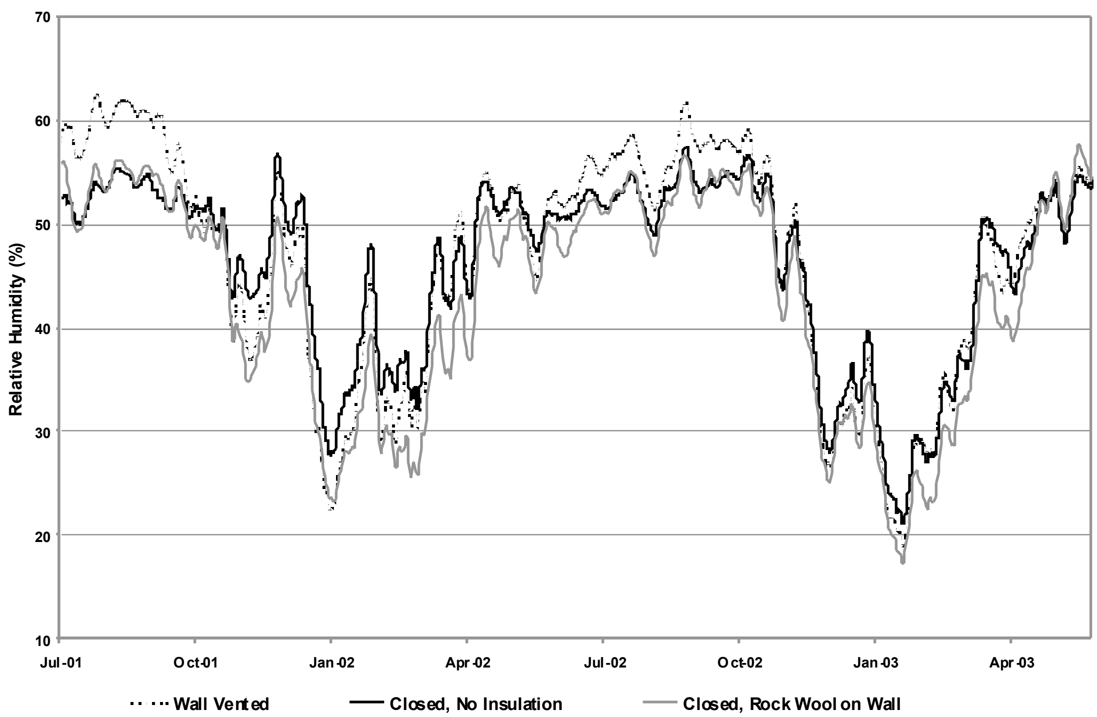


**Figure 39: Phase I relative humidity inside the conditioned space (rolling weekly averages)**

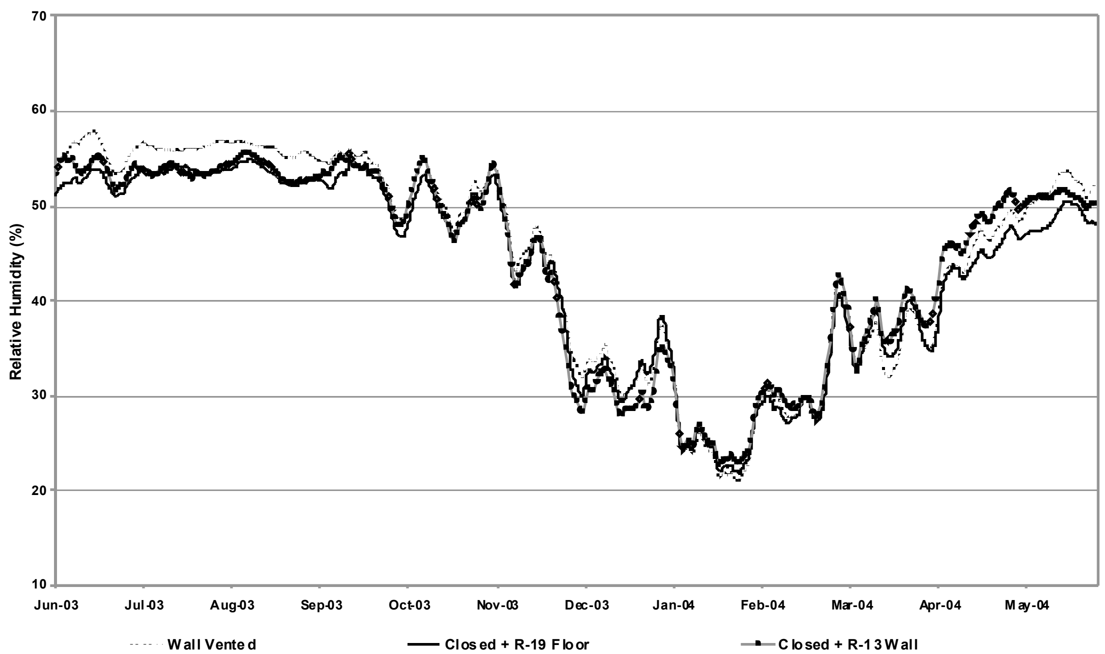


**Figure 40: Phase II relative humidity inside the conditioned space (rolling weekly averages)**

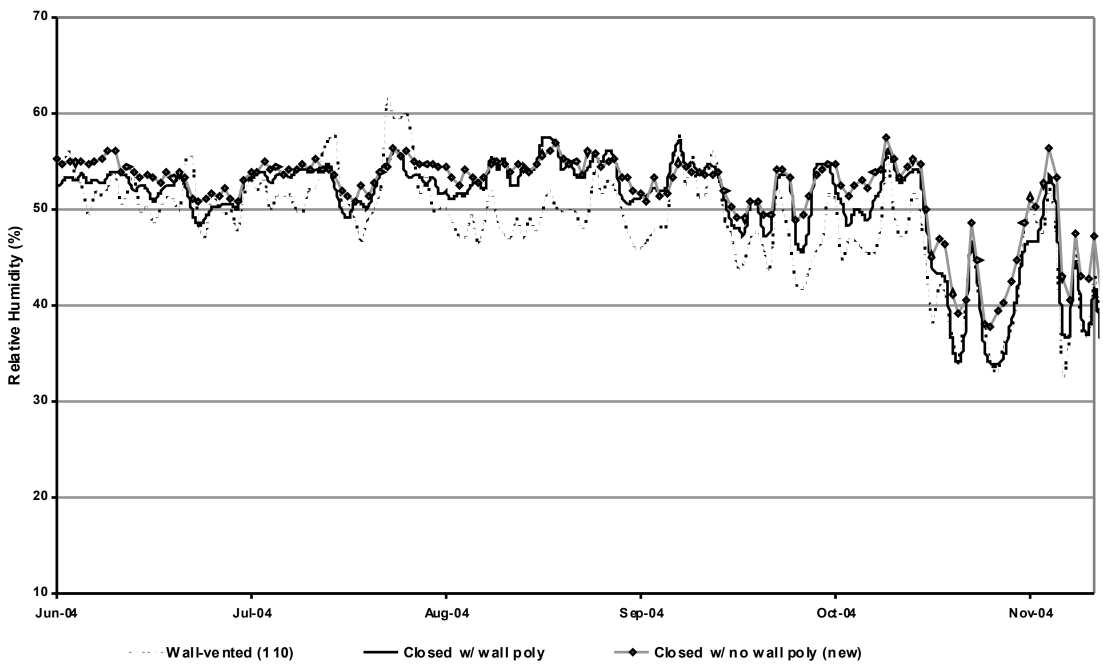


**Figure 41: Phase III relative humidity inside the conditioned space**

### 6.3.4 Crawl Space Temperature Comparisons

Figure 42 shows daily average crawl space temperatures during Phase II. While temperatures are fairly consistent among the different groups during the cooling season, there are significant differences in temperature during the heating season, with the closed crawl spaces remaining significantly warmer during the winter.

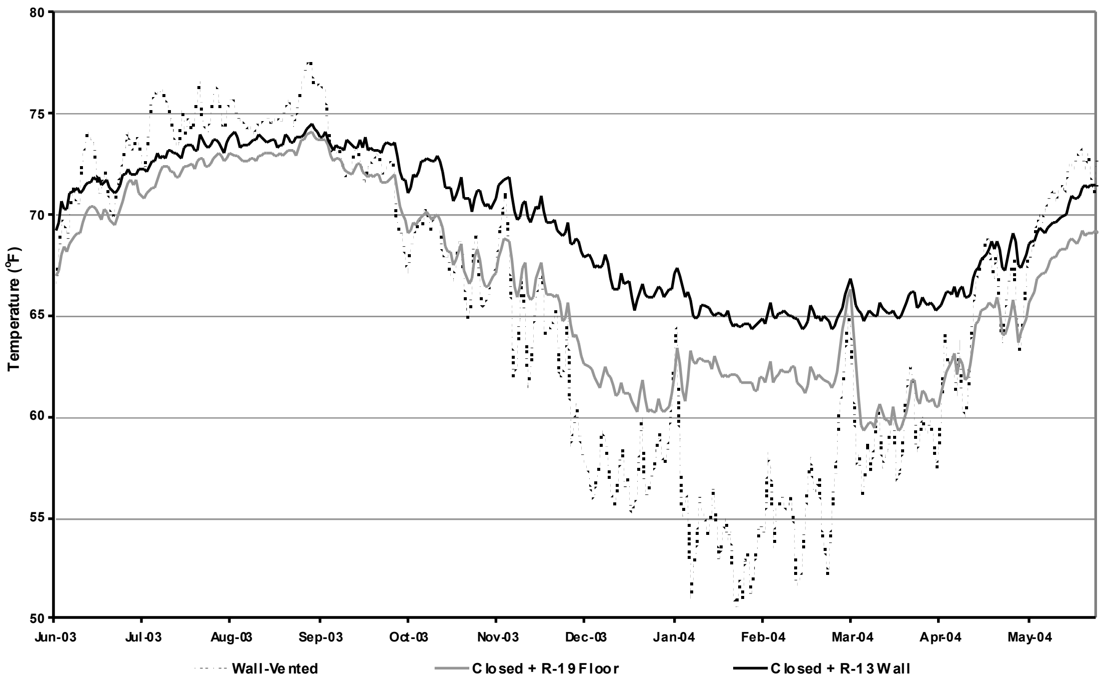


**Figure 42: Phase II crawl space temperatures**

Figure 43 shows outside dew point temperature and crawl space temperatures during the summer of 2003. Note that the vented crawl space temperature is just slightly above the outside dew point for the majority of the time, indicating that there is high condensation potential when outside air enters the crawl space, as is the intention of the design. Even during the drought summer of 2002, graphed in Figure 44, there are periods when the outside dew point temperature is higher than the crawl space temperature despite what would expected to be more favorable conditions for crawl space drying. The data plotted is the daily average readings over all the homes in each group.

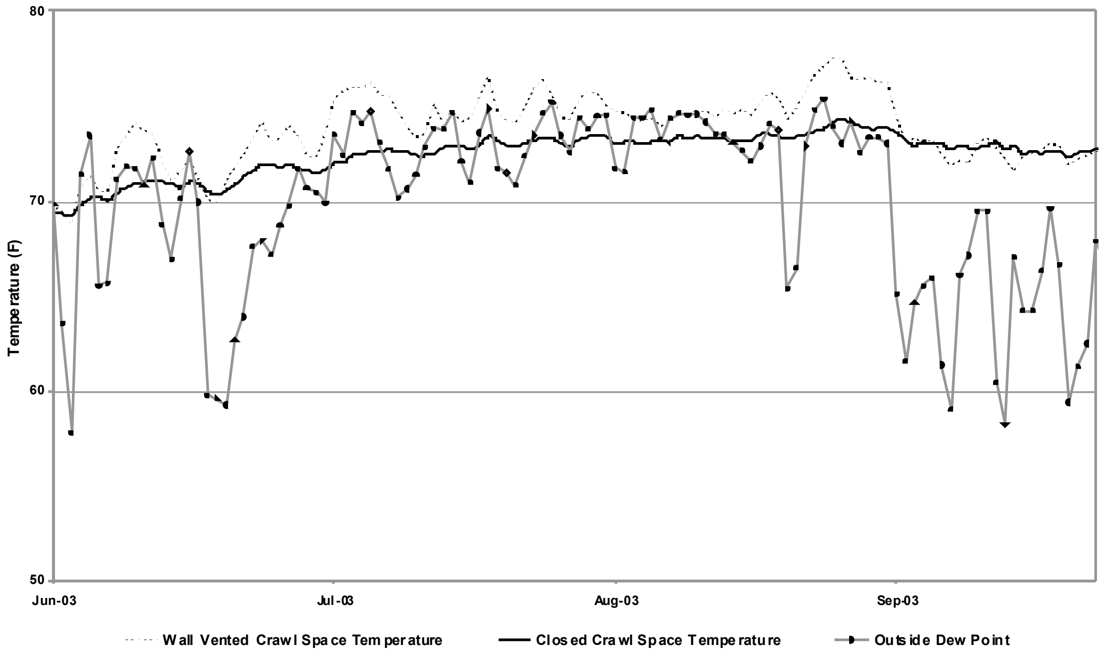


**Figure 43: Summer 2003 crawl space temperature and outside dew point**

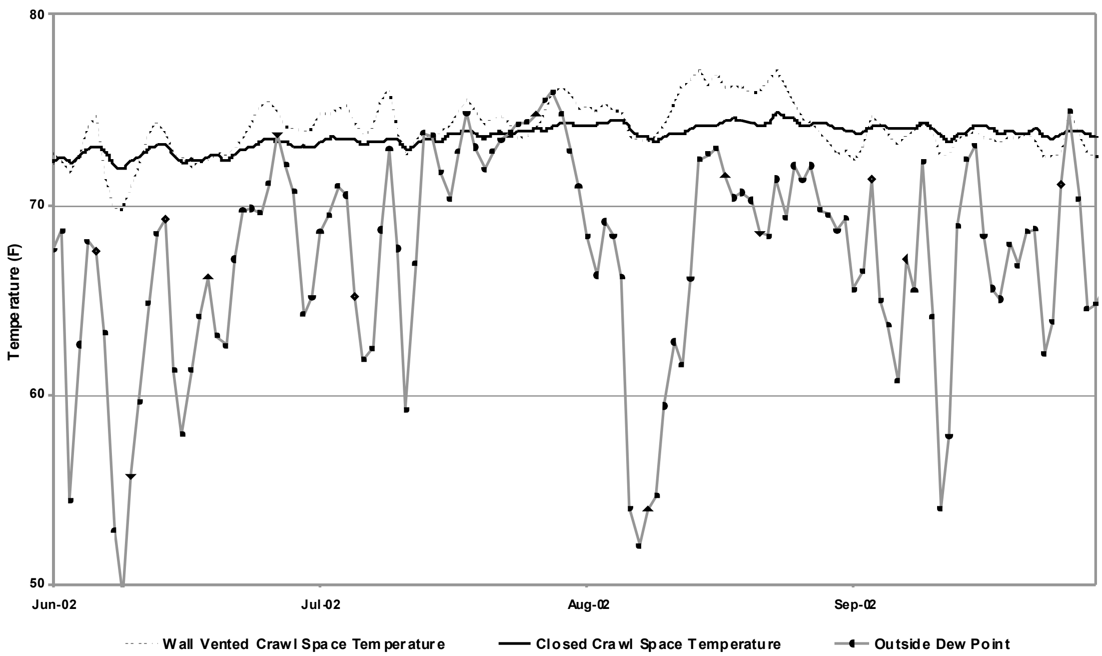


**Figure 44: Summer 2002 crawl space temperature and outside dew point**

Figure 45 shows a detailed view (using 15-minute interval data) of a worst-case 48 hour period of very humid conditions in which the outside dew point is above the wall-vented crawl space temperature for the majority of the time. If this outside air enters the wall vented crawl spaces, the water vapor in the air will condense on surfaces inside the crawl space. This was not a period of heavy rainfall; less than 0.2 inches of rainfall were recorded in the area during this period. However, these conditions are easily capable of fostering mold germination and growth activity.

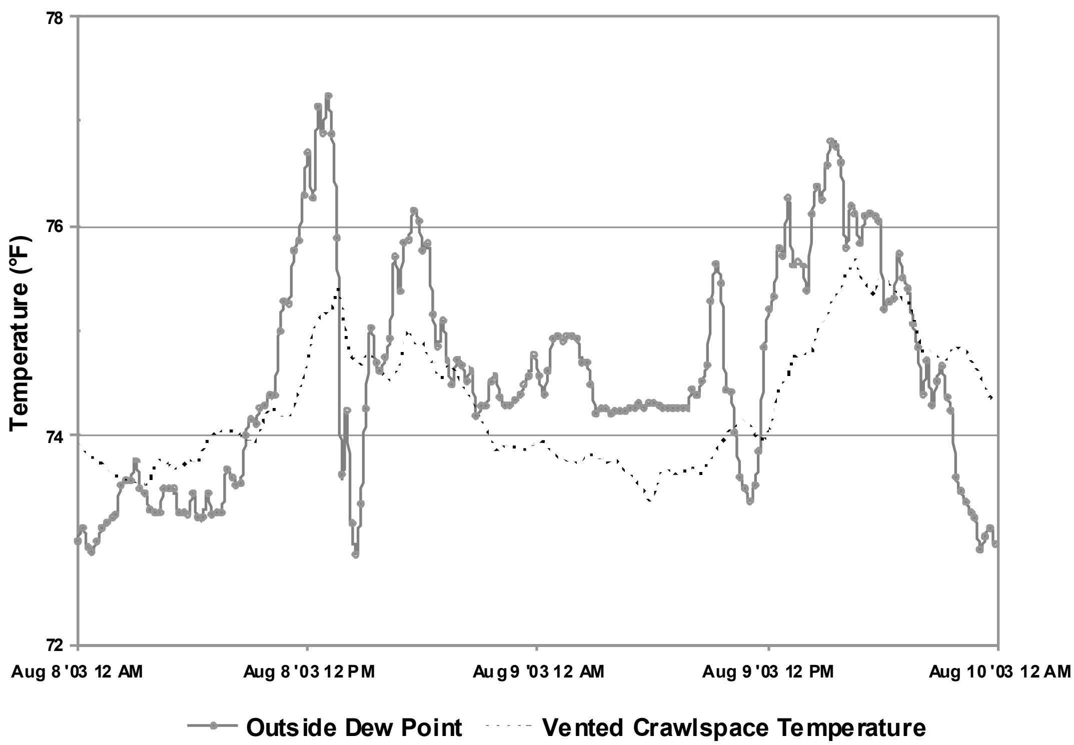


**Figure 45: Summer 2003 detail: outside dew point and vented crawl space temperatures**

### 6.4 Wood Moisture Readings

Another component of data acquisition involved measuring the moisture content of the wood in the crawl space. The two objectives of this component are to compare the wood moisture content in closed versus wall vented crawl spaces and also to observe the variation in wood moisture over time and based on location within the crawl space. As stated earlier, ten wood moisture readings were taken in each crawl space:

1. the sill plate next to the access
2. band joist next to the access
3. sill plate at worst location
4. band joist at worst location
5. center beam in the middle
6. floor joist next to access below insulation
7. floor joist next to access above insulation
8. floor joist at worst location below insulation
9. floor joist at worst location above insulation
10. sub-flooring in the center

These locations were marked and numbered with a black permanent marker. During Phase I, the "worst location" was defined to be above the water service penetration in the foundation perimeter wall. In October 2003, we changed the definition such that the "worst location" readings (# 3, 4, 8, 9) were taken behind the attached porch at the rear of the house. Anecdotal evidence from pest control industry stakeholders indicated that attached porches are a higher-risk area for water damage in residential structures, which spurred the change. In addition, the center beam and subfloor sample sites (# 5, 10) were replaced by a joist and subfloor site located midway between the center beam and the perimeter of the foundation in order to assess areas hypothesized to be at greater risk of moisture build-up.

Average wood moisture content (WMC) during the start-up of the site is shown for each group in Figure 46. The averages are based on all WMC readings except sub-floor and sill plate because of the misleading numbers that could result from OSB composition or pressure-preservative treatment. The experiment group's average WMC on July 17, 2001 showed a significant decrease after researchers began running dehumidifiers in these spaces at the beginning of July. The average WMC in both experiment groups continued to stay low, less than 10%, one month after researchers turned off the dehumidifiers at the end of July. WMC then increased slightly over the next two months.

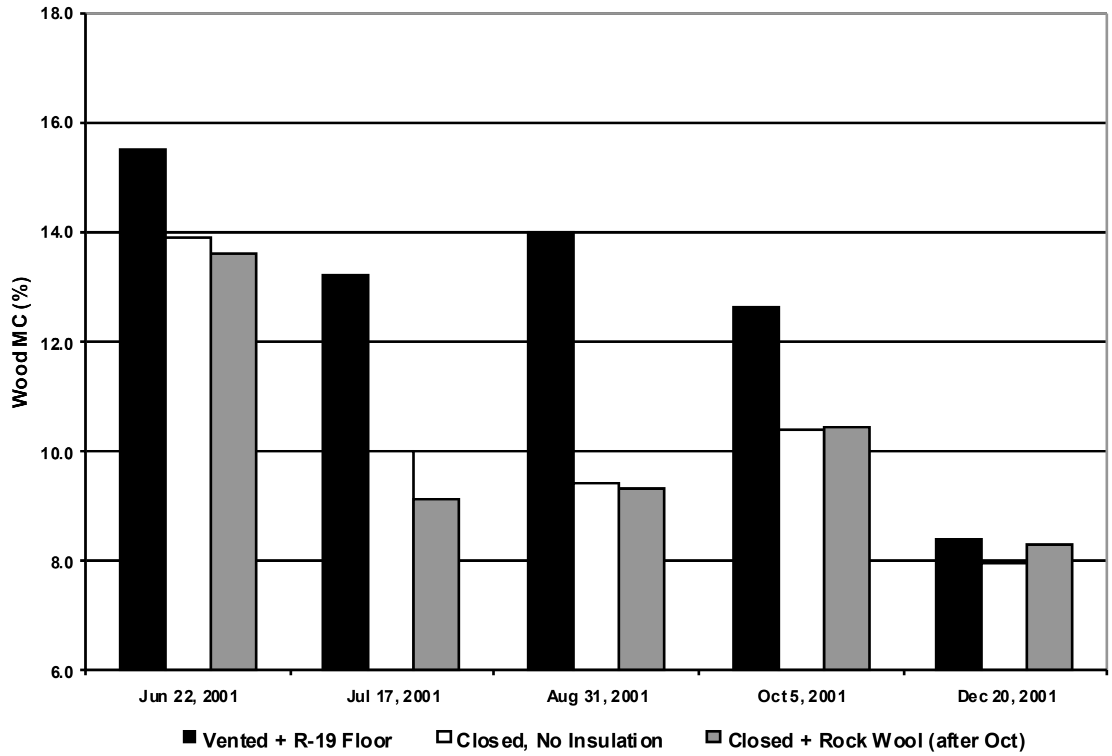


**Figure 46: Phase I Average WMC**

Note that the average WMC of the control homes also decreased. The first wood moisture reading on all homes was done on June 22 and sealing work was not complete on all homes by this date. The original vapor barrier coverage for the control homes was estimated to be about 60%. However, by the second reading July 17, complete vapor barriers had been installed for a couple of weeks, plumbing problems were repaired, and drainage was made away from crawl space access. These modifications coincide with the decline in wood moisture content, which decreased about 2 percentage points by July 17. Taking these moisture sources away from the crawl space is important.

Figure 47 shows the maximum WMC readings in any of the crawl spaces in each group, again excluding the OSB sub-floor and pressure-treated sill plate readings. These readings support the indication from the averaged data that ground cover improvements and repairs to plumbing and drainage make a significant improvement in the wall-vented crawl spaces, and that dehumidifier operation is a quick and effective way to control accumulated moisture.

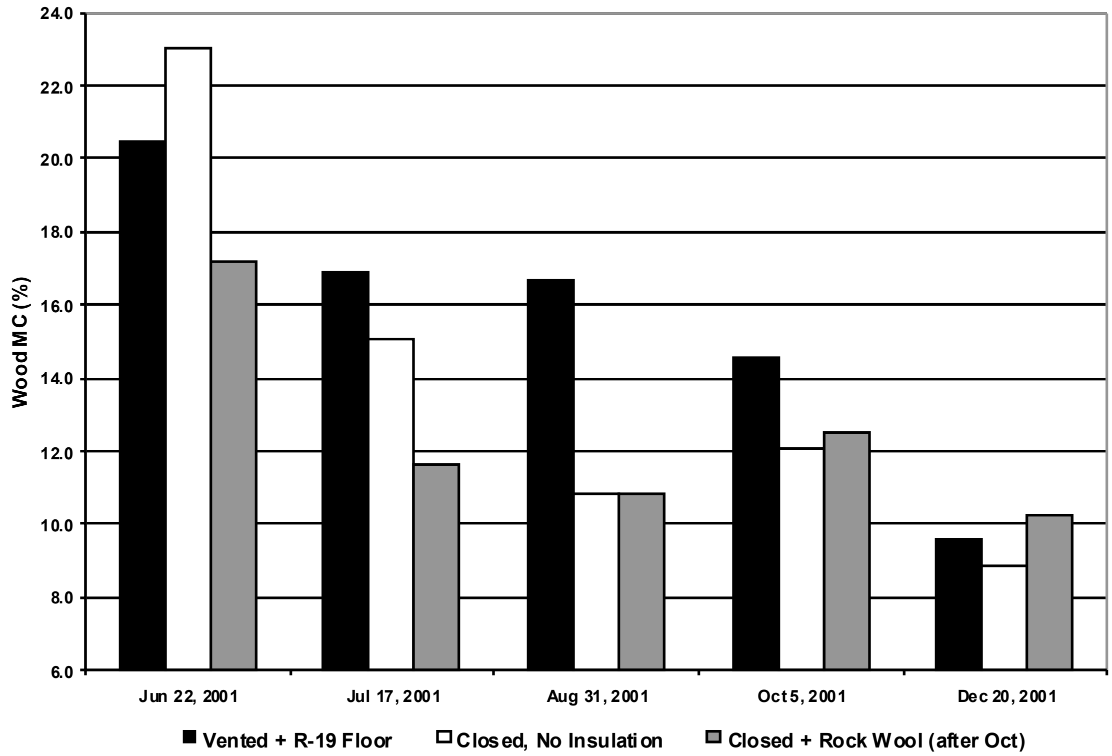


**Figure 47: Phase I Maximum WMC**

Phase II average and maximum WMC readings are shown in Figures 48 and 49. The maximum WMC values above 14% recorded during August, October, February and April occurred in the band or floor joist at the new "worst location" measurement site behind the back porch attachment.

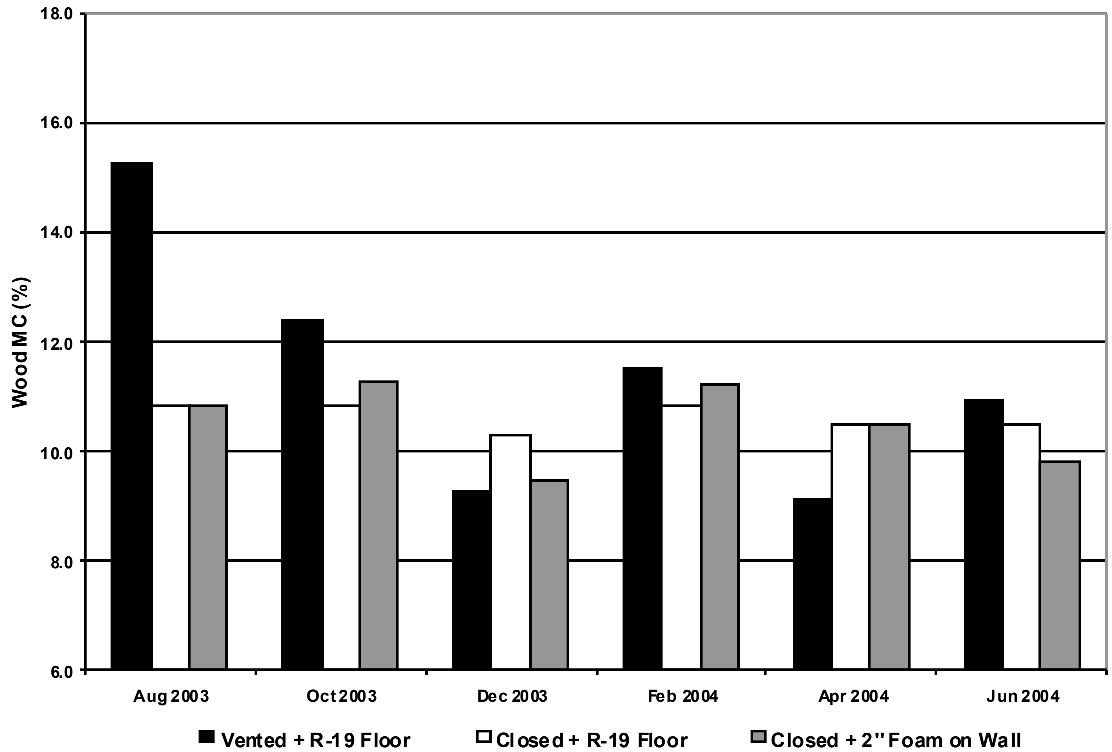


**Figure 48: Phase II Average WMC**

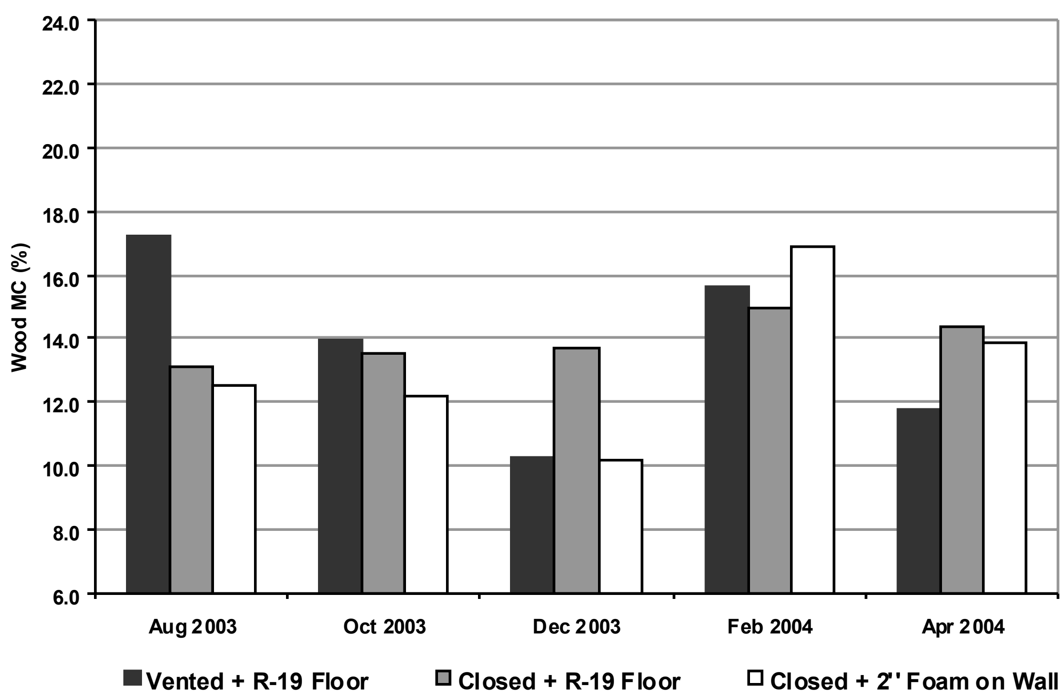


**Figure 49: Phase II Maximum WMC**

Both average and maximum WMC are combined in Figure 50 for the one month's reading at the beginning of August in the Phase III experiment configuration. The lone remaining wall-vented home (110) exhibits levels consistent with previous years' summer performance. Meanwhile, the three control homes that were converted to the experiment 3 group at the end of June, 2004 (by sealing the foundation vent openings and installing a crawl space supply duct without sealing the ground vapor retarder or installing any wall vapor retarder material) quickly exhibited performance similar to that of the other closed crawl space designs.

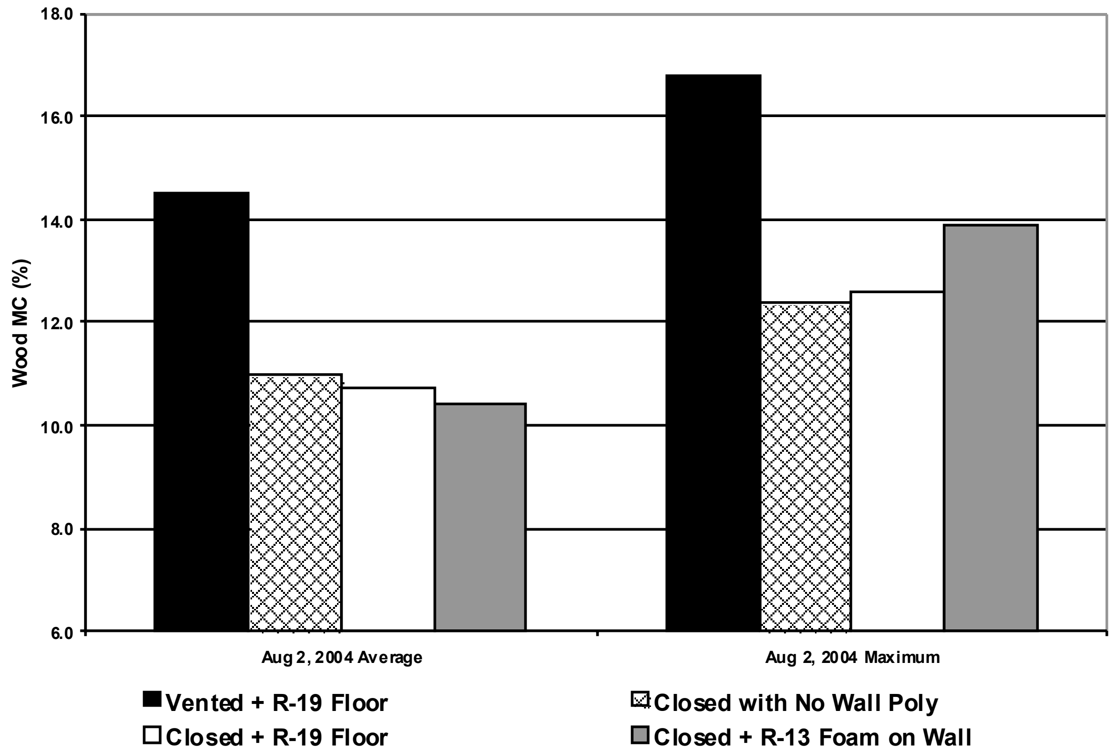


**Figure 50: Phase III Average and Maximum WMC**

## 6.5 Mold

### 6.5.1 Introduction

In analyzing the performance of crawl spaces, it is important to consider the impact of mold. Crawl spaces can provide an ideal environment for mold to grow. Mold growth can damage the integrity of some building materials. And exposure to mold growth can cause adverse health effects to the home's occupants.

Health effects associated with mold exposure are of four types: allergy, irritation, infection, and toxicity. The most common health effects are allergic reactions and asthma events. The symptoms 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 a nerve ending in the back of the throat (trigeminal nerve) that reacts to pungency and irritation. People are sometimes infected by molds. Generally, people become colonized by molds only if their immune system is not functioning well.

The most frequent infections are by *aspergillus* species, which may colonize lungs or mouth. A recent study at the Mayo Clinic found evidence of active *aspergillus* growth in lavages from the sinus cavities of people suffering from chronic sinusitis. Some molds produce toxins (mycotoxins). The toxins are not produced as part of the act of living, as the compounds from respiration and nutrient decomposition are. They are produced only some of the time by some of the species. It's 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. The toxins do exist and some of them are very toxic. For example, the toxicity of satratoxin is on a level with nerve gases like VX (LD50 less than 1 mg/kg).

Mold, together with mushrooms, bracket fungi, and puffballs are fungi. These organisms consist of a mat of hair-like strands (hyphae) that form the 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 reproduces by sending microscopic spores sailing on the breeze or floating on rainwater. A small colony may release millions of spores. When it's 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 to them.

In order to sprout and grow into a colony, spores need to have a location that provides water, a source of carbon, temperatures between 45 and 100 degrees F and no direct sunlight. 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 exude enzymes that are good at digesting sugars and starches, but are not good at digesting cellulose (*stachybotrys* and *fusarium* are able to digest cellulose). Wood decaying fungi are the organisms that actually decompose solid wood. For solid heartwood with intact cell walls, mold growth is limited to the surface. It can be cleaned up and the wood salvaged. Composite materials consisting of bits of wood and adhesives that mold enzymes can digest can be structurally degraded by molds. Composite materials must be dried and cleaned very quickly to prevent damage.

For this study, the mold inspection and sampling strategy was developed to assess:

- whether mold growth was occurring in crawlspaces,
- if mold was being transported into the occupied space,
- whether crawlspace detailing had a significant effect on mold growth.

The inspection protocol included visual inspection for mold growth and moisture problems in the crawl spaces, moisture content measurements of wooden materials in the crawlspace (as documented previously in this report) and both surface and air sampling for mold spores. Surface samples of suspect sites were taken using clear tape (which was examined microscopically) and sterile water swabs (which were cultured).

As stated previously, there were many grading problems on site. Unfortunately, the extent of the grading problems was not realized until after a few days of heavy rains. A couple of crawl spaces had water coming in due to heavy rain. In F108, the doorway had a puddle on Friday, June 15. This house also experienced a major plumbing leak that saturated the flooring. Drainage was trenched away from the crawl space door for several houses. There was no vapor retarder installed yet. By the next week, a major mold bloom had occurred. On July 13, all houses and crawl spaces were tested for both viable and nonviable spores to establish a baseline of bioaerosol presence in these homes.

Airborne fungal samples were taken at each home in the crawl space, on the first floor, and outdoors. Both viable and total spore counts were measured. Viable spores (those able to reproduce) were measured using an Anderson sampler. Anderson samplers consist of an inlet orifice, a perforated aluminum disk (with 200 holes) suspended just above the surface of nutrient in a petri dish, and an air pump. Air is drawn through the inlet, through the filters and out through the pump at the rate of 28.3 liters per minute (lpm). The sampler is designed so particles in the size range of fungal spores are collected on the sticky surface of the nutrient. Smaller particles, predominantly, pass out through the pump. The plate is incubated and the resulting colonies can be counted and identified by microscopic examination. The fraction of the 200 holes that grew a colony combined with the amount of air sampled forms the basis for calculating the number of culturable spores present in each cubic meter of air. If there are high concentrations of fungal spores or the sampling time is too long, colonies will grow at each pinhole location, so only an upper bound can be calculated.

In this study a total of 84.9 liters of air was drawn for each Anderson sample taken. The samples were then sent to Aerobiology Laboratory Associates, Inc. for incubation and identification.

The total spore count (those able to reproduce and those not) was established using a Burkard sampler. The Burkard sampler draws particles through a slit and deposits particles by inertia onto a greased glass slide at a flow rate of 10 lpm for a period of nine minutes. The Burkard samples were also sent to Aerobiology Laboratory Associates, Inc where microscopic counting and identification of fungal matter was performed.

The protocol for taking samples included the following requirements:

- Crawl space samples were taken at center of crawl, near the Hobo data loggers, approximately 12" above the earth floor.
- Double samples were taken simultaneously on the Burkard sampler and sequentially with the Anderson sampler.
- Tape and swab wipe samples were taken at the same time as the air samples.
  - Tapes and wipes of visible growth were chosen to reflect variation.
  - Where there was little or no visible mold in the crawl space, the technicians sampled locations that appeared likely to support mold growth.
  - Tape and swab wipe locations were marked by the technicians.
- Conditioned space air samples were taken near the return grill with the air handler running.
- No tape or swab wipe samples were taken in the conditioned space.
- Outdoor air samples were taken at multiple locations (two samples at each location), approximately 12" off ground, spread across the field site. The outdoor samples were taken in both the morning and afternoon.

### 6.5.2 Sampling Uncertainty

Interpreting the results of fungal sampling is fraught with sources of uncertainty. Generally accepted practice, as laid out in the ACGIH Bioaerosol guidance, 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 may be growing inside the building. Unfortunately, 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.

Difficulties in interpreting bioaerosol samples:

- Airborne fungal spore concentrations vary a great deal over the course of hours, days, weeks, and seasons. The concentrations are effected by events over which the person collecting the sample has no control. Variations are the result of spore release and transport dynamics, e.g. spore setting strategy of species present, moisture availability, substrate drying or wetting, temperature, change in temperature, reservoirs of settled spores, disturbance of settled spore reservoirs
- There are no consensus numerical standards to which test results can be compared.

- Viable spore samples are a fractional subset of the total spore count. They represent the species that can best compete on the collection nutrient at the temperature and relative humidity they were exposed to during the incubation period. So, it is likely that there are viable spores present in the sample that did not compete well under culture conditions. They have better collection efficiencies for the smaller diameter spores (e.g. *penicillium* and *aspergillus*) than total spore samplers. Viable spore counts can be speciated better than total spore counts (only morphologically distinct spores can be speciated by microscopic examination. Speciation provides better evidence for distinguishing whether there is mold growth in a building (e.g. inside 250 cfu/m3 *penicillium chrysogenum* and outside 300 cfu/m3 *polonicum* indicating that the indoor spores may not have originated outdoors but are from indoor mold). *Chrysoginum* and *polonicum* cannot be distinguished by microscopic examination of a total spore count plate, so you'd have only 250 cfu *penicillium* inside to 300 cfu outside and nothing could be said.
- Many of the smaller spores pass right through the spore traps like the Burkard, so it is likely that the *penicillium* and *aspergillus* species will be under counted in spore trap results.

### 6.5.3 Results

Samples were taken in the crawl spaces, conditioned spaces, and outdoors in July of 2001 and again in September of 2002. The results of the sampling from 2001 are presented in Figures 51-56. The first two figures show the results of the Anderson viable spore samples for the outdoors, the crawl space, and the first floor. The second two figures show the results for the Burkard total spore samples for the outdoors, the crawl space, and the first floor. Because of the extreme differences between first floor, outdoor, and crawl space concentrations, outdoor sample results are shown on all graphs to make comparisons easier. Indoor first floor levels are the lowest, crawl space levels far and away the highest, and outdoor levels in between.

- Total spore counts are significantly higher in the vented crawl spaces than in the experiment crawl spaces. Levels in the crawl space in the experiment houses 100, 103 and 106 are actually lower than outdoor levels.
- Viable and total spore counts upstairs are much lower than outdoor levels in all houses. Houses 100 and 109, with experiment crawl spaces have very low counts on both viable and total samples. Houses 107 and 110, both with vented crawl spaces, have the highest total and viable counts upstairs. Viable levels in these two houses are several times higher than the upstairs levels in the rest of the houses.

- Large numbers of mold spores existed in the crawl spaces at the time of the measurements. These levels are among the highest reported in the literature. Generally, viable and total spore counts in the tens of thousands are found only in the presence of very large sources – e.g. harvesting fields, contaminated rooms, composting facilities. In the case of these crawl spaces, there are 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 may have contributed to crawl space levels being as strikingly high as they were.
- *Penicillium* species dominate the indoor crawl space and first floor viable samples and were present in all the tape lifts and swab samples. *Penicillium* levels were significant in the outdoor viable samples as well, but are only a tiny fraction of the outdoor total spore counts. In addition, the viable *penicillium* counts in crawl spaces sometimes were greater than the total spore count found by the Burkards. These results may be explained by three factors. Anderson samplers are more efficient at sampling the small spores like *penicillium* than Burkard samplers. A great deal of the mold growing in the crawl spaces was *penicillium* (supported by the tape lifts and swab samples) so there were lots of fresh *penicillium* spores present in the crawl space. When viables are greater than total, it may be because, when stirred, dust draws whole heads of pen/asp spores into the sampler which then break up and fill all the holes.
- The total spore counts in the crawl space indicate that *penicillium/aspergillus* species are growing in the crawl space and that very little material is getting inside from outside.
- The levels upstairs are very low compared to the crawl space levels, and are generally lower than outdoor levels. However, there are relatively high viable *penicillium* levels on the first floor in Houses 107 and 110 providing some evidence that *penicillium* is growing upstairs or that air is more easily transported from the crawl spaces to the upstairs in these houses. In addition, viable samples found some *aspergillus* species on the first floor of houses 105 and 107. There's none present in the viable samples taken outdoors or the crawl space in 107. In the crawl space in house 105 there is only a tiny amount of *aspergillus* present. This is evidence that *aspergillus* may be growing upstairs in these two houses.
- The hurricane and consequent flooding may well have played a dominant role in the development of mold blooms.

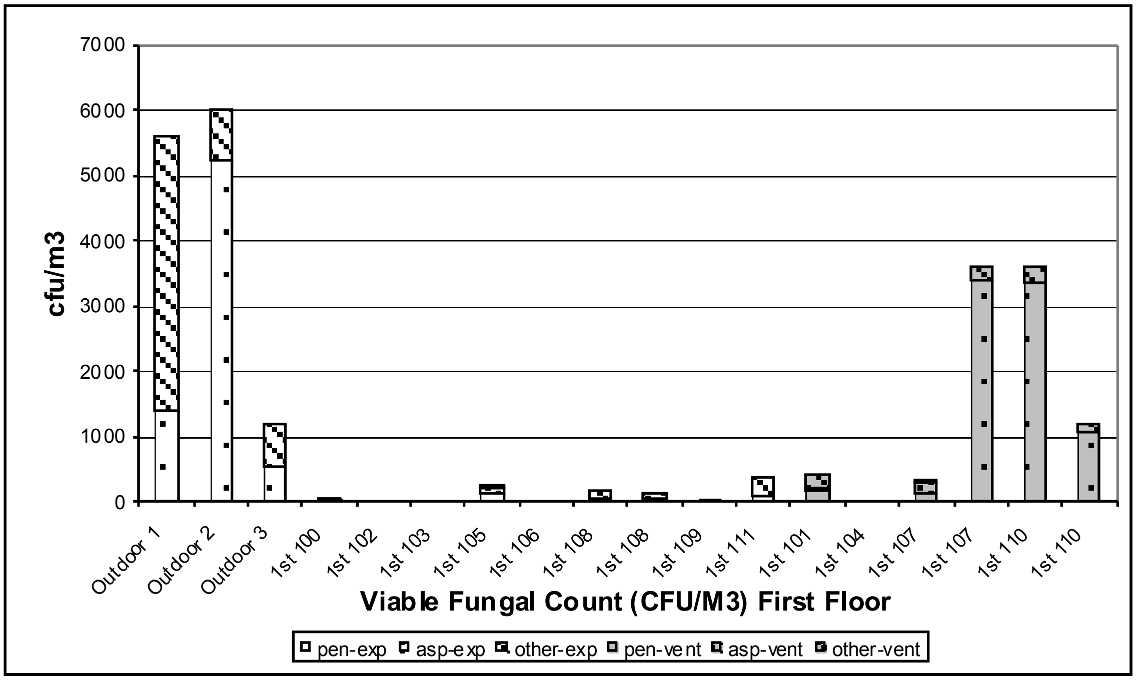


**Figure 51: Notice that all viable counts on the first floors are lower than the outdoor levels.**

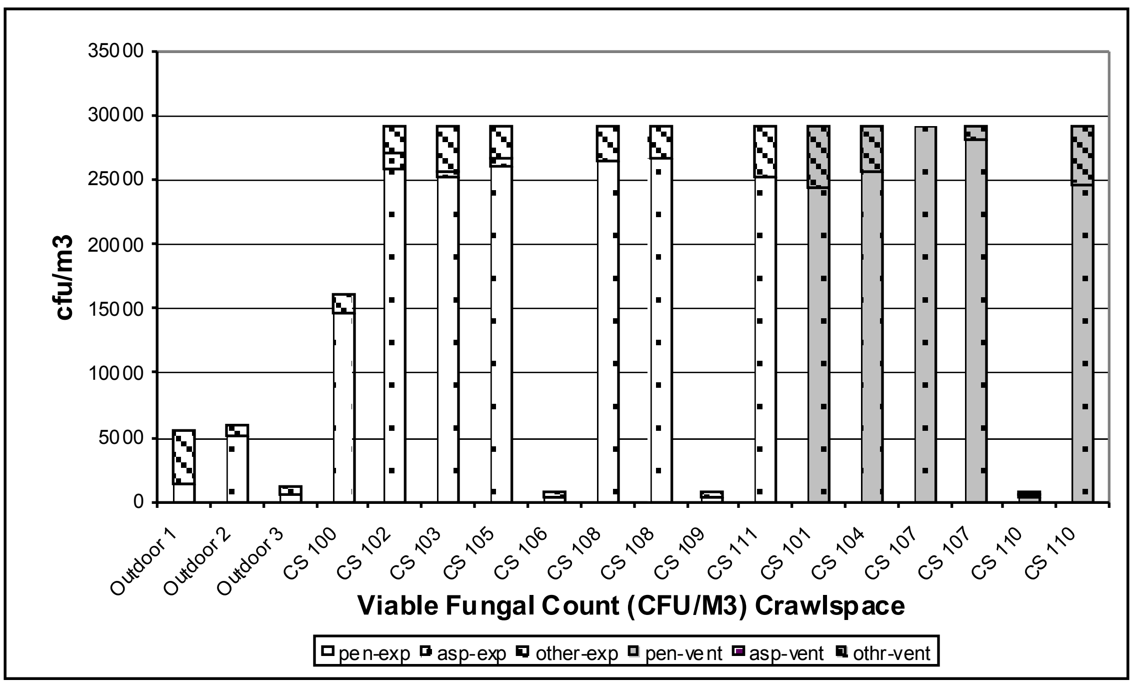


**Figure 52: It is clear that penicillium species dominate the crawl space levels. Very low levels in 106 and 109 are interesting given the sampling method probably biased the results on the high side and very little penicillium is present in these crawl spaces.**

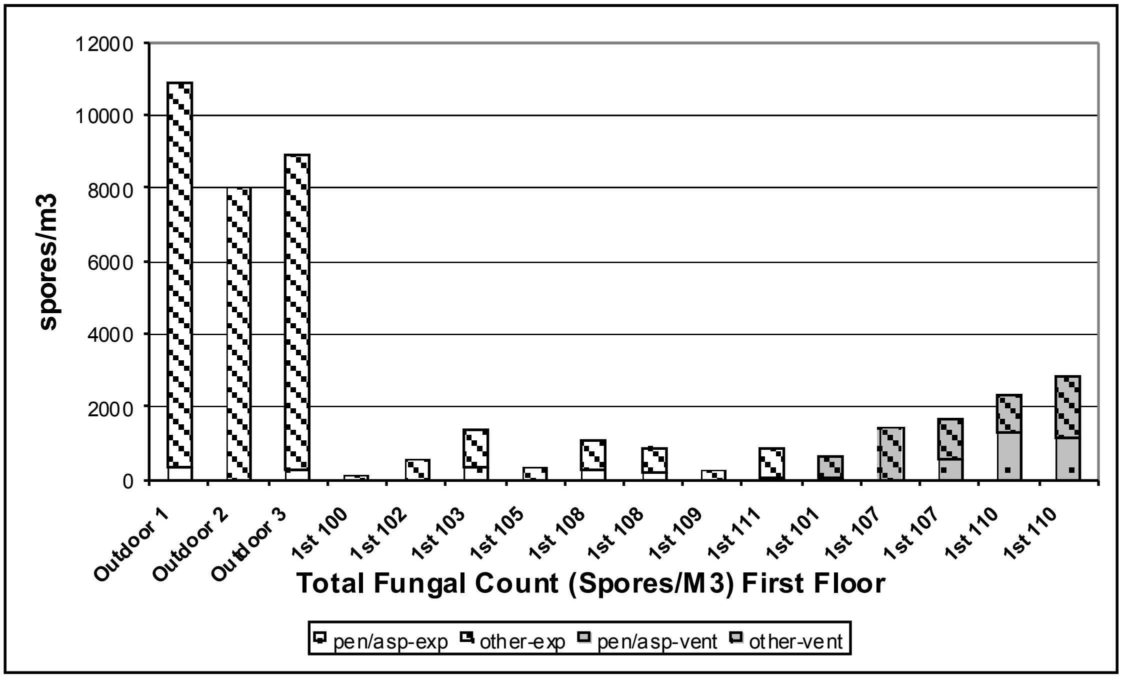


**Figure 53: Total spore counts in the upstairs show evidence of outdoor air contribution, but are all much lower than outdoor air. Cladosporium and hyphal fragments are present in both the indoor and outdoor samples.**

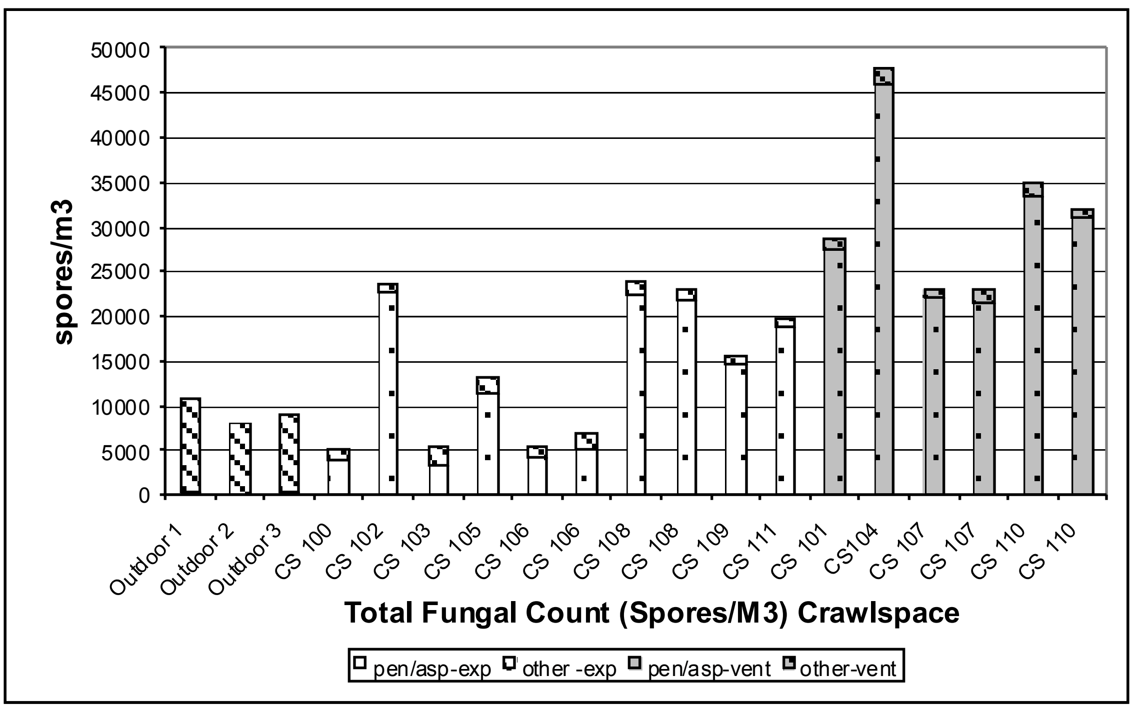


**Figure 54: Total spore counts in the experiment crawl spaces are generally lower than in the control crawl spaces.**

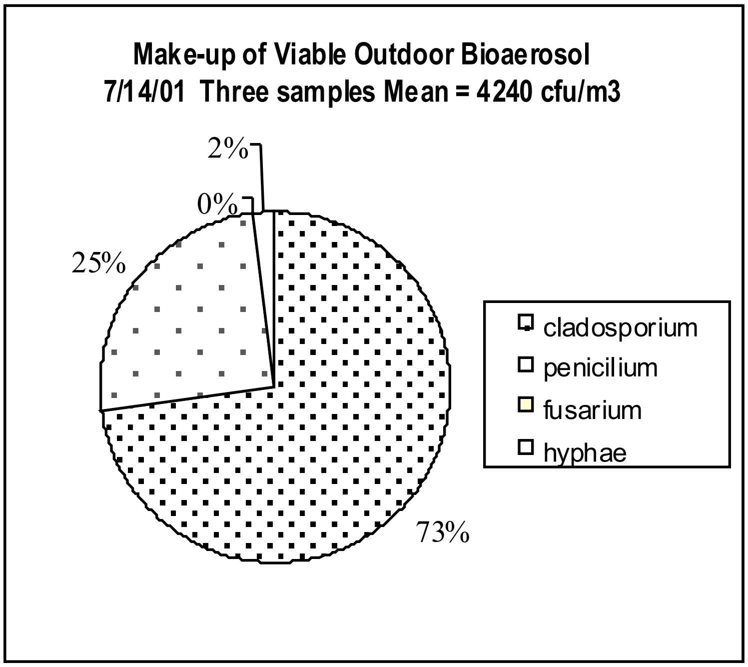


**Figure 55: Unlike the indoor viable samples, which are dominated by penicillium, the outdoor samples are dominated by cladosporium, followed by penicillium.**

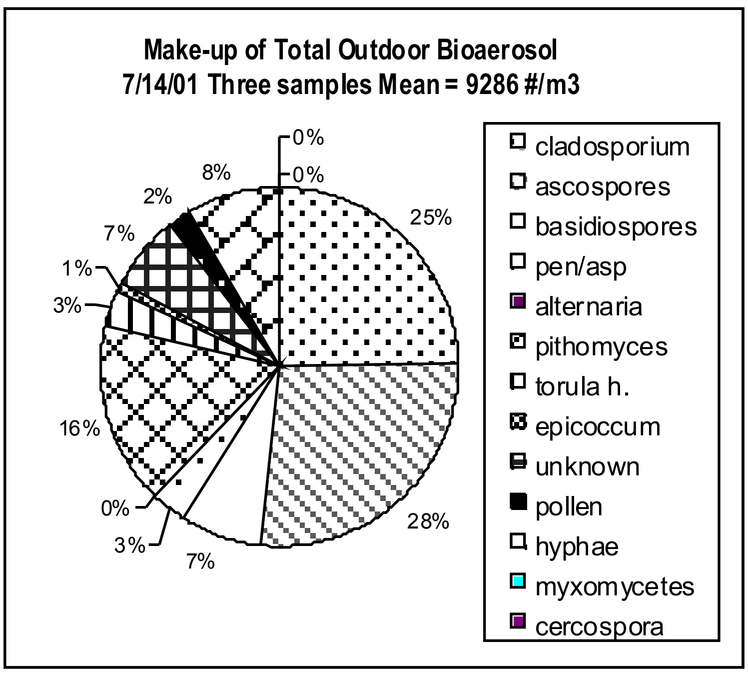


**Figure 56: Total spore sample outdoors are dominated by ascospores, cladosporium and pithomices. These are not surprising, commonly found in outdoor air.**

Tape lifts and swab wipe samples were taken in all crawl spaces. The results are reported in Tables 23 and 24. These samples were taken from visible mold colonies in crawl spaces. They support the bioaerosol data, identifying penicillium as the dominant colonizer in the crawl spaces.

| Sample ID | P/A | Clad | hyphae | conidophores | |
|---|---|---|---|---|---|
| 100CT1 | 1 | | | | |
| 100CT2 | 1 | | | 1 | |
| 101CT1 | 1 | 1 | 1 | | |
| 101CT2 | 1 | 1 | | 1 | |
| 103CT1 | 1 | 1 | 1 | | |
| 104CT1 | 1 | | | 1 | |
| 105CT1 | 1 | | | 1 | |
| 106CT1 | 1 | | | | very few spores |
| 107CT1 | 1 | 1 | | | |
| 107CT2 | 1 | 1 | | 1 | |
| 108CT1 | 1 | | 1 | | |
| 110CT1 | 1 | | | 1 | |
| 111CT1 | 1 | 1 | | 1 | |

**Table 23: Tape lift results.**

| Sample ID | CFU/IN2 | Pen | asp. | Clad | aureo | asp glaucus | description |
|---|---|---|---|---|---|---|---|
| 104CW1 | 190000 | 78 | | 9 | 13 | | grey/green |
| 105CW2 | 200000 | 100 | | | | | paprika |
| 106CW1 | 21000 | 4 | | | 96 | | white powder |
| 107CW1 | 600000 | 67 | | 33 | | | grey/brown dots white center |
| 107CW2 | 180000 | 83 | | 6 | | 11 | red center white |
| 108CW1 | 140000 | 24 | 63 | | 13 | | thick black dots |
| 110CW2 | 79000 | 15 | | 46 | 38 | | |

**Table 24: Swab wipe results.**

For the second round of samples taken in September of 2002, the air sampling procedure was modified so that there was minimal disturbance in the crawl space. Unlike the upstairs and outdoor samples, the crawl space samples are particularly susceptible to interference from dust raised by the technician doing the sampling. For these samples, the sampler was mounted at the end of a pole which was extended into the crawl space while the technician remained outside. All the samples collected in September of 2002 were viable spore air samples, which were taken with an Anderson N-6 sampler head and MEA culture plates.

Samples were taken at two experiment houses (102 and 106) and two control houses (107 and 110). At each house, samples were taken outdoors, in the crawl space, in the conditioned space near the heat pump return air grill with the air handler turned off, and in the conditioned space at a heat pump supply air duct termination with the air handler turned on.

The following observations can be made from the data:

- The outdoor, crawl space and first floor data are dominated by *cladosporium* species. *Cladosporium* is probably the most commonly found spore in outdoor air in much of the United States. The average crawl space levels are close to the average outdoor levels. The average first floor levels for both experiment houses are less than 10% of average outdoor levels (102 = 4%, 106 = 9%), while those for the control houses are significantly higher (107 = 17%, 110 = 42%). The level of *cladosporium* in the air of house 110 may indicate that *cladosporium* is growing in the house. The levels in the supply air samples are all very low, regardless of indoor concentrations, which is evidence that the return air filters are effective. In the first round of sampling the outdoor air samples were dominated by *cladosporium* while the indoor samples were dominated by *penicillium* species.
- For species other than *cladosporium,* crawl space levels are much lower in the 2002 sampling (a few hundred cfu/$m^3$) than in the 2001 sampling (5000 to 30000 cfu/$m^3$). Some of this difference can be explained by the change in sampling methodology in the crawl spaces: the pole mounted crawl space samples are much lower (by 50% to 75%) than samples taken by the technician crawling into the crawl space. However, it is likely that there is far less mold growth in the crawl spaces than there was initially.
- There is evidence of some mold growth in the crawl spaces, indicated by levels of organisms present at significantly higher values than in the outdoor air, and mold growth in the conditioned space, indicated by levels of organisms present at higher values than in the crawl space. For example, P. *oxalicum* is much higher in the conditioned space than in the crawl space of 110, *alternaria* is present at low levels in the conditioned space but not in the crawl space of 102, and *trichoderma* is present at moderate levels in the conditioned space but not in the crawl space of 107. There is also evidence that spores are being transported from the crawl space to the conditioned space: P. *oxalicum* is present in all the crawl spaces and conditioned spaces.

Table 25 summarizes the species that are likely to be growing in the crawl space and conditioned space of each house sampled in September 2002.

| House | Crawl space | Conditioned space |
|---|---|---|
| 102 (E1) | P. *oxalicum*, P. *citrinum* | P. *oxalicum*, *Alternaria* |
| 106 (E2) | P. *oxalicum* | P. *oxalicum* |
| 107 (C) | P. *oxalicum*, P. *citrinum* | P. *oxalicum*, *Trichoderma* |
| 110 (C) | P. *oxalicum*, *Trichoderma* | P. *oxalicum* |

**Table 25: Organisms likely to be growing, based on September 2002 samples**

Graphical results of the September 2002 sampling are presented by location (crawl space, conditioned space, and supply air duct) in figures 57, 58 and 59, respectively. Note that a number of organisms were present at very low levels (i.e., less than 3 spores in any one sample), which is too low to be useful as evidence for growth. Only organisms that were measured at levels greater than 3 spores per sample are shown in the figures.

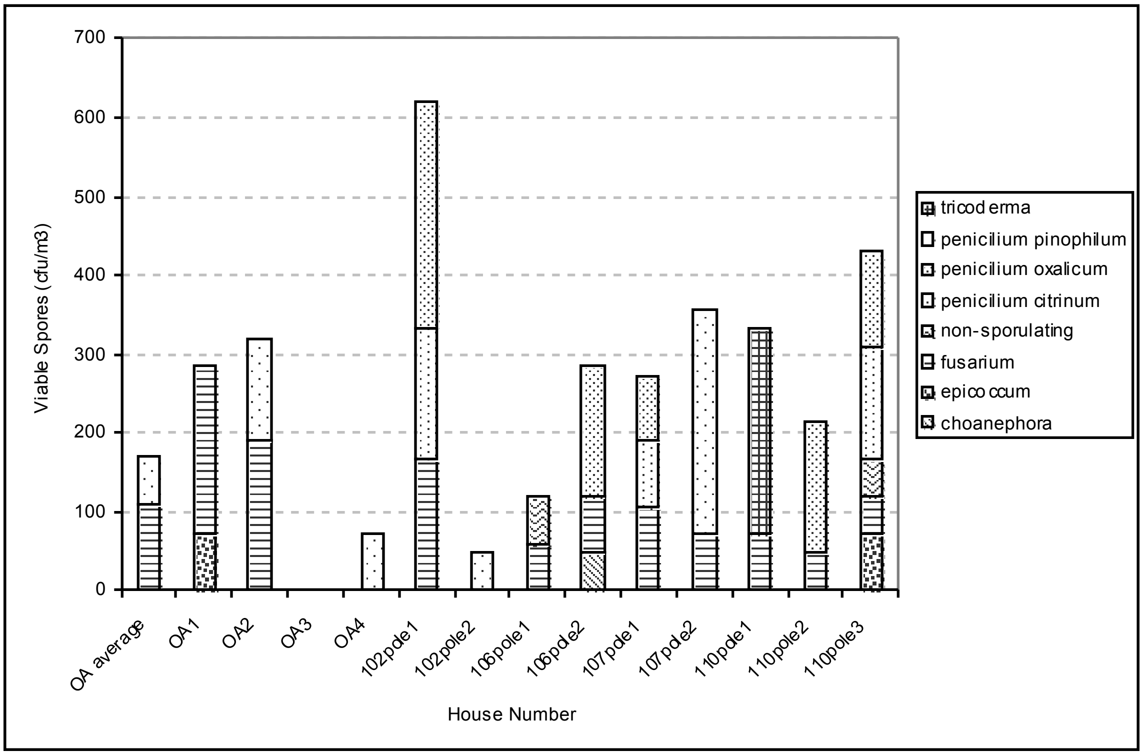


**Figure 57: Crawlspace viable spore counts, September 2002**

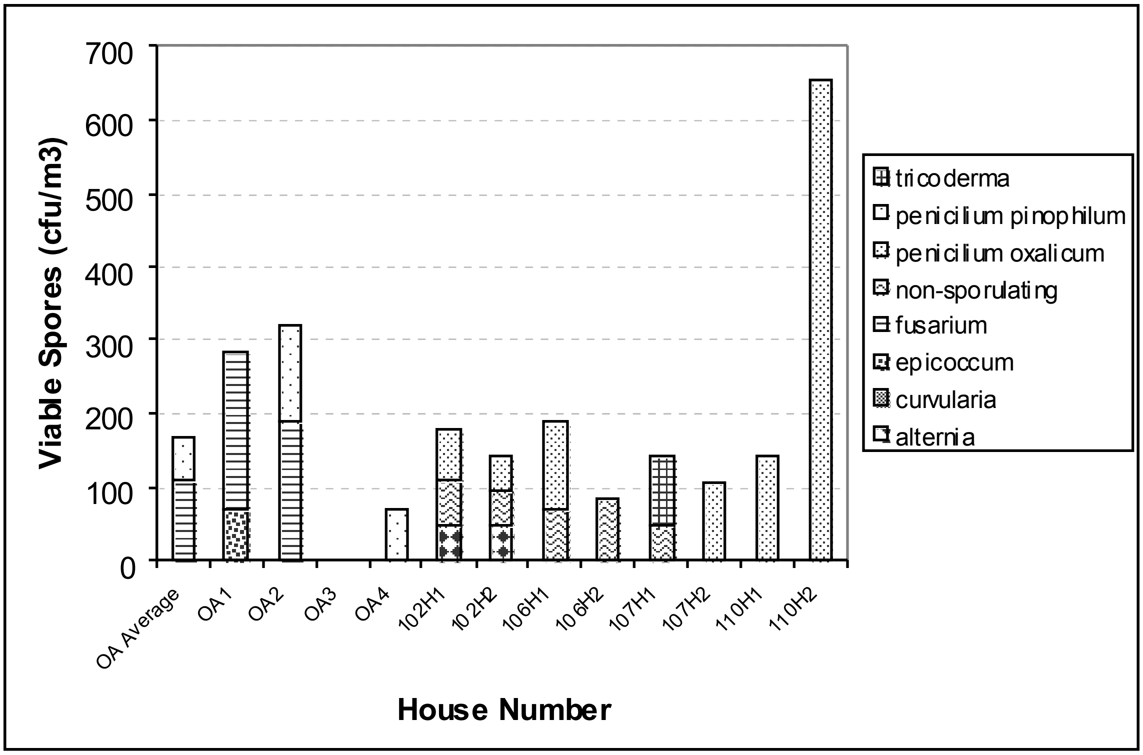


**Figure 58: Conditioned space viable spore counts, September 2002**

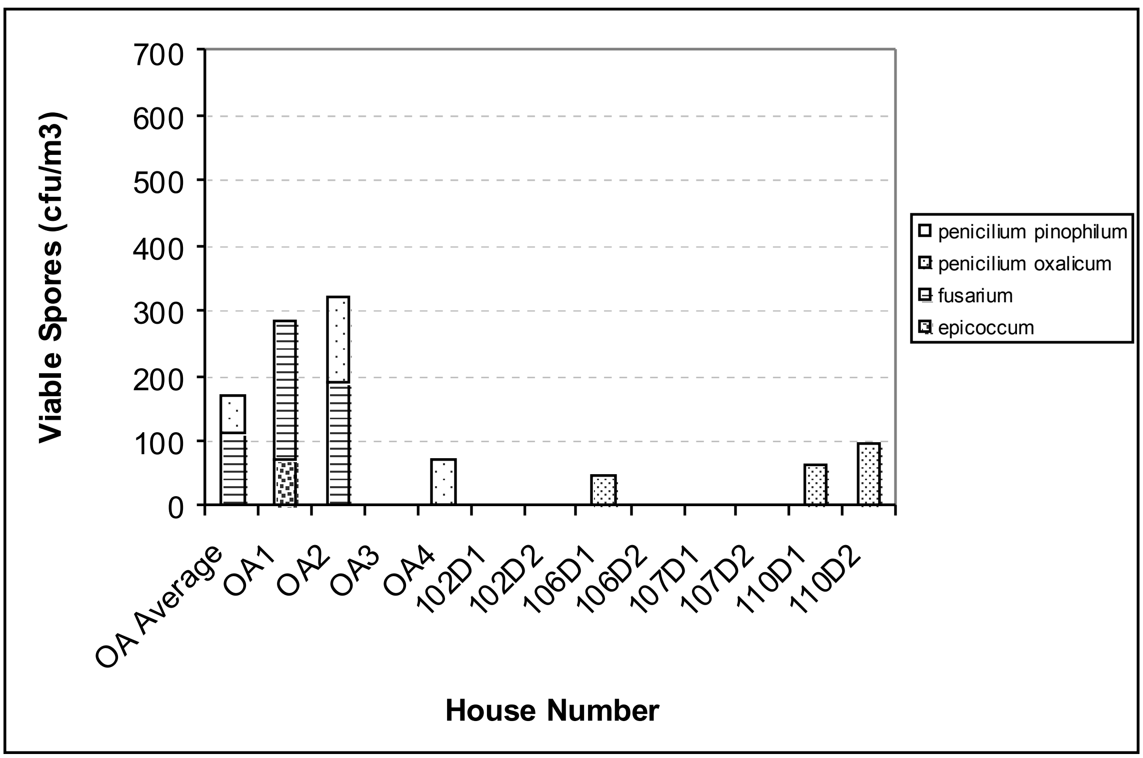


**Figure 59: Supply air duct viable spore counts, September 2002**

**6.6 Radon**

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.

To provide due diligence concerning the health of the homeowners, 48 – 96 hour radon canisters were placed in all the crawl spaces at the beginning of the study. Table 26 reports the results from crawl space monitoring performed during the initial phase of the summer 2001 field study work. As expected given the site location, the measured radon levels within the twelve crawl spaces are within safe levels, although one house (105) fell into the range of 2-4 pCi/L.

| House | Average Radon Concentration (pCi/L) |
|---|---|
| F100 | 0.3[1] |
| F101 | 0.6[2] |
| F102 | 1.9 |
| F103 | 1.7 |
| F104 | 0.5 |
| F105 | 3.4 |
| F106 | 0.8 |
| F107 | 0.4[2] |
| F108 | 0.6[1] |
| F109 | 1.4 |
| F110 | 0.4[2] |
| F111 | 1.8 |

***Note:***
*1- Results may or may not be accurate due to improper sealing of canister*
*2- Test results may be compromised due to excessive canister weight gain*

**Table 26: 2001 Short-term Radon Levels in the Crawl Space**

We subsequently installed long-term radon monitors during both Phase I and Phase II to evaluate radon levels in both the crawl space and conditioned space of each home.

Table 27 and Figure 60 show the results of the Phase I long term monitoring, which was carried out between July of 2001 and February of 2002. This monitoring indicated higher average concentrations in the conditioned spaces of the houses on closed crawl spaces, with measurements averaging 0.5 pCi/l in the vented crawl spaces and 1.9 pCi/l in the closed crawl spaces. This monitoring also indicated higher average concentrations in the closed crawl spaces versus vented crawl spaces, with measurements averaging 0.8 pCi/l in the vented crawl spaces and 2.9 pCi/l in the closed crawl spaces. The higher radon measurements in both the crawl spaces and the conditioned spaces appeared to be correlated with the closed crawl space foundations.

| House | House Radon Concentration (pCi/L) | Crawl Space Radon Concentration (pCi/L) |
|---|---|---|
| **Control** | | |
| F101 | 0.6 | 0.9 |
| F104 | 0.6 | 0.9 |
| F107 | 0.5 | 0.7 |
| F110 | 0.4 | 0.6 |
| **Exp 1** | | |
| F102 | 2.6 | 4.1 |
| F103 | 2.2 | 2.5 |
| F109 | 2.1 | 3.1 |
| F111 | 1.6 | 3 |
| **Exp 2** | | |
| F100 | 1.6 | 2.9 |
| F105 | 2.6 | 3.4 |
| F106 | 1.2 | 2.5 |
| F108 | 1.1 | 1.9 |

**Table 27: Long-term Radon Levels in the Crawl Space and Conditioned Space, July 2001 to February 2002**

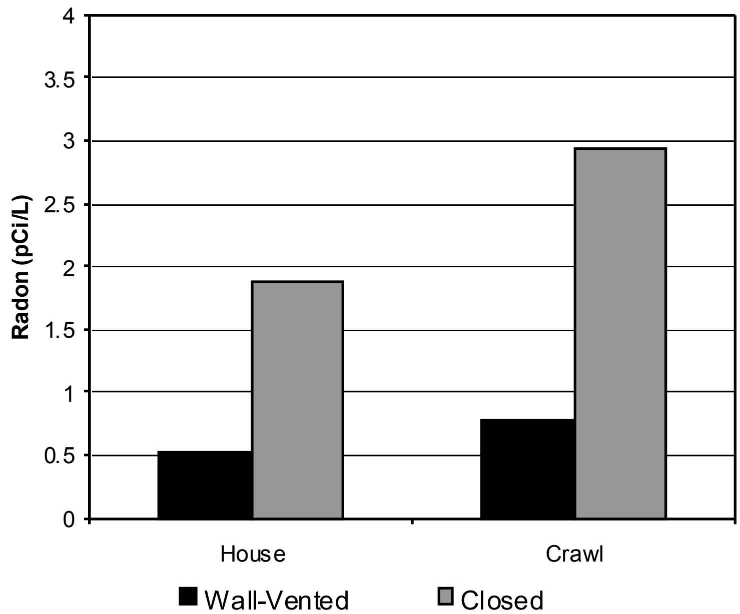


**Figure 60: Average Long-term Radon Levels by Crawl Space Design, July 2001 to February 2002**

Table 28 and Figure 61 show the results of the Phase II long term monitoring, which was carried out between July of 2003 and July of 2004. This monitoring indicated 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 conditioned spaces do not show any difference correlated with the type of foundation they are on; 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.

| House | House Radon Concentration (pCi/L) | Crawl Space Radon Concentration (pCi/L) |
|---|---|---|
| **Control** | | |
| F101 | 0.4 | 0.6 |
| F104 | 0.4 | 0.4 |
| F107 | 0.4 | 0.4 |
| F110 | 0.4 | 0.4 |
| **Exp 1** | | |
| F102 | 0.7 | 1.4 |
| F103 | 0.4 | 0.7 |
| F109 | 0.4 | 0.8 |
| F111 | 0.7 | 0.9 |
| **Exp 2** | | |
| F100 | 0.6 | 2 |
| F105 | 0.7 | 1.5 |
| F106 | 0.4 | 0.7 |
| F108 | 0.4 | 0.6 |

**Table 28: Long-term Radon Levels in the Crawl Space and Conditioned Space, July 2003 to July 2004**

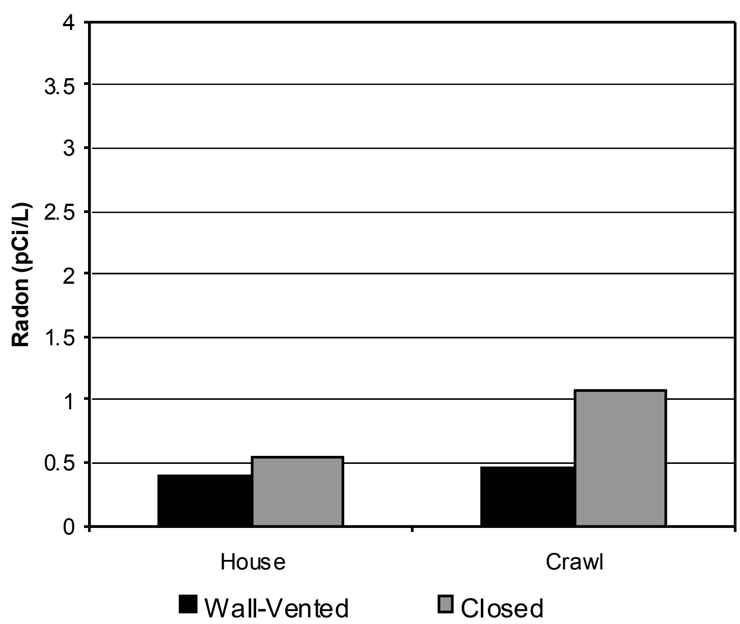


**Figure 61: Average Long-term Radon Levels by Crawl Space Design, July 2003 to July 2004**

# 7. Findings

## 7.1 General

The key finding is that the experiment design has successfully demonstrated field deployment of a variety of closed crawl space designs using off-the-shelf components installed by readily available labor resources and practical construction methods. The data that has been collected clearly shows significant differences between the control and experiment groups in all phases of operation in terms of energy and moisture performance. This is despite the fact that the study was conducted on occupied homes, where there are clear differences in occupancy and use of heating and air conditioning equipment.

The minimal-cost monitoring system was successful. This monitoring system utilizes Hobo Pro battery operated data loggers; three of which are installed in each home plus three that are installed in outdoor air locations. These units, which record temperature, relative humidity, dew point and absolute humidity levels, tolerated the high moisture levels that were demonstrated in the control group crawl spaces with few failures. Outdoor units failed more frequently, but data collection has been complete due to the redundancy of having multiple units in operation. Regular site visits were performed to measure all variables, to perform outside air filter changes and other routine maintenance, and to make timely repairs whenever they were required. In summary, there has been no significant data loss on any of the twelve monitored homes.

The 12-home sub-development of newly-constructed residences provided a clustered group of identical homes in terms of age, size, and climate. Within the group there are two, six home, subgroup conditions in terms of mirror-image floorplans, and two orientations. In addition to these similarities, the elevated site grading, which was in-filled to provide site flood protection, provided consistent soil conditions below and adjacent to all the crawl spaces. Further, all twelve homeowners volunteered to participate in the multi-year study. The owners remained cooperative and enthusiastic throughout the project, despite the fact that site visits and home inspections have been more frequent than originally planned. Lastly, the fact that all twelve homes are located at one site provided cost efficiencies in site data collection and maintenance.

The crawl space set up costs turned out to be close to three times more than was first proposed. There were several reasons for the cost increase. First, the May 2001 experiment design meeting specified additional site refinements. Second it was decided to add dehumidifiers to the eight experiment group crawl spaces and minimal ventilation systems to all twelve homes. Third, the set up work was very labor intensive even though the homes were brand new. Finally, site drainage problems that should have been resolved by the time certificates of occupancy were issued to these homes in May 2001 persisted until October 2001.

The crawl space construction techniques employed in this study should provide for long-term moisture control. The supplemental drying mechanism was provided by the house space conditioning equipment. Homeowners would be motivated to repair the system should it malfunction and thus will maintain the crawl space drying function. The airflow damper was manually set and should not require additional adjustment. The backflow damper on the HVAC supply air to the crawl space was a simple gravity model with a non-metallic hinge. The liner material is reasonably durable and repairable and there are more durable materials available for areas with heavy use. The outside ventilation air, brought in by the heat pump return duct, more than made up for the airflow to the crawl space and has an easily accessible filter. Air that would normally flow out of the house because of the outside air intake was used to dry the crawl space. The homeowner was provided with a remote sensing temperature and relative humidity meter so that they would be able to be informed if the crawl space relative humidity were to rise, as well as a liquid water alarm near likely sites of water leaks in the crawl space.

It is always the case that homeowner behaviors can overwhelm any building or equipment system. For the system to maintain its performance the homeowner must change air filters, provide basic home and equipment maintenance over time, and observe the meter reading and react as necessary. On the construction industry side there are always builders and subcontractors who provide faulty housing. This is true today for houses built on slabs, basements, or wall vented crawl spaces. There are several alternative approaches to maintain these systems. For example, some forward-thinking pest control operators are installing dehumidifiers in closed crawl spaces and including equipment service during their annual crawl space inspection for termites. Other manufacturers have liquid water alarms to install in crawl spaces. Closed crawl space construction is not a magic, silver bullet that will solve all construction failures. Its practical construction methods must also be properly applied.

### 7.2 Energy Performance

The minimum goal of this study was to have the experiment modifications result in comparable space conditioning energy consumption relative to the controls. However, both experiment house groups were documented to have reduced space conditioning energy consumption by 15% relative to the conventional crawl space control group. The closed, wall insulated (experiment group two) houses performed best during the summer. The closed, floor insulated (experiment group one) houses performed best during the winter. The magnitude of the impact of this research for national energy policy is important. What these levels of energy savings could mean for crawl space houses in the United States has not yet been calculated but it would be significant. A simple analysis for the Southeast, assuming approximately 70,000 new homes built on crawl space foundations per year, 40% typical energy use for space conditioning, and 19,000 kWh per year per house typical consumption, predicts savings equivalent to not building 4,000 houses per year, or the equivalent of 4.2 billion kWh saved over ten years. There are an estimated 9 million homes already in existence on crawl spaces in the Southeast that are potential retrofit candidates. In addition to the potential annual energy savings there are the added benefits of preventing several common moisture problems, which in turn reduce the rate of deterioration of structures, and the costs of those associated repairs. Pleasantly (and fortunately!), the construction solution that provides these benefits is a practical, straightforward measure.

A clear difference between study groups has been demonstrated in energy performance. Air testing results show a marked decrease in house air leakage rates due to the sealing of the crawl space walls and the creation of the secondary air/pressure boundary at the sub-floor level. The control group had 66% more air leakage through the floor and crawl space ducts than the experiment groups during the first phase of research. Sealing the crawl space greatly reduced the amount of leakage into the house through the floor and duct system. The experiment homes had higher percentages of wall and ceiling air leakage during the blower door test. The control houses had 16% more component air leakage when all air paths are considered.

For the first time, the protocols developed for this project have provided component air-leakage estimates of duct leakage within the crawl space, duct leakage to outside, and leakage across the floor plane. Up to now, when duct systems are located in the crawl space, this leakage component breakdown had not been determined.

The wall insulation choices for the experiment groups are compromised from a purely thermal perspective by building code provisions for termite protection. However, significant energy savings over the wall-vented group were documented for all the different variants of closed crawl spaces.

Fiberglass batts applied in the framed floor cavities in closed crawl spaces in the southeastern United States has proved to be an effective insulation strategy. Rigid foam board insulation applied against the inside of the foundation wall with termite inspection gaps has also been proven to be effective in the same environment. These two approaches have different performance characteristics for the different seasons, but on an annual basis they both outperform conventional crawl space construction methods with over 15% reduction in space conditioning energy used. This magnitude of space conditioning energy savings was unexpected and when combined with the moisture benefits of closed crawl spaces bolsters the argument for adoption of closed crawl spaces in the construction industry.

Conditions of the insulation and duct systems in the Princeville control houses are significantly better than the conditions commonly found in residential construction, as documented in the Characterization Study portion of this project. Therefore, it could be hypothesized that comparison of the performance of closed crawl space techniques implemented in the Princeville experiment groups to "typical" wall-vented houses would indicate an even greater amount of energy savings and moisture performance improvement.

When the choice is made to place insulation on the foundation wall for a closed crawl space, many current building codes requires that the insulation be continuous from the subfloor down to 24-in (61 cm) below outside grade or to turn the insulation in and lay it on the ground to achieve the equivalent of that 24 in (61 cm) of insulation. This is referred to as the "L" shaped installation of insulation. This method of installation is not viable in the construction industry for two reasons. First there are the multiple stakeholders in crawl space construction whose positions will need to be accommodated. For example, the pest management industry demands an inspection gap at the top of the masonry foundation wall. We provided a 3 in (7.6 cm) gap or insulation void. Second, there is also the need for construction practicality when changing crawl space construction techniques. With regard to the "L" shaped installation there are no practical materials at this point in time that would not interfere with access, inspections, real life construction sequences, and potential pest treatments. Our energy savings were achieved without continuous insulation and without the "L" shaped application. The wall insulation was installed to a depth of only about 3 in (7.6 cm) below outside soil grade. Had the inside soil level been deeper relative to outside soil level, the insulation would have been installed further below outside soil grade. When we did install insulation in the "L-shaped" configuration, we saw no appreciable improvement in performance.

**7.3 Moisture**

The control and experiment group crawl spaces were found to have significantly different moisture conditions during the humid seasons throughout the project. Perhaps Table 22 best summarizes this difference. In all the years of the study, the measured results indicate that the moisture load of summer outdoor air regularly exceeded that of the air inside the control crawl spaces designed according to the default requirements of the North Carolina and International Code Council residential code requirements for crawl space ventilation. The result has been that these wall-vented crawl spaces became wetter rather than drier from the exchange of air for the duration of the summer seasons. In contrast, using a crawl space design that has no intentional ventilation openings to the outside in conjunction with a variety of moisture control mechanisms and insulation strategies has demonstrated robust, long-term performance that is significantly drier than standard wall-vented crawl space construction.

Closed crawl space construction techniques appear to be robust measures, in the hostile Southeastern humid climate, for providing dry crawl spaces for new construction and for retrofitting existing houses. These crawl spaces have a sealed polyethylene film liner system to reduce moisture intrusion from the soil, the masonry walls and from outside air flow into the space. They require that both ground and surface water be prevented from entering the crawl space. They also require some type of supplemental drying mechanism to control the limited amount of moisture vapor that will still migrate to the space and would accumulate over time. Phase I of this study has demonstrated that a measured amount of duct air leakage would provide that control. However, we are not advocating duct leakage as a standard moisture control strategy. For a temporary period during Phase I the study also demonstrated that small dehumidifiers would easily provide even greater control for crawl space relative humidity. Phase II has demonstrated that a measured amount of HVAC supply air [1 $ft^3$/min (0.5 L/s) for each 30 $ft^2$ (2.8 $m^2$) of crawl space ground surface] also provided the necessary supplemental moisture vapor control. Other supplemental drying mechanisms have not yet been evaluated. Closed crawl space construction produced an environment that slowed down and reduced the extremes of the moisture and temperature swings that were experienced in wall vented crawl spaces.

Closed crawl space experiment groups one and two maintained average daily crawl space relative humidity below 60% and dew point temperature between $55^0$F and $60^0$F ($16^0$C). Closed crawl space experiment group 3 (which had no wall vapor retarder and no seams sealed in the ground vapor retarder) maintained average daily crawl space relative humidity below 70% and dew point temperature just above $60^0$F. Wall vented crawl spaces exhibited extended periods with crawl space relative humidity above 80% and dew point temperature in the mid $70s^0$F ($21^0$C). In addition they experienced periodic episodes of dew point condensation. These conditions resulted in microclimate conditions that supported mold growth and moisture deterioration of materials and equipment located in these types of crawl spaces.

The moisture performance of closed crawl spaces in this project has been so improved as to almost eliminate the risk of rot in the crawl spaces not due to plumbing leaks. The closed designs reduce the potential for mold growth by reducing the occurrence of conditions that support mold growth, specifically by reducing average daily relative humidity significantly below 70%. Dew point measurements indicate a reduced risk of condensation in the experiment crawl spaces, which further reduces the risk of mold growth and potential for rot. The experiment group crawl spaces were found to have about 30% lower wood moisture content readings than the control group.

The well-constructed, extensively wall vented control crawl spaces in this study, which had a 100 % ground vapor retarder and which were protected against water intrusion, were protected against wood rot. For these houses the wood moisture content in the vented crawl spaces did rise but did not reach critical levels during the period studied. This crawl space configuration did not, however, prevent moisture condensation and surface mold growth in these same crawl spaces. Crawl spaces with reduced wall vent area as allowed by the North Carolina and International Code Council residential codes were not examined in this study and it is not known whether that configuration would perform as well as the wall vented crawl spaces in this control group.

Observations about the ground vapor retarder are particularly notable. The installation of a 100% ground vapor retarder in the control group did not prevent high relative humidity and mold growth in the crawl spaces. New, full coverage ground vapor retarders were installed in the four wall-vented crawl spaces. The 6-mil polyethylene sheets were carefully installed, seams were overlapped, and all sheets were staked in place without gaps or tear damage. The ground vapor retarder installations clearly meet the full intent of the North Carolina and International Code Council residential code provisions for covering the ground surface of a crawl space with an approved vapor barrier material. Despite these careful installations, the wall vented crawl spaces had high humidity levels, although wood moisture readings were kept within the ranges for avoiding rot.

The observations about the impacts of quality ground moisture barriers appears to support the contention that air moisture controls are mandatory to building dry crawl space assemblies.

**7.4 Indoor Air Quality**

The first set of bioaerosol samples, made in July of 2001, found very large numbers of mold spores in the crawl spaces. By the time the second, more limited, set of samples was taken in September of 2002, overall spore levels in the crawl spaces had fallen by a factor of six. The dominant species in the first set of samples (*penicillium* and *aspergillus*) had fallen by a factor of a hundred (from 25,000 cfu/$m^3$ to a few hundred cfu/$m^3$ for *penicillium* and from a few thousand cfu/$m^3$ to essentially zero cfu/$m^3$ for the *aspergillus*). The initial levels are among the highest reported in the literature. Generally, viable and total spore counts in the tens of thousands 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 taken. This is reflected in both the crawl space and outdoor air data. Second, the sampling procedure may have contributed to the crawl space levels being as strikingly high as they were.

Viable spore levels from the first round of sampling in 2001 found that the experiment houses had viable spore levels ranging from virtually none to 400 spores per cubic meter while the viable spore levels in the control homes ranged from 400 to 3500 spores per cubic meter (with half the control houses having thousands of spores per cubic meter). However, in the second round of testing both the experiment and control houses had fairly low levels of viable spores, ranging from 100 to 200 cfu/$m^3$, with the exception of one sample in control house 110 which was nearly 700 cfu/$m^3$.

It appeared that the crawl spaces developed visible mold blooms very quickly during several days of heavy rains in mid-June, 2001. The mold blooms developed about one month after the new owners moved in and began air conditioning their homes. The best performing house in terms of absence of visible mold and low counts of viable and total spore counts during that period was house 106. The crawl space of house 106 was substantially closed as a test demonstration in early May 2001.

In September, 2002 the mold levels in the crawl spaces and houses appeared to be in line with more typical houses, showing evidence of some small amount of mold growth. However, it must be stressed that a small number of samples have been taken at only two different points in the study, July 2001 and September 2002. Nearly three years have passed since the last samples were taken and by the conclusion of the study, all of the houses have been converted to one of the test configurations.

Given the high levels of spores measured in the crawl spaces in both the field study and the characterization study, workers in crawl spaces should wear fitted respirators. Combined HEPA and activated carbon filters are recommended. Persons with beards should use powered air-purifying respirators. All workers should be tested for fit and lung function according to applicable OSHA regulations while using a respirator.

## 8. Recommendations

It is strongly recommended that the Princeville study site be operated for many years. The study has established a smoothly-operating research site, an effective set of protocols and experiment designs, and a mechanism that has generated a wide range of practical, real world information on crawl space performance. This information has been successfully conveyed to building code officials, builders and homeowners, resulting in major changes to the NC residential code that improve the implementation of both wall-vented and closed crawl spaces. The information has also been presented to an array of stakeholders in the pest management, water-proofing, private home inspection, and weatherization industries where it has been wholeheartedly adopted for implementation by a growing group of private businesses.

Continuing the operation of the Princeville site can be accomplished at a fraction of the cost required to establish a new site and would go forward with a group of homeowners with whom AE staff have established very positive working relationships. A rough estimate of price to gather data once per quarter and analyze basic temperature, humidity, energy consumption and wood moisture data using the methodologies described in this report is $45,000 per year.

Additional data collection and analysis at Princeville will likely support arguments that closed crawl space construction is a robust, long-lived feature that adds significant benefits to the operation of residential structures. Additional funding could allow the implementation of new design variations for field validation in this well-documented house group, or new instrumentation to evaluate areas of performance that have not been evaluated to date. Such evaluations could address areas of performance like:

- Potential peak energy load reduction due to reduced need for space conditioning
- Impacts on HVAC capacity requirements
- Influences on attic moisture levels
- Characterization of occupant base load behavior and its impact on space conditioning energy use
- Homeowner comfort and its impact on space conditioning behaviors

Long-term study will help to identify any maintenance requirements that are currently unanticipated, and could provide opportunities to develop information, components, tools, or techniques that will encourage further deployment of the technology in the marketplace so that the significant energy savings potential is realized. For example, using HVAC supply air to provide the necessary crawl space drying mechanism is appealing due to its low cost, ease of installation, durability, and longevity by virtue of being driven by the mechanical system, which homeowners are likely to keep in operation and repair when damaged. However, the code requirements for the proper air flow present a challenge to building inspectors who are not equipped to assess air flow. Designing a system that obviates the need for inspection (e.g. it will provide rated air flow automatically) or a simple tool for the market to demonstrate proper flow to the code official will lower the regulatory obstacles to the design and speed acceptance.

The market for closed crawl spaces in North Carolina has already developed to the point that hundreds of new homes are being built every year with closed crawl spaces, and hundreds more existing homes are having closed crawl space retrofits. Study should begin immediately to evaluate the performance of large numbers of these crawl spaces as installed in the context of general construction practice, not formal research. Performance should be verified against expectation and failures identified and cataloged in order to continually improve processes for successful delivery of this technology in the marketplace. Gathering market data such as numbers of installations, typical cost, and other financial factors will be helpful to businesses developing new markets for closed crawl spaces.

It appears as though closed crawl spaces can be thought of as a short basement with regard to radon mitigation, since similar measures are applicable for assessment and control of risk where needed, as specified in Appendix F of the International Residential Code.

There is a need to make building codes accommodate and provide for closed crawl space construction. During our work to set up the houses in this study the scattered and conflicting nature of different elements within the building code became evident. For closed crawl spaces to be practical for both builders and code enforcement officials we recommend a separate section in the code that is specifically dedicated to these construction methods. We have successfully changed the NC Residential Code to improve the regulatory approval process for closed crawl spaces and to improve the requirements for wall vented crawl spaces. However, closed crawl space construction is still disallowed or presented as a fragmented set of exceptions in the code for traditional wall vented crawl spaces in many other jurisdictions. We recommend an investment of effort to (1) evaluate the success of the new NC code in enabling or fostering successful market deployment of closed crawl spaces, (2) evaluate the appropriate code modifications required to support closed crawl space deployment in other key markets, and (3) to evaluate the appropriate activities necessary to achieve such modifications.

Significant additional effort is required to inform building code officials of the new code requirements for crawl spaces as well as specific design and implementation issues that will be encountered in the field. Helping code officials to be more familiar with the technology and the building science behind the designs will likely reduce regulatory barriers to deployment in many jurisdictions.

During the development and operation of this study, we developed a categorization of design strategies for properly closing crawl spaces under the following six areas: (1) pest management, (2) moisture management, (3) fire safety standards, (4) thermal standards, (5) combustion safety and (6) radon management. Implementation strategies required attention to the following construction management issues: (1) selecting a closed crawl space system, (2) overcoming conventional wisdom about ventilation and moisture performance (3) applying codes and working with code officials (4) pricing closed crawl space work, (5) managing labor, and (6) managing job site logistics. Closed crawl space construction is a very effective measure but it is not a magic, silver bullet. One can inadequately apply closed crawl space details and sequences as easily as any other construction detail. Installers have to have a process for planning and delivering the work to achieve the total package of benefits. Deployment of closed crawl spaces in NC has been fostered by the sharing of this information with the pest management, foundation waterproofing, private home inspection, and weatherization industries. Future efforts to present the findings of this and other future projects with these key stakeholders is encouraged.

Testing of energy analysis software for closed crawl spaces was outside the scope of this project, but we did attempt to model the closed crawl space performance in one software package. We found (in this admittedly limited, informal test) that the energy benefits of closed crawl spaces were not completely predicted by a popular energy analysis software package and in fact it was impossible to even input some of the designs tested in the study. As a result, we believe it may be some time before closed crawl spaces get their due respect when builders choose house specifications aimed at achieving a certified minimum energy rating. We hope that our research findings will spur refinements in the analysis tools and that in the meantime the data will reinforce the argument that consumers can improve their homes by building or retrofitting a properly closed crawl space.

A final caution is appropriate. We expect the findings of this study to transfer well to houses of similar geometry and geography to the study homes. However, additional consideration and scientific study are required for houses in other locations and with different geometry. Given the matched pair experiment design there should be considerable transfer of results for both moisture control and energy savings. 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, the homes in this study have shallow foundations, and Advanced Energy has not tested crawl space foundations with deeper footing depths (and crawl space floors potentially much deeper below grade) such as may be found farther north. A wall insulation strategy may 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, and we are now starting up a project to gather that data in multiple climate zones while formally demonstrating and documenting the ability of the production housing market to incorporate closed crawl space technology into their construction processes. In the meantime, several production builders and some product manufacturers are already benefiting by promoting and selling dry crawl space construction techniques and this segment of the construction industry seems to be poised for substantial growth. We believe that the widespread application of these construction methods, where it is determined to be appropriate, will benefit homeowners, construction businesses, energy efficiency policy and the environment.

# Field Study Appendix

*HFHI Princeville Announcement*
*Field Study Photographs*
*Mold Photographs*

## 1.1 HFHI Princeville Announcement

HABITAT FOR HUMANITY INTERNATIONAL

Habitat News

HOME | GET INVOLVED | WHERE WE BUILD | HOW IT WORKS | TRUE STORIES

### HABITAT FOR HUMANITY TO BUILD 12 HOUSES IN PRINCEVILLE, N.C.

AMERICUS, Ga., Dec. 28, 2000—Habitat for Humanity volunteers from around the country will join members of the Princeville community to "blitz build" 12 homes in Princeville, N.C. Jan. 3-15, 2001. The build, coordinated by Tarboro/Edgecombe Habitat for Humanity, is part of the Hurricane Floyd Recover Build Program, a joint effort of Habitat for Humanity International's Disaster Response Office and Habitat for Humanity affiliates in eastern North Carolina. These recovery houses will replace homes destroyed by flooding caused by Hurricane Floyd in September 1999.

"We are pleased that Habitat for Humanity is able to play a role in helping Princeville recover from Hurricane Floyd," said Sara Coppler, Director of Habitat for Humanity International's Disaster Response Office. "Tarboro/Edgecombe HFH and the Princeville build are prime examples of the resources Habitat for Humanity can bring to communities recovering from disasters. After the immediate needs of a community are met, Habitat for Humanity and its affiliates can play a vital role in renovating and rebuilding housing damaged or lost because of the disaster."

Lowe's Home Improvement Warehouse, the world's second largest home improvement retailer, is the largest sponsor of the build. Lowe's has donated $350,000 in gifts and grants to the build and its employees are traveling to Princeville to participate in the build. The Town of Princeville is also participating, with local and civic leaders joining the build. The Federal Emergency Management Authority has provided infrastructure support for the build and the Mennonite Disaster Service is providing workers who will arrive several days before the build to lend pre-build support and help organize the build. Habitat for Humanity affiliates from North Carolina are also sending volunteers who will lend their support and expertise to the build.

Dedicated to eliminating poverty housing, Habitat for Humanity International is an ecumenical Christian ministry founded by Millard Fuller along with his wife, Linda. HFHI and its affiliates in more than 2,000 communities in 76 nations have built and sold more than 100,000 homes to partner families at no profit with zero-interest mortgages.

Patti Fowler
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Princeville site – west side

Princeville site – east side

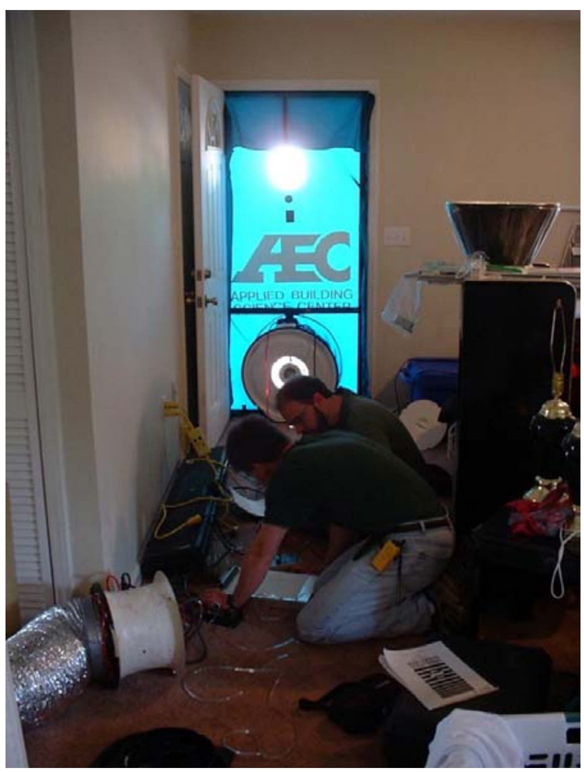
Princeville house – front view

Princeville house – end view

Return and supply ducts for package heat pump

Foundation vent

Air flow and pressure measurements




Air flow and pressure measurements

House address 100: No continuous vapor barrier

House address 100: No continuous vapor barrier

House address 100: Panned return air

House address 102: Return duct cross-section


House address 102: Warning label for subcontractor
to protect crawl space techniques

House address 103: Poor HVAC duct seal

House address 103: Return duct trench

House address 104: Buried condensate drain

House address 104: Fallen batt and mold


In line filter for outside air ventilation system

Transition for outside air intake

Transition installed in foundation


House address 105: Filter for ventilation system air
– no mold on framing


House address 106: Access panel frame

Heat pump duct crawl space wall penetration seal

House address 106: Duct seal at package heat pump

Heat pump duct crawl space penetration seal

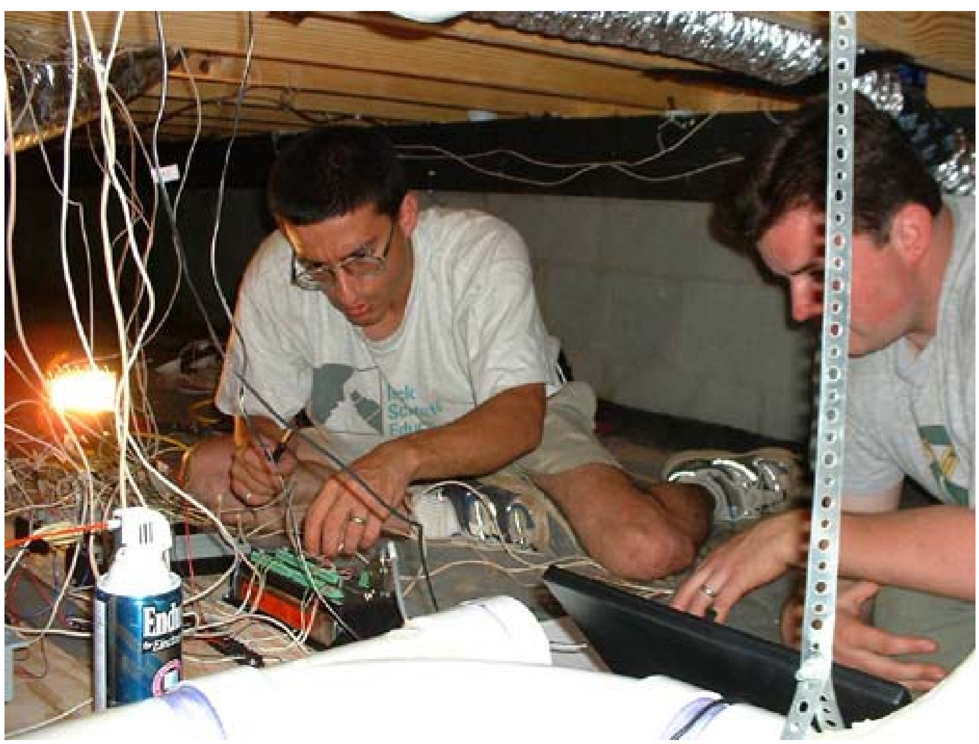
House address 106: Foundation vent and heat pump duct wall penetration sealing


House address 106: Seal floor poly seams

House address 106: Poly seal wall in progress

House address 106: Termite view strip and wall vapor barrier

House address 106: Return duct air leakage



House address 106: Cyrus and Chris install data loggers

House address 106: Data logger installed

House address 106: Weather station

House address 107: Poor wall seal at dryer vent

House address 109: Crawl space wall insulation

House address 109: Band joist and crawl space wall insulation

House address 109: Dehumidifier and wall insulation

House address 110:
Condensation sump pump – temporary until site grading completed

House address 110: Crawl space as found

House address 110: Good sandbagging

House address 110: Sandbagged access

House address 110: Poor supply seal

House address 110: Hobo data loggers for crawl space temperature and relative humidity

House address 110: Data logger sensors - hygrothermal

House address 110: Data logger installation - hygrothermal

House address 110: Final grade

Finish grading

House address 111: Faulty plumbing trap at tub

House address 111: Unsealed plumbing hole

Heat pump condensate drain to gravel-filled pit

Return closet

Return closet sensors

Crawl space dehumidifier

Calibrating ventilation air flow

Checking heat pump refrigerant charge and air flow

Sealed trunk ducts and package unit penetration

Duct Blaster as powered flow hood to calibrate crawl space supply


Taking velocity measurement reference to set remaining supplies

Balancing and butterfly dampers visible in well-supported crawl space supply duct

Sub-meter visible at left of duct cowling


Wall-insulated closed crawl space, Phase II

Floor-insulated closed crawl space, Phase II

Horizontal ground insulation added to wall insulation for Phase IV

Attaching constant air flow regulator to new ventilation intake/filter

Sealing joint between CAR and ventilation intake with duct mastic

New intake assembly in old vent penetration, CAR visible


Sealing ventilation intake to perimeter wall

Sealing duct to ventilation intake with fiberglass mesh tape and duct mastic

Sealing outside of ventilation intake to perimeter wall


Typical original-design ventilation filter after 90 days – lots of dirt trapped

Old ventilation duct prior to filter – substantial soiling

Old ventilation duct after filter

New ventilation intake opens without a tool

Filter behind the intake grill can be removed, washed, and reused

House address 100: Light mold

House address 100: Early mold

House address 101: Mold

House address 104: Light red mold


House address 105: Mold with labeling

House address 106: Slight mold

House address 107: Mold

House address 107: Mold

House address 107: Mold

House address 107: Mold beam and joist

House address 107: Red mold

***House address 108: Mold***

House address 108: Heavy mold

House address 108: Mold in subfloor

House address 110: Mold

House address 110: Mold

Princeville outdoor air sample