FINAL REPORT NCEMBT-091231

CLOSED CRAWL SPACE PERFORMANCE: PROOF OF CONCEPT IN THE PRODUCTION BUILDER MARKETPLACE

DECEMBER 2009

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FOR ENERGY MANAGEMENT

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NATIONAL CENTER FOR ENERGY MANAGEMENT AND BUILDING TECHNOLOGIES TASK 06-13: CLOSED CRAWL SPACE PERFORMANCE: PROOF OF CONCEPT IN THE PRODUCTION BUILDER MARKETPLACE

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NOTICE

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EXECUTIVE SUMMARY

This project had two main objectives. The first was to quantify the impact of installing properly closed crawl space foundations in occupied homes constructed by production homebuilders in cold and hot-humid U.S. climate zones. The second was to determine whether popular software programs used to forecast residential energy consumption could accurately predict the impact of the closed crawl space foundations on the amount of energy used to heat and cool the homes.

Researchers from Advanced Energy carried out the project at two sites: twelve new site-built homes in one neighborhood in Flagstaff, AZ and fifteen new modular homes built in one neighborhood in Baton Rouge, LA. In order to reduce experimental variability, the homes at each site were built to consistent specifications for insulation levels, glazing performance, and mechanical efficiency. They were all built as part of a high-performance home program that provided third-party quality assurance inspections during construction and performance testing for envelope and duct leakage. Finally, homes were assigned to control and experimental groups in a manner that balanced variables like conditioned floor area and solar orientation across the groups as much as possible.

The Flagstaff site tested two versions of closed crawl space: one with fiberglass batt insulation in the framed floor structure above the crawl space and another with rigid foam board insulation on the crawl space perimeter wall. The Baton Rouge site tested three versions of closed crawl space: one with fiberglass batt insulation in the framed floor structure and two with rigid foam board insulation on the crawl space perimeter wall. One of the wall-insulated groups had all mechanical ductwork located in the crawl space, while the other two closed crawl space groups and the control homes had mechanical supply ductwork in the attic.

The homes were instrumented to monitor temperature and relative humidity in the crawl space and living space, to monitor energy used for space conditioning separately from total home energy use, and to measure radon concentrations in the crawl space and living space. Data was collected from August 2007 to October 2008 at the Baton Rouge field site and from October 2007 to March 2008 at the Flagstaff field site. The Flagstaff study was terminated early due to the discovery of elevated radon concentrations.

The project findings support researchers' first hypothesis that "*Closed crawl space systems will control daily average relative humidity inside the crawl space below 70% regardless of climate zone or season*."

- In the very humid Baton Rouge climate, the closed crawl space systems were actually able to control crawl space relative humidity closer to 60% on a daily average, while the control group humidity hovered around 80% for most of the spring and summer months.
- In Flagstaff's dry climate even the control crawl spaces stayed under 70% for all but a few days, but the closed crawl spaces were even drier, with levels around 50% under the same conditions.

The research findings are mixed with regard to the second hypothesis that "*Homes with closed crawl space systems will realize 15% or greater annual savings on energy used for space conditioning as compared to homes with vented control crawl spaces located in the same climate zone*."

- In Baton Rouge, the performance of closed crawl space systems with perimeter insulation and distribution ducts in the crawl space supports this hypothesis, but clearly the location of the ductwork in the crawl space versus the attic in the control homes is a significant variable. The results are less clear in the other groups, with indoor and crawl space temperature comparisons supporting a conclusion that thermal loads from the floor are lower in the homes with closed crawl space foundations, but the space-conditioning energy data does not indicate lower usage, likely because of confounding occupant behavior variables.

- In Flagstaff, the performance of the closed crawl space system with floor insulation supports the hypothesis, while the performance of the closed crawl space system with wall insulation rejects the hypothesis.

Finally, the research findings are mixed or uncertain with regard to the third hypothesis that "*Popular residential energy modeling software programs are unable to accurately forecast the energy savings that result from installation of a properly closed crawl space foundation.*" The study results indicate that there is a need for improvement of the energy modeling software, but the small data set of field performance raises uncertainty.

- In Baton Rouge, the modeling results for the floor-insulated closed crawl space group has the most uncertainty. REM/Rate and EnergyGauge predict very well the energy use for the vented crawl space with floor insulation and the closed crawl space with wall insulation and ducts in the crawl space, but are not able to predict the performance of the other two designs.
- In Flagstaff, the even smaller data set due to meter failures and truncated study period raises too much uncertainty to draw a conclusion.

The study results provide strong support for the application of closed crawl space foundations as a moisture control method for crawl space homes in the hot-humid U.S. climate zone, and provide even stronger support for wall-insulated closed crawl spaces to provide a more hospitable location for mechanical ductwork in that region, resulting in energy savings in addition to the moisture control.

The results also provide support for application of floor-insulated closed crawl space foundations in cold climates, both as a moisture control and energy-saving home improvement.

The study results suggest that any recommendations or requirements to install closed crawl space foundations should also include requirements for radon testing and mitigation if indicated. In areas of elevated radon risk, it could be suggested that builders rough-in soil gas collection hardware prior to installation of the foundation ground vapor retarder or flooring to reduce potential future mitigation costs. Ideally these recommendations would apply to all homes, since basement or slab foundations would likely more expensive to remediate. Slab and basement foundations may also put the residents at higher risk due to fostering occupancy in the parts of the home where the radon is entering the structure.

These results suggest at least four additional studies that would help improve understanding of the benefits of closed crawl space foundations and foster their adoption in the marketplace:

1. Convert the four control homes at the existing Baton Rouge field site to closed crawl space foundations, retaining the existing floor insulation, and then monitor all homes at the site using the current methodology for another 12-month period to have a basis for correcting the performance results with respect to occupant behavior.
2. Perform a commercialization assessment for closed crawl spaces in the Gulf Coast to determine strategies for overcoming the lack of qualified installers, which poses a significant barrier to market adoption in that region.
3. Perform a study in the Gulf Coast market to compare energy usage, indoor humidity control and installation costs for closed crawl space foundations versus slab foundations.
4. Identify or create improved radon risk data and recommendations for identifying and reducing radon in residential structures.

1. PROJECT OBJECTIVE

This project had two main objectives. The first was to quantify the impact of installing properly closed crawl space foundations in occupied homes constructed by production homebuilders in cold and hot-humid U.S. climate zones. The second was to determine whether popular software programs used to forecast residential energy consumption could accurately predict the impact of the closed crawl space foundations on the amount of energy used to heat and cool the homes.

Four high-level goals were defined in order to achieve the project objectives:

1. First, to recruit the participation of two production-oriented (i.e. not custom-design) residential home builders, one in each of the desired U.S. climate zones. The project required each builder to construct at least twelve homes on crawl space foundations, ideally all within one neighborhood or community. In addition, each builder was required to construct the homes as part of a high-performance home program that included third-party verification of compliance with program requirements.
2. Second, to work with each builder, along with local contractors and code officials, to define at least two acceptable closed crawl space designs to be installed and monitored. The closed crawl space designs were then to be installed in sub-groups of the total set of homes in each neighborhood, with one sub-group of homes remaining as a control group with a wall-vented crawl space design.
3. Third, to install meters and data loggers in every home to measure and record hourly temperature and humidity levels, monthly energy consumption, and long-term radon concentrations such that researchers could quantify the impact of the closed crawl space foundations over a twelve-month post-occupancy period.
4. Finally, to then use the measured energy data to assess the accuracy of three popular software programs that are used to predict residential energy consumption:
    a. REMRate, by Architectural Energy Corp.,
    b. TREAT, by PSD Consulting, Inc., and
    c. EnergyGauge, by the Florida Solar Energy Center.

The project's research hypotheses were that:

1. Closed crawl space systems will control daily average relative humidity inside the crawl space below 70% regardless of climate zone or season.
2. Homes with closed crawl space systems will realize 15% or greater annual savings on energy used for space conditioning as compared to homes with vented control crawl spaces located in the same climate zone.
3. Popular residential energy modeling software programs are unable to accurately forecast the energy savings that result from installation of a properly closed crawl space foundation.

2. BACKGROUND

Advanced Energy completed its first federally-funded crawl space research project with the U.S. Department of Energy in 2005. That project, funded under award number DE-FC26-00NT40995, was titled "A Field Study Comparison of the Energy and Moisture Performance Characteristics of Ventilated Versus Sealed Crawl Spaces in the South" and it demonstrated that substantial energy efficiency and moisture management benefits can result from installing properly closed crawl space foundations instead of traditional wall vented crawl space foundations in Southeastern U.S. residential construction.

The key design differences between a traditional wall-vented crawl space foundation and a properly "sealed" or "closed" crawl space foundation are that the closed crawl space has:

- A ground vapor retarder with sealed seams covering 100% of the crawl space floor.
- A mechanically secured vapor retarder covering masonry perimeter walls with the exception of a nominal 3" termite inspection gap at the top of the wall and wherever the masonry wall abuts wooden structure.
- Air-sealed perimeter walls, with no intentional openings to the outside.
- Thermal insulation installed either on the perimeter walls (without obscuring the termite inspection gap) or in the framed floor structure above the crawl space.
- A mechanical drying mechanism to provide supplemental control of humidity when installed in climates with a humid season.

Two of the main objectives of this project included (1) an assessment of ten existing homes to document commonly observed energy and moisture failures associated with traditional code-compliant wall-vented crawl space foundations and (2) a detailed literature review that documented both the history of closed crawl space research and the historical lack of scientific justification for building code requirements for crawl space ventilation.

The third main objective of the 2005 project proved to have the most profound impact in North Carolina: a field demonstration of various closed crawl space designs which were implemented over the course of three years in a set of twelve small (1040 square feet), simply-designed homes in the eastern town of Princeville. These homes were divided into three groups of four homes each, with each home having the same envelope, mechanical and architectural designs, and comparable performance characteristics with regard to infiltration, duct leakage, site grading and site drainage. One group was kept as a control group with wall-vented crawl spaces while the other two groups had closed crawl space systems installed. In the final phase of the project, researchers installed closed crawl space systems in one group of homes using fiberglass batt insulation located in the framed floor structure above the crawl space and installed systems in the final group with polyisocyanurate board insulation located on the crawl space perimeter wall. Researchers expected these two designs to have the most widespread potential for application based not only on the expected field performance, but also on input regarding code compliance and practicality from residential homebuilders, pest control professionals, code officials, installers, and building scientists.

The key findings from this North Carolina field demonstration were that:

- The homes built on the closed crawl space foundations saved, on average, more than 15% on annual energy used for heating and cooling.
- The closed crawl spaces stayed substantially drier than the wall-vented crawl spaces during humid seasons, with average daily relative humidity controlled below 70%.

Full details and results of this project are available at **www.crawlspaces.org** .

If the Princeville research findings can be extrapolated to the mainstream housing industry, they indicate the potential for large energy savings and moisture control improvements over conventional construction. However, those findings were observed in small, simple (rectangular footprint, single-story with flat-ceiling) homes built by a non-profit developer, which do not reflect the mainstream housing market. Furthermore, the findings were observed only in the mixed-humid climate of eastern NC.

It is not known whether the same scale of energy and moisture performance improvements will result from application of closed crawl spaces to the larger, more complex home designs typically built by for-profit builders. It is also not known whether the same improvements will result from application of closed crawl spaces in different climate zones.

The U.S. residential housing stock has a significant market for crawl space foundations, spread across multiple climate zones. Market data compiled by the National Association of Homebuilders (NAHB) in 2006 indicated that approximately 35% of existing homes and 18% of new-construction homes are built on traditional wall-vented crawl space foundations.

According to the same NAHB data, of the approximately 200,000 homes built each year on crawl space foundations, an estimated 92,000 (44%) are built in the mixed-humid climate zone, 73,000 (35%) are built in the cold climate zone, and 13,000 (9%) are built in the hot-humid climate zone. Furthermore, ICF Consulting estimated that over 300,000 homes must be replaced in the Gulf Coast region due to destruction resulting from hurricanes Katrina and Rita in their 2006 report "Rebuilding After the Gulf Coast Hurricane: Sustainable Communities Using Energy Efficiency." The manufactured housing industry is expected to provide a large share of the necessary reconstruction, which may result in significantly larger numbers of homes being built on crawl space foundations in the hot-humid Gulf Coast region for the next several years.

Therefore, this project has conducted the field studies that are needed to validate the extrapolation of the North Carolina results to a broader segment of the U.S. housing industry. The new field studies were designed similarly to the North Carolina research with respect to sample size and installation details. However, the current project utilized mainstream housing stock built by for-profit corporations in cold and hot-humid climate zones outside the Southeastern U.S.

Furthermore, this project has compared the field data on energy consumption to the predictions generated by popular residential energy modeling software programs in order to assess the programs' ability to accurately predict the impact of the closed crawl space intervention. Computer models are increasingly used in the building industry to predict building energy use and to assess compliance with high-performance building programs (e.g. EnergyStar) that may qualify the builder or homeowner for tax incentives, rebates, or other financial incentives. The predictions are generally based on design inputs (insulation, windows, HVAC, etc.) and construction practices (building and duct tightness, quality of installation, etc.). While the Princeville findings showed energy savings attributable to the use of closed crawl spaces, when the Princeville homes were modeled in a common residential modeling program it predicted that the closed crawl space systems would cause an energy penalty. To understand this contradiction and to help ensure that those who install closed crawl spaces receive appropriate credit towards certification in high performance home programs, a broader computer modeling effort is included in the current project. The current project will survey a number of modeling applications to assess whether they are able to accurately predict the energy impact of closed crawl spaces and to provide feedback to the application developers so they can correct their models, if indicated.

3. METHODOLOGY

3.1 Builder Recruitment

The project's recruitment goal was completed under the first phase of funding with NETL. The researchers canvassed a national network of building science research organizations, building performance contractors, and construction companies to identify potential candidates. The project required the participation of two production-oriented (i.e. not custom-design) residential home builders, first because the project objective was to assess mainstream homes, and second because production builders were most likely to have the capacity to construct the number of homes required for the project in the target time frame.

The project required each builder to construct at least twelve homes on crawl space foundations, ideally all within one neighborhood or community, in a unique climate zone outside the Southeastern U.S. In addition, each builder was required to construct the homes as part of a high-performance home program that included third-party verification of compliance with program requirements. Researchers included this requirement in order to ensure more consistent performance among the project homes, so that subsequent performance comparisons could be more legitimately attributed to the experimental variations in the foundation design instead of other building variables like insulation quality, envelope leakage, and duct leakage.

In 2006, researchers secured commitments from two builders: Palm Harbor Homes, a modular home manufacturer based in Addison, Texas, and Empire Communities, a conventional builder based in Ontario, CA.

Palm Harbor was building fifteen homes for a new Habitat for Humanity (Habitat) neighborhood in Baton Rouge, LA as part of the reconstruction effort there after Hurricane Katrina displaced tens of thousands of New Orleans residents to the Baton Rouge area. Habitat partnered with the Florida Solar Energy Center (FSEC) to achieve EnergyStar certification for the homes, receiving technical support and on-site inspections and performance testing from FSEC staff.

Severe heat and humidity is a routine condition in the Gulf Coast, so moisture control would be a very positive study outcome, along with any potential savings in cooling energy.

Empire Communities operated several offices in northern Arizona, and their Flagstaff office was building several neighborhoods. One neighborhood had a sufficient number of single-family detached homes being built on crawl space foundations to meet the project requirements, and Empire had committed to participating in the high-performance home program provided by E3 Energy.

Except for the short “monsoon” season, (July through September), Flagstaff receives very little rain. Because of the generally low humidity, researchers do not expect to encounter the chronic moisture problems suffered by crawl spaces in the Southeast and other humid climates. However, the monsoon season presents significant short-term water impacts that are anecdotally reported to cause moisture problems in traditional vented crawl spaces in the region, and the cold winters present the opportunity to achieve heating savings.

3.2 Experimental Design

Researchers consulted with each builder, along with local contractors, code officials, building performance specialists and pest control professionals, to define two acceptable closed crawl space designs to be installed and monitored at the Flagstaff field site and three acceptable closed crawl space designs to be installed and monitored at the Baton Rouge field site. The closed crawl space systems were then assigned to sub-groups of the total set of homes in each site, with one sub-group of homes remaining as a control group with a wall-vented crawl space foundation. Researchers then compared the performance of each group of homes with a closed crawl space system to the performance of the control group at the same field site with regard to crawl space temperature and humidity, living space temperature and humidity, energy used for space conditioning and radon concentrations in the crawl space and living space.

3.2.1 Baton Rouge Crawl Space Designs

This section describes the specifications for the three closed crawl space systems as originally designed for the Baton Rouge field site. For each system, there was only one significant difference between the actual installations and the specifications provided below. The difference is that only one crawl space drain was installed in the crawl space access door, near the bottom of the frame, instead of the two drains, one on each side of the crawl space, passing through the footer as described in callout number 21 listed below. This variation was implemented due to site grading that prevented any drains passing through the footer from terminating to daylight. The drain through the access door still utilized the ProSet TrapGuard backflow preventer and a rodent-excluding grate at the termination.

3.2.1.1 Baton Rouge Closed Crawl Space with Floor Insulation and Supply Ducts in the Attic (CCS-F)

1. Air seal all foundation stem wall penetrations with weather-resistant caulk, silicone sealant or spray foam.
2. Air seal the mating surfaces at the top and bottom of the sill plate and at the top and the bottom of the band joist. Material options are sill seal gasket, weather resistant caulk or silicone sealants, Dow Froth-Pak 25FS or equivalent spray foam (interior only) or construction adhesive.
3. The frame and body of the crawl space access panel are to be made of pressure-treated wood materials approved for masonry contact or equivalent.
4. The frame of the mechanical access panel to the crawl space is to be made of pressure treated wood approved for masonry contact or equivalent and the body is to be made of an approved cementitious material.
5. Both frames are to be sealed to the masonry with an approved exterior grade waterproof sealant.
6. Crawl space access shall be nominally 24” high and 30” wide.
7. Weather-strip the crawl space access panel.
8. Secure the crawl space access panel with four exterior-grade wood screws or equivalent.
9. Slope the exterior grade away from the foundation stem wall per local code.
10. Air seal all duct, plumbing, electrical, cable and other penetrations through the sub-floor per local fire-blocking requirements or with any combination of metal flashing, duct mastic, or fire-stop caulk.
11. Insulate floor joist cavities with R-19 batt insulation. Install the insulation in full contact with the subfloor and ensure that it is secured in place. Install the insulation without gaps, voids, or compression.

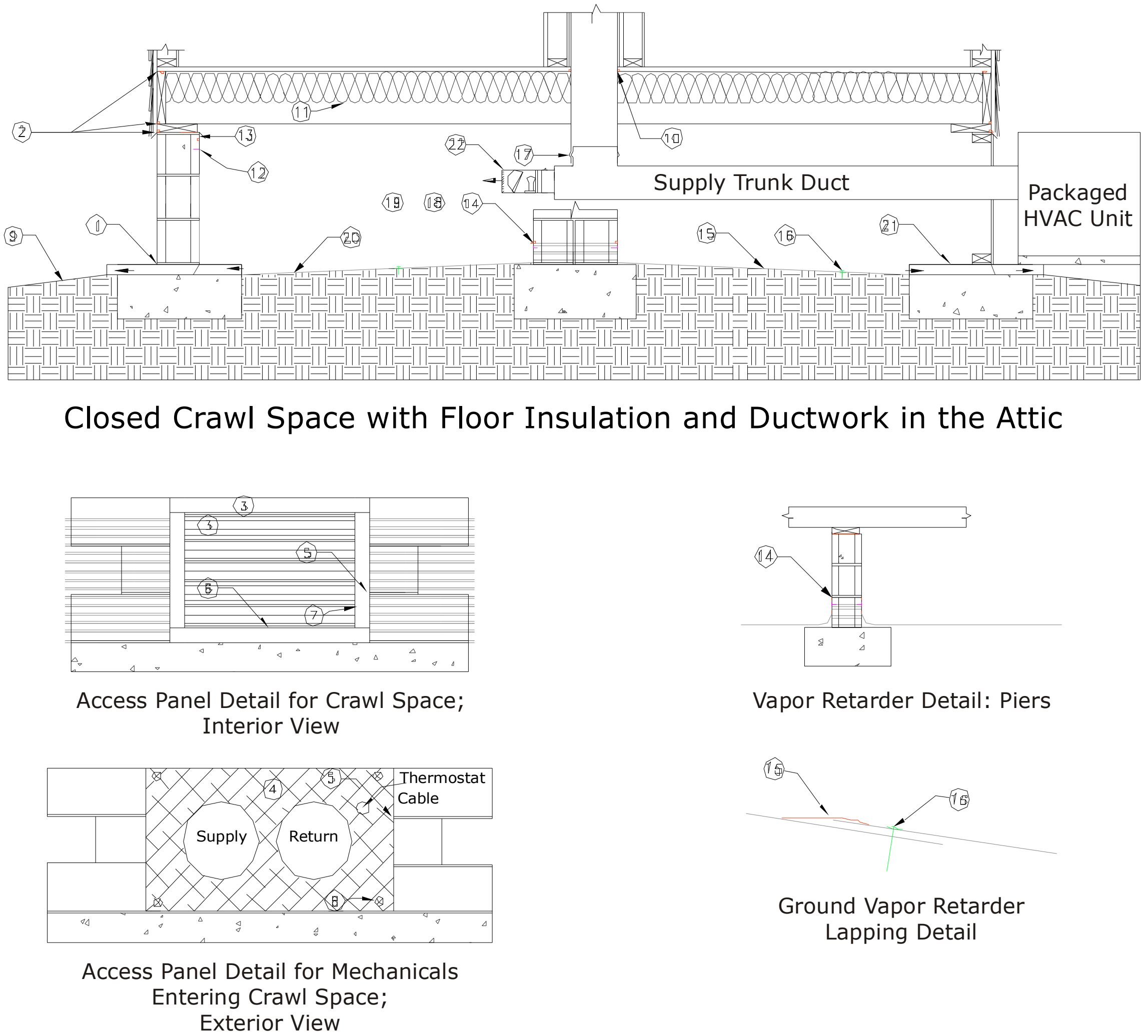


Figure 1. Baton Rouge schematic design for floor-insulated closed crawl space

12. Attach 6 mil thick, translucent, fiberglass-reinforced wall vapor retarder material to the foundation stem wall with Hilti X-GN 20MX or equivalent masonry fasteners driven through Hilti 23MM GX 100 or equivalent washers. The fastener and washer combo shall be installed in a single row within 4" of the top edge of the vapor retarder. At least one fastener and washer combo shall be installed within 6" of each corner in the foundation stem wall. The fastener and washer combo shall be spaced no more than 48" apart. When the wall vapor retarder extends higher than 48" above interior crawl space grade, the fastener and washer combos shall be spaced no more than 36" apart. Install wall vapor retarder to a height such that foundation vents are covered. Install one fastener and washer combo within 6" of each corner of each foundation vent. Overlap seams in the wall vapor retarder material at least 2" and seal the seam with Nail Power or equivalent construction adhesive, Raven Industries 4" wide VaporBond TVB-4 or equivalent tape, or fiberglass mesh tape embedded in mastic. Extend the wall vapor retarder nominally 12" horizontally onto the crawl space floor.

13. Leave a nominal 3" termite inspection gap between the top of the wall vapor retarder and the top of the masonry wall and any untreated wood in contact with the masonry wall (e.g. support beams on pilasters, sill plates, etc.). Seal the edges of the wall vapor retarder to the stem wall with Nail Power construction adhesive or fiberglass mesh tape embedded in mastic or equivalent.

14. Attach minimum 6-mil fiberglass reinforced vapor retarder material around each interior pier at least 4" above the crawl space floor. Overlap the seam at least 2". Mechanically attach the vapor retarder to the pier with at least one fastener and washer combo (as defined in item 10) per side. Seal the top edge of the vapor retarder to the pier with Nail Power or equivalent construction adhesive or fiberglass mesh tape and mastic. Seal the seam in the pier vapor retarder and seal the pier vapor retarder to the ground vapor retarder with Raven Industries 4" wide VaporBond TVB-4 or equivalent tape or minimum 4" wide fiberglass mesh tape embedded in mastic.

15. Cover 100% of the crawl space floor with minimum 8 mil thick, fiberglass-reinforced polyethylene vapor retarder. Lap the floor vapor retarder material on top of the wall vapor retarder material. When overlapping seams in the field of the ground vapor retarder, ensure that downhill pieces of vapor retarder lap over uphill pieces of vapor retarder. Overlap all seams by a minimum 6" and seal all seams with Raven Industries 4" wide VaporBond TVB-4 or equivalent tape or minimum 4" wide fiberglass mesh tape embedded in mastic. Areas where tape is to be applied must be cleaned of dust and debris prior to application of tape.

16. Secure the ground vapor retarder to the crawl space floor with nominal 6" galvanized spikes or turf staples. Install at least one spike or staple within 2' of each corner in the foundation stem wall. If spikes are used, insert the spikes through a minimum 1" diameter plastic or metal washer. If spikes are optionally inserted through a lapped seam, ensure that they are centered in the seam. Seal across the top of any spike/staple penetrations or any other penetrations through the vapor retarder with Raven Industries VaporBond TVB-4 or equivalent tape or mastic.

17. Air seal the heating and cooling ductwork per Florida Solar Energy Center's EnergyStar program requirements.

18. Terminate any water heater drains, temperature/pressure relief pipes, furnace condensate or air conditioner condensate lines outside the crawl space.

19. Terminate all kitchen, bathroom, and clothes dryer vents outside the crawl space.

20. Grade the crawl space floor to one low point on the downhill side of the crawl space.

21. Install a 2" positive drain on each side of the crawl space. The drain pipe should extend to daylight and include a ProSet Systems Trap Guard backflow preventer. The drain intake may pass through the foundation stem wall at crawl space grade level or below. The drain shall be capped with a rodent-excluding screen or grate.

22. Provide a conditioned air supply off the supply trunk with a backflow damper and either a balancing damper or constant airflow regulator to provide airflow of 1 cubic foot per minute per 30 square feet of crawl space floor area.

3.2.1.2 Baton Rouge Closed Crawl Space with Wall Insulation and Supply Ducts in Attic (CCS-W-A)

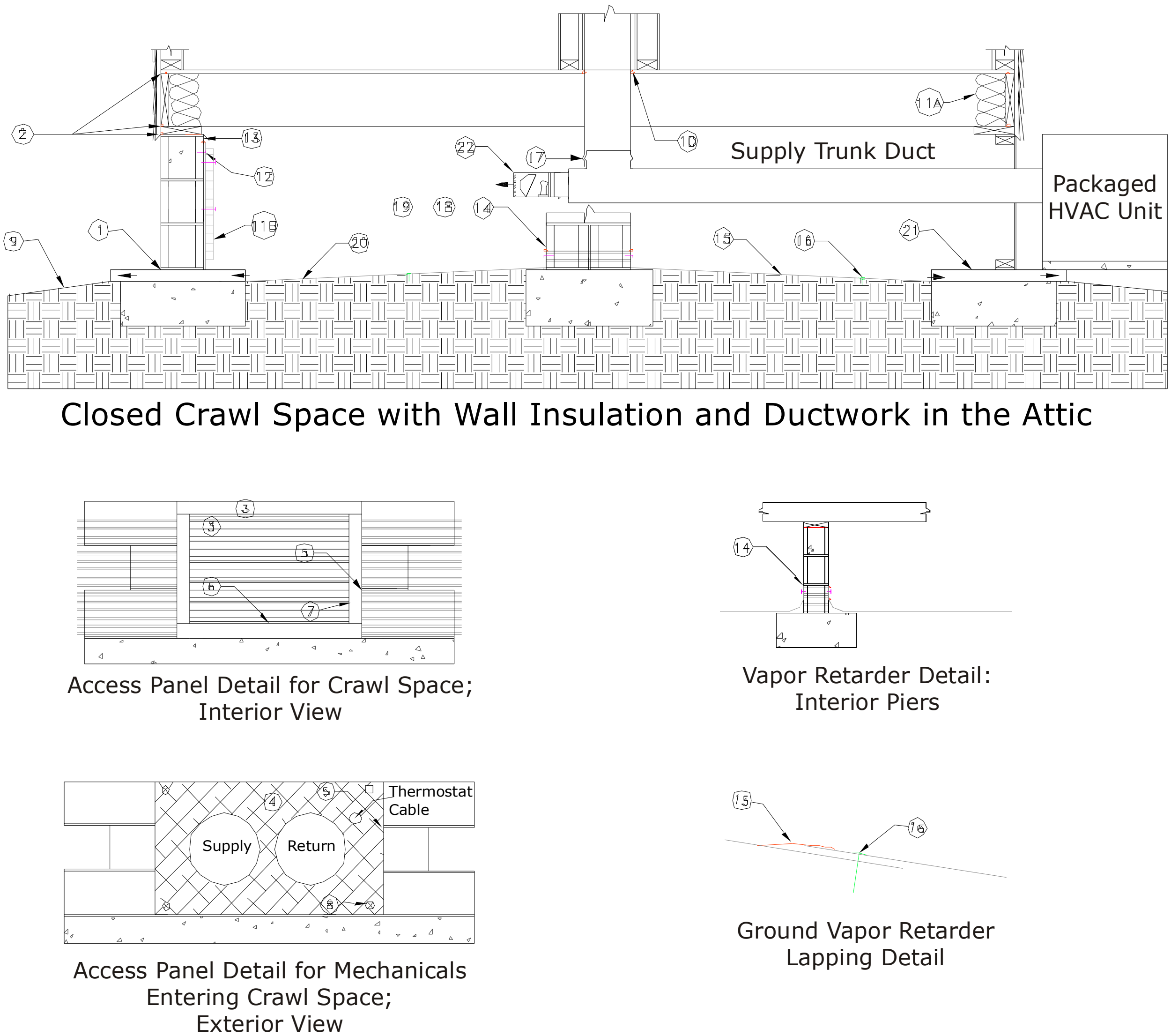


Figure 2. Baton Rouge schematic design for wall-insulated closed crawl space with attic supply ducts.

1. Air seal all foundation stem wall penetrations with weather-resistant caulk, silicone sealant or spray foam.
2. Air seal the mating surfaces at the top and bottom of the sill plate and at the top and the bottom of the band joist. Material options are sill seal gasket, weather resistant caulk or silicone sealants, Dow Froth-Pak 25FS or equivalent spray foam (interior only) or construction adhesive.
3. The frame and body of the crawl space access panel are to be made of pressure-treated wood materials approved for masonry contact or equivalent.
4. The frame of the mechanical access panel to the crawl space is to be made of pressure treated wood approved for masonry contact or equivalent and the body is to be made of an approved cementitious material.

5. Both frames are to be sealed to the masonry with an approved exterior grade waterproof sealant.
6. Crawl space access shall be nominally 24” high and 30” wide.
7. Weather-strip the crawl space access panel.
8. Secure the crawl space access panel with four exterior-grade wood screws or equivalent.
9. Slope the exterior grade away from the foundation stem wall per local code.
10. Air seal all duct, plumbing, electrical, cable and other penetrations through the sub-floor per local fire-blocking requirements or with any combination of metal flashing, duct mastic, or fire-stop caulk.
11. Insulate the band joist area with friction-fit pieces of R-19 unfaced batt insulation. Install the insulation without voids, gaps, or compression.
12. Insulate the foundation stem wall with minimum R-8 Dow Thermax insulation or equivalent. Install the insulation in contact with the wall vapor retarder. Secure the insulation to the stem wall with Hilti X-IE 6-50-D152 type fastener or equivalent. The fasteners shall be installed in two rows per piece of insulation, the first row being within the top quarter of the vertical dimension of the piece and the second row being within the bottom quarter of the vertical dimension of the piece. The top row shall be installed with maximum 48” spacing between fasteners, with at least two fasteners in the top row for each piece. The bottom row shall be installed as one fastener per piece, centered horizontally. Pieces of insulation smaller than 24” x 48” may be installed with only two fasteners. Seal seams in the insulation material with foil tape. Ensure that there is a nominal 3” gap between the insulation and the top of the stem wall or between the insulation and any untreated wood in contact with the masonry wall (e.g. support beams on pilaster, sill plate, etc.). Ensure that there is a nominal 3” gap between the bottom of the Thermax insulation and the finished interior grade of the crawl space.
13. Attach 6 mil thick, translucent, fiberglass-reinforced wall vapor retarder material to the foundation stem wall with Hilti X-GN 20MX or equivalent masonry fasteners driven through Hilti 23MM GX 100 or equivalent washers. The fastener and washer combo shall be installed in a single row within 4" of the top edge of the vapor retarder. At least one fastener and washer combo shall be installed within 6" of each corner in the foundation stem wall. The fastener and washer combo shall be spaced no more than 48" apart. When the wall vapor retarder extends higher than 48" above interior crawl space grade, the fastener and washer combos shall be spaced no more than 36" apart. Install wall vapor retarder to a height such that foundation vents are covered. Install one fastener and washer combo within 6" of each corner of each foundation vent. Overlap seams in the wall vapor retarder material at least 2" and seal the seam with Nail Power or equivalent construction adhesive, Raven Industries 4" wide VaporBond TVB-4 or equivalent tape, or fiberglass mesh tape embedded in mastic. Extend the wall vapor retarder nominally 12" horizontally onto the crawl space floor.
14. Leave a nominal 3" termite inspection gap between the top of the wall vapor retarder and the top of the masonry wall and any untreated wood in contact with the masonry wall (e.g. support beams on pilasters, sill plates, etc.). Seal the edges of the wall vapor retarder to the stem wall with Nail Power construction adhesive or fiberglass mesh tape embedded in mastic or equivalent.
15. Attach minimum 6-mil fiberglass reinforced vapor retarder material around each interior pier at least 4" above the crawl space floor. Overlap the seam at least 2". Mechanically attach the vapor retarder to the pier with at least one fastener and washer combo (as defined in item 10) per side. Seal the top edge of the vapor retarder to the pier with Nail Power or equivalent construction adhesive or fiberglass mesh tape and mastic. Seal the seam in the pier vapor retarder and seal the

pier vapor retarder to the ground vapor retarder with Raven Industries 4" wide VaporBond TVB-4 or equivalent tape or minimum 4" wide fiberglass mesh tape embedded in mastic.

16. Cover 100% of the crawl space floor with minimum 8-mil thick, fiberglass-reinforced polyethylene vapor retarder. Lap the floor vapor retarder material on top of the wall vapor retarder material. When overlapping seams in the field of the ground vapor retarder, ensure that downhill pieces of vapor retarder lap over uphill pieces of vapor retarder. Overlap all seams by a minimum 6" and seal all seams with Raven Industries 4" wide VaporBond TVB-4 or equivalent tape or minimum 4" wide fiberglass mesh tape embedded in mastic. Areas where tape is to be applied must be cleaned of dust and debris prior to application of tape.

17. Secure the ground vapor retarder to the crawl space floor with nominal 6" galvanized spikes or turf staples. Install at least one spike or staple within 2' of each corner in the foundation stem wall. If spikes are used, insert the spikes through a minimum 1" diameter plastic or metal washer. If spikes are optionally inserted through a lapped seam, ensure that they are centered in the seam. Seal across the top of any spike/staple penetrations or any other penetrations through the vapor retarder with Raven Industries VaporBond TVB-4 or equivalent tape or mastic.

18. Air seal the heating and cooling ductwork per Florida Solar Energy Center’s EnergyStar program requirements.

19. Terminate any water heater drains, temperature/pressure relief pipes, furnace condensate or air conditioner condensate lines outside the crawl space.

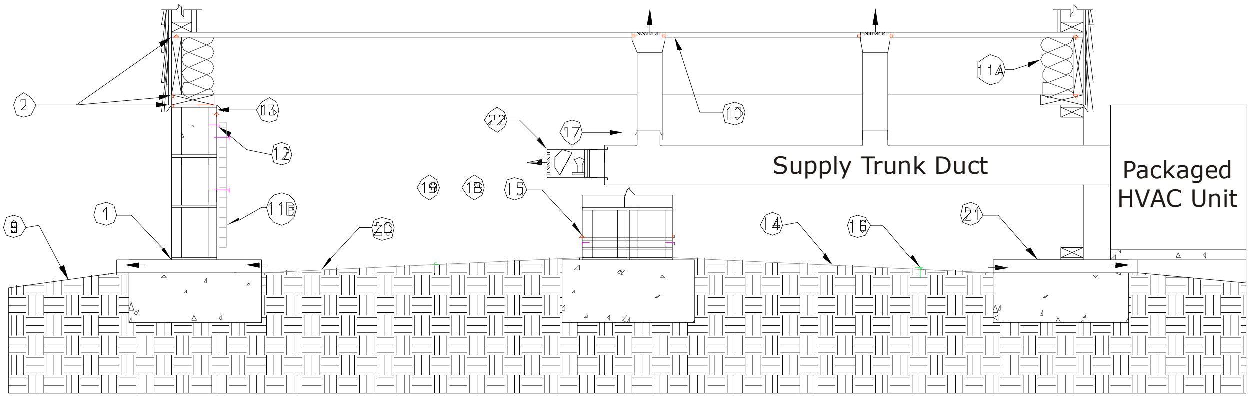
20. Terminate all kitchen, bathroom, and clothes dryer vents outside the crawl space.

21. Grade the crawl space floor to one low point on the downhill side of the crawl space.

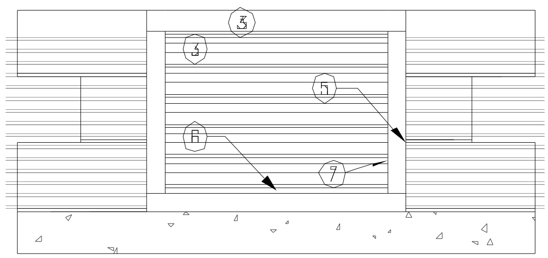
22. Install a 2” positive drain on each side of the crawl space. The drain pipe should extend to daylight and include a ProSet Systems’, Trap Guard backflow preventer. The drain intake may pass through the foundation stem wall at crawl space grade level or below. The drain shall be capped with a rodent-excluding screen or grate.

23. Provide a conditioned air supply off the supply trunk with a backflow damper and either a balancing damper or constant airflow regulator to provide airflow of 1 cubic foot per minute per 30 square feet of crawl space floor area.

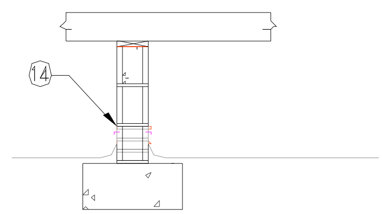
3.2.1.3 Baton Rouge closed crawl space with wall insulation and supply ducts in crawl (CCS-W-C)



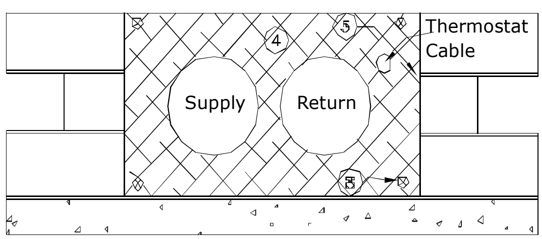
Closed Crawl Space with Wall Insulation and Ductwork in the Attic



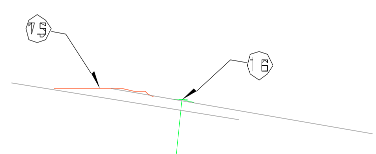
Access Panel Detail for Crawl Space;
Interior View



Vapor Retarder Detail:
Interior Piers



Access Panel Detail for Mechanicals
Entering Crawl Space;
Exterior View



Ground Vapor Retarder
Lapping Detail

Figure 3. Baton Rouge schematic design for wall-insulated closed crawl space with crawl space supply ducts.

1. Air seal all foundation stem wall penetrations with weather-resistant caulk, silicone sealant or spray foam.
2. Air seal the mating surfaces at the top and bottom of the sill plate and at the top and the bottom of the band joist. Material options are sill seal gasket, weather resistant caulk or silicone sealants, Dow Froth-Pak 25FS or equivalent spray foam (interior only) or construction adhesive.
3. The frame and body of the crawl space access panel are to be made of pressure-treated wood materials approved for masonry contact or equivalent.
4. The frame of the mechanical access panel to the crawl space is to be made of pressure treated wood approved for masonry contact or equivalent and the body is to be made of an approved cementitious material.
5. Both frames are to be sealed to the masonry with an approved exterior grade waterproof sealant.
6. Crawl space access shall be nominally 24” high and 30” wide.
7. Weather-strip the crawl space access panel.
8. Secure the crawl space access panel with four exterior-grade wood screws or equivalent.
9. Slope the exterior grade away from the foundation stem wall per local code.
10. Air seal all duct, plumbing, electrical, cable and other penetrations through the sub-floor per local fire-blocking requirements or with any combination of metal flashing, duct mastic, or fire-stop caulk.
11. Insulate the band joist area with friction-fit pieces of R-19 unfaced batt insulation. Install the insulation without voids, gaps, or compression
12. Insulate the foundation stem wall with minimum R-8 Dow Thermax insulation or equivalent. Install the insulation in contact with the wall vapor retarder. Secure the insulation to the stem wall with Hilti X-IE 6-50-D152 type fastener or equivalent. The fasteners shall be installed in two rows per piece of insulation, the first row being within the top quarter of the vertical dimension of the piece and the second row being within the bottom quarter of the vertical dimension of the piece. The top row shall be installed with maximum 48” spacing between fasteners, with at least two fasteners in the top row for each piece. The bottom row shall be installed as one fastener per piece, centered horizontally. Pieces of insulation smaller than 24” x 48” may be installed with only two fasteners. Seal seams in the insulation material with foil tape. Ensure that there is a nominal 3” gap between the insulation and the top of the stem wall or between the insulation and any untreated wood in contact with the masonry wall (e.g. support beams on pilaster, sill plate, etc.). Ensure that there is a nominal 3” gap between the bottom of the Thermax insulation and the finished interior grade of the crawl space.
13. Attach 6 mil thick, translucent, fiberglass-reinforced wall vapor retarder material to the foundation stem wall with Hilti X-GN 20MX or equivalent masonry fasteners driven through Hilti 23MM GX 100 or equivalent washers. The fastener and washer combo shall be installed in a single row within 4" of the top edge of the vapor retarder. At least one fastener and washer combo shall be installed within 6" of each corner in the foundation stem wall. The fastener and washer combo shall be spaced no more than 48" apart. When the wall vapor retarder extends higher than 48" above interior crawl space grade, the fastener and washer combos shall be spaced no more than 36" apart. Install wall vapor retarder to a height such that foundation vents are covered. Install one fastener and washer combo within 6" of each corner of each foundation vent. Overlap seams in the wall vapor retarder material at least 2" and seal the seam with Nail Power or equivalent construction adhesive, Raven Industries 4" wide VaporBond TVB-4 or equivalent tape, or fiberglass mesh tape embedded in mastic. Extend the wall vapor retarder nominally 12" horizontally onto the crawl space floor.

14. Leave a nominal 3" termite inspection gap between the top of the wall vapor retarder and the top of the masonry wall and any untreated wood in contact with the masonry wall (e.g. support beams on pilasters, sill plates, etc.). Seal the edges of the wall vapor retarder to the stem wall with Nail Power construction adhesive or fiberglass mesh tape embedded in mastic or equivalent.
15. Attach minimum 6-mil fiberglass reinforced vapor retarder material around each interior pier at least 4" above the crawl space floor. Overlap the seam at least 2". Mechanically attach the vapor retarder to the pier with at least one fastener and washer combo (as defined in item 10) per side. Seal the top edge of the vapor retarder to the pier with Nail Power or equivalent construction adhesive or fiberglass mesh tape and mastic. Seal the seam in the pier vapor retarder and seal the pier vapor retarder to the ground vapor retarder with Raven Industries 4" wide VaporBond TVB-4 or equivalent tape or minimum 4" wide fiberglass mesh tape embedded in mastic.
16. Cover 100% of the crawl space floor with minimum 8 mil thick, fiberglass-reinforced polyethylene vapor retarder. Lap the floor vapor retarder material on top of the wall vapor retarder material. When overlapping seams in the field of the ground vapor retarder, ensure that downhill pieces of vapor retarder lap over uphill pieces of vapor retarder. Overlap all seams by a minimum 6" and seal all seams with Raven Industries 4" wide VaporBond TVB-4 or equivalent tape or minimum 4" wide fiberglass mesh tape embedded in mastic. Areas where tape is to be applied must be cleaned of dust and debris prior to application of tape.
17. Secure the ground vapor retarder to the crawl space floor with nominal 6" galvanized spikes or turf staples. Install at least one spike or staple within 2' of each corner in the foundation stem wall. If spikes are used, insert the spikes through a minimum 1" diameter plastic or metal washer. If spikes are optionally inserted through a lapped seam, ensure that they are centered in the seam. Seal across the top of any spike/staple penetrations or any other penetrations through the vapor retarder with Raven Industries VaporBond TVB-4 or equivalent tape or mastic.
18. Air seal the heating and cooling ductwork per Florida Solar Energy Center's EnergyStar program requirements.
19. Terminate any water heater drains, temperature/pressure relief pipes, furnace condensate or air conditioner condensate lines outside the crawl space.
20. Terminate all kitchen, bathroom, and clothes dryer vents outside the crawl space.
21. Grade the crawl space floor to one low point on the downhill side of the crawl space.
22. Install a 2" positive drain on each side of the crawl space. The drain pipe should extend to daylight and include a ProSet Systems', Trap Guard backflow preventer. The drain intake may pass through the foundation stem wall at crawl space grade level or below. The drain shall be capped with a rodent-excluding screen or grate.
23. Provide a conditioned air supply off the supply trunk with a backflow damper and either a balancing damper or constant airflow regulator to provide airflow of 1 cubic foot per minute per 30 square feet of crawl space floor area.

3.2.2 Baton Rouge Experimental Groups

The Baton Rouge field site consists of fifteen single-story modular homes of similar size and footprint. The homes are assembled from two separate factory-built halves that were shipped and placed on 24-inch high site-built foundation footings and walls. The homes were built with comparable above-grade wall areas, window areas and insulating features, and space conditioning for all homes is provided by the same make and model of package-unit heat pump. The heat pump is located beside each home with the main supply and return trunks running into the crawl space. In twelve of the homes, the supply trunk turns up through a central chase and the distribution ducts are installed in the attic. The remaining three homes have distribution ducts in the crawl space. Complete design specifications for the homes are included in the computer energy program assessment section of this report.

The project homes are located on two adjacent streets, with back yards that connect via a common area between the two rows of homes. All the homes are within an approximately 75 yard radius from the center of the group. Homes were assigned to the control and intervention groups in order to balance the impact of differing floor area, glazing area, and solar orientation. The homes were performance tested to ensure that there was no significant bias toward the experimental groups with regard to envelope leakage, duct leakage, and mechanical ventilation rates. The site is flat, with all homes at the same elevation and having crawl spaces that are approximately two feet high.

Baton Rouge is located in a hot-humid climate as defined by the U.S. Department of Energy's Building America Program. Figure 4 below illustrates the site layout (not to scale) and experimental designations for each participating home within the test site.

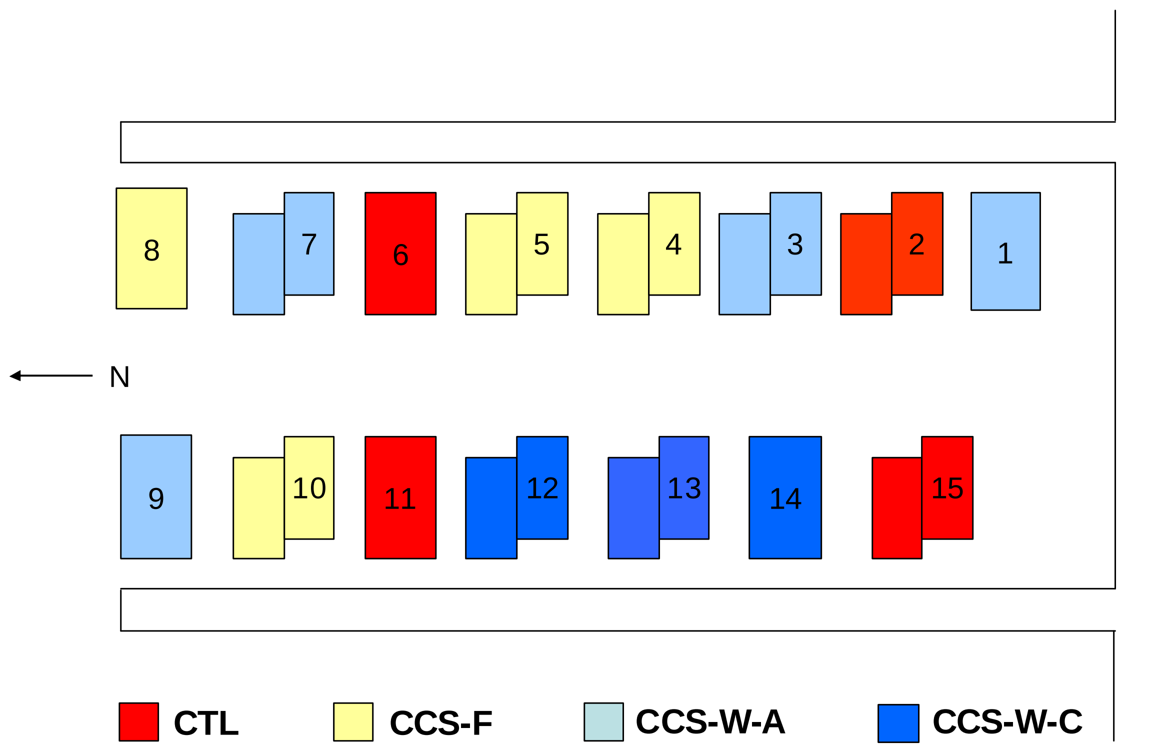


Figure 4. Baton Rouge site layout and experimental designations by lot.

Table 1 summarizes the average home characteristics and performance data by group for Baton Rouge. The East-West glazing column holds the sum of the east- and west-facing glazing, since windows on these elevations contribute disproportionately to the heating and cooling loads compared to glazing on the north and south elevations. The house- and duct-leakage measures are presented as ratios of envelope area and floor area, respectively, to account for the slight variations in home size. Intentional outside-air ventilation was provided beginning in April 2008 by a dampered, filtered six inch diameter intake duct connected from outside to the return duct of the heat pump system. Note that while the percentage differences in the ventilation rates are large, the absolute differences are quite small. The ventilation occurs only when the heat pump air handler is operating. As a whole, these characteristics indicate that the experimental groups may be slightly biased towards using more energy for heating and cooling than the control group. This is somewhat offset by the lower duct leakage ratios for two of the experimental groups.

Table 1. Baton Rouge building characteristic comparisons by group.

Crawl Space Type	Floor Area (Sq. Ft.)	Volume (Cu. Ft.)	Envelope Area (Sq. Ft.)	Total Glazing (Sq. Ft.)	East-West Glazing (Sq. Ft.)	House Leakage Ratio (CFM50 per Sq. Ft. Envelope Area)	Duct Leakage Ratio (CFM25 per Sq. Ft. Floor Area)	Ventilation Rate (CFM)
CTL (Control)	1144	9152	3456	183	78	0.26	10.1%	18
CCS-F	1196 (4%)	9568 (5%)	3616 (5%)	186 (2%)	81 (5%)	0.25 (-4%)	8.5% (-16%)	23 (30%)
CCS-W-A	1196 (4%)	9568 (5%)	3592 (4%)	183 (0%)	78 (0%)	0.27 (3%)	9.5% (-5%)	20 (16%)
CCS-W-C	1213 (6%)	9707 (6%)	3653 (6%)	185 (1%)	80 (3.2%)	0.25 (-4%)	12.7% (26%)	24 (37%)

The following figures are representative pictures of the Baton Rouge field site and crawl space systems:

Figure 5. Baton Rouge street view.

Figure 6. Baton Rouge typical home.

Figure 7. Baton Rouge vented control crawl space.

Figure 8. Baton Rouge liner system installation.

Figure 9. Baton Rouge finished floor-insulated closed crawl space.

Figure 10. Baton Rouge finished wall-insulated closed crawl space.

Figure 11. Baton Rouge closed crawl space drying mechanism.

3.2.3 Flagstaff Crawl Space Designs

There was only one significant deviation in the Flagstaff field installations from the specifications provided below. Some homes were equipped with a sump pump instead of a floor or wall gravity drain. This was due to site grading that prevented the gravity drains from terminating to daylight if they exited through the foundation floor or wall as specified.

3.2.3.1 Flagstaff closed crawl space with floor insulation (CCS-F)

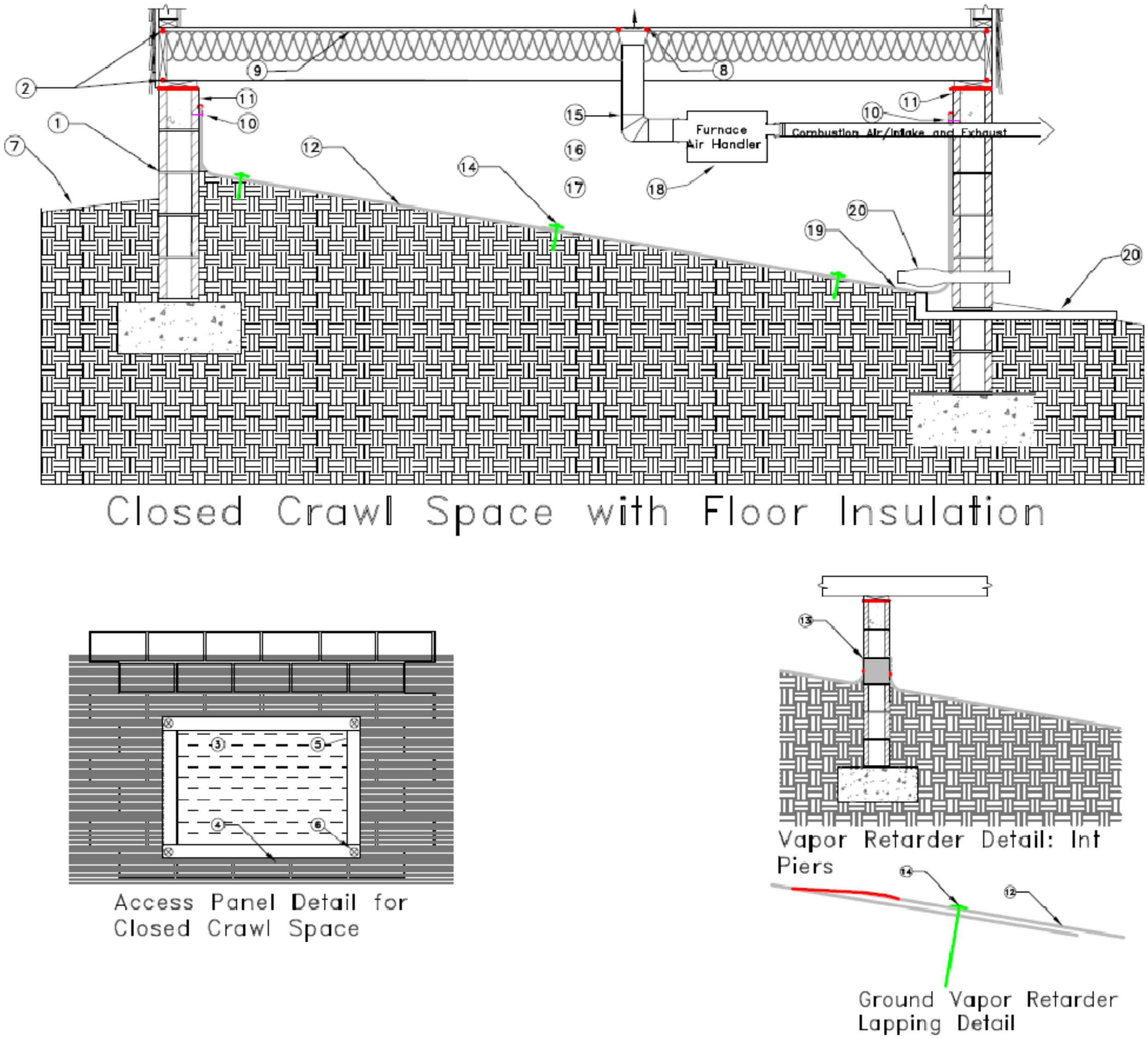


Figure 12. Flagstaff schematic design for floor-insulated closed crawl space.

1. Air seal all foundation stem wall penetrations with weather-resistant caulk, silicone sealant or spray foam.
2. Air seal the mating surfaces at the top and bottom of the sill plate and at the top and the bottom of the band joist. Material options are sill seal gasket, weather resistant caulk or silicone sealants, Dow Froth-Pak 25FS or equivalent spray foam (interior only) or construction adhesive.
3. The frame and body of the crawl space access panel are to be made of pressure-treated wood materials approved for masonry contact or equivalent.

4. Locate the crawl space access opening such that the bottom edge of the opening is a minimum of 6" above exterior and interior finished grades.
5. Weather-strip the crawl space access panel.
6. Secure the crawl space access panel with four exterior-grade wood screws or equivalent.
7. Slope the exterior grade away from the foundation stem wall per local code.
8. Air seal all duct, plumbing, electrical, cable and other penetrations through the sub-floor per local fire-blocking requirements or with any combination of metal flashing, duct mastic, or fire-stop caulk.
9. Insulate floor joist cavities with R-30 batt insulation. Install the insulation in full contact with the subfloor and ensure that it is secured in place. Install the insulation without gaps, voids, or compression.
10. Attach 6 mil thick, translucent, fiberglass-reinforced wall vapor retarder material to the foundation stem wall with Hilti X-GN 20MX or equivalent masonry fasteners driven through Hilti 23MM GX 100 or equivalent washers. The fastener and washer combo shall be installed in a single row within 4" of the top edge of the vapor retarder. At least one fastener and washer combo shall be installed within 6" of each corner in the foundation stem wall. The fastener and washer combo shall be spaced no more than 48" apart. When the wall vapor retarder extends higher than 48" above interior crawl space grade, the fastener and washer combos shall be spaced no more than 36" apart. Install wall vapor retarder to a height such that foundation vents are covered. Install one fastener and washer combo within 6" of each corner of each foundation vent. Overlap seams in the wall vapor retarder material at least 2" and seal the seam with Nail Power or equivalent construction adhesive, Raven Industries 4" wide VaporBond TVB-4 or equivalent tape, or fiberglass mesh tape embedded in mastic. Extend the wall vapor retarder nominally 12" horizontally onto the crawl space floor.
11. Leave a nominal 3" termite inspection gap between the top of the wall vapor retarder and the top of the masonry wall and any untreated wood in contact with the masonry wall (e.g. support beams on pilasters, sill plates, etc.). Seal the edges of the wall vapor retarder to the stem wall with Nail Power construction adhesive or fiberglass mesh tape embedded in mastic or equivalent.
12. Cover 100% of the crawl space floor with minimum 8 mil thick, fiberglass-reinforced polyethylene vapor retarder. Lap the floor vapor retarder material on top of the wall vapor retarder material. When overlapping seams in the field of the ground vapor retarder, ensure that downhill pieces of vapor retarder lap over uphill pieces of vapor retarder. Overlap all seams by a minimum 6" and seal all seams with Raven Industries 4" wide VaporBond TVB-4 or equivalent tape or minimum 4" wide fiberglass mesh tape embedded in mastic. Areas where tape is to be applied must be cleaned of dust and debris prior to application of tape.
13. Attach minimum 6-mil fiberglass reinforced vapor retarder material around each interior pier at least 4" above the crawl space floor. Overlap the seam at least 2". Mechanically attach the vapor retarder to the pier with at least one fastener and washer combo (as defined in item 10) per side. Seal the top edge of the vapor retarder to the pier with Nail Power or equivalent construction adhesive or fiberglass mesh tape and mastic. Seal the seam in the pier vapor retarder and seal the pier vapor retarder to the ground vapor retarder with Raven Industries 4" wide VaporBond TVB-4 or equivalent tape or minimum 4" wide fiberglass mesh tape embedded in mastic.
14. Secure the ground vapor retarder to the crawl space floor with nominal 6" galvanized spikes or turf staples. Install at least one spike or staple within 2' of each corner in the foundation stem wall. If spikes are used, insert the spikes through a minimum 1" diameter plastic or metal washer. If spikes are optionally inserted through a lapped seam, ensure that they are centered in the seam. Seal across

the top of any spike/staple penetrations or any other penetrations through the vapor retarder with Raven Industries VaporBond TVB-4 or equivalent tape or mastic.

15. Air seal the heating and cooling ductwork to comply with E3 Energy's EnergyStar program requirements and insulate the ductwork to R-6.
16. Terminate any water heater drains, temperature/pressure relief pipes, furnace condensate or air conditioner condensate lines outside the crawl space.
17. Terminate all kitchen, bathroom, and clothes dryer vents outside the crawl space.
18. Natural gas-fired furnace and any other combustion appliance in the crawl space must receive all combustion air from outside and exhaust all combustion gases directly to the outside. Any natural gas regulators, valves, or other fixtures that may vent natural gas must be vented outside the crawl space.
19. Grade the crawl space floor to one low point on the downhill side of the crawl space.
20. Provide a minimum 2" diameter drain pipe through the foundation stem wall at the lowest point of the crawl space floor. Extend this crawl space drain pipe to daylight. The drain intake may pass through the foundation stem wall at crawl space grade level or below. The drain shall be capped with a rodent-excluding screen or grate.

3.2.3.2 Flagstaff closed crawl space with wall insulation (CCS-W)

1. Air seal all foundation stem wall penetrations with weather-resistant caulk, silicone sealant or spray foam.
2. Air seal the mating surfaces at the top and bottom of the sill plate and at the top and the bottom of the band joist. Material options are sill seal gasket, weather resistant caulk or silicone sealants, Dow Froth-Pak 25SF or equivalent spray foam (interior only) or construction adhesive.
3. The frame and body of the crawl space access panel are to be made of pressure-treated wood materials approved for masonry contact or equivalent.
4. Locate the crawl space access opening such that the bottom edge of the opening is a minimum of 6" above exterior and interior finished grades.
5. Weather-strip the crawl space access panel.
6. Secure the crawl space access panel with four exterior-grade wood screws or equivalent.
7. Slope the exterior grade away from the foundation stem wall per local code.
8. Air seal all duct, plumbing, electrical, cable and other penetrations through the sub-floor per local fire-blocking requirements or with any combination of metal flashing, duct mastic, or fire-stop caulk.
9. Insulate the band joist area with friction-fit pieces of R-19 unfaced batt insulation. Install the insulation without voids, gaps, or compression.
10. Insulate the foundation stem wall with minimum R-13 Dow Thermax insulation or equivalent. Install the insulation in contact with the wall vapor retarder. Secure the insulation to the stem wall with Hilti X-IE 6-50-DI52 type fastener or equivalent. The fasteners shall be installed in two rows per piece of insulation, the first row being within the top quarter of the vertical dimension of the piece and the second row being within the bottom quarter of the vertical dimension of the piece. The top row shall be installed with maximum 48" spacing between fasteners, with at least two fasteners in the top row for each piece. The bottom row shall be installed as one fastener per piece, centered horizontally. Pieces of insulation smaller than 24" x 48" may be installed with only two fasteners. Seal seams in

the insulation material with foil tape. Ensure that there is a nominal 3" gap between the insulation and the top of the stem wall or between the insulation and any untreated wood in contact with the masonry wall (e.g. support beams on pilasters, sill plate, etc.). Ensure that there is a nominal 3" gap between the bottom of the Thermax insulation and the finished interior grade of the crawl space.

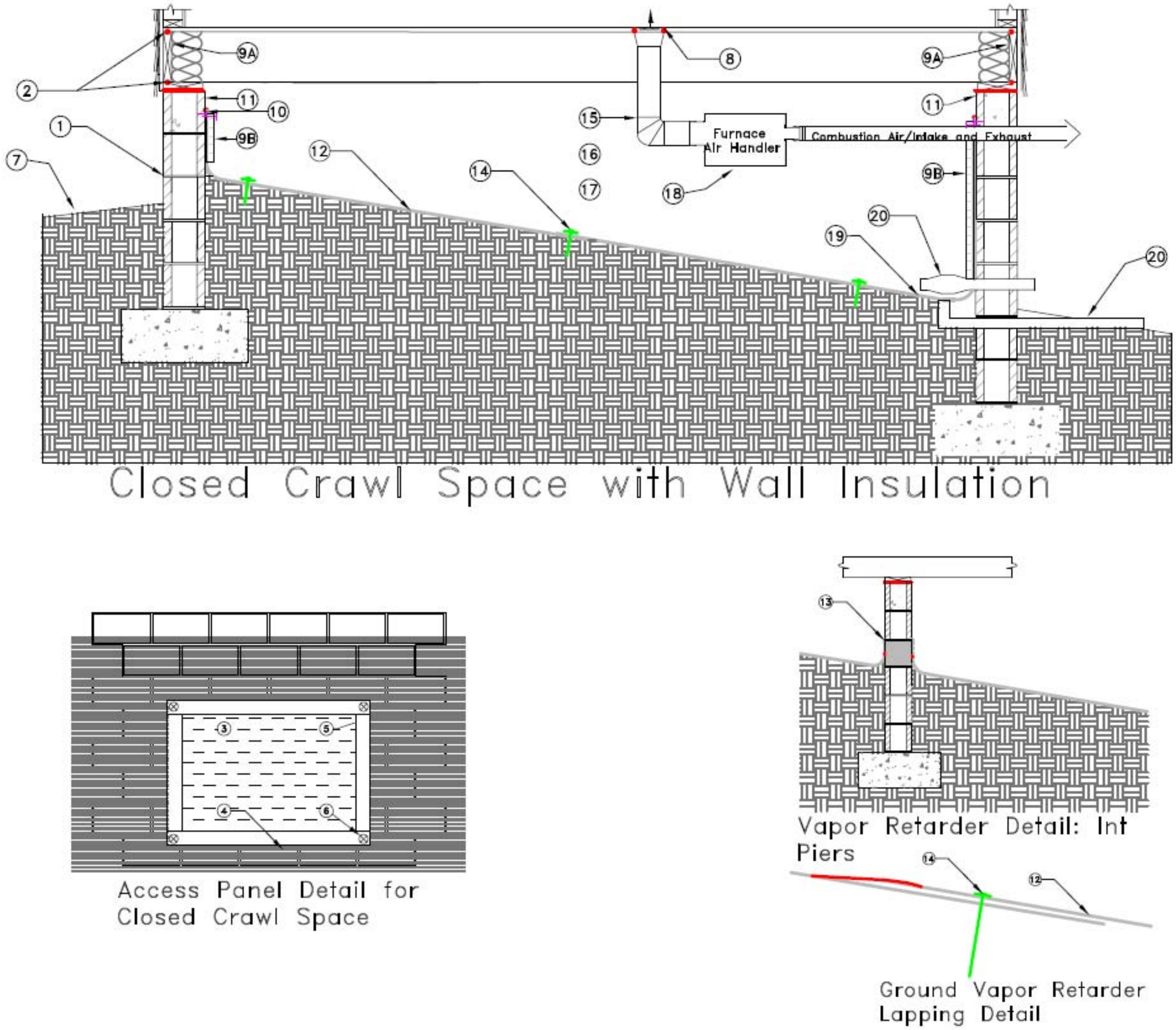


Figure 13. Flagstaff schematic design for wall-insulated closed crawl space.

11. Attach 6 mil thick, translucent, fiberglass-reinforced wall vapor retarder material to the foundation stem wall with Hilti X-GN 20MX or equivalent masonry fasteners driven through Hilti 23MM GX 100 or equivalent washers. The fastener and washer combo shall be installed in a single row within 4" of the top edge of the vapor retarder. At least one fastener and washer combo shall be installed within 6" of each corner in the foundation stem wall. The fastener and washer combo shall be spaced no more than 48" apart. When the wall vapor retarder extends higher than 48" above interior crawl space

grade, the fastener and washer combos shall be spaced no more than 36" apart. Install wall vapor retarder to a height such that foundation vents are covered. Install one fastener and washer combo within 6" of each corner of each foundation vent. Overlap seams in the wall vapor retarder material at least 2" and seal the seam with Nail Power or equivalent construction adhesive, Raven Industries 4" wide VaporBond TVB-4 or equivalent tape, or fiberglass mesh tape embedded in mastic. Extend the wall vapor retarder nominally 12" horizontally onto the crawl space floor.

12. Leave a nominal 3" termite inspection gap between the top of the wall vapor retarder and the top of the masonry wall, and between the vapor retarder and any untreated wood in contact with the masonry wall (e.g. support beams on pilasters, sill plate, etc.). Seal the edges of the wall vapor retarder to the stem wall with Nail Power construction adhesive or fiberglass mesh tape embedded in mastic or equivalent.

13. Cover 100% of the crawl space floor with minimum 8 mil thick, fiberglass-reinforced polyethylene vapor retarder. Lap the floor vapor retarder material on top of the wall vapor retarder material. When overlapping seams in the field of the ground vapor retarder, ensure that downhill pieces of vapor retarder lap over uphill pieces of vapor retarder. Overlap all seams by a minimum 6" and seal all seams with Raven Industries 4" wide VaporBond TVB-4 or equivalent tape or minimum 4" wide fiberglass mesh tape embedded in mastic. Areas where tape is to be applied must be cleaned of dust and debris prior to application of tape.

14. Attach minimum 6-mil fiberglass reinforced vapor retarder material around each interior pier at least 4" above the crawl space floor. Overlap the seam at least 2". Mechanically attach the vapor retarder to the pier with at least one fastener and washer combo (as defined in item 10) per side. Seal the top edge of the vapor retarder to the pier with Nail Power or equivalent construction adhesive or fiberglass mesh tape and mastic. Seal the seam in the pier vapor retarder and seal the pier vapor retarder to the ground vapor retarder with Raven Industries 4" wide VaporBond TVB-4 or equivalent tape or minimum 4" wide fiberglass mesh tape embedded in mastic.

15. Secure the ground vapor retarder to the crawl space floor with nominal 6" galvanized spikes or turf staples. Install at least one spike or staple within 2' of each corner in the foundation stem wall. If spikes are used, insert the spikes through a minimum 1" diameter plastic or metal washer. If spikes are optionally inserted through a lapped seam, ensure that they are centered in the seam. Seal across the top of any spike/staple penetrations or any other penetrations through the vapor retarder with Raven Industries VaporBond TVB-4 or equivalent tape or mastic.

16. Air seal the heating and cooling ductwork to comply with E3 Energy’s EnergyStar program requirements and insulate the ductwork to R-6.

17. Terminate any water heater drains, temperature/pressure relief pipes, furnace condensate or air conditioner condensate lines outside the crawl space.

18. Terminate all kitchen, bathroom, and clothes dryer vents outside the crawl space.

19. Natural gas-fired furnace and any other combustion appliance in the crawl space must receive all combustion air from outside and exhaust all combustion gases directly to the outside. Any natural gas regulators, valves, or other fixtures that may vent natural gas must be vented outside the crawl space.

20. Grade the crawl space floor to one low point on the downhill side of the crawl space.

21. Provide a minimum 2" diameter drain pipe through the foundation stem wall at the lowest point of the crawl space floor. Extend this crawl space drain pipe to daylight. The drain intake may pass through the foundation stem wall at crawl space grade level or below. The drain shall be capped with a rodent-excluding screen or grate.

3.2.4 Flagstaff Experimental Groups

The Flagstaff field site includes twelve homes of variable sizes and footprints. The homes were site-built and stick-framed using standard wood framing construction. All homes were built to meet EnergyStar certification requirements, with additional requirements for outside air ventilation and combustion safety. Space conditioning for all houses is provided by a high-efficiency gas furnace (90+ AFUE, direct vented). The furnace is located inside the crawl space along with the air handler and distribution duct work. Closed crawl space systems and data acquisition systems were installed in the homes as they were constructed, beginning in August 2006 and ending in October 2007 when the final project home was completed. Complete design specifications for the homes are located in the computer energy program assessment section of this report.

The participating homes are located on three adjacent streets within the same neighborhood. All the homes are within an approximately 0.25 mile radius from the center of the group. Homes were assigned to the control and intervention groups in order to balance the impact of differing floor area, glazing area, and solar orientation. The homes were performance tested to ensure that there was no significant bias toward the experimental groups with regard to envelope leakage, duct leakage, and mechanical ventilation rates. Each house is located on a slight grade, typically dropping at least 4’ from the front of the lot to the back, which resulted in crawl space interior heights ranging from approximately 3’ to over 8’ in some cases.

Flagstaff is located in a cold climate as defined by the U.S. Department of Energy’s Building America Program and is also very dry except for the monsoon season. Below are two maps; the first shows the location of the test site (marked as “The Retreat”), and the second is a drawing representing the lots and experimental designation for each participating house within the test site.

Figure 14. The Flagstaff field site is located at “The Retreat.”

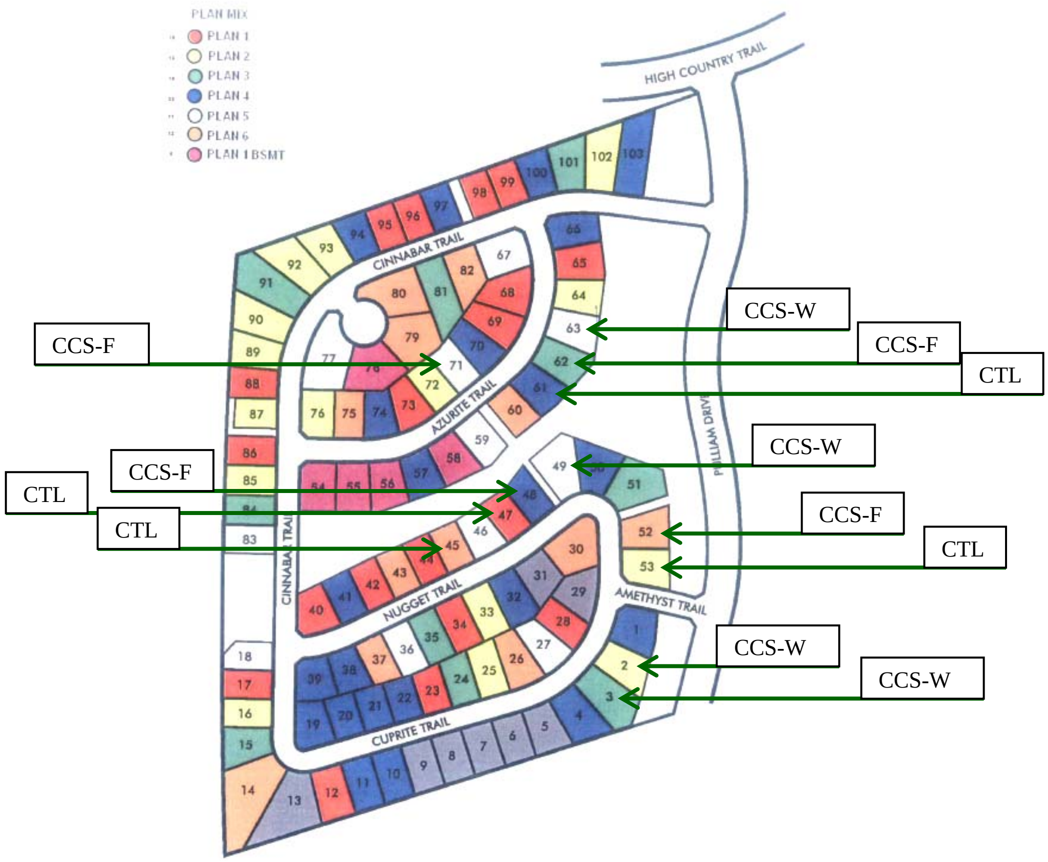


Figure 15. Experimental designations of lots in the Flagstaff field site. The top of the lot plan is North, and the front of all homes faces the street that they are built on.

Table 2 summarizes the average home characteristics and performance data by group for Flagstaff. Volume and envelope area are shown for the Flagstaff homes since there is a range of one- and two-story homes and ceiling heights are not constant, with many homes having some amount of vaulted ceiling areas. The East-West glazing column holds the sum of the east- and west-facing glazing, since windows on these elevations contribute disproportionately to the heating and cooling loads compared to glazing on the north and south elevations. The house- and duct-leakage measures are presented as ratios of envelope area and floor area, respectively, to account for the significant variations in home size at the Flagstaff site. Note that the duct leakage to outside is reported here, while in Baton Rouge total duct leakage is reported. This is due to differences in the protocols of the EnergyStar testers at each site. Intentional outside-air ventilation was provided throughout the study period by a dampered four inch diameter intake duct connected from outside to the return duct of the furnace system. The ventilation occurs only when the furnace air handler is operating. Ventilation flows were not measured by the building performance consultant at this site, so we have not included such data here. As a whole, these characteristics appear to indicate that the experimental groups are biased towards using less energy for heating and cooling than the control group, due to their smaller size and glazing area. The higher leakage ratios likely mitigate this to some extent, but as a result researchers chose to present all energy performance data as a ratio to the cubic volume of the homes.

Table 2. Flagstaff building characteristic comparisons by group.

Crawl Space Type	Floor Area (Sq. Ft.)	Volume (Cu. Ft.)	Envelope Area (Sq. Ft.)	Total Glazing (Sq. Ft.)	East-West Glazing (Sq. Ft.)	House Leakage Ratio (CFM50 per Sq. Ft. Envelope Area)	Duct Leakage to Outside Ratio (CFM25 per Sq. Ft. Floor Area)
CTL (Control)	2477	24225	6595	366	129	0.18	1.2%
CCS-F	2184 (-12%)	20921 (-14%)	6016 (-9%)	318 (-13%)	141 (9%)	0.22 (19%)	1.32% (10.6%)
CCS-W	2277 (-8%)	21986 (-9%)	6349 (-4%)	320 (-13%)	121 (-7%)	0.19 (7%)	1.52% (26.7%)

The following figures are representative pictures of the Flagstaff field site and crawl space systems:

Figure 16. Flagstaff site during construction.

Figure 17. Flagstaff typical home.

Figure 18. Flagstaff vented crawl space.

Figure 19. Flagstaff wall liner installation.

Figure 20. Flagstaff finished floor-insulated closed crawl space.

Figure 21. Flagstaff finished wall-insulated closed crawl space (doubling as an Advanced Energy field office).

3.3 Field Data Acquisition Systems

Researchers specified data acquisition systems to measure and record hourly temperature and humidity levels, monthly energy consumption, and long-term radon concentrations in order to quantify the impact of the closed crawl space foundations on the experimental home groups over a twelve-month post-occupancy period.

3.3.1 Temperature and Humidity

At the Flagstaff site, researchers recorded indoor temperature and humidity data from both the living space and the crawl space using HOBO Pro standalone data loggers. One logger was installed behind the grill cover of the central furnace return duct to measure living space conditions, and two loggers were installed on a support girder in the center of the crawl space to measure crawl space conditions. Two loggers were used in the crawl space to guard against data loss in the case of a logger failure.

The HOBO Pro loggers, model number H08-032-08, were manufactured by Onset Computer Corporation (www.onsetcomp.com). They measure temperature and relative humidity at user-programmable time intervals. Onset provides the following specifications for the Hobo Pro series loggers:

Temperature (internal sensor)

- Range: -30° to 50°C (-22° to 122°F)
- Accuracy: ±0.2° at 21°C (±0.33° at 70°F) in high-resolution mode and ±0.5°C (±0.9°F) in standard-resolution mode
- Resolution: 0.02° at 21°C (.04° at 70°F) in high-resolution mode and 0.41°C (0.7°F) in standard-resolution mode
- Response time in still air: <35 minutes typical to 90%

Relative humidity:

- Range: 0% to 100% RH*
- Accuracy: ±3% RH over the range of 0 to 50°C (32° to 122°F); ±4 in condensing environments
- Drift: 1% per year typical; an additional temporary drift up to 3% can occur when the average humidity is above 70%; factory tune-up available
- Response time: 5 minutes typical to 90% (independent of temperature)
- Sensor operating environment: 0° to 50°C (32° to 122°F) in intermittent condensing environments up to 30°C, and above 30°C in non-condensing environments
- Note: Sensor requires protection from rain, splashing, mist, and airborne chemicals such as salt and ammonia.

To retrieve data from a HOBO Pro, a cable is connected from the HOBO Pro to either a HOBO Shuttle temporary storage device or directly to a laptop computer via the serial communications port. Data stored on a Shuttle device can be transferred to a computer via the same cable. HOBO Boxcar software, also available through Onset Corporation, is used to transfer and display data files as text and in graphical form.

A different system was used to collect temperature and humidity data at the Baton Rouge site. The close proximity of the homes there allowed researchers to use a wireless, Internet-based sensor network as the primary temperature and humidity data acquisition system, and to install HOBO Pros only as a back-up system. The primary system selected was the OmniSense™ Facility Monitoring System (www.omnisense.com). The HOBO Pro backup loggers were installed next to the OmniSense devices (See representative pictures in Figure 22 and Figure 23) behind the grill cover of the return duct to record conditions in the living space and on a floor joist or central support girder in the crawl space to record conditions there.

The OmniSense sensors can record temperature, humidity, and wood moisture data. When applicable, wood moisture readings can be taken via mounting screws used to attach the sensors. With regard to measurement parameters, the OmniSense sensors have the limitations and levels of accuracy given in Table 3.

Table 3. Technical specifications for the OmniSense Facility Monitoring System.

Parameter	Values	Accuracy range typical (max)	Units
Temperature measurement range	-40 to 185	±0.5 (±3.6)	°F
Humidity measurement range	0 to 100	±3.5 (±5.0)	%RH
Wood moisture range, USDA Douglas Fir	7 to 40		%
Battery life	15	up to 45	years
Sensor length x width x height	2.4 x 1.6 x 2.5		inches
Sensor weight	2		ounces
Wireless range	328		ft

The sensors of the OmniSense monitoring system communicate wirelessly with a gateway that is connected to a standard high-speed home internet connection (dial-up is also available with extra equipment). The gateway sends data to an online database for storage and retrieval, and data can be collected from any computer with Internet access. While this makes installation of the gateway simple and straightforward, it also makes the system vulnerable to down periods when power to the gateway is cut off or the internet connection lost. Notifications are sent via email when a sensor or gateway is inactive for 24 hours, making it possible to diagnose problems quickly. Thresholds can also be set to send email alarms when, for instance, relative humidity is higher than a user-definable threshold.

Each OmniSense sensor is about half the size of a deck of playing cards. Because of their small size, the sensors can be mounted anywhere: inside exterior walls, at roof lines, inside ductwork, etc. Their long (+15 year typical) battery life means the sensors can be mounted in areas that are inaccessible after construction is complete. The sensors can be mounted flush to a surface for surface readings or held off a surface 1.5” with mounting legs (see Figure 22 and Figure 23).

Figure 22. Crawl space OmniSense sensor mounted on floor framing.

Figure 23. HVAC return OmniSense sensor mounting with adjacent HOBO logger.

The OmniSense sensors can also be programmed to take measurements at user-defined intervals, from as often as one minute to every few days or even weeks.

The data collection interval for both the HOBO Pros and the OmniSense sensors was set to one hour at both the Baton Rouge and the Flagstaff field sites. Data was downloaded quarterly from the HOBO Pro data loggers by Advanced Energy staff during regularly-scheduled field site inspections. OmniSense data was downloaded as desired from the OmniSense web site.

Outdoor weather data were collected from local airport readings through the NOAA Climactic Data Center website:

http://hurricane.ncdc.noaa.gov/pls/plclimprod/poemain.accessrouter?datasetabbv=DS3505

Hourly temperature and dew point temperature data were downloaded from the local airport (Ryan Airport for Baton Rouge and Flagstaff Airport for Flagstaff) and incorporated into the HOBO and OmniSense data set for each location. Relative humidity for the outdoor data was calculated using formulas from the 2005 ASHRAE Fundamentals Handbook.

3.3.2 Energy

At both sites, whole-house energy consumption was recorded using the main meters supplied by the local utility companies – one electric meter in Baton Rouge, and one electric meter and one gas meter in Flagstaff. Energy used for space conditioning was measured with additional sub-meters installed on the heating and cooling equipment. The Baton Rouge homes are conditioned by package-unit heat pumps, so one standard utility kWh meter (GE model I-70-S or equivalent, with cyclometer-style display) was sufficient to record all energy used for space conditioning.

- The Flagstaff homes employed split-systems for space conditioning, with gas furnaces for heating and conventional air conditioners for cooling. This design required three sub-meters to capture the desired energy data: an electric meter for the air handler fan, another electric meter for the air conditioner condensing unit, and a gas meter for the furnace. The electric meters were the same model as used in Baton Rouge.

- The electric meters have an accuracy of +/- 0.2% under full- or part-load conditions, and readings were rounded to the nearest whole unit of kWh. The gas meter used to measure the furnace consumption was a Sensus S-275, with an accuracy of +/- 100 cubic feet (approximately 1 therm of natural gas).

Energy data was collected on a monthly basis by staff of Dugas Pest Control in Baton Rouge and E3 Energy in Flagstaff. Those monthly meter readings were recorded on a paper field form, then transferred to an electronic spreadsheet and sent via e-mail to Advanced Energy. Every energy reading was also documented with a digital photograph of the corresponding meter, which was labeled with the house lot number and meter type for automatic identification in the picture. Advanced Energy staff confirmed every data value in the spreadsheet against the photo of the corresponding meter to ensure there were no errors in the recording process.

3.3.3 Radon

Researchers documented radon concentrations in the living space and crawl space of every home to identify potential radon hazards due to reduced crawl space ventilation. Short-term (vapor diffusion charcoal canister) and long term (AT-100 alpha-track) radon testers from AccuStar Labs (www.accustarlabs.com) were used to measure radon concentrations.

3.4 Energy Modeling Program Selection

An initial look into the most popular modeling applications was performed during the DOE-funded first phase of the current work (Dastur, Carter, Hannas). Results from this effort narrowed down the list of desired modeling applications from nine to three based on DOE descriptions and reviews, ability to input the closed crawl space designs, ability to model any location in the United States, ease of use and relative energy prediction accuracy. The three applications chosen were: REM/Rate, from Architectural Energy Corporation, EnergyGauge from the Florida Solar Energy Center, and TREAT, from PSD Consulting.

3.5 Energy Modeling Program Analysis Plan

After the 15 houses in Baton Rouge, LA, and 12 houses in Flagstaff, AZ, were constructed for this project and energy use data were collected, each house was modeled in each of the three modeling applications using as many known inputs as possible, including indoor conditions and actual building orientations. To aide in reducing effort and increasing accuracy, the developers of the software applications provided support and two of the developers provided modeled the houses themselves. Advanced Energy staff conducted a final quality assurance check to ensure that all building model inputs were consistent with the actual home construction and consistent across the modeling applications.

Once all of the houses were modeled in each program, the heating and cooling energy use and the total energy use were compared against the sub-metered energy use for each house. Summaries were created for group averages in each location.

House by house building characteristics used in the computer modeling are presented in the following subsections.

3.5.1 Baton Rouge Modeling Specifications

The following inputs were used in the Baton Rouge computer models. All homes were single-story and had very similar floor plans with slight variations, as can be seen in Table 4.

Table 4. Baton Rouge lot-by-lot specifications for computer modeling.

						Leakage to Outside		Glazing (sqft)				Setpoints	
Group	Lot	Front Orient	Floor (sqft)	Volume (cuft)	Envelope (sqft)	Duct CFM25	House CFM50	E	S	W	N	Cool	Heat
Vented + Floor	2	E	1144	9152	3504	66	850	60	60	25	45	74	67
	6	E	1144	9152	3408	70	919	45	60	25	45	72	72
	11	W	1144	9152	3408	55	890	25	45	45	60	78	71
	15	W	1144	9152	3504	46	960	25	45	60	60	75	68
Closed + Floor	4	E	1144	9152	3504	69	870	60	60	25	45	67	70
	5	E	1144	9152	3504	49	910	60	60	25	45	74	71
	8	E	1352	10816	3952	54	1028	45	60	25	45	71	70
	10	W	1144	9152	3504	46	848	25	45	60	60	68	69
Closed + Wall, Attic Ducts	1	E	1144	9152	3408	51	1125	45	60	25	45	75	76
	3	E	1144	9152	3504	43	910	60	60	25	45	70	68
	7	E	1144	9152	3504	36	909	60	60	25	45	75	73
	9	W	1352	10816	3952	64	895	25	45	45	60	71	67
Closed + Wall, Crawl Ducts	12	W	1144	9152	3504	153	1030	25	45	60	60	71	71
	13	W	1144	9152	3504	102	820	25	45	60	60	71	71
	14	W	1352	10816	3952	146	1000	25	45	45	60	74	71

The group categories had the following characteristics:

- Vented + Floor is a vented crawl space under an R-19 insulated framed floor
- Closed + Floor is a closed (unvented) crawl space under an R-19 insulated framed floor
- Closed + Wall, Attic Ducts is a closed crawl space with R-8 rigid foam board on the perimeter wall, R-19 insulation in the band joist, and supply ducts in the attic
- Closed + Wall, Crawl Ducts is a closed crawl space with R-8 rigid foam board on the perimeter wall, R-19 insulation in the band joist, and supply ducts in the crawl space

For completeness, the following characteristics were consistent across all homes:

- Heating/cooling provided by a 13 SEER/7.7 HSPF packaged unit heat pump located adjacent to the house
- Water heater is an electric tank, 50 gal, at 0.92 EF
- On 12 homes, supply and return trunks run through the crawl space, then up through vertical chases to the home
  - Return pulls from side of hall wall in conditioned space
  - Supply runs to the attic and ducts run through the attic to ceiling registers
- On 3 homes (lots 12, 13, and 14) the supply ducts run through the crawl space to floor registers
- Ducts are R-6 flex
- A supply air duct to the crawl space provides 50 cfm of conditioned air to the closed crawl spaces whenever the system is running (only in closed crawl spaces)

- Ventilation is provided in all homes by a duct running from outside to the return plenum, and draws the amount specified in the table above whenever the air handler is running
- Single-family detached, modular (factory built), stick frame construction
- R-13 fiberglass batts plus R-3 continuous foam sheathing in above-grade walls
- R-30 blown fiberglass attic insulation
- Crawl space walls are 8" thick concrete block (CMU) walls
- Window U-value = 0.35, SHGC = 0.3
- Windows are double-glazed with vinyl frame
- Doors are insulated steel, U = 0.46
- The crawl space is 2 ft high, and the interior grade is the same as the exterior grade
- Appliance and Lighting values were left as the software defaults

3.5.2 Flagstaff Modeling Specifications

The following inputs were used in the Flagstaff computer models. Compared to Baton Rouge, Flagstaff had more variation in the floor plans, as can be seen in Table 5.

Table 5. Flagstaff lot-by-lot specifications for computer modeling.

							Leakage to Outside		Glazing (sqft)				Setpoints	
Group	Lot	Front Orient	Floor (sqft)	Volume (cuft)	Envel (sqft)	Floors	Duct CFM25	House CFM50	E	S	W	N	Cool	Heat
Vented + Floor	45	S	2776	27780	7200	2	20	1350	96	79	33	209	n/a	65
	47	S	2998	29778	7200	2	23	1304	84	79	63	209	n/a	65
	53	W	1910	17343	5499	1	27	1111	127	85	36	66	n/a	71
	61	N	2223	21999	6481	2	42	1010	34	148	45	75	n/a	63
Closed + Floor	48	S	2223	21999	6481	2	28	1750	45	75	34	148	n/a	55
	52	W	2998	29778	7200	2	26	1160	206	63	79	96	n/a	65
	62	N	1910	17343	5499	1	32	1160	56	127	85	36	n/a	63
	71	S	1605	14563	4882	1	24	1100	38	50	21	113	n/a	65
Closed + Wall	2	N	1874	19705	5411	1	22	1050	50	104	68	35	n/a	75
	3	N	2776	27780	7200	2	35	1425	96	209	33	79	n/a	60
	49	S	2228	20230	6393	2	43	1090	68	49	50	136	n/a	67
	63	N	2228	20230	6393	2	38	1360	50	136	68	49	n/a	64

The group categories had the following characteristics:

- Vented + Floor is a vented crawl space under an R-30 insulated framed floor
- Closed + Floor is a closed (unvented) crawl space under an R-30 insulated framed floor
- Closed + Wall is a closed crawl space with R-13 rigid foam board on the perimeter wall and R-19 insulation in the first floor band joist

For completeness, the following characteristics were consistent across all homes:

- 12 SEER air conditioner
- 90% AFUE direct-vent furnace
- Gas water heater is located in the garage with EF = 0.62
- The furnace/AHU is located in the crawl space and there is only one system per home
- Ducts are R-6 flex
- First floor ducts are located in the crawl space
- If there is a second story, the ducts are chased up to run through the space between the floors to registers in the floor/baseboard of the second story
- There were no supply or return air ducts to the crawl space used at this field site
- Single-family detached, site-built, stick frame construction
- R-19 in all above-grade walls
- R-19 floor insulation over garage when applicable
- R-30 attic insulation
- Window U-value = 0.38; SHGC = 0.40
- Windows are double-glazed with vinyl frame
- Front and garage doors are R-5
- Appliance and Lighting values were left as the software defaults

4. RESULTS

The closed crawl space systems for Baton Rouge were installed in the appropriate eleven homes during the week of August 9 through August 16, 2007. Researchers were unable to secure sufficient qualified labor in Baton Rouge to carry out the work, so travel expenses were paid for members of the CrawlSpace Care Technology network and E3 Energy to come to Baton Rouge to perform the installation. They were directed and assisted by staff from Advanced Energy, and supported by staff from Habitat for Humanity of Greater Baton Rouge and AmeriCorps volunteers who were on assignment with Habitat for Humanity. CrawlSpace Care Technology (CCCT) is a closed crawl space installation company and product distributor based in Greensboro, NC. The CCCT staff has provided technical support and regulatory consulting to Advanced Energy since 2004, beginning with AE's crawl space work in North Carolina.

The closed crawl space systems and data acquisition systems were installed at the Flagstaff site as the appropriate homes were completed, which ranged from August of 2006 to October of 2007. All Flagstaff installations were performed by the staff of E3 Energy, a local high-performance building contractor.

Advanced Energy staff installed and tested all data acquisition systems with the exception of the electric and gas sub-meters, which were installed by licensed electrical and mechanical contractors, respectively.

Researchers achieved a twelve-month data collection period for the Baton Rouge site, concluding the field study there in early October 2008. However, the Flagstaff field study was discontinued ahead of schedule in April of 2008 due to the identification of radon hazards in the homes with experimental closed crawl spaces.

4.1 Baton Rouge Crawl Space Temperature and Humidity

The temperature and humidity results are presented in two time intervals: the dry-down period and the entire study period. The dry-down period begins a week before the crawl space interventions were installed and continues through the week after the installations were complete. This focus on the period around the installation shows how quickly the closed crawl space systems are able to reduce the moisture load in the crawl space. The second time interval, covering the entire study period, shows how the closed crawl space systems perform from the dry-down period through the end of the field study.

Figure 24 and Figure 25 show the moisture load in the crawl spaces during the dry-down period. Figure 24 is a graph of the dew point group averages on an hourly basis and Figure 25 is a graph of the relative humidity group averages on an hourly basis. As an explanatory variable, the outdoor dew point and relative humidity are included in the graphs, respectively.

Evidence of the closed crawl space installations and their impact on dew point and relative humidity can be seen in these graphs. After the end of the initial installations on August 16, the control houses continued to follow outdoor environmental conditions, while all three configurations of the closed crawl space system show a clear decline in dew point and relative humidity. By August 17, relative humidity dropped to below 70 percent in the intervention homes. Within a few days, relative humidity dropped further to below 60 percent and remained at that level for the majority of the study.

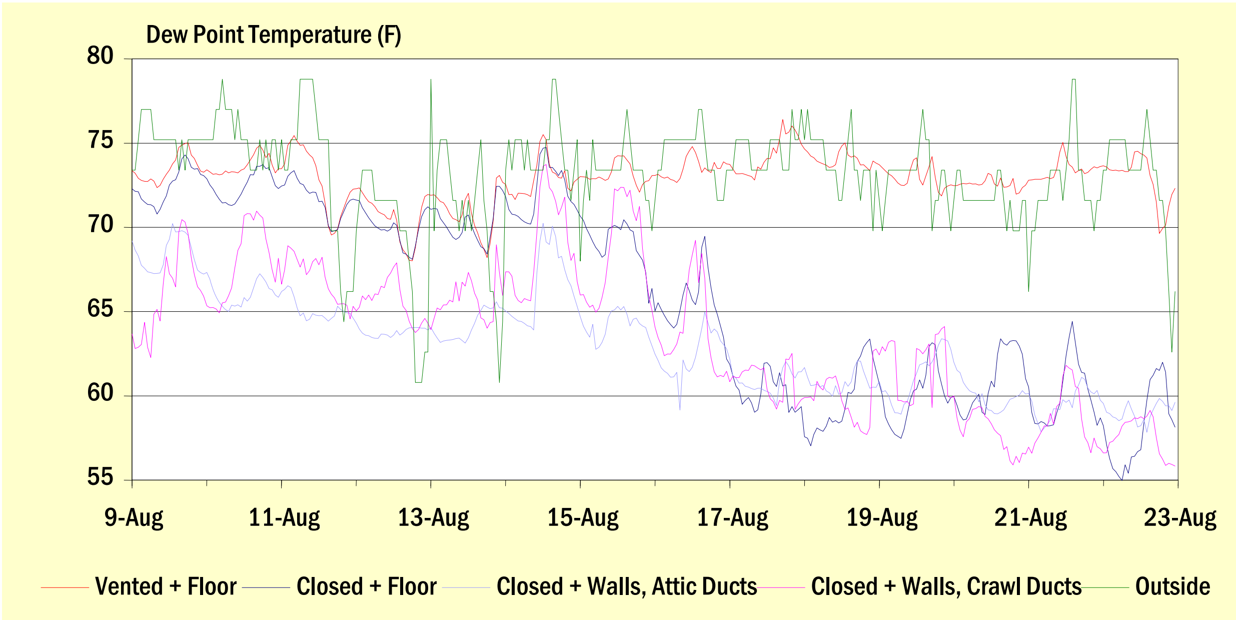


Figure 24. Baton Rouge – Hourly crawl space and outdoor Dew Point Temperatures by group for the dry down period.

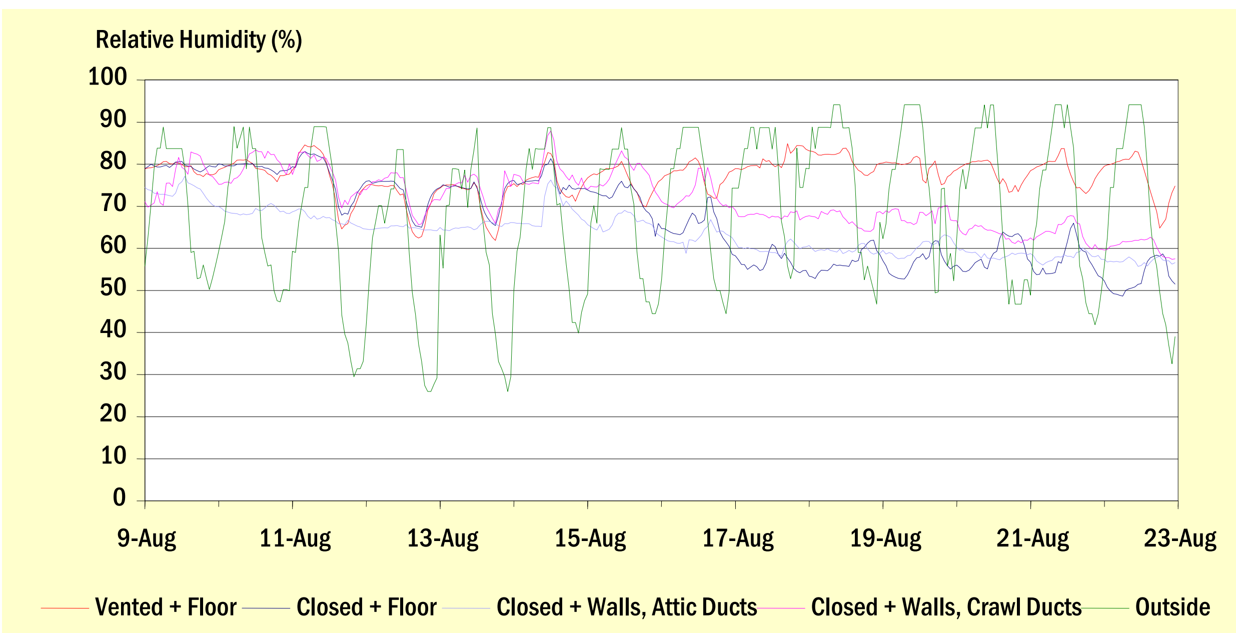


Figure 25. Baton Rouge – Hourly crawl space and outdoor Relative Humidity (RH) by group for dry down.

In the graphs of data for the entire study period, the dry down segment is just barely visible at the far left of each graph. Figure 26 and Figure 27 show the moisture load in the crawl spaces during the entire field study period. Figure 26 is a graph of the dew point group averages on a daily basis and Figure 27 is a graph of the relative humidity group averages on a daily basis. As an explanatory variable, the outdoor dew point and relative humidity are included in the graphs, respectively. A third graph, Figure 28, shows the temperature in each crawl space type and outdoor for the entire period.

These graphs clearly show the impact of the closed crawl space systems to reduce dew point and relative humidity across multiple seasons. After the end of the installation period on August 16, the control houses follow outdoor environmental conditions, while all three configurations of the closed crawl space system show a clear decline in dew point and relative humidity. During the late summer of 2007 and in the summer of 2008, the three crawl space interventions control relative humidity to less than 60 percent on average, while the vented crawl spaces vary between 60 and 90 percent relative humidity.

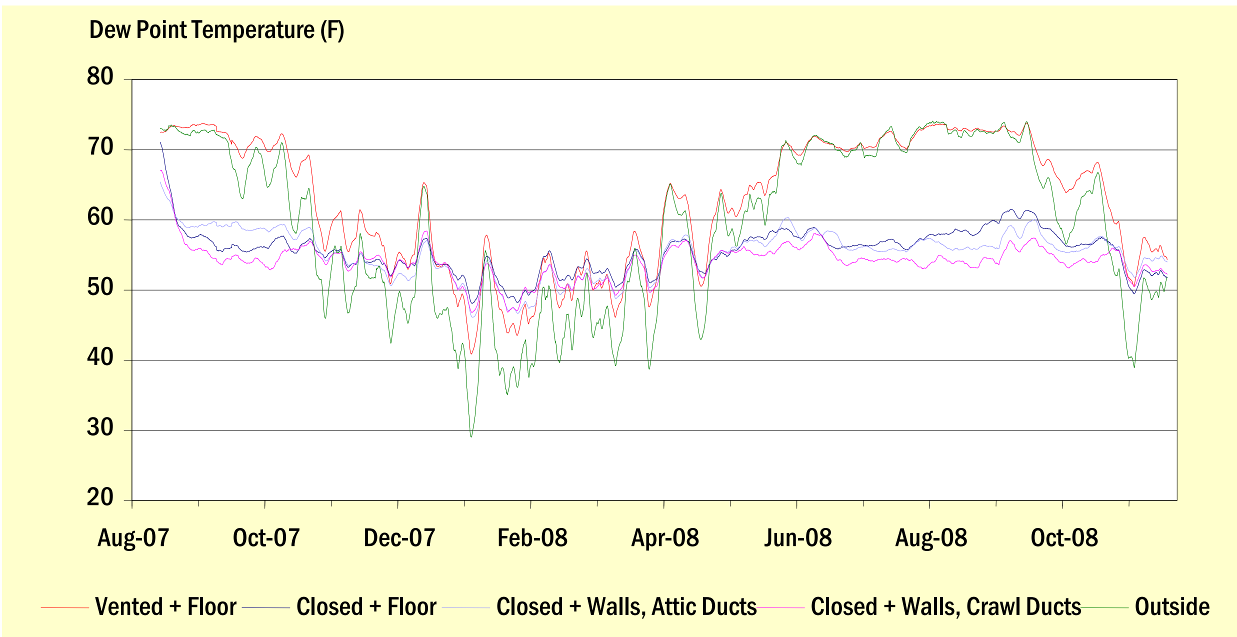


Figure 26. Baton Rouge – Daily crawl space and outdoor Dew Point (DP) by group.

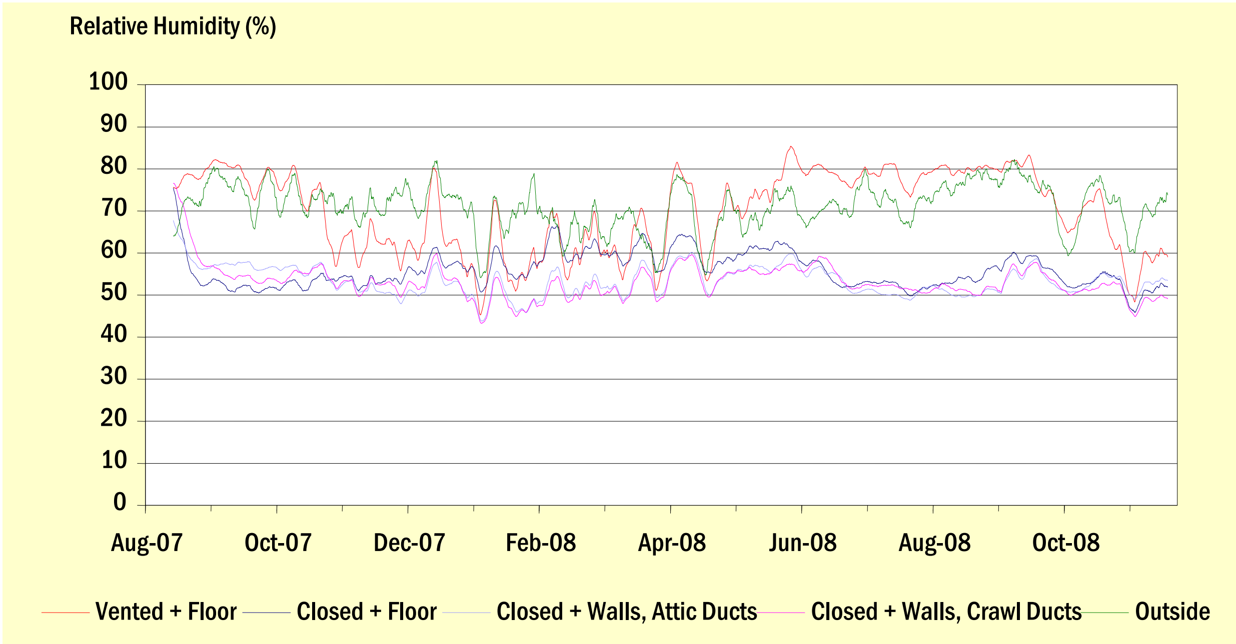


Figure 27. Baton Rouge – Daily crawl space and outdoor Relative Humidity (RH) by group.

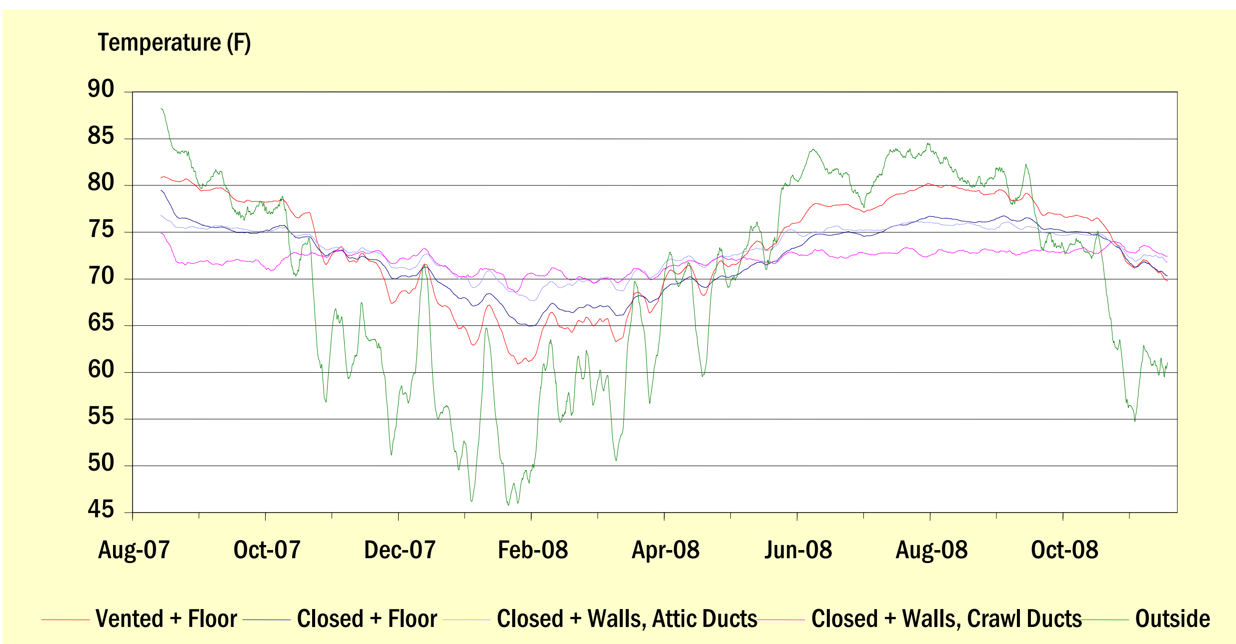


Figure 28. Baton Rouge – Daily crawl space and outdoor temperature by group.

4.2 BATON ROUGE LIVING SPACE TEMPERATURE AND HUMIDITY

Figure 29 and Figure 30 show the average daily temperature and relative humidity, respectively, inside each of the research groups over time. The data indicate a difference in thermostat set points for the cooling months (April through October), but little or no difference in thermostat set points for the heating months (January through March) and very little difference in relative humidity for the entire study. Thermostat differences seen in the 2007 cooling season are not as pronounced in 2008, but there are still distinct differences in occupant behavior.

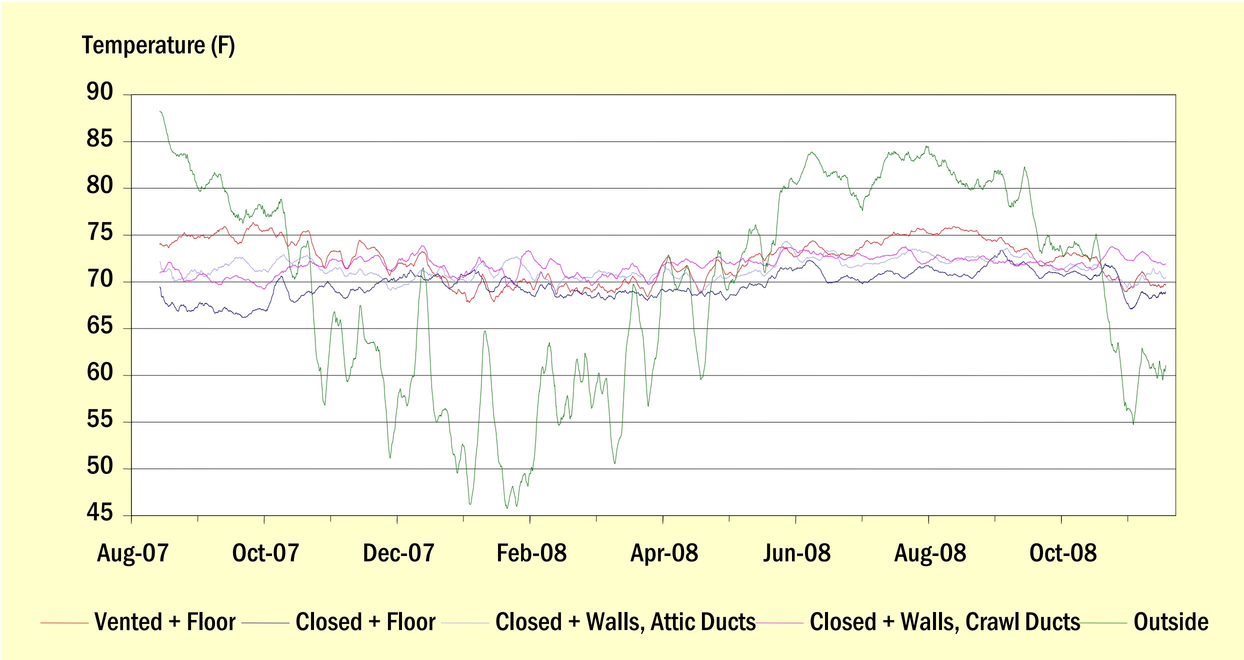


Figure 29. Baton Rouge – Daily indoor temperature by group.

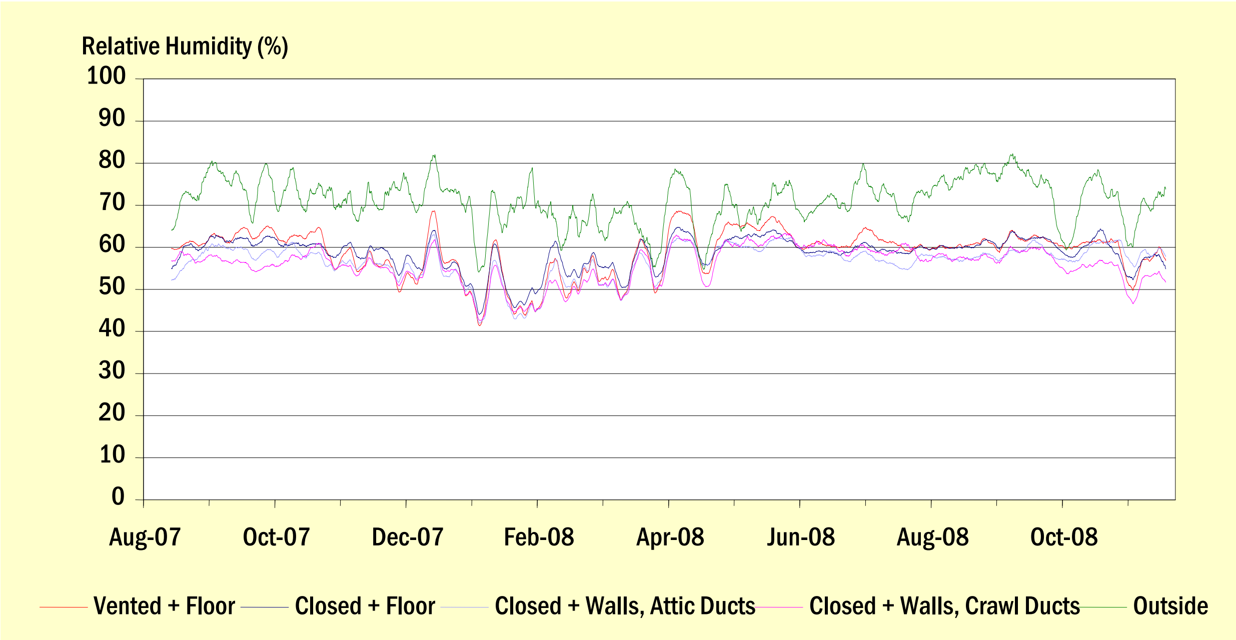


Figure 30. Baton Rouge – Daily indoor relative humidity by group.

4.3 Baton Rouge Energy Consumption

In order to adjust for homeowner behavior, two months of energy use were recorded before performing the interventions. From this baseline set of data it can be seen that the Control group homes tend to use less energy in total and for space conditioning than homes in the other groups (see Figure 31 and Figure 32, respectively).

Values are reported in average kWh per day to adjust for varying lengths of time between meter readings. The labels in the graphs represent energy for that particular season, with the following definitions of seasons:

- Summer – June through August
- Fall – September through November
- Winter – December through February
- Spring – March through May

The raw energy meter readings were adjusted so that results could be presented in a calendar-month or seasonal format even though the raw data was typically collected a few days after the first day of each month. The adjustment method uses a linear interpolation to estimate the energy reading for the last day of a given month. The previous month's reading is then subtracted from the interpolated cumulative reading to determine the given month's energy use. The method then divides the monthly energy usage by the number of days in that month to calculate the average daily kWh use for that month. These monthly readings are then combined to generate seasonal totals using a weighting scheme for number of days per month. Because meter readings were typically taken during the first week of each month, interpolating to the last day of the previous month does not significantly reduce accuracy. The only months when the readings were taken in the second week of the month were July and August of 2007.

As a reminder, the experimental abbreviations listed in bold text below represent the corresponding system descriptions in the tables and figures below:

- **CTL –** Control homes with code-compliant, traditionally vented crawl spaces. R-19 fiberglass batts were installed between the floor framing members. Insulated supply ducts are located in the attic. (Four homes)
- **CCS-F** – Test homes with closed crawl space with R-19 fiberglass batt insulation installed between the floor framing members. Insulated supply ducts are located in the attic. (Four homes)
- **CCS-W-A –** Test homes with closed crawl space with R-8 rigid foam insulation installed on the foundation perimeter wall. The band joist was insulated with R-19 fiberglass batts. Insulated supply ducts are located in the attic. (Four homes)
- **CCS-W-C –** Test homes with closed crawl space with R-8 rigid foam insulation installed on the foundation perimeter wall. The band joist was insulated with R-19 fiberglass batts. Insulated supply ducts are located in the crawl space. (Three homes)

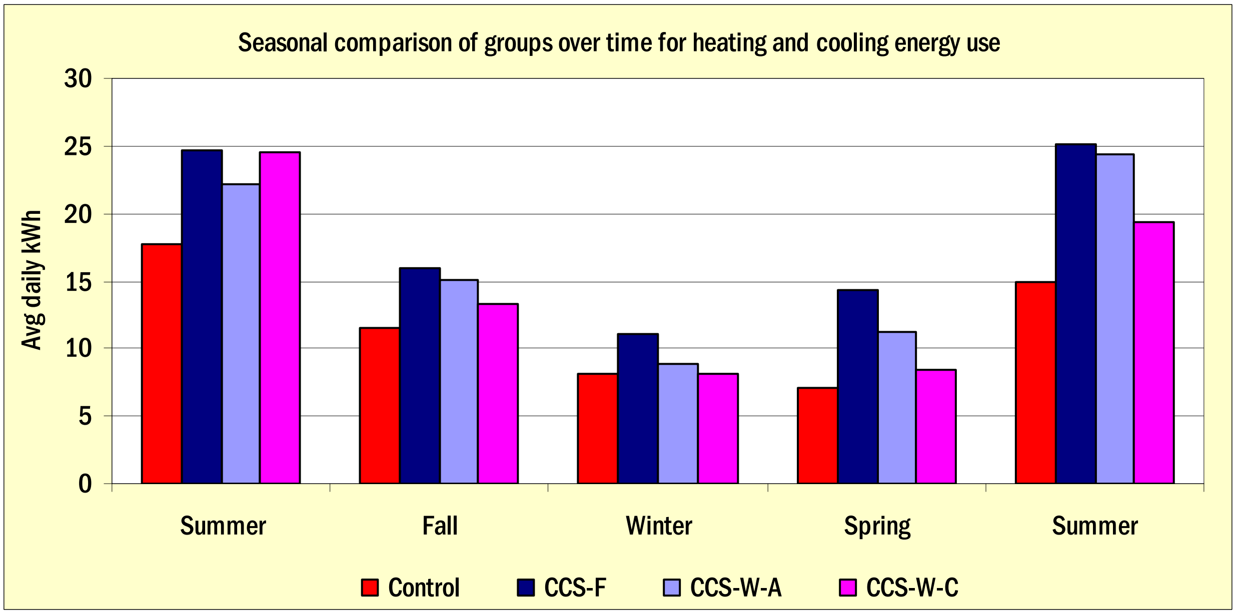


Figure 31. Baton Rouge – Average daily kWh usage showing differences in heating and cooling energy use from the June and July, 2007 baseline months (the first Summer season) through Summer 2008.

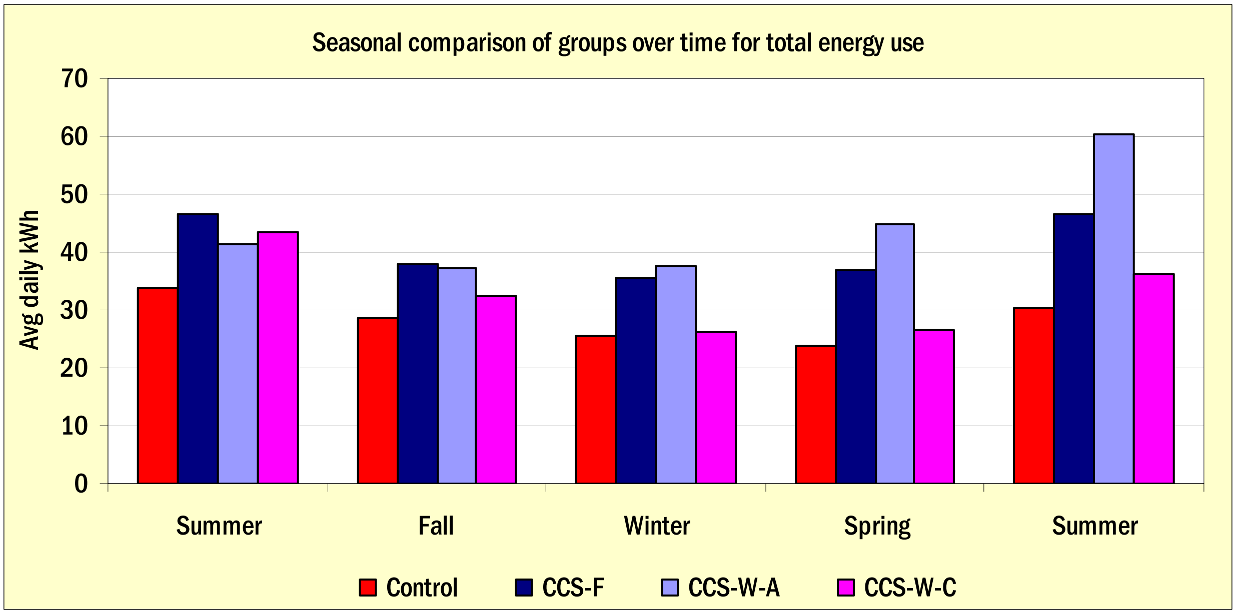


Figure 32. Baton Rouge – Average daily kWh usage showing differences in total energy use from the June and July, 2007 baseline months (the first Summer season) through Summer 2008.

In order to interpret the energy readings taken after the experimental closed crawl space systems were installed in mid-August 2007, we first assessed whether the energy usages of the study groups were comparable before the experimental installation using the energy readings from June and July of 2007. During these pre-installation "baseline" months, the energy readings indicate that the homes that were subsequently assigned to the control group used significantly less energy than the homes that were assigned to the closed crawl space groups.

Due to the similarities in building envelope and mechanical characteristics, variation in homeowner behavior is likely the primary reason for these differences. Such variations typically include thermostat usage (choice of internal temperature set point, and whether homeowners employ a "set it and forget it" thermostat control strategy versus a manual adjustment strategy), plug loads (computers, TVs, lights, etc.), occupancy levels, personal schedules (occupancy and activity levels during the day versus the night versus both), vacations, etc. Researchers did not ask any homeowners to vary their home energy habits for the purposes of the study. Another variable that could have affected the baseline readings that was not assessed during the project is variation in heat pump efficiency. However, this variable was minimized by the use of the same make, model and capacity of heat pump at each home.

To account for these differences in homeowner behavior, the data from June and July 2007 were used to adjust the baseline energy use to comparable levels, and then apply the same adjustment to subsequent months. Adjustments were made by averaging the percent difference from each experimental group versus the control group over those two months, and then applying these group-based adjustments to each month after the intervention. For instance, the CCS-W-C group total energy is 33% and 38% higher than the control group for June and July, respectively, so each post-installation monthly data point for the total energy of CCS-W-C group is divided by 1.35. The adjusted results can be found in Figure 33 and Figure 34.

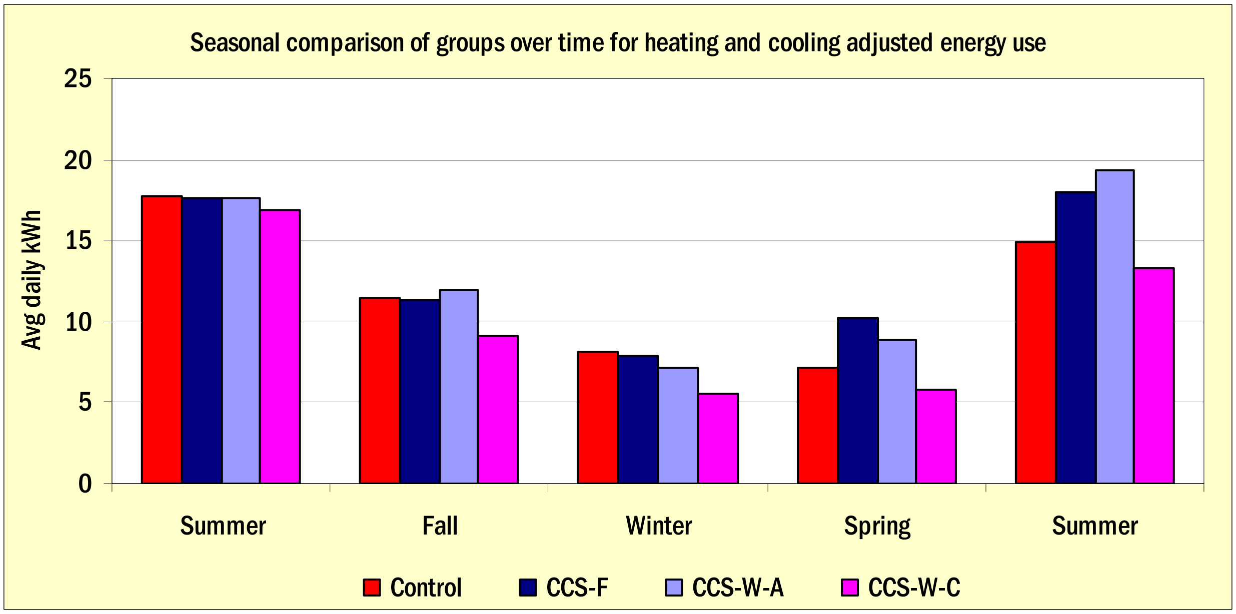


Figure 33. Baton Rouge – Adjusted heating and cooling average daily kWh usage showing differences before (Summer 2007) and after (through Summer 2008) the intervention in early August.

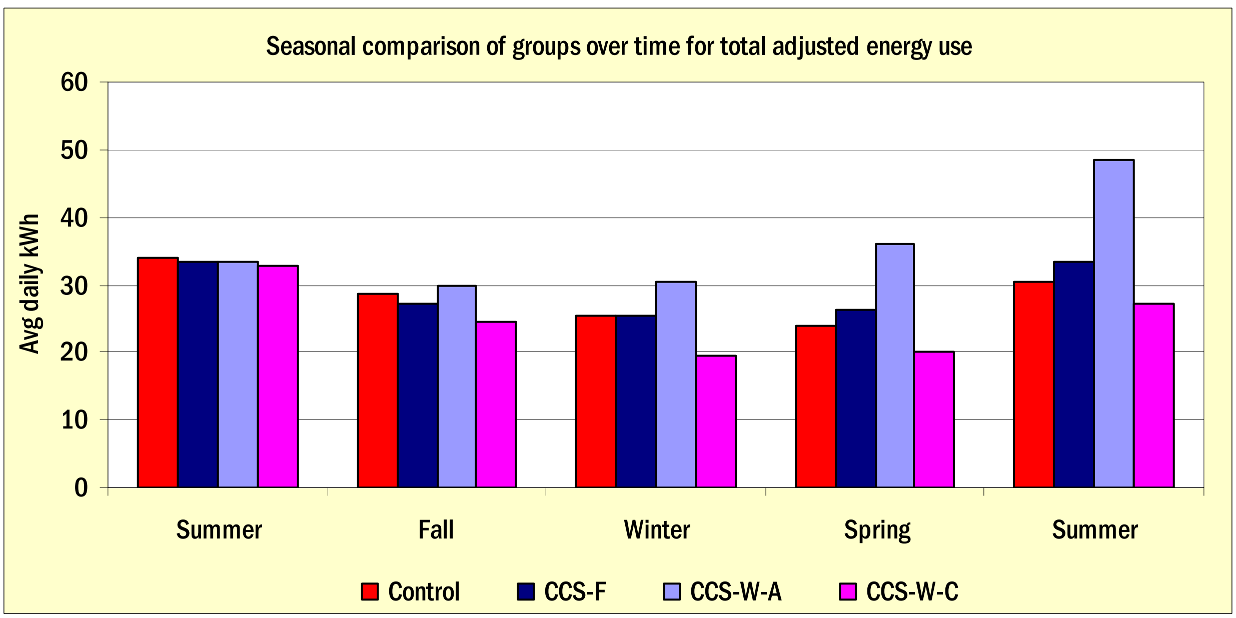


Figure 34. Baton Rouge – Adjusted total average daily kWh usage showing differences before (Summer 2007) and after (through Summer 2008) the intervention in early August.

The percent differences of the data represented in the previous two graphs can be found in Table 6. The CCS-W-A group data may be artificially high because of one particular homeowner (House 1), but no investigation has been performed yet to determine root cause of the elevated energy use.

Table 6 . Baton Rouge – Percent differences of each group from baseline of adjusted average kWh/day. Positive percentage is energy penalty and negative percentage is energy savings.

Period of Use	Heating and Cooling Energy			Total Energy			Notes*
	CCS F	CCS W-A	CCS W-C	CCS F	CCS W-A	CCS W-C	
June 2007	4.4%	6.0%	4.3%	2.4%	4.7%	2.5%	Base
July 2007	-4.4%	-6.0%	-4.3%	-2.4%	-4.7%	-2.5%	Base
August 2007	-0.2%	0.3%	-11.3%	-4.3%	-3.9%	-9.6%	Inter
Summer 2007	-0.4%	-0.4%	-4.4%	-1.6%	-1.6%	-3.5%	Base/Inter
Fall 2007	-1.3%	3.7%	-20.7%	-5.2%	4.0%	-14.7%	
Winter 2007-08	-3.0%	-13.0%	-31.9%	-0.5%	18.5%	-23.2%	
Spring 2008	43.0%	24.5%	-19.1%	10.3%	51.1%	-16.0%	
Summer 2008	20.7%	29.8%	-10.5%	10.3%	60.0%	-10.5%	
* Base = baseline month and Inter = intervention installed during first two weeks of August							

Table 7 combines two data sets – energy from Figure 33/Table 6 and indoor temperatures from Figure 29. Temperature sensors were installed during the intervention, so August average temperatures do not represent the entire month. The values in the energy part of the table are the average daily adjusted energy use values from Figure 33 above.

Table 7. Baton Rouge – Adjusted heating and cooling energy use (average kWh per day) with average indoor temperatures per group.

Period	Heating and Cooling Energy				Indoor Temperature				Avg Out. Temp	Notes*
	CCS F	CCS W-A	CCS W-C	Cont	CCS F	CCS W-A	CCS W-C	Cont		
June	15.9	16.2	15.9	15.3	-	-	-	-	82	Base
July	18.3	18.0	18.3	19.1	-	-	-	-	82	Base
August	18.5	18.6	16.5	18.6	68	71	71	74	86	Inter
Summer 2007	17.6	17.6	16.9	17.7	-	-	-	-	83	Base/Inter
Fall	11.4	11.9	9.1	11.5	68	71	71	74	70	
Winter	7.9	7.1	5.6	8.2	70	71	71	70	56	
Spring	10.2	8.9	5.8	7.1	69	71	72	71	69	
Summer 2008	17.9	19.3	13.3	14.9	71	72	73	75	82	
Annual average	11.8	11.8	8.4	10.4						
Annual comparison	13.8%	13.3%	-19%							
* Base = baseline month and Inter = intervention installed during first two weeks of August										

4.4 Baton Rouge Radon

Advanced Energy staff collected long-term radon detectors from all of the crawl spaces and living spaces during the April 2008 site visit. The detectors were sent to AccuStar Labs for analysis. The results are listed in Table 8 and they indicate that all but one home have a radon concentration below 1.0 pCi/L inside the living space, with the remaining home at 1.4 pCi/L. The U.S. Environmental Protection Agency has established a mitigation action level of 4.0 pCi/L for radon, with a goal of reducing the concentration to 2.0 pCi/L or less if mitigation is indicated.

Table 8 . Baton Rouge – Group averages for Radon levels in crawl spaces and living spaces.

Foundation type	Crawl (pCi/L)	Return (pCi/L)
Control (CTL)	0.600	0.400
CCS (all)	1.045	0.700
CCS-W-A	1.100	0.733
CCS -W-C	1.033	0.700
CCS-F	1.000	1.000

4.5 Flagstaff Crawl Space Temperature and Humidity

In Figure 35 below, the effect of the crawl space intervention can be seen at the far left of the graph where the data is overlapping and then splits. The last data collection of temperature and moisture conditions was downloaded on April 12, 2008. Figure 35 and Figure 36 show the moisture load in the crawl spaces during the entire study period. Figure 35 is a graph of the dew point group averages on a daily basis and Figure 36 is a graph of the relative humidity group averages on a daily basis. As an explanatory variable, the outdoor dew point and relative humidity are included in the graphs, respectively.

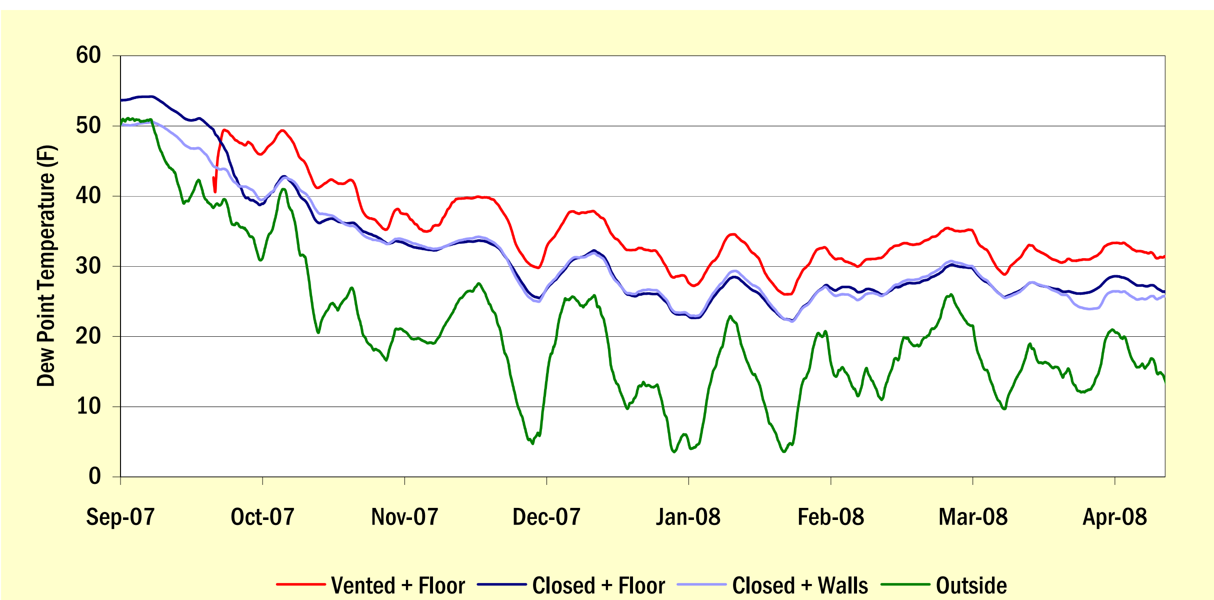


Figure 35 . Flagstaff – Daily crawl space and outdoor Dew Point (DP) by group.

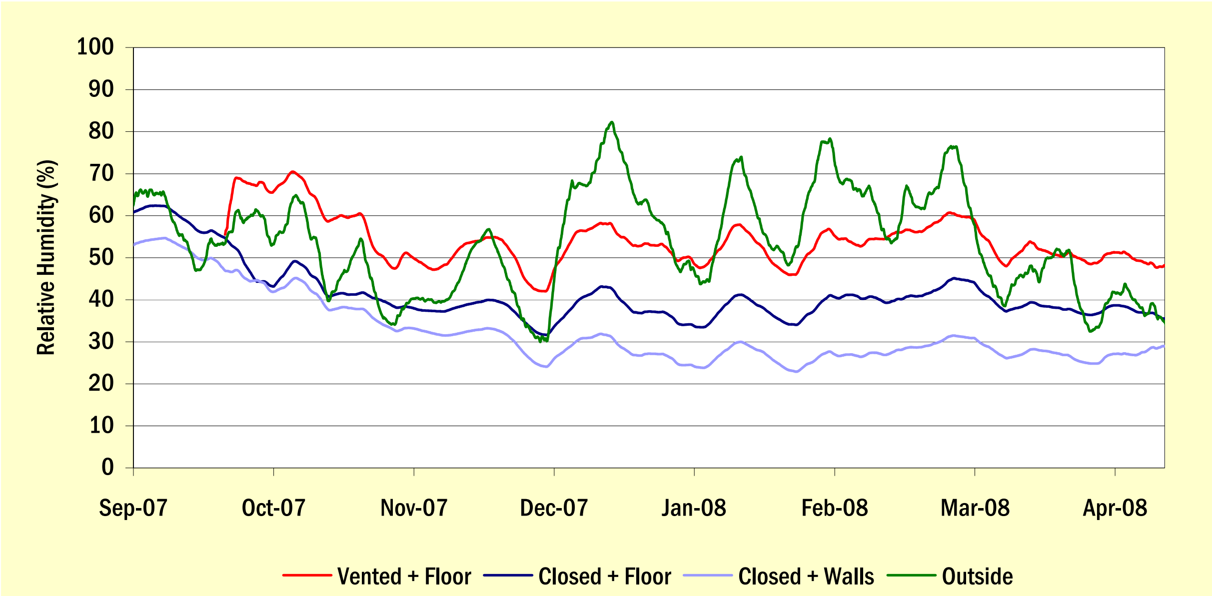


Figure 36. Flagstaff – Daily crawl space and outdoor Relative Humidity (RH) by group.

4.6 Flagstaff Living Space Temperature and Humidity

Figure 37 shows the average daily temperature inside each of the home groups over time. The data indicates a slight difference in thermostat set point for the CCS-F group, but the other two groups show similar performance.

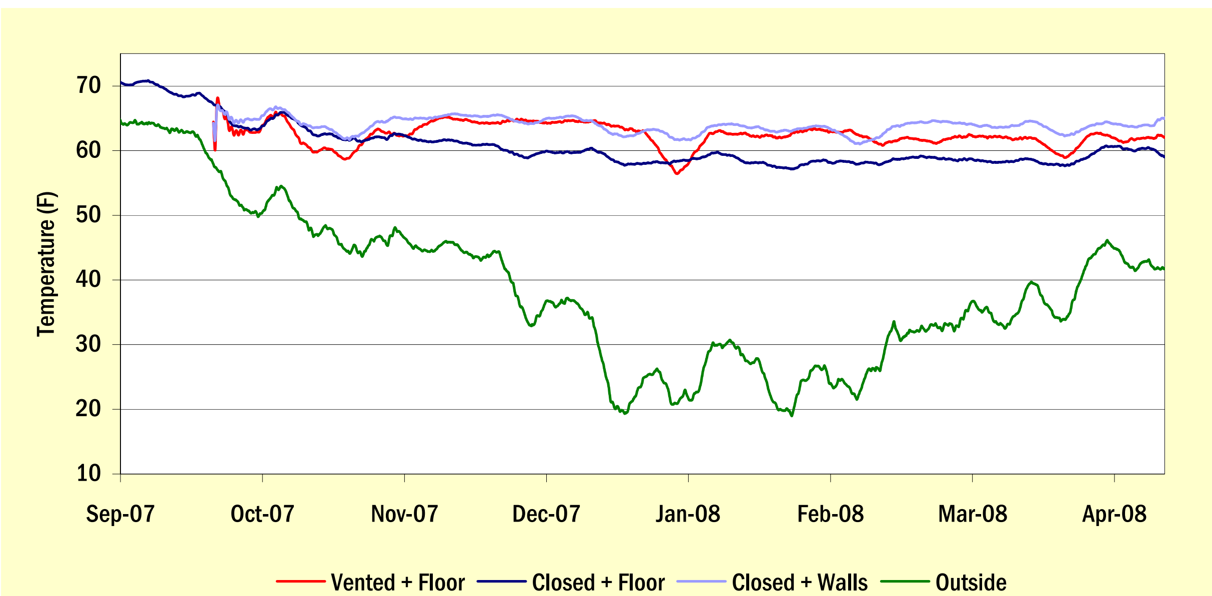


Figure 37. Flagstaff – Daily indoor temperature by group.

4.7 Flagstaff Energy Consumption

Construction and occupancy schedules did not allow for pre-intervention energy use data to be gathered at the Flagstaff field site. Therefore, comparisons will be made based on direct usage rates. Differences in Flagstaff homeowner behavior were determined based on homeowner conversations and measurements of interior conditions. The first valid data set was taken in November of 2007.

Values in all of the following graphs are per cubic foot of house volume to account for differences in house size. Volume was used instead of floor area to account for conditioning the entire space, since these homes do not have constant ceiling heights. Values are also reported in average energy used per day to adjust for varying lengths of time between meter readings. The dates in the graphs represent energy for that particular month. The raw energy meter readings were adjusted so that results could be presented in a calendar-month or seasonal format even though the raw data was typically collected a few days after the first day of each month. The adjustment method uses a linear interpolation to estimate the energy reading for the last day of a given month. The previous month's reading is then subtracted from the interpolated cumulative reading to determine the given month's energy use. The method then divides the monthly energy usage by the number of days in that month to calculate the average daily kWh use for that month. These monthly readings are then combined to generate seasonal totals using a weighting scheme for number of days per month. Because meter readings were typically taken during the first week of each month, interpolating to the last day of the previous month does not significantly reduce accuracy.

The study homes in Flagstaff use a combination of gas and electricity for space conditioning. For heating the home, gas is the primary fuel with a small amount of electricity used to run the fan in the distribution system (1-2 kWh per day max, which is roughly 5% of the total electric use of the homes). Figure 38 and Figure 39 show the main gas meter readings and furnace gas meter readings, respectively, for the groups.

As a reminder, the experimental abbreviations listed in bold text below represent the corresponding system descriptions in the tables and figures below:

- **CTL –** Control home with code-compliant, traditionally vented crawl spaces. R-30 fiberglass batts were installed between the floor framing members. Insulated ducts (R-6) were located in the crawl space. (Four homes)
- **CCS-F** – Test home with closed crawl space with R-30 fiberglass batt insulation installed between the floor framing members. Insulated ducts were located in the crawl space. (Four homes)
- **CCS-W** – Test home with closed crawl space with R-13 rigid foam insulation installed on the foundation perimeter wall. The band joist was insulated with R-19 fiberglass batts. Insulated ducts were located in the crawl space. (Four homes)

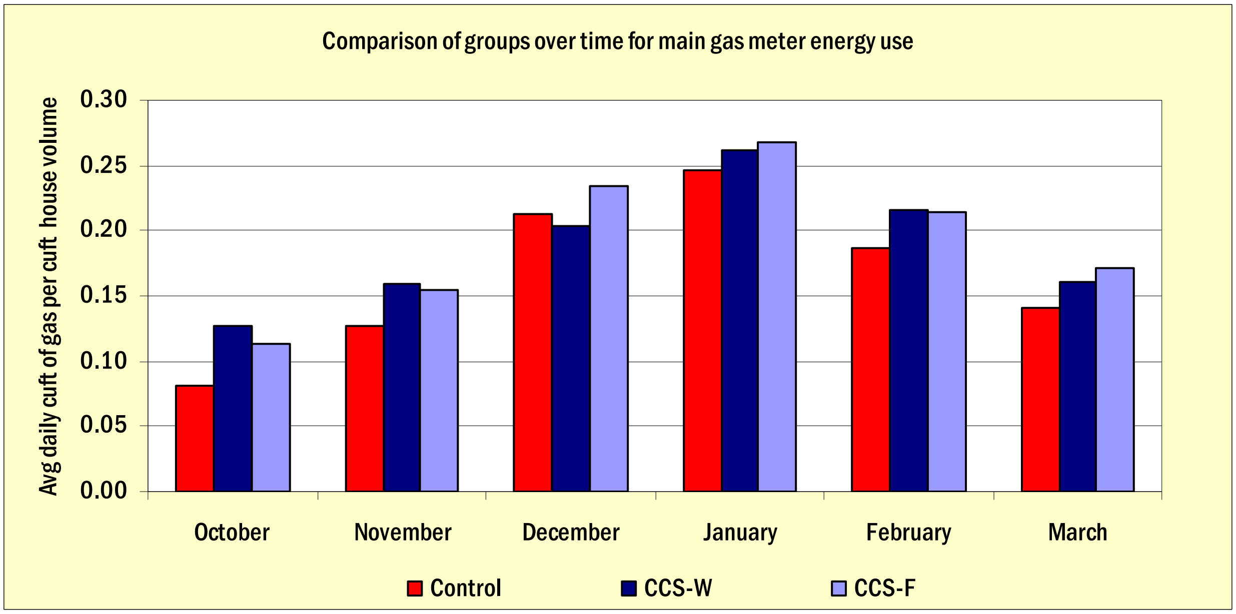


Figure 38. Flagstaff – Main gas meter readings across the three groups, October 2007 through March 2008.

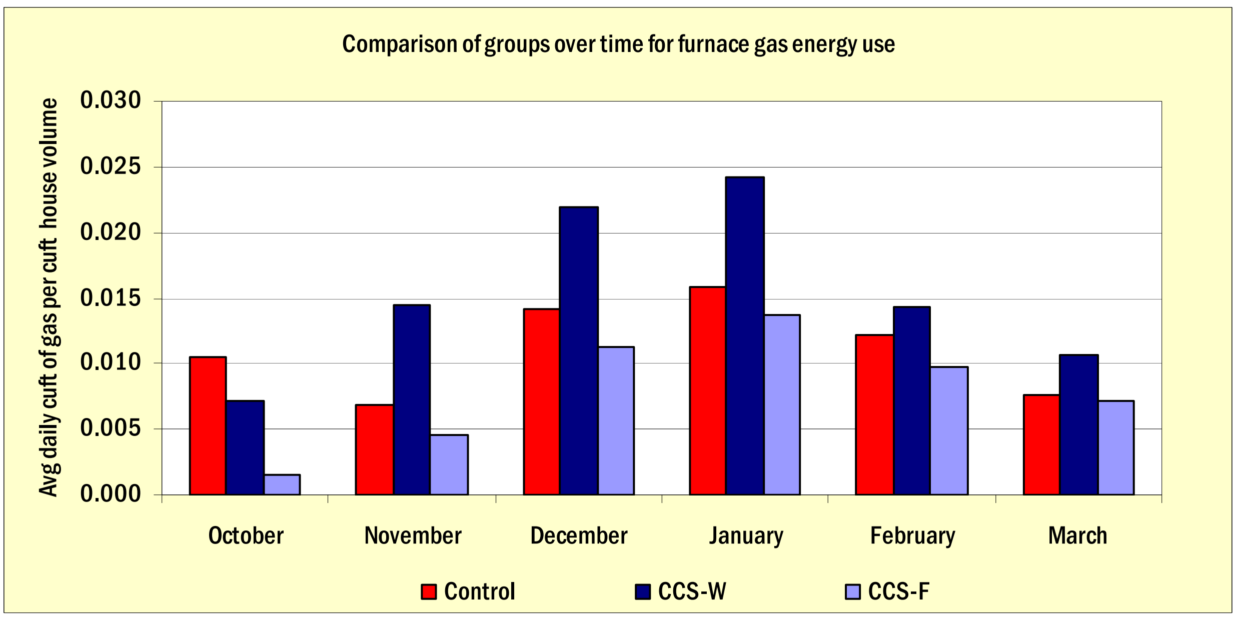


Figure 39. Flagstaff – Gas furnace sub-meter readings across the three groups, October 2007 through March 2008.

The data presented in Figure 39 indicate that the closed crawl space systems with floor insulation appears to have saved on average 20% of the gas used for space heating as compared to the gas usage for space heating in the control homes. In contrast, the wall-insulated closed crawl spaces appear to have used significantly more gas for heating as compared to that of the control homes. The analysis is more complex for this group due to the failure of several gas meters during the first two months of the monitoring period, but it is clear that the wall-insulated closed crawl space design has a strong negative impact on heating energy consumption in the cold climate of Flagstaff.

Total electricity use of the groups can be seen in Figure 40. Values are given as average kWh per day to account for varying reading interval lengths. Electric energy use for heating the home, which consists of the energy needed to run the fan on the distribution system, can be found in Figure 41. Both graphs are also adjusted for the volume of the homes.

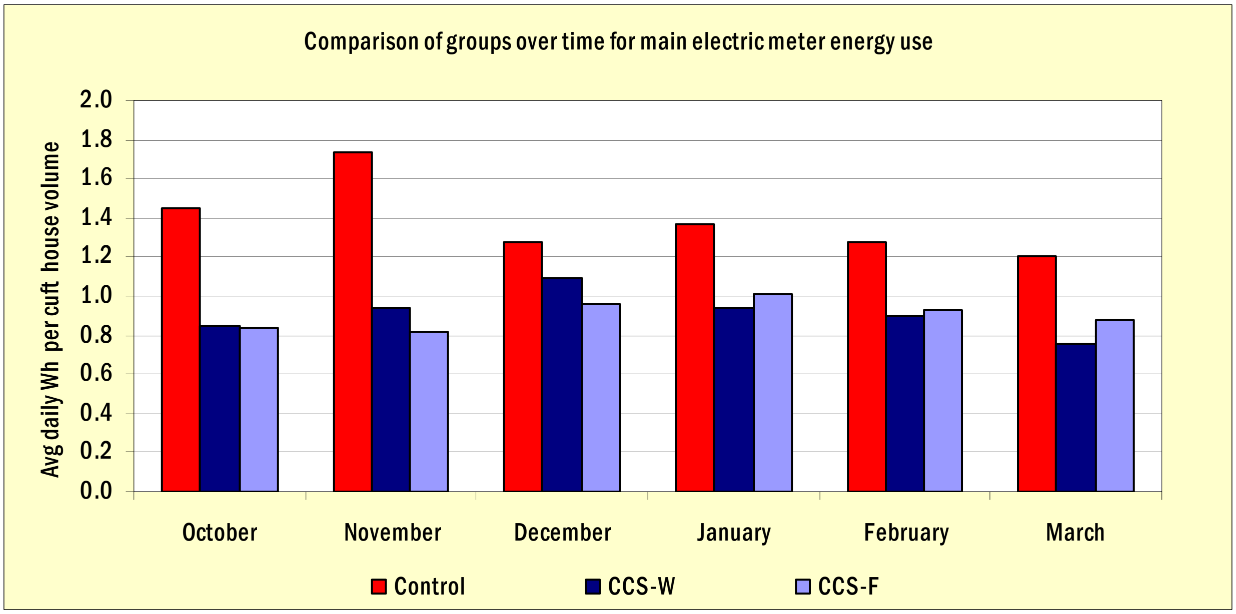


Figure 40. Flagstaff – Total average electricity use of homes in each group, October 2007 through March 2008.

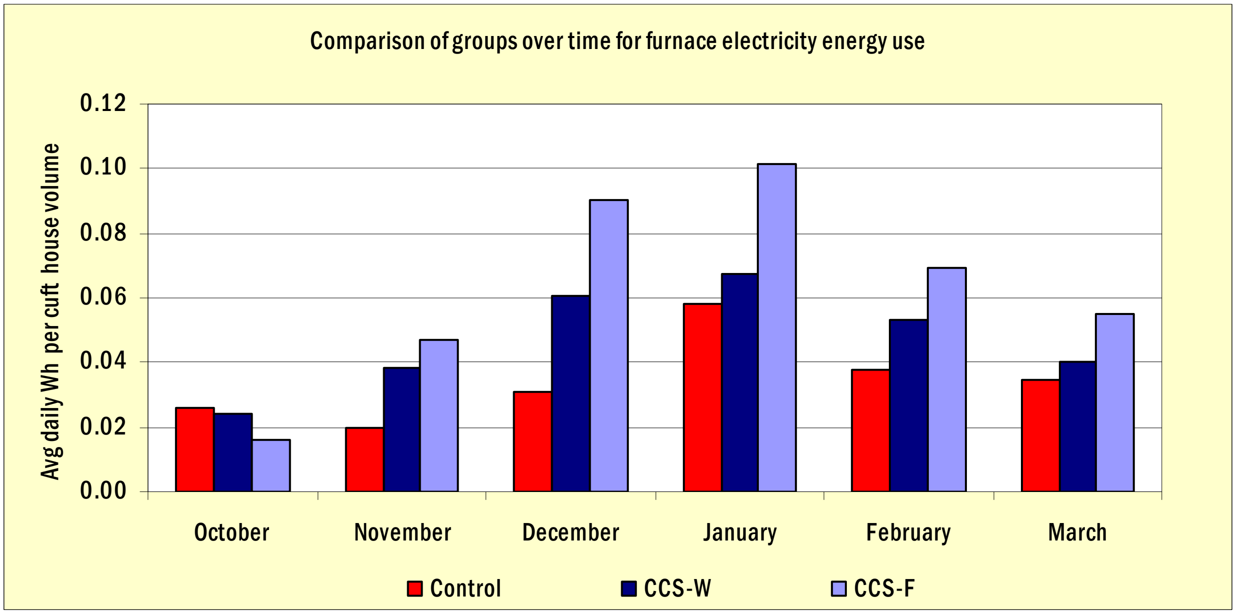


Figure 41. Flagstaff – Electricity used to run the heating distribution system, October 2007 through March 2008 (outliers removed due to potential faulty meters).

In Figure 41 above, three houses were removed due to no electricity being registered for the entire study. These are potentially faulty meters. The houses removed are 71 (CCS-F), 47 (Control), and 61 (Control). Due to these sources of error, conclusions on furnace electrical energy use in Flagstaff are not reliable.

The primary sources of uncertainty for the Flagstaff energy monitoring include missing data (some meters were not reliable until February or March, after a major part of the heating season was over), and variations in housing characteristics. Although interior temperatures were not used in energy calculations, they indicate potential bias due to occupant behavior, and our interior temperature measurements may not have been accurate due to both the placement of the sensor in the return and potential fireplace use. Placing the sensor in the return of the home may have allowed cool air from the outdoor air intake to generate false low readings, and fireplace use could cause the heat in the home to be localized in one room and thus not reach the sensor (particularly if the air handler is off to conserve energy).

4.8 Flagstaff Radon

In January 2008, field staff analyzed the long-term alpha-track radon testers after the minimum three-month exposure period required to obtain accurate test results. Winter creates a worst-case scenario for radon levels in the cold climate of Flagstaff, considering that residents likely keep windows and doors closed and stack pressure is at its annual peak, which would tend to increase infiltration from below the house into the living space while ventilation is at a minimum. The radon analysis indicated elevated radon levels (greater than the U.S. EPA action level of 4.0 pCi/L) in eight of twelve crawl spaces, ranging from 4.0 to 22.2 pCi/L. The analysis also indicated elevated radon levels in four of the twelve conditioned spaces, ranging from 4.1 to 9.8 pCi/L. The home-specific and group-average radon concentrations are presented in Table 9 and Table 10 respectively.

Table 9 . Flagstaff – Initial three-month alpha-track radon test results in the crawl spaces and living spaces.

Foundation Type	Crawl Space (pCi/L)	Living Space (pCi/L)
CTL	1.8	1.7
CTL	1.9	0.5
CTL	1.3	1.4
CTL	4.0	1.1
CCS-F	6.8	1.3
CCS-F	4.7	1.0
CCS-F	17.7	4.1
CCS-F	22.2	9.8
CCS-W	11.6	5.3
CCS-W	18.7	4.4
CCS-W	2.9	0.9
CCS-W	17.3	3.0

Table 10. Flagstaff – Group averages for initial three-month radon test results in the crawl spaces and living spaces.

Foundation Type	Crawl (pCi/L)	Living Space (pCi/L)
CTL	2.250	1.175
CCS-F	12.850	4.050
CCS-W	12.625	3.400

The radon levels in the living spaces indicated the need for mitigation. Researchers decided to discontinue the study and revert the closed crawl spaces to a wall-vented configuration because leaving the crawl space closed and installing a mitigation system in accordance with EPA recommendations proved to be too far outside the project scope and budget. EPA-style mitigation would also introduce significant long-term liability to the homeowner due to the need for roof penetrations. Unfortunately, the builder had not roughed-in a radon exhaust pipe during construction of the homes.

Advanced Energy provided and discussed the radon measurements with all affected homeowners and notified them both verbally and in writing of our mitigation plan prior to implementation. Advanced Energy staff re-opened the wall vents in the closed crawl spaces in April 2008. This change also required the installation of R-30 floor insulation in the four homes that had a closed crawl space with wall insulation. Advanced Energy staff specified, paid for, and verified the proper installation of this insulation in those four homes.

Researchers created a monitoring plan to verify the effectiveness of the additional ventilation on the radon levels in each home. Researchers installed one additional long-term (alpha track) radon monitor in the furnace return inside each home and installed two additional long-term monitors in each crawl space. Researchers also installed one short-term radon tester in each crawl space. This short-term tester was removed and analyzed within two to four days of opening the crawl space vents. Analysis of the short-term testers verified that opening the crawl space vents had allowed radon to dissipate from the crawl spaces, as shown in Table 11. The original experimental foundations now have lower crawl space radon concentrations than the control foundations, as shown in Table 12. After opening the vents, radon levels in the previously closed crawl spaces ranged from 0.6 pCi/L to 1.7 pCi/L and levels in the control crawl spaces ranged from 1.3 pCi/L to 3.0 pCi/L. During a July 2008 site visit, Advanced Energy staff removed one of the alpha track testers from each crawl space for analysis. The results reconfirmed that radon levels had decreased to below EPA action levels after opening the crawl space vents, as shown in Tables 9 and 10. Advanced Energy reported all radon measurements to the homeowners as they became available. Study participants are not obligated to allow researchers to remove and analyze the remaining long-term testers since it is outside the official study period, but Advanced Energy has offered that service as a courtesy since the longer-term exposure will give the most reliable confirmation of performance.

Table 11. Flagstaff – Short-term radon levels in the crawl spaces after opening crawl space vents.

Foundation Type	Crawl Space (pCi/L)
CTL	1.6
CTL	1.3
CTL	1.3
CTL	3.0
CCS-F*	1.0
CCS-F*	0.6
CCS-F*	1.7
CCS-F*	0.9
CCS-W + *F	0.9
CCS-W + F*	1.7
CCS-W + F*	1.2
CCS-W + F*	1.6
* Sealed vapor retarder is still in place on the crawl space floor and walls, but the crawl space vents are now open	

Table 12. Flagstaff – Group averages for radon levels in crawl spaces after opening crawl space vents.

Foundation Type	Crawl (pCi/L)
CTL	1.800
LINER	1.200
*Short-term radon detectors in the crawl space	

Table 13. Flagstaff – Three-month alpha-track radon levels in the crawl spaces after opening crawl space vents.

Foundation Type	Crawl Space (pCi/L)
CTL	1.0
CTL	1.7
CTL	1.1
CTL	2.0
CCS-F*	0.9
CCS-F*	<0.4
CCS-F*	1.3
CCS-F*	2.0
CCS-W + F*	0.8
CCS-W + F*	1.6
CCS-W + F*	<0.4
CCS-W + F*	1.4
* Sealed vapor retarder is still in place on the crawl space floor and walls, but the crawl space vents are now open	

Table 14. Flagstaff – Group averages for three-month alpha-track radon levels in crawl spaces after opening crawl space vents.

Foundation Type	Crawl space radon concentration (pCi/L)
CTL (vented crawl space with no vapor retarder)	1.45
LINER (vented crawl space with sealed ground/wall vapor retarder)	1.1

4.9 Energy Modeling Program Assessment

4.9.1 Baton Rouge

Between the two locations, Baton Rouge is more likely to see distinct differences between the intervention groups. This is due to the very consistent nature of the houses – very slight variations between each of the simple floor plans.

Results from modeling the homes can be seen in Figure 42 below. These are group averages for each of the four crawl space groups. The focus of the graph is on the pattern of the actual energy use versus the pattern for each of the modeling applications (i.e., do the models predict a savings or penalty for the different designs?).

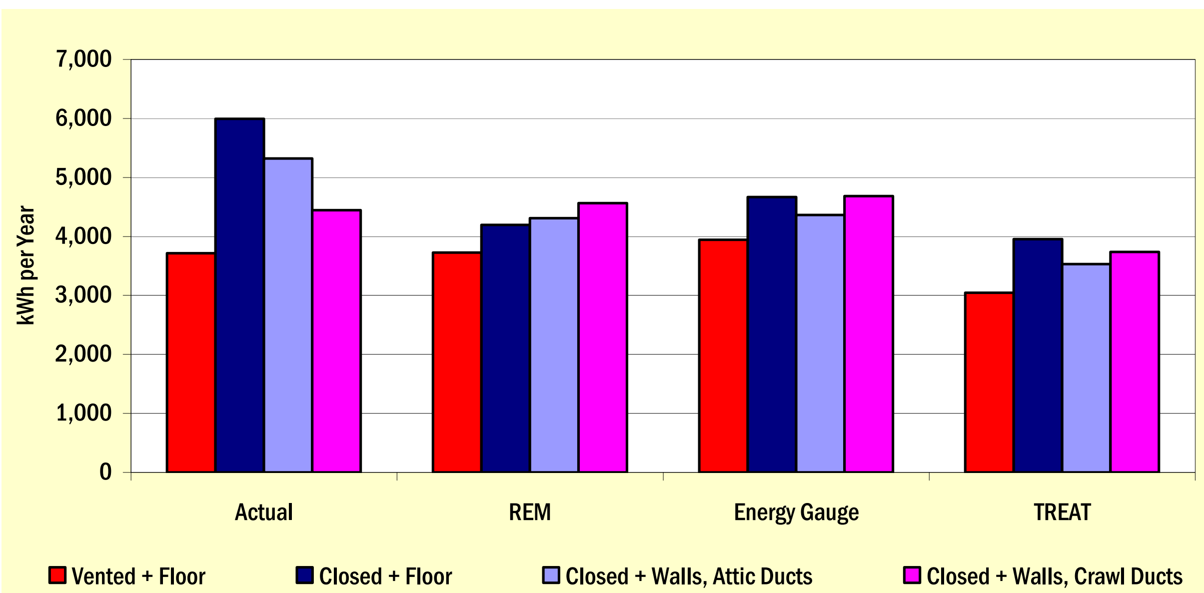


Figure 42. Modeled energy use versus actual energy use across the four groups in Baton Rouge.

Another way to view the same information is to combine the crawl space groups together for each of the energy use methods. Figure 43 displays the information in this way and includes error bars showing the minimum and maximum values for each group. In this view, the variability in the actual data for the floor insulated closed crawl space can be seen. The other three groups have a low variability comparable to the variability in modeling the houses.

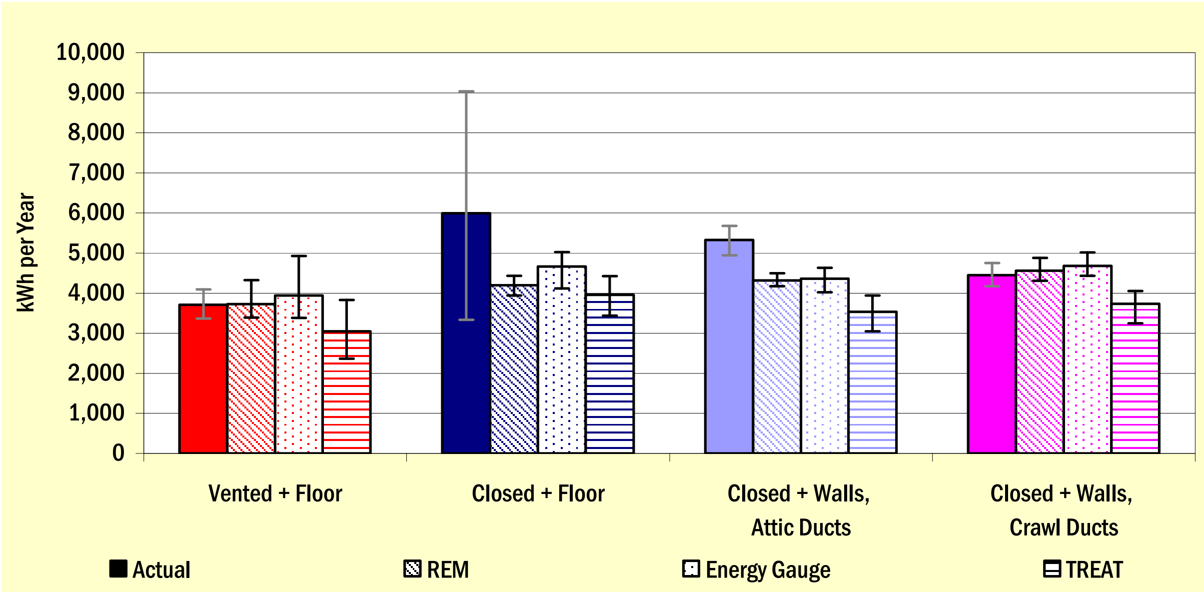


Figure 43. Actual versus predicted energy use for each of the crawl space design groups in Baton Rouge.

Table 15 is a display of the same data in tabular form. The added piece of information is percent savings (negative values) or penalty (positive values) compared to the vented crawl space design.

Table 15. Actual and Modeled energy use with percent differences between groups and modeling application type.

		Heating/Cooling			Total Energy		
Group	Application	Energy (kWh/yr)	Difference from Vented	Difference from Actual	Energy (kWh/yr)	Difference from Vented	Difference from Actual
Vented + Floor	Actual	3,714			9,860		
	REM/Rate	3,728		0%	11,744		19%
	EnergyGauge	3,942		6%	11,438		16%
	TREAT	3,047		-18%	18,260		85%
Closed + Floor	Actual	5,993	61%		14,314	45%	
	REM/Rate	4,198	13%	-30%	12,477	6%	-13%
	EnergyGauge	4,670	18%	-22%	12,211	7%	-15%
	TREAT	3,956	30%	-34%	19,410	6%	36%
Closed + Walls, Attic Ducts	Actual	5,325	43%		16,511	67%	
	REM/Rate	4,313	16%	-19%	12,585	7%	-24%
	EnergyGauge	4,365	11%	-18%	11,899	4%	-28%
	TREAT	3,532	16%	-34%	18,986	4%	15%
Closed + Walls, Crawl Ducts	Actual	4,448	20%		11,281	14%	
	REM/Rate	4,564	22%	3%	12,922	10%	15%
	EnergyGauge	4,685	19%	5%	12,234	7%	8%
	TREAT	3,737	23%	-16%	19,271	6%	71%

4.9.2 Flagstaff

Because the study was terminated early due to elevated radon concentrations, actual energy use for a year-long period is not available from the Flagstaff field site for comparison with the models. However, the models were still created in order to see if there were any differences in the models and to see if there are any pitfalls with the models. An added complexity in Flagstaff was the use of both electricity and natural gas for space conditioning. The measured indoor conditions (from a data logger in the central return) for each of the homes may also be questionable due to the at least one homeowner reporting use of a fireplace for heating a specific room of the home and not centrally heating the entire home, and the location of the outside air intakes in the return box. This may be the reason that some of the sensors recorded temperatures under 60 degrees F inside some of the houses for long periods of time. The use of fireplaces would also skew the comparison of the actual energy use to the modeled energy use if the actual energy use data were available.

Figure 44 and Figure 45 show the electricity and gas energy predictions from the modeling applications for space conditioning.

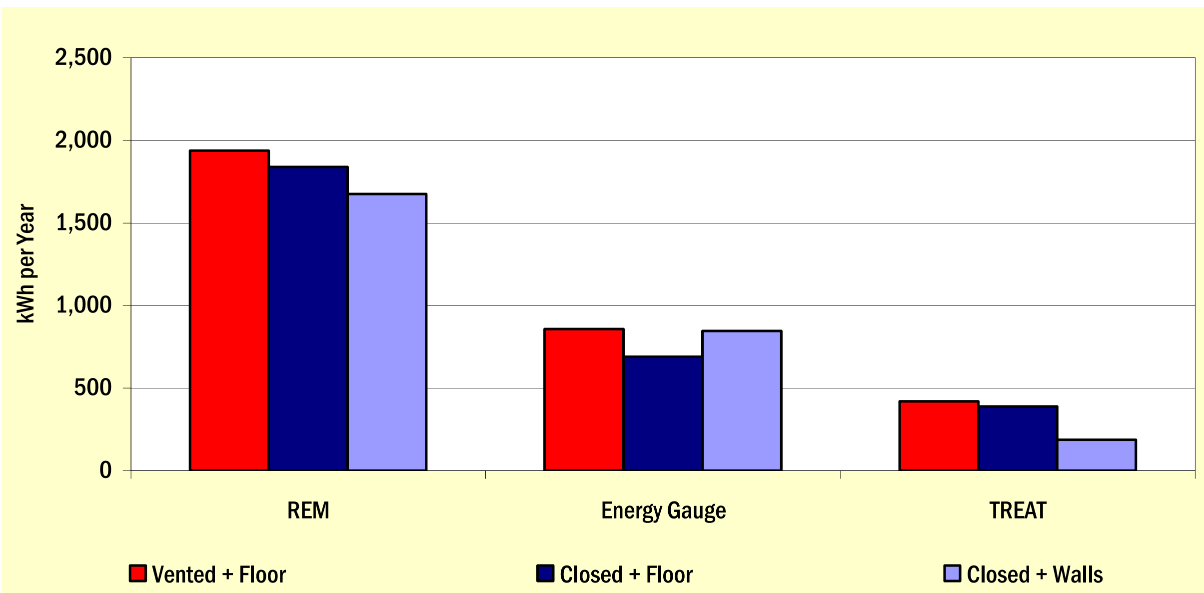


Figure 44. Predicted space conditioning electricity use for each of the modeling applications.

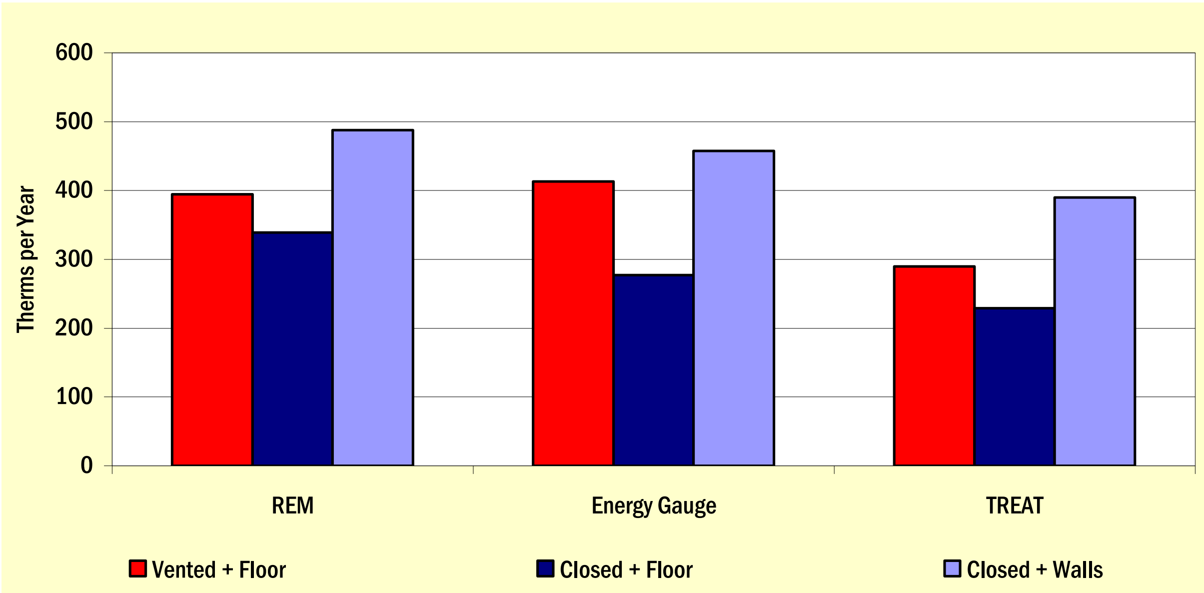


Figure 45. Predicted space conditioning gas use for each of the modeling applications.

5. DISCUSSION

5.1 Baton Rouge

The improvement of humidity control in the Baton Rouge closed crawl spaces was robust and occurred very quickly after installation of the systems. It should also be noted that these improvements came despite lingering plumbing leaks in several of the crawl spaces, some of which resulted in standing water on the crawl space liner. The closed crawl space systems not only controlled any additional humidity load from the leaks, but also made the leaks easier to detect by capturing the water on the liner, making the problem easier to discover. In these cases, the liner was temporarily cut so that the water could drain into the soil underneath, the plumbing leak was repaired, and once the water was gone the liner was cleaned and dried. At that point the cut in the liner was sealed with the same tape used to seal seams in the floor liner during the installation.

The higher space-conditioning energy consumption of the homes with closed crawl space systems and mechanical ducts in the attic as compared to the control homes is difficult to interpret. Several observations from the temperature and humidity data indicate that these systems should lower energy needed for space conditioning, but that occupant behavior may be overwhelming those factors. The crawl space temperatures under these homes is warmer in the winter months and cooler in the summer months, indicating that the closed crawl space foundations are reducing the thermal space conditioning load from the floor, but these temperatures could also be significantly affected by the crawl space being air sealed and having a small supply duct installed for drying during the humid seasons. The drier conditions in those crawl spaces also means that any return duct leakage puts a lower latent load on the system during cooling periods. With regard to occupant behavior, researchers only monitored temperature and humidity in the living spaces. During the summer of 2008, the floor-insulated closed crawl space homes had interior temperatures an average of four degrees F cooler than the interior temperatures in the control homes. During the same period, the homes with wall-insulated closed crawl spaces and attic ducts had interior temperatures an average of three degrees F cooler than interior temperatures in the control homes. There were also significant differences in other internal loads due to occupancy, lighting, and appliance operation that were not formally assessed in this study.

This study did not assess mechanical system efficiencies, so variations in the installed performance of the systems cannot be ruled out as a significant variable. However, all units are the same make and model and, as package-unit systems the factory charge should be consistent.

The performance of the homes with wall-insulated closed crawl spaces and all ductwork inside the crawl space is noteworthy not only because it was better than the performance of the controls, but also because that performance occurred despite having the leakiest ductwork and 6% greater floor area than the controls. Furthermore, in the summer of 2008, these homes outperformed the control homes with interior temperatures that were an average of two degrees F cooler than those of the control homes.

Also in regard to market adoption of closed crawl spaces in the Gulf Coast, the impact of flooding on the foundation must be considered. Conversations with Baton Rouge project partners and anecdotal reports from installers in North Carolina suggest that closed crawl spaces with a sealed liner system and rigid foam perimeter wall insulation would be significantly easier to clean and dry after a flooding event than would be a comparable vented crawl space with porous insulation in the floor structure. While Advanced Energy does not recommend the construction of crawl space foundations in flood-prone locations, upgrading to a closed crawl space may provide this additional benefit if applied to existing homes in those locations.

5.2 Flagstaff

Despite the generally very dry climate in Flagstaff, during the recruitment phase of the project the local installation partners reported moisture problems associated with vented crawl space foundations. The moisture problems were primarily associated with what is locally referred to as the “monsoon” season, a period from approximately July through September when Flagstaff experiences frequent late afternoon thunderstorms. Foundation waterproofing is not required by local building codes, so during the monsoon season the installers reported that water intrusion into crawl space foundations is a problem.

In contrast to the humidity performance pattern in Baton Rouge and in previous work in North Carolina, the moisture load inside the Flagstaff control homes with vented crawl spaces does not appear to follow the outside dew point. In fact, the dew point temperatures of the crawl spaces in the homes with closed crawl spaces appear to be closer to the outside dew point than the dew point temperatures in the control home crawl spaces. This is likely the result of the lack of ground vapor retarder in the control homes and the dominance of the exposed earth under the house as the primary moisture source since the outside air is very dry outside of the monsoon season.

Besides the potential for energy savings, one benefit that researchers expected from the closed crawl space systems in Flagstaff was higher temperatures in the crawl space and thus improved freeze protection for plumbing. The data indicate warmer conditions, but only by approximately ten degrees F. These temperatures were measured at the center of the crawl space, so it is possible that temperature improvement is much better at the perimeter, especially during windy weather.

The owners of the wall-insulated closed crawl space homes were reimbursed for the extra fuel costs they incurred due to the experimental system.

5.3 Energy Modeling Program Assessment

5.3.1 Baton Rouge

From Figure 42 it can be seen that none of the modeling applications are able to predict the pattern of the actual energy use, which has the closed crawl space with floor insulation having the most energy used for heating and cooling (although Figure 43 shows this group has a very high variance), followed by the closed crawl space with wall insulation and ducts in the attic, closed crawl space with wall insulation and ducts in the crawl and, finally, the vented crawl space with floor insulation. The one item consistent in the models and actual energy use is the low energy use of the vented crawl space with floor insulation compared to each of the other groups.

Looking at the modeled energy use versus actual in Figure 43, it appears TREAT consistently underestimates the energy use for all houses modeled. The other items of note are how well both REM/Rate and EnergyGauge predict the energy use for the vented crawl space with floor insulation and the closed crawl space with wall insulation and ducts in the crawl space, but are not able to predict the other two groups. REM/Rate and Energy Gauge both have similar predictions across the board with TREAT always estimating lower.

A way to interpret the percent differences in Table 15 is to convert the error term into a dollar amount. For a house using 4,000 kWh per year for heating and cooling, a 10% error in estimating the energy use will result in a $20 swing in energy cost to the homeowner (using $0.048 per kWh).

5.3.2 Flagstaff

Without a full year of heating and cooling data, a comparison of the relative accuracies in the modeling applications is not possible. However, some of the shortcomings of the modeling applications can still be seen in the outputs. For instance, REM/Rate models a much higher energy use for space conditioning electricity use than the other two applications, and TREAT estimates a very low energy use for space conditioning electricity. The large discrepancies for electricity are due to REM/Rate estimating a higher cooling load than the other two and TREAT estimating a null load for heating. When looking at gas predictions for space conditioning, however, the estimates are fairly consistent across modeling applications. TREAT still has a pattern of having a lower estimate for energy use compared to the other two applications.

Across groups for gas energy use, all of the models predict an energy savings for the closed crawl space with floor insulation compared to the other two groups. In addition, the wall insulated crawl spaces show a penalty – most likely due to the thermal losses through the ground in the cold months. These predictions appear to indicate that the modeling tools are accurately identifying the fundamental trend of performance due to the installation of a closed crawl space system.

6. CONCLUSIONS

6.1 Assessment of Success of Objectives

The research findings support the first hypothesis that "Closed crawl space systems will control daily average relative humidity inside the crawl space below 70% regardless of climate zone or season."

- In the very humid Baton Rouge climate, the closed crawl space systems were actually able to control crawl space relative humidity closer to 60% on a daily average, while the control group humidity hovered around 80% for most of the spring and summer months.
- In Flagstaff's dry climate even the control crawl spaces stayed under 70% for all but a few days, but the closed crawl spaces were even drier, with levels around 50% under the same conditions.

The research findings are mixed with regard to the second hypothesis that "Homes with closed crawl space systems will realize 15% or greater annual savings on energy used for space conditioning as compared to homes with vented control crawl spaces located in the same climate zone."

- In Baton Rouge, the performance of closed crawl space systems with perimeter insulation and distribution ducts in the crawl space supports this hypothesis, but clearly the location of the ductwork in the crawl space versus the attic in the control homes is a significant variable. The results are less clear in the other groups, with indoor and crawl space temperature comparisons supporting a conclusion that thermal loads from the floor are lower in the homes with closed crawl space foundations, but the space-conditioning energy data does not indicate lower usage, likely because of confounding occupant behavior variables.
- In Flagstaff, the performance of the closed crawl space system with floor insulation supports the hypothesis, while the performance of the closed crawl space system with wall insulation rejects the hypothesis.

Finally, the research findings are mixed or uncertain with regard to the third hypothesis that "Popular residential energy modeling software programs are unable to accurately forecast the energy savings that result from installation of a properly closed crawl space foundation." The study results indicate that there is a need for improvement of the energy modeling software, but the small data set of field performance raises uncertainty.

- In Baton Rouge, the modeling results for the floor-insulated closed crawl space group has the most uncertainty. REM/Rate and EnergyGauge predict very well the energy use for the vented crawl space with floor insulation and the closed crawl space with wall insulation and ducts in the crawl space, but are not able to predict the performance of the other two designs.
- In Flagstaff, the even smaller data set due to meter failures and truncated study period raises too much uncertainty to draw a conclusion.

6.2 Implications for Future Recommendations and Requirements

The study results provide strong support for the application of closed crawl space foundations as a moisture control method for crawl space homes in the hot-humid U.S. climate zone, and provide even stronger support for wall-insulated closed crawl spaces to provide a more hospitable location for mechanical ductwork in that region, resulting in energy savings in addition to the moisture control.

The results also provide support for application of floor-insulated closed crawl space foundations in cold climates, both as a moisture control and energy-saving home improvement.

The study results suggest that any recommendations or requirements to install closed crawl space foundations should also include requirements for radon testing and mitigation if indicated. In areas of elevated radon risk, it could be suggested that builders rough-in soil gas collection hardware prior to installation of the foundation ground vapor retarder or flooring to reduce potential future mitigation costs. Ideally these recommendations would apply to all homes, since basement or slab foundations would likely more expensive to remediate. Slab and basement foundations may also put the residents at higher risk due to fostering occupancy in the parts of the home where the radon is entering the structure.

6.3 Recommended Future Research

We recommend that the four control homes at the Baton Rouge field site be converted to closed crawl spaces with a sealed liner and supply air drying mechanism, retaining the existing floor insulation, and that all homes at the site are then monitored for another 12-month period. Such a “flip-flop” study design (assuming that occupancy remains similar to the current situations, and normalizing for weather variations from year-to-year) would allow researchers to clarify the true impact of the closed crawl space systems on space-conditioning energy usage in all the homes. Assessing the installed performance of the heat pump systems would reduce uncertainty in the energy analysis. This data would further guide the selection of the most appropriate designs for the Gulf Coast climate and provide cost-benefit data to businesses and homeowners making the decision of whether to upgrade from vented crawl space foundations to properly closed crawl space foundations.

The lack of qualified installers in the Baton Rouge market suggests that a commercialization assessment would be useful for the Gulf Coast region. With the significant moisture control and energy savings benefits fostering adoption, the lack of qualified installers poses a significant barrier to this market adopting closed crawl space foundations. A commercialization assessment could introduce appropriate shelter industry organizations to the technology, encourage quality product offerings and identify necessary market drivers.

Another useful study for the Gulf Coast market would be a comparison of energy usage, indoor humidity control and installation costs for closed crawl space foundations versus slab foundations. Such a comparison would provide additional support for builders and owners choosing between those two construction options and allow for better life-cycle comparisons between slab foundations having very high embodied energy but have generally lower first cost and crawl space (or “raised floor”) foundations which utilize renewable resources and can offer improved flood protection but generally have higher first cost.

Finally, the radon results in Flagstaff indicate the need to better quantify and understand radon risk in that market, and to provide viable solutions, especially for homes with slab and basement foundations which are expensive to remediate and which may put the residents at higher risk due to occupancy where radon is entering the structure. The results also beg the question of risk in other U.S. regions. If the current radon risks are underestimated in Flagstaff, is that true in other locations? Given the significant public health risk of radon and the trend towards tighter construction techniques that are not necessarily accompanied by improved ventilation, residential radon exposure is an issue that deserves renewed attention.

7. REFERENCES

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