



FINAL REPORT NCEMBT-XXXXXX

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

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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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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: 12 new site-built homes in one neighborhood in Flagstaff, AZ, and 15 new modular homes built in one neighborhood in Baton Rouge, LA. In order to reduce research 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 research 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 configurations 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. Mechanical ductwork was located in the crawl space.

The Baton Rouge site tested three configurations 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 measure energy used for space conditioning separately from total home energy use, and to measure radon concentrations in the crawl space and living space. Data were 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 percent regardless of climate zone or season."

- In the very humid Baton Rouge climate, the closed crawl space systems were able to control crawl space relative humidity close to 60 percent on a daily average, while the control group humidity hovered around 80 percent for most of the spring and summer months.
- In Flagstaff's dry climate even the control crawl spaces stayed under 70 percent for all but a few days, but the closed crawl spaces were even drier, with levels around 50 percent 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 percent 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 does not support the hypothesis, with a range of performance from 6 percent savings to a 29 percent penalty across the three systems. However, living space and crawl space temperature comparisons support a conclusion that thermal loads from the floor are lower in the homes with closed crawl space foundations. It appears that confounding occupant behavior variables had a greater influence than the foundation system improvements.
- In Flagstaff, the performance of the closed crawl space system with floor insulation supports the

hypothesis, showing a savings of 20 percent in heating season gas usage, while the performance of the closed crawl space system with wall insulation does not support the hypothesis, showing a large penalty of 53 percent.

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

- In Baton Rouge, REM/Rate and EnergyGauge do a very good job of predicting 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. TREAT consistently underestimates the energy usage across all study groups. The modeling results for the floor-insulated closed crawl space group have the most uncertainty.
- In Flagstaff, the even smaller data set due to meter failures and truncated study period raises too much uncertainty to draw any conclusions about the performance of the modeling programs.

The Baton Rouge study results provide strong support for the application of closed crawl space systems as a humidity control method for crawl spaces under homes in the hot-humid U.S. climate zone, and the results provide even stronger support for the use of wall-insulated closed crawl spaces, which provide energy savings in addition to humidity control.

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

Regardless of climate zone, contractors or occupants who install closed crawl space systems should perform testing to confirm the absence of a radon hazard whenever crawl space ventilation to the outside is eliminated. Any recommendations or requirements to install closed crawl space foundations should include requirements for radon testing followed by mitigation if needed.

In areas of elevated radon risk, it should 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 such homes, since homes with basement or slab foundations would likely be more expensive to remediate. Slab and basement foundations may also put the residents at higher risk due to supporting occupancy in the parts of the home where the radon is entering the structure.

The results of this project suggest at least four additional studies that would improve understanding of the performance 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 verifying heat pump efficiency. Monitor all homes at the site using the current methodology for another 12-month period to generate a basis for correcting the current performance results with respect to occupant behavior and for doing year-over-year weather-corrected comparisons on the control homes.
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 major 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 provide updated recommendations for identifying and reducing radon in residential structures with more practical solutions.

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 12 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, both prescriptive and performance-based.
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 12 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. REM/Rate, 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:

1. Closed crawl space systems will control daily average relative humidity inside the crawl space below 70 percent regardless of climate zone or season.
2. Homes with closed crawl space systems will realize 15 percent 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:

1. A ground vapor retarder with sealed seams covering 100 percent of the crawl space floor.
2. A mechanically secured vapor retarder covering masonry perimeter walls with the exception of a nominal three inch termite inspection gap at the top of such walls and at locations where the masonry wall abuts wooden structure.
3. Air-sealed perimeter walls, with no intentional openings to the outside, and a weather-stripped access door.
4. Thermal insulation installed either on the perimeter walls (without obscuring the termite inspection gap) or in the framed floor structure above the crawl space.
5. A mechanical drying mechanism to provide supplemental control of humidity when installed in climates having a humid season.

Two of the main objectives of this project included (1) an assessment of 10 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 12 small (1040 square feet), simply-designed homes in the eastern town of Princeville, NC. 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 intervention groups had closed crawl space systems installed. In the final phase of the project, researchers installed closed crawl space systems with fiberglass batt insulation located in the framed floor structure above the crawl space in the first group of intervention homes. In the remaining group they installed systems with polyisocyanurate board insulation located on the crawl space perimeter wall. Researchers anticipated 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:

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

Full details and results of this first crawl space project are available at www.crawlspaces.org.

2.1 CURRENT KNOWLEDGE GAP

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 builder, 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 percent of existing homes and 18 percent 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 percent) are built in the mixed-humid climate zone, 73,000 (35 percent) are built in the cold climate zone, and 13,000 (nine percent) 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, though the current economic recession has certainly reduced all of these estimates.

Therefore, this project has conducted the field studies 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 North Carolina.

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., ENERGY STAR) 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 the closed crawl space systems would cause an energy penalty. To understand this contradiction and to help ensure those who install closed crawl spaces receive appropriate credit towards certification in high performance home programs, a broader computer modeling effort was included in the current project. The current project surveyed a number of modeling programs to assess whether they are able to accurately predict the energy impact of closed crawl spaces and to provide feedback to the software developers so they can correct their models, if indicated.

2. BACKGROUND

3. METHODOLOGY

3.1 BUILDER RECRUITMENT

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 12 homes on crawl space foundations, ideally all within one neighborhood or community, in a unique climate zone outside North Carolina. 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 to ensure more consistent performance among the project homes, so subsequent performance comparisons could be more legitimately attributed to the intentional variations in the foundation design instead of other unintended 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 15 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 ENERGY STAR 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 did 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 FIELD RESEARCH 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

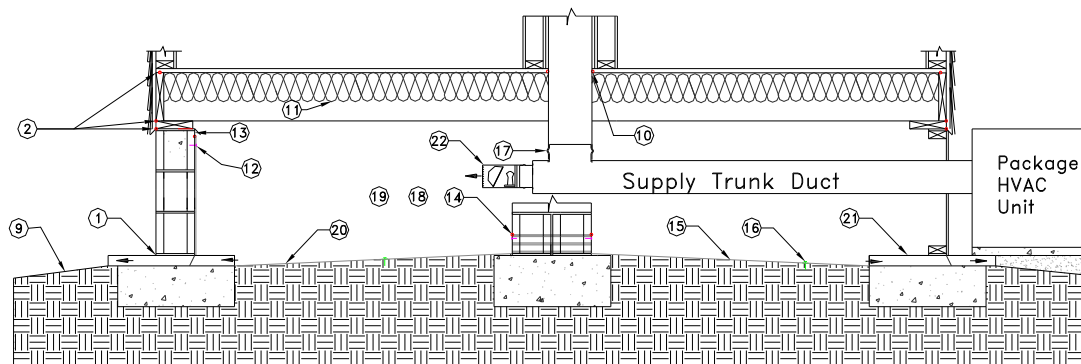
3. METHODOLOGY

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 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)



Closed Crawl Space with Floor insulation and Ductwork in the Attic

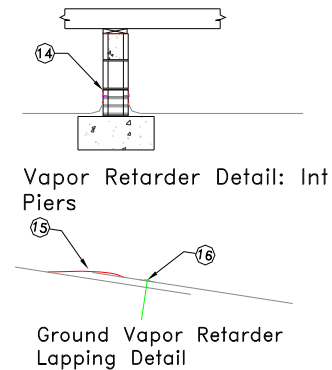
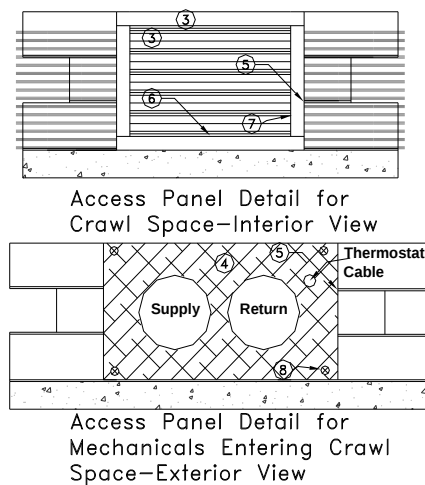


Figure 1. Baton Rouge schematic design for floor-insulated closed crawl space.

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. 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.

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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 it is secured in place. Install the insulation without gaps, voids, or compression.
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 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 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 ENERGY STAR 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.

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3.2.1.2 Baton Rouge closed crawl space with wall insulation and supply ducts in attic (CCS-WA)

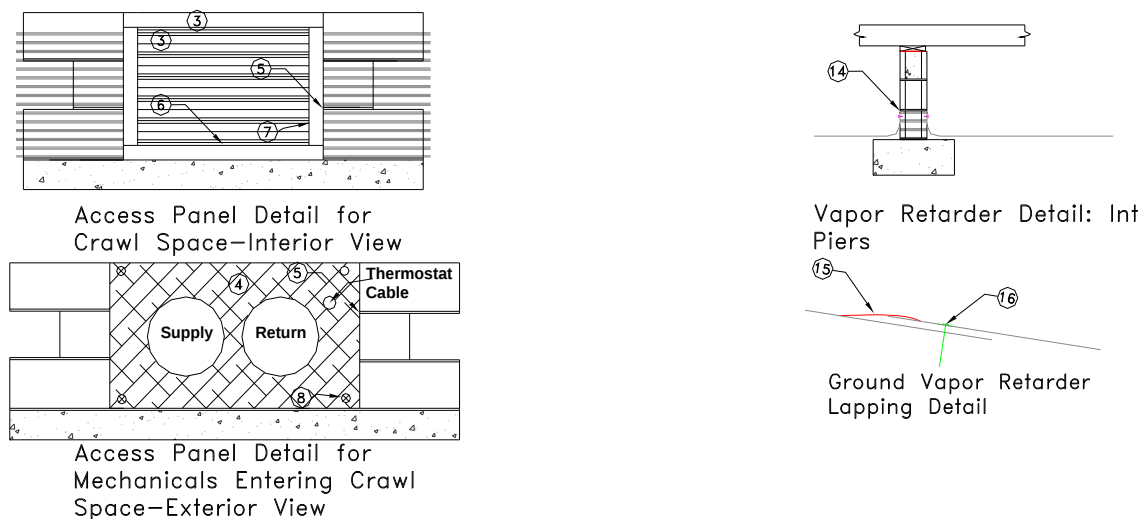
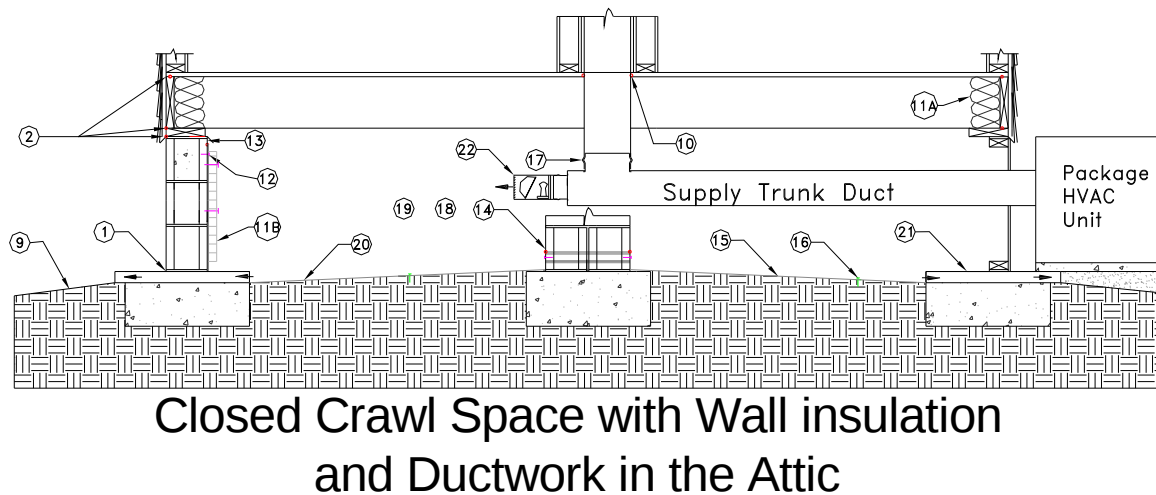


Figure 2. Baton Rouge schematic design for wall-insulated closed crawl space with attic supply ducts.

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.
- 11A. Insulate the band joist area with friction-fit pieces of R-19 unfaced batt insulation. Install the insulation without voids, gaps, or compression.
- 11B. 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 there is a nominal 3" gap between the bottom of the Thermax insulation and the finished interior grade of the 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.

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- 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 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 ENERGY STAR 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.

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

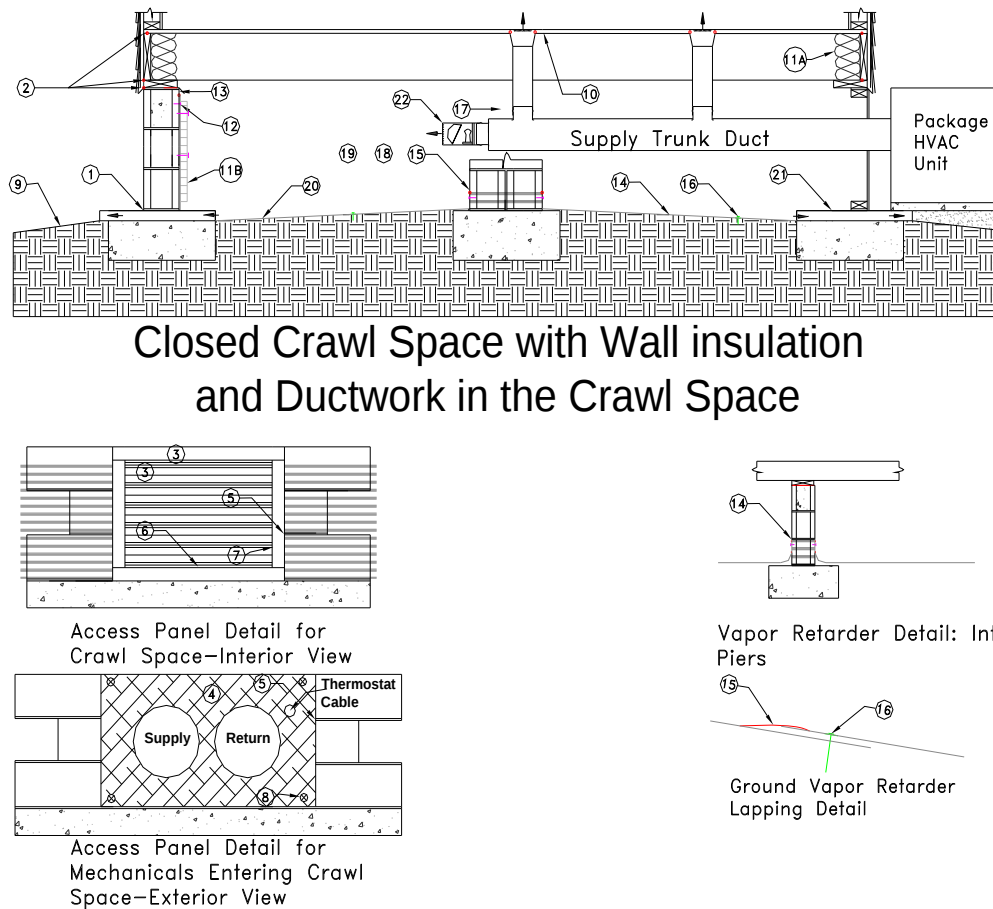


Figure 3. Baton Rouge schematic design for wall-insulated closed crawl space with crawl space supply ducts.

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.

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- 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.
- 11A.** Insulate the band joist area with friction-fit pieces of R-19 unfaced batt insulation. Install the insulation without voids, gaps, or compression
- 11B.** 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.
- 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

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 ENERGY STAR 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.

3.2.2 Baton Rouge Research Groups

The Baton Rouge field site consists of 15 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 two foot 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 12 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 research 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 Building America Program. Figure 4 below illustrates the site layout (not to scale) and research designations for each participating home within the test site.

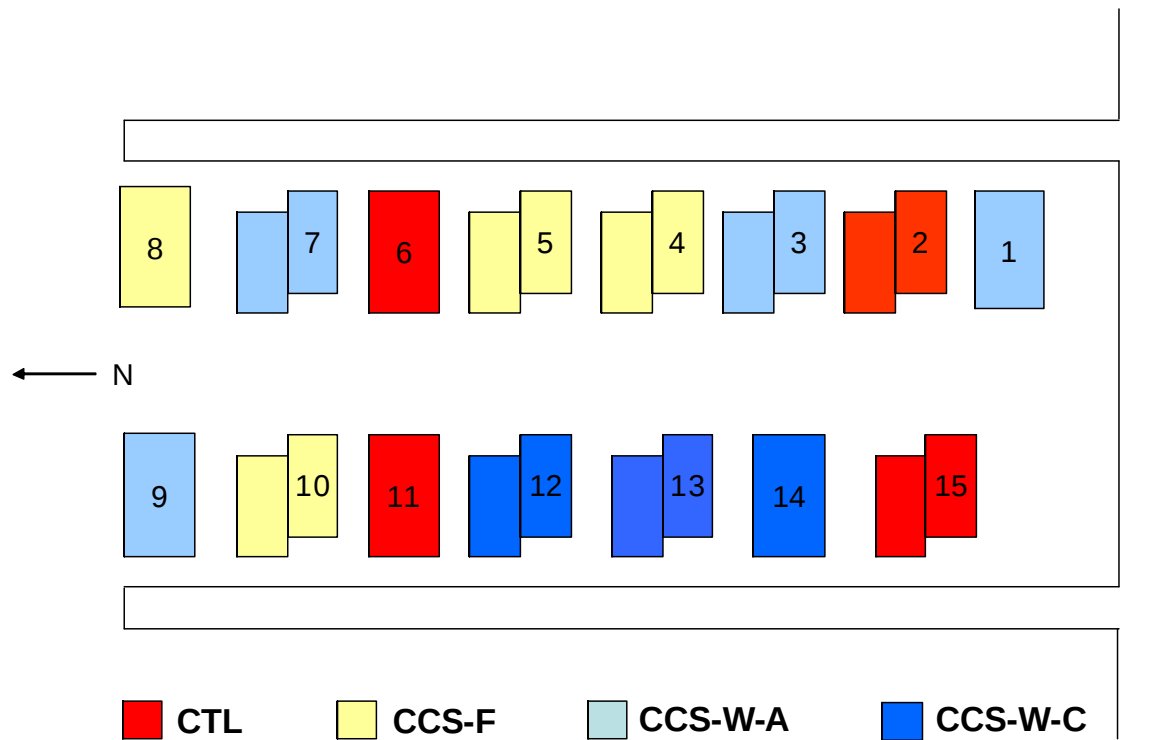


Figure 4. Baton Rouge site layout and research designations by lot.

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 the research 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 research 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	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-WA	1196 (4%)	9568 (5%)	3592 (4%)	183 (0%)	78 (0%)	0.27 (3%)	9.5% (-5%)	20 (16%)
CCS-WC	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.

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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)

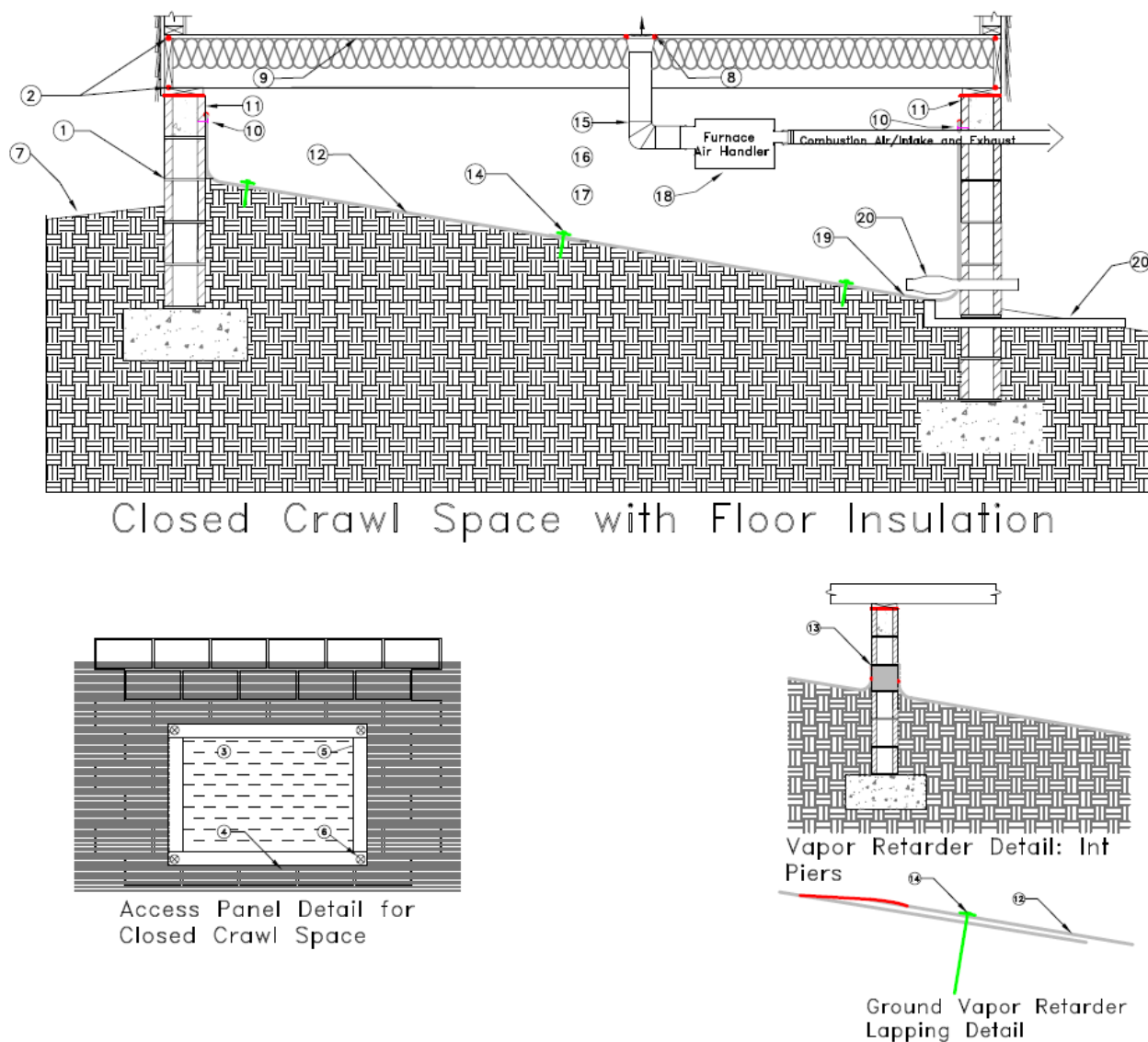


Figure 12. Flagstaff schematic design for floor-insulated closed crawl space.

1. Air seal all foundation stem wall penetrations with weather-resistant caulk, silicone sealant, or spray foam.

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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 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 ENERGY STAR 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.

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

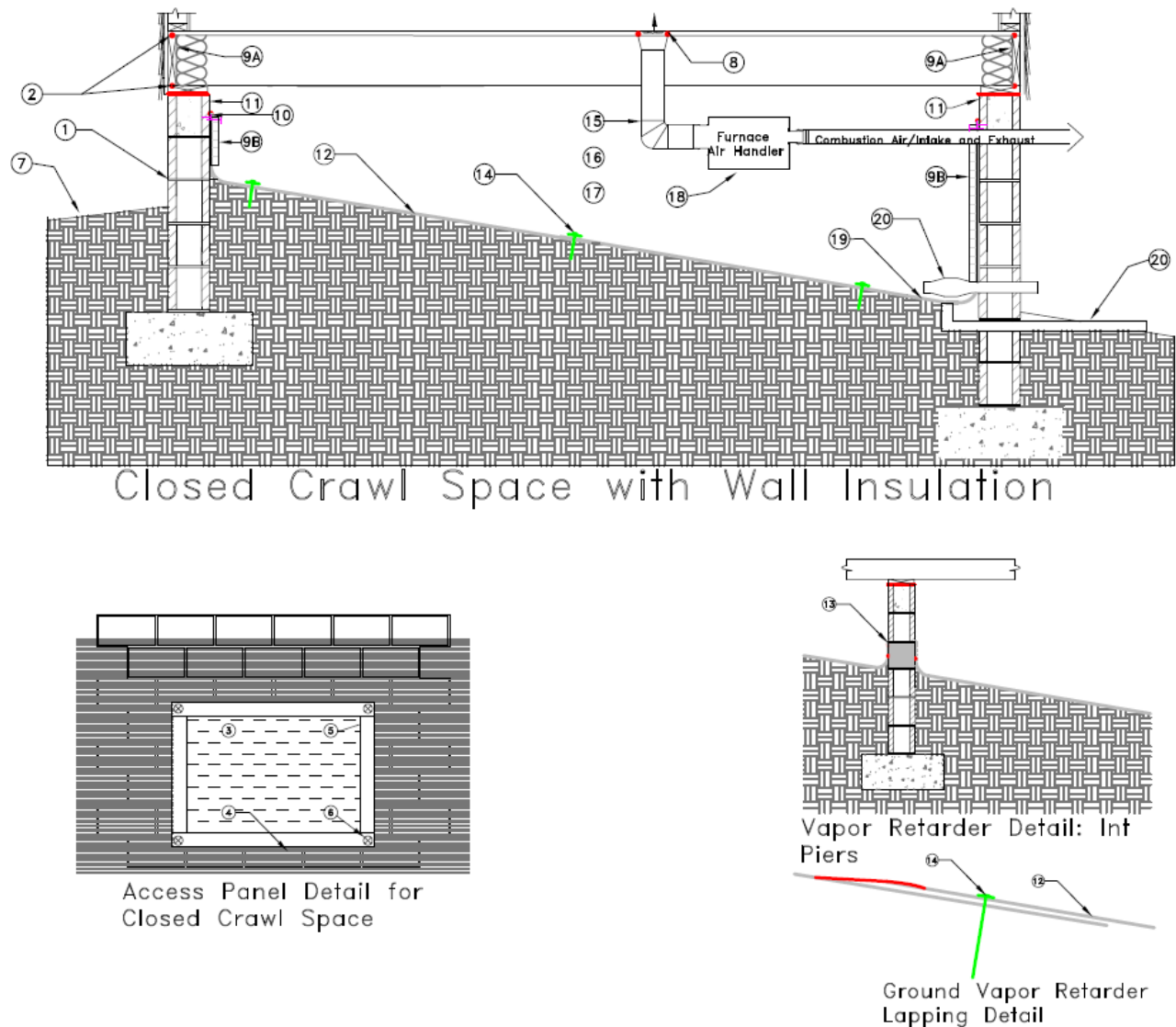


Figure 13. Flagstaff schematic design for wall-insulated closed crawl space.

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 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.
- 9A. Insulate the band joist area with friction-fit pieces of R-19 unfaced batt insulation. Install the insulation without voids, gaps, or compression.
- 9B. 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 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 there is a nominal 3" gap between the bottom of the Thermax insulation and the finished interior grade of the crawl space.
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 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.
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 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.

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- 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 ENERGY STAR 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.

3.2.4 Flagstaff Research Groups

The Flagstaff field site includes 12 homes of variable sizes and footprints. The homes were site-built and stick-framed using standard wood frame construction. All homes were built to meet ENERGY STAR 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 research groups with regard to envelope leakage, duct leakage, and mechanical ventilation rates. Each house is located on a slight grade, typically dropping at least four feet from the front of the lot

to the back, which resulted in crawl space interior heights ranging from approximately three feet to over eight feet in some cases.

Flagstaff is located in a cold climate as defined by the U.S. Department of Energy 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 research designation for each participating house within the test site.



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

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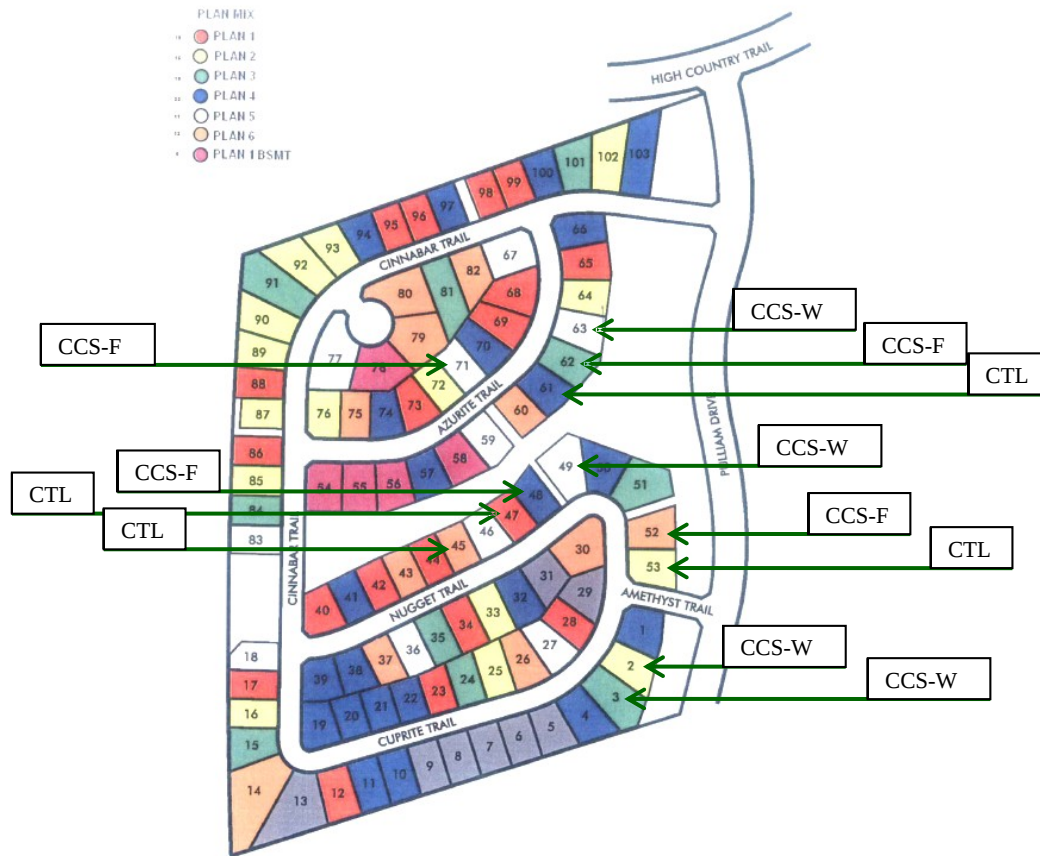


Figure 15. Research designations of lots in the Flagstaff field site. The top of the lot plan is North, and the front of all homes faces the street they are built on.

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 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 ENERGY STAR 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 these data are not included. As a whole, these characteristics appear to indicate that the research 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	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.

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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 over a 12 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: $\pm 0.2^\circ$ at 21°C ($\pm 0.33^\circ$ at 70°F) in high-resolution mode and $\pm 0.5^\circ$ C ($\pm 0.9^\circ$ 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: $\pm 3\%$ 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.

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

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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 inch 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 were downloaded quarterly from the HOBO Pro data loggers by Advanced Energy staff during regularly-scheduled field site inspections. OmniSense data were 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 $\pm 0.2\%$ 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 one 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, and all the meters were labeled with the appropriate house lot number and meter type to ensure accurate identification of the picture. Advanced Energy staff confirmed every data value in the spreadsheet against the photograph 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 assessment of the most popular residential energy modeling programs was performed prior to the current project (Dastur, Carter, Hannas). Results from that assessment narrowed down the list of desired modeling programs for this project 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

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use, and relative energy prediction accuracy. The three programs chosen were: REM/Rate from Architectural Energy Corporation, EnergyGauge from the Florida Solar Energy Center (FSEC), and TREAT from PSD Consulting (PSD).

3.5 ENERGY MODELING PROGRAM ANALYSIS PLAN

After the 15 homes in Baton Rouge, LA, and 12 homes in Flagstaff, AZ, were constructed for this project and energy use data were collected, each home was modeled in each of the three programs using as many known inputs as possible, including indoor conditions and actual building orientations. In order to increase accuracy, the developers of the programs provided technical support to Advanced Energy staff and two of the developers (FSEC and PSD) actually created the appropriate modeling files for each of the homes themselves. Advanced Energy staff conducted a final quality assurance check to ensure all building model file inputs were consistent with the actual home construction and consistent across the modeling programs.

Once all of the homes 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.

Home-specific building characteristics used in the energy 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.

Group	Lot	Front Orient	Floor (Sq. Ft.)	Volume (Cu. Ft.)	Envelope (Sq. Ft.)	Leakage to Outside		Glazing (Sq. Ft.)				Setpoints	
						Duct CFM25	House CFM50	E	S	W	N	Cool	Heat
CTL	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
CCS-F	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
CCS-WA	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
CCS-WC	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 distinguishing 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

The following characteristics were consistent across all homes:

- Heating and cooling is provided by a 13 SEER/7.7 HSPF packaged unit heat pump located adjacent to the house
- Water heating is provided by an electric tank located in the conditioned space, with a 50 gallon capacity and 0.92 EF
- In twelve homes, supply and return trunks run through the crawl space, then up through vertical chases to the home
 - ▶ The return is located in the hallway wall in conditioned space
 - ▶ The supply trunk duct runs to the attic and individual room supply ducts then run through the attic to ceiling registers
- In three homes (lots 12, 13, and 14) the individual room supply ducts run through the crawl space to floor registers
- All ducts are R-6 flexible duct
- A supply duct in the closed crawl spaces provides 50 cubic feet per minute of conditioned air to the crawl space whenever the system is running (this duct is not present in the vented crawl spaces)
- Ventilation is provided in all homes by a duct running from outside to the return plenum, which draws the amount specified in the table above whenever the air handler is running
- Construction type is single-family detached, modular (factory built), stick frame
- R-13 fiberglass batts plus R-3 continuous foam sheathing insulate the above-grade walls
- R-30 blown fiberglass insulates the attic (located at the ceiling plane)
- Crawl space walls are eight inch thick concrete block (CMU) walls
- Window parameters are: U-value = 0.35 and Solar Heat Gain Coefficient = 0.3
- Window type is double-glazed with vinyl frame
- Exterior doors are insulated steel, U = 0.46
- The crawl space is two feet 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.

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

Group	Lot	Front Orient	Floor (Sq. Ft.)	Volume (Cu. Ft.)	Envel (Sq. Ft.)	Floors	Leakage to Outside		Glazing (Sq. Ft.)				Setpoints	
							Duct CFM25	House CFM50	E	S	W	N	Cool	Heat
CTL	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
CCS-F	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
CCS-W	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 distinguishing 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

The following characteristics were consistent across all homes:

- 12 SEER air conditioner used for cooling (when installed)
- 90% AFUE direct-vent furnace for heating
- Water heating provided by a natural gas conventional tank located in the garage, with a 50 gallon capacity and 0.62 EF
- The furnace/air handler unit is located in the crawl space and there is only one system per home
- Ducts are R-6 flexible duct
- First floor ducts are located in the crawl space
- If there is a second story, the ducts are routed 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 the Flagstaff field site
- Construction type is single-family detached, site-built, stick frame construction
- R-19 insulation is installed in all above-grade walls
- R-19 fiberglass batts insulate the floor over the garage (when applicable)
- R-30 insulation is installed in the attic
- Window parameters are: U-value = 0.38; Solar Heat Gain Coefficient = 0.40
- Window type is 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 11 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 (CSCT) is a closed crawl space installation company and product distributor based in Greensboro, NC. The CSCT 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 2006 to October 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 12 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 2008 due to the identification of radon hazards in the homes with 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.

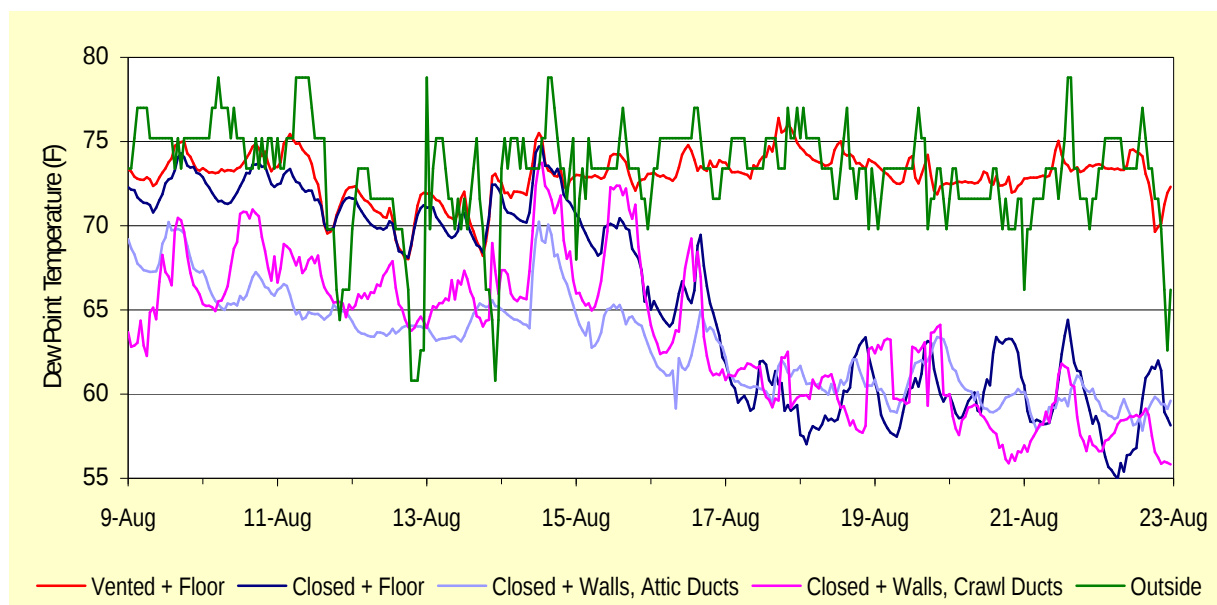


Figure 24. Baton Rouge – Hourly crawl space and outdoor dew point temperatures by group for the dry-down period.

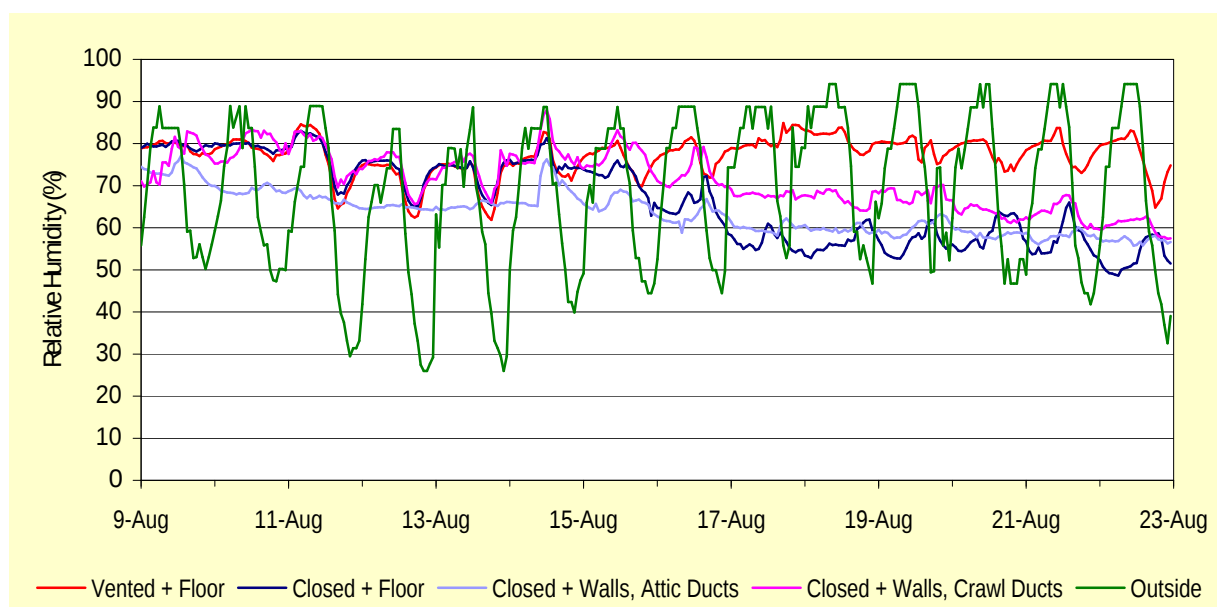


Figure 25. Baton Rouge – Hourly crawl space and outdoor relative humidity by group for dry-down.

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

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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 late summer 2007 and in summer 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.

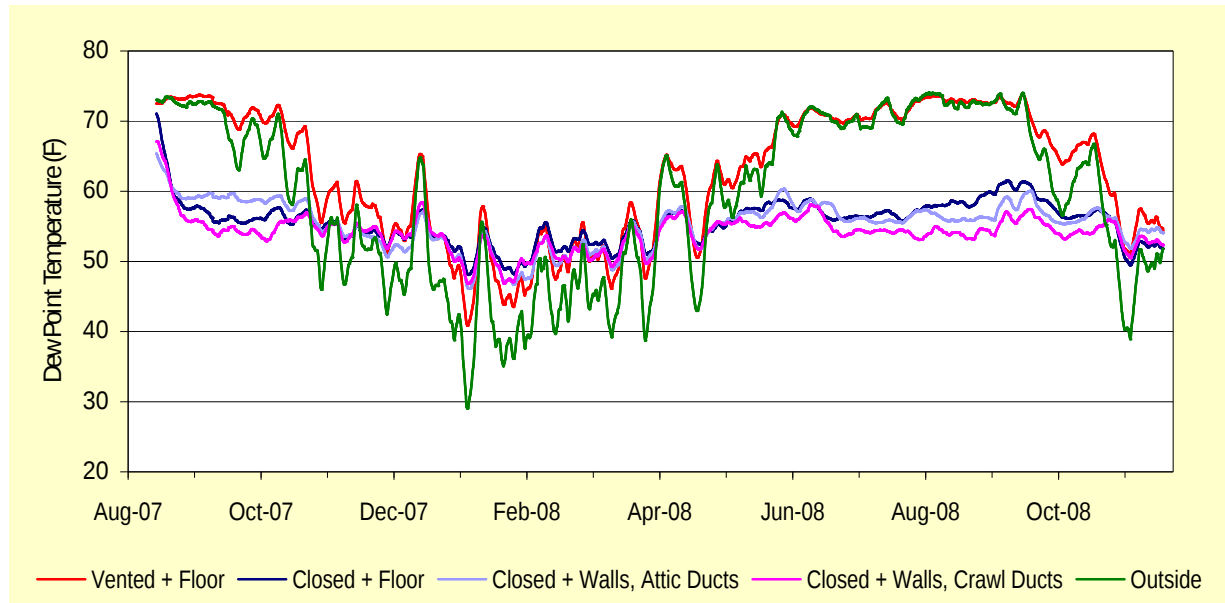


Figure 26. Baton Rouge – Daily crawl space and outdoor dew point by group.

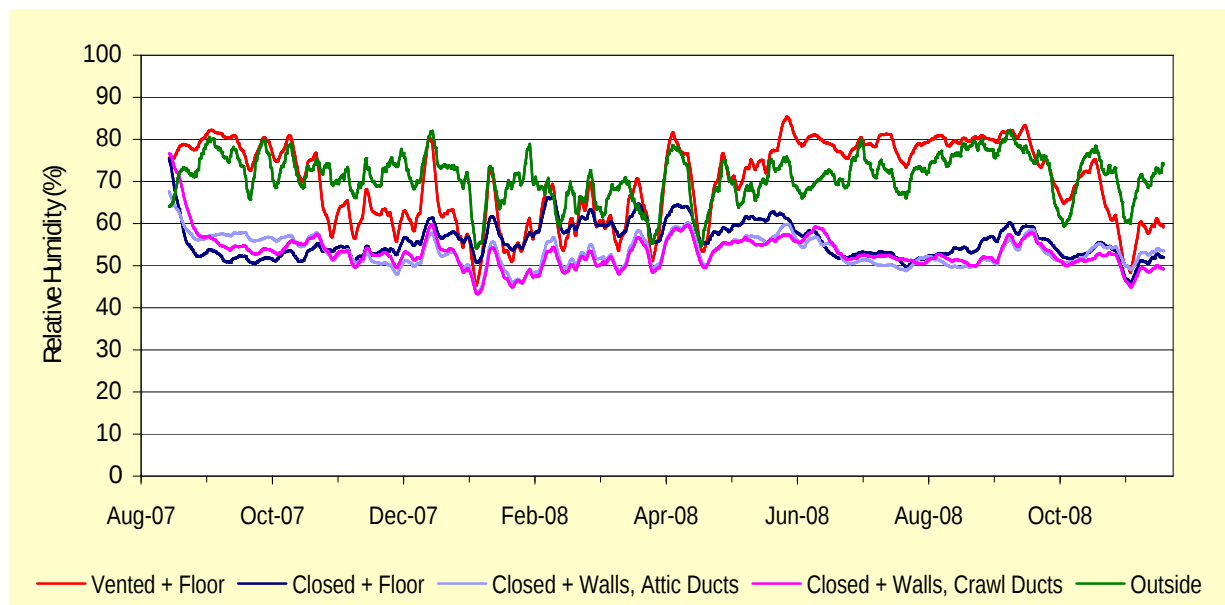


Figure 27. Baton Rouge – Daily crawl space and outdoor relative humidity by group.

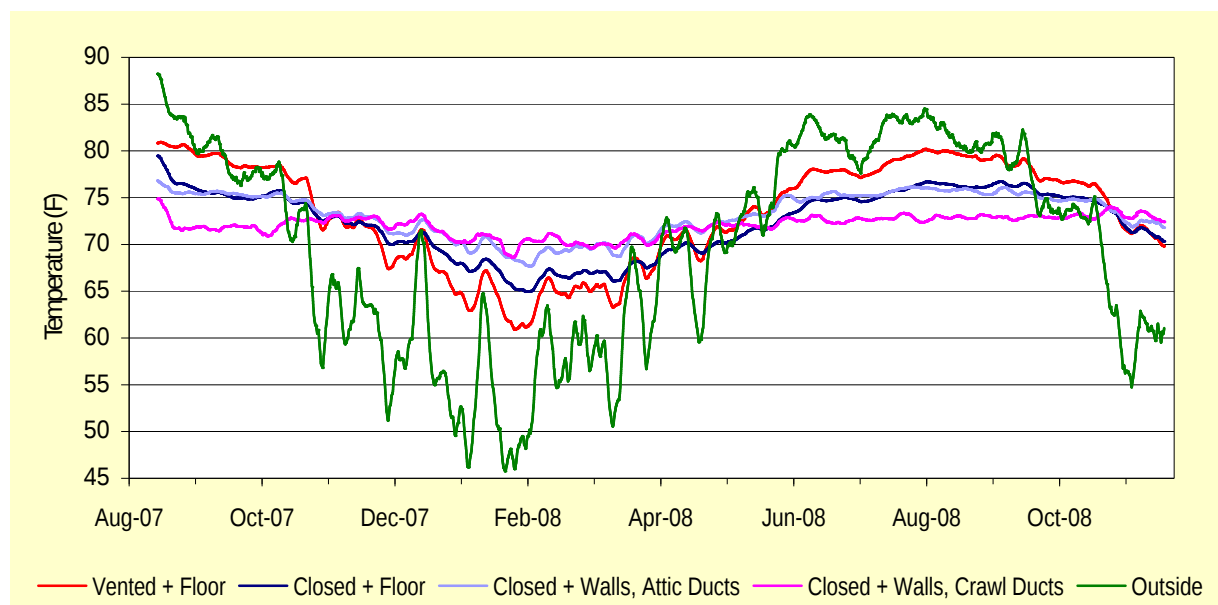


Figure 28. Baton Rouge – Daily crawl space and outdoor temperature by group.

Another way to summarize the crawl space performance is to compare how often the closed and vented crawl spaces are above different relative humidity thresholds. To do this, a bin analysis of the data presented in Figure 27 is created using increments of 10 percent relative humidity. Table 6 below shows the percentage of days during which the average relative humidity was above each threshold, for both closed and vented crawl spaces during the summer of 2008 as well as for the entire study year.

Table 6. Percent of time each type of crawl space spent above different relative humidity (RH) thresholds.

RH Threshold	Summer 2008 (Jun 2008 – Aug 2008)		Entire Year (Oct 2007 – Sep 2008)	
	Vented (CTL)	Closed (CCS)	Vented (CTL)	Closed (CCS)
Above 90 percent	0%	0%	0%	0%
Above 80 percent	47%	0%	27%	0%
Above 70 percent	99%	0%	58%	0%
Above 60 percent	100%	1%	76%	11%
Above 50 percent	100%	84%	91%	82%
Above 40 percent	100%	100%	99%	99%
Above 30 percent	100%	100%	100%	100%

The summary in Table 6 shows a significant difference in the percentage of days the two crawl space types spent in the higher relative humidity conditions. In particular, the percentage of days spent above 70 percent relative humidity in the summer was 99 percent for the vented crawl spaces, but zero percent for the closed crawl spaces. In fact, the closed crawl spaces had only one percent of days with average relative humidity above 60 percent during the summer of 2008. This significantly reduces the risk of mold growth in the closed crawl spaces.

For context, the moisture climate of Baton Rouge appeared to be close to normal during the summer of 2008. No detailed analysis was conducted by the study team, but rainfall during this time was slightly low in June and July and slightly high in August. Monthly climate summaries created by the National Weather Service Forecast Office of New Orleans and Baton Rouge are available for 2007 and prior, but not yet

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available for 2008. These reports have a small paragraph climate summary for every month of the year (see <http://www.srh.noaa.gov/lix/html/weather2007.htm> for the 2007 report).

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.

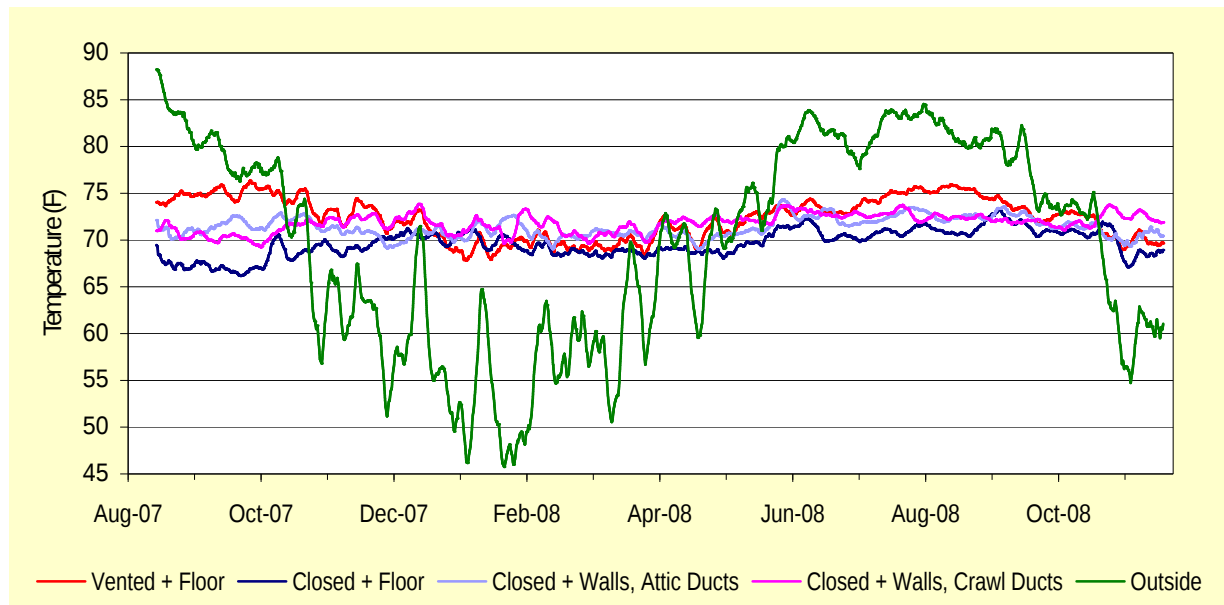


Figure 29. Baton Rouge – Daily indoor temperature by group.

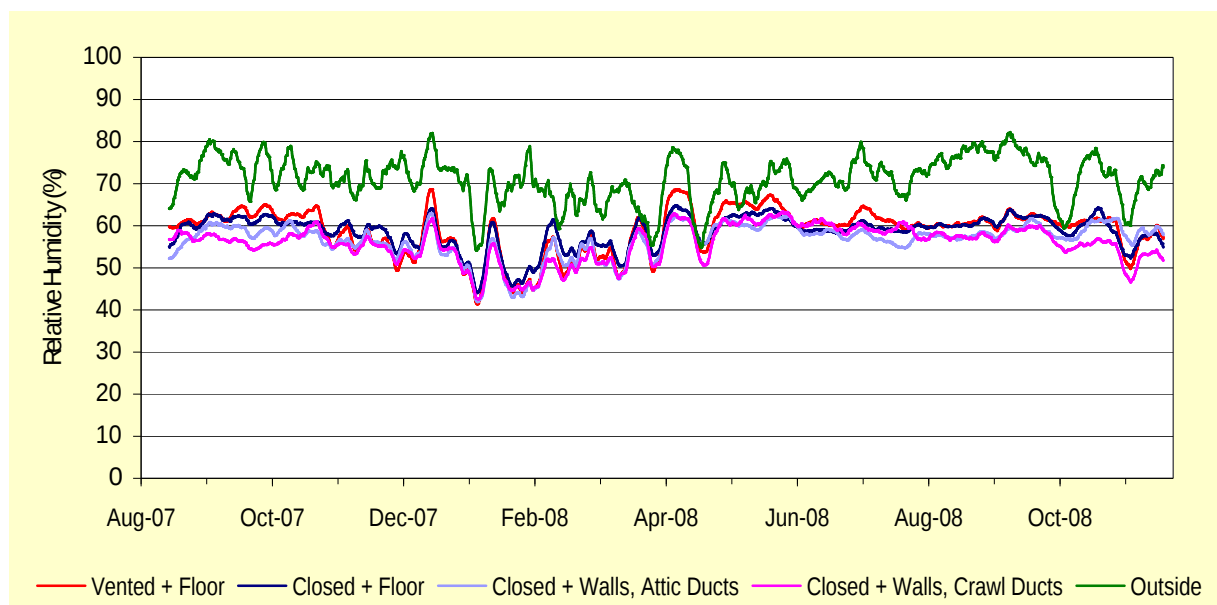


Figure 30. Baton Rouge – Daily indoor relative humidity by group.

4.3 BATON ROUGE ENERGY CONSUMPTION

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 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 energy reading from the previous month is then subtracted from the interpolated cumulative reading to determine the energy use of a given month. 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.

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The abbreviations listed in bold text below represent the corresponding system descriptions in the tables and figures below:

1. **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)
2. **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)
3. **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)
4. **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)

4.3.1 Unadjusted Baton Rouge Energy Use

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).

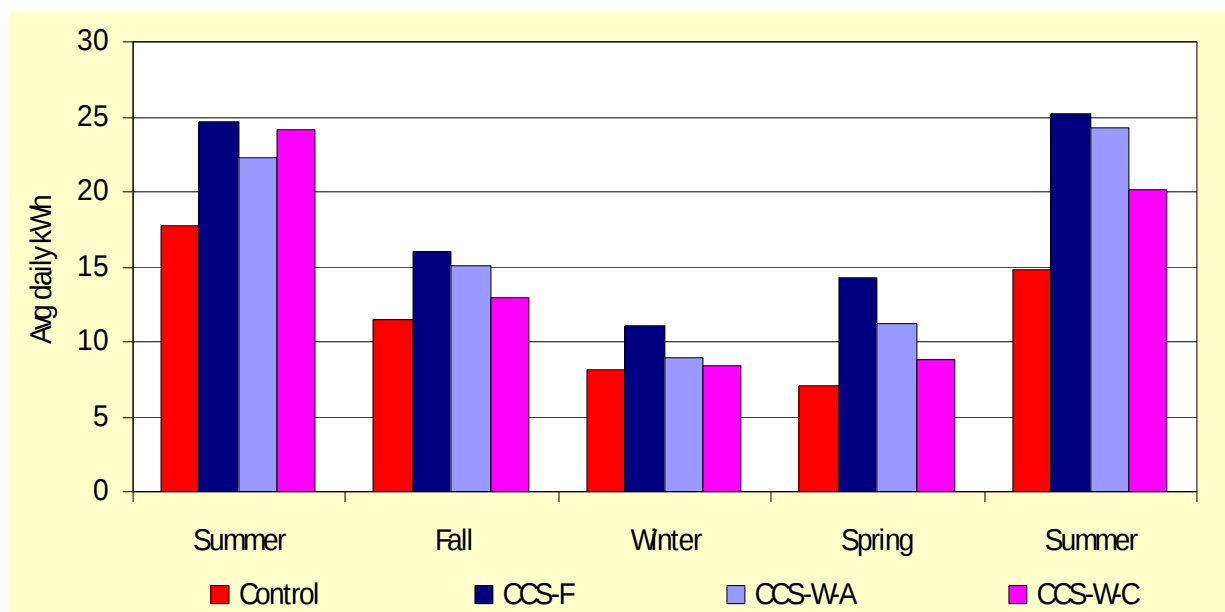


Figure 31. Baton Rouge – Average daily kWh usage showing differences in heating and cooling energy use from June 2007 and July 2007 baseline months (the first Summer season) through Summer 2008.

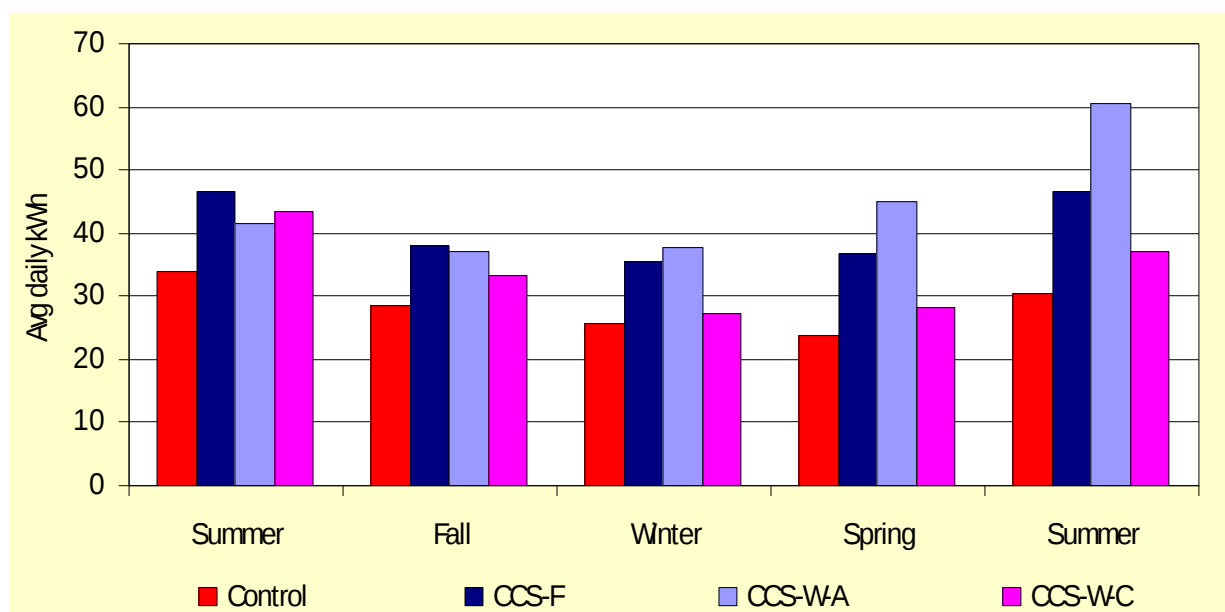


Figure 32. Baton Rouge – Average daily kWh usage showing differences in total energy use from the June 2007 and July 2007 baseline months (the first Summer season) through Summer 2008.

4.3.2 Seasonally Adjusted Baton Rouge Energy Use

In order to interpret the energy readings taken after the closed crawl space systems were installed in mid-August 2007, the study team first assessed whether the energy usages of the study groups were comparable before the installation using the energy readings from June and July of 2007. During these pre-installation “baseline” months, the energy readings indicate the homes that were subsequently assigned to the control group used significantly less energy than the homes 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, and by using a package unit model that has a factory-installed refrigerant charge, not a field-installed charge.

To account for these differences in homeowner behavior, 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 closed crawl space 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 37 percent and 27 percent 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 1.32. The adjusted results can be found in Figure 33 and Figure 34. Because the baseline months were during the summer, and homeowner behavior seemed to be more consistent in the winter and spring, the adjustments were only made to the summer and fall data. No adjustments were made for winter and spring data.

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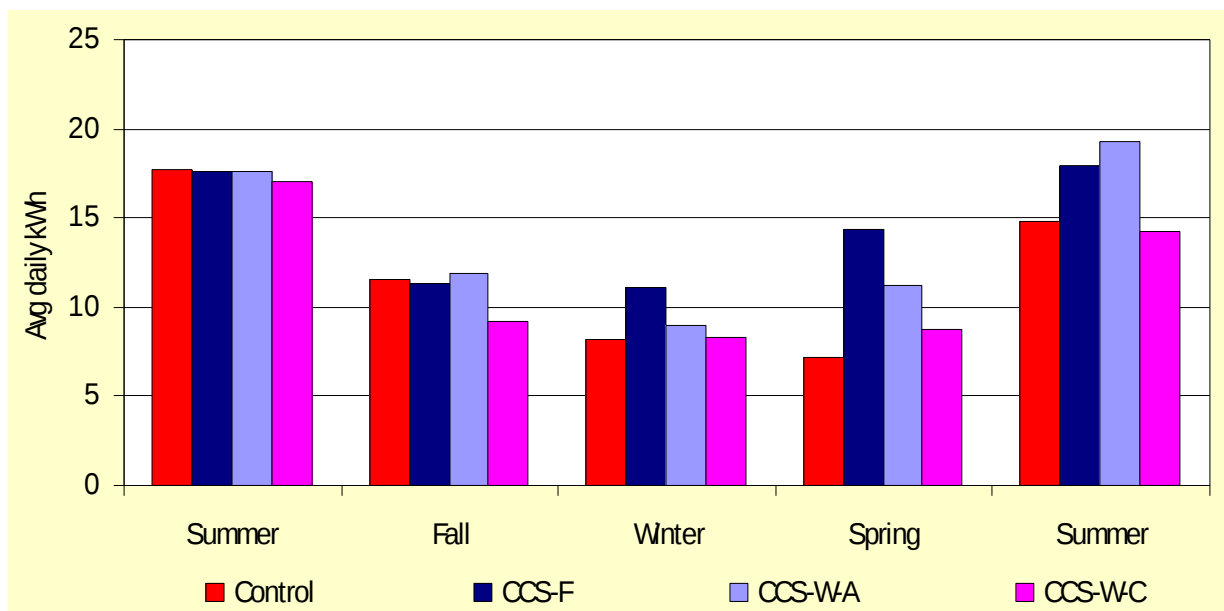


Figure 33. Baton Rouge – Summer and fall adjusted heating and cooling average daily kWh usage showing differences before (Summer 2007) and after (through Summer 2008) the intervention .

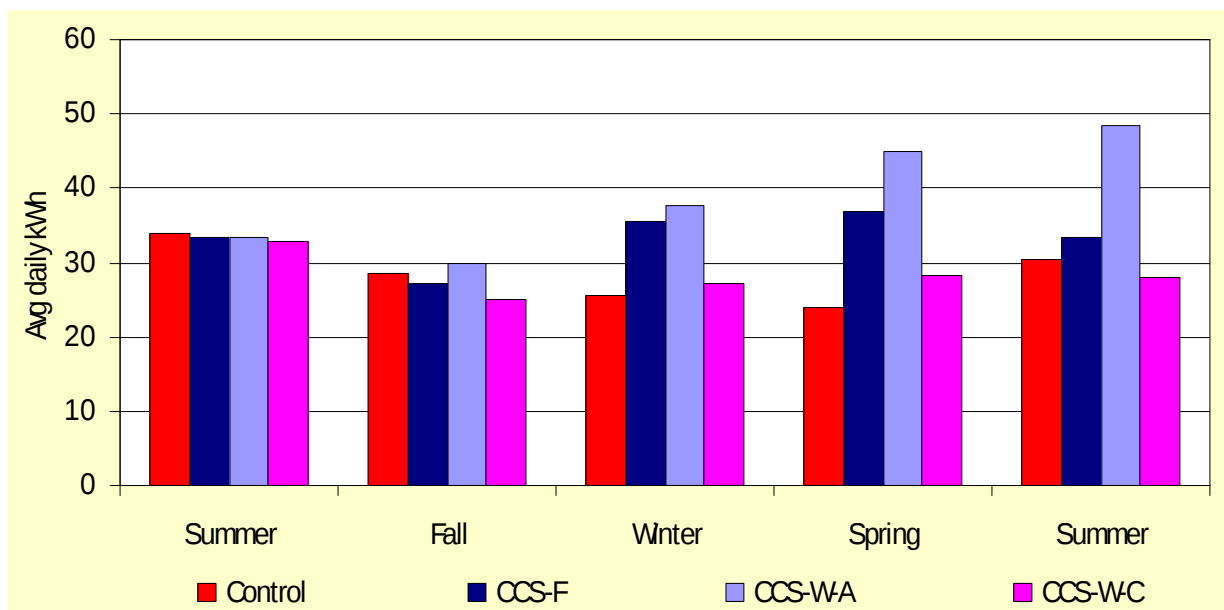


Figure 34. Baton Rouge – Summer and fall adjusted total average daily kWh usage showing differences before (Summer 2007) and after (through Summer 2008) the intervention.

The percent differences and kWh per day values of the data presented in the previous two graphs can be found in Table 7 through Table 10. The CCS-W-A group data may be artificially high because of one particular homeowner (House 1), but no investigation has been performed to determine root cause of the elevated energy use. Possible outliers are discussed in the next section beginning on page 52.

The following tables show the summer/fall adjusted total energy use (Table 7), base load energy use (Table 8), heating and cooling energy use with indoor temperature summary (Table 9), and percent differences in the heating and cooling energy use (Table 10).

Table 7 . Baton Rouge — Summer and fall adjusted energy use and percent differences from Control for total energy use by group. Positive percentage is energy penalty and negative percentage is energy savings.

Period of Use	Total Energy (kWh/day)				Percent Differences			Notes*
	CCS F	CCS W/A	CCS W/C	Control	CCS F	CCS W/A	CCS W/C	
June 2007	32.0	32.7	32.4	31.3	2.4%	4.7%	3.6%	Baseline
July 2007	34.2	33.4	33.7	35.0	-2.4%	-4.7%	-3.6%	Baseline
August 2007	33.7	33.9	31.9	35.2	-4.3%	-3.9%	-9.3%	Intervention
Summer 2007	33.3	33.3	32.7	33.9	-1.6%	-1.6%	-3.4%	Base/Inter
Fall 2007	27.2	29.8	25.0	28.6	-5.2%	4.0%	-12.5%	
Winter 2007-08	35.5	37.7	27.1	25.6	38.8%	47.6%	6.1%	Not adj.
Spring 2008	36.7	44.9	28.1	23.9	53.9%	88.3%	17.9%	Not adj.
Summer 2008	33.5	48.5	28.0	30.3	10.3%	60.0%	-7.8%	
Annual comparison	33.2	40.3	27.1	27.1	22.5%	48.7%	-0.1%	
Annual difference	6.1	13.2	0.0	n/a				

* Base = baseline month and Inter = intervention installed during first two weeks of August

Not adj. = Winter and Spring seasons were not adjusted, only Summer and Fall based on indoor temperature differences

Table 8. Baton Rouge — Summer and fall adjusted energy use and percent differences from Control for base load energy use by group. Positive percentage is energy penalty and negative percentage is energy savings.

Period of Use	Base Load Energy (kWh/day)				Percent Differences			Notes*
	CCS F	CCS W/A	CCS W/C	Control	CCS F	CCS W/A	CCS W/C	
June 2007	16.1	16.6	16.4	16.0	0.3%	3.4%	2.5%	Baseline
July 2007	15.8	15.3	15.5	15.9	-0.3%	-3.4%	-2.5%	Baseline
August 2007	15.1	15.2	15.1	16.7	-9.2%	-8.9%	-9.3%	Intervention
Summer 2007	15.7	15.7	15.7	16.2	-3.2%	-3.1%	-3.2%	Base/Inter
Fall 2007	15.8	17.9	16.5	17.1	-7.8%	4.6%	-3.8%	
Winter 2007-08	24.4	28.8	18.8	17.4	39.9%	65.4%	7.9%	Not adj.
Spring 2008	22.4	33.8	19.4	16.7	33.8%	101.6%	15.7%	Not adj.
Summer 2008	15.5	29.4	13.8	15.5	0.0%	89.7%	-11.1%	
Annual comparison	19.5	27.5	17.1	16.7	16.8%	64.7%	2.4%	
Annual difference	2.8	10.8	0.4	n/a				

* Base = baseline month and Inter = intervention installed during first two weeks of August

Not adj. = Winter and Spring seasons were not adjusted, only Summer and Fall based on indoor temperature differences

Table 9 combines two data sets – energy from Figure 33 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 summer adjusted energy use values from Figure 33 above. Percent differences for the heating and cooling energy use can be found in Table 10.

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Table 9. Baton Rouge – Summer and fall adjusted heating and cooling energy use (average kWh per day) with average indoor temperatures per group.

Period	Heating and Cooling Energy (kWh/day)				Indoor Temperature (degree F)				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	16.1	15.3	-	-	-	-	82	Baseline
July	18.3	18.0	18.1	19.1	-	-	-	-	82	Baseline
August	18.5	18.6	16.8	18.6	68	71	71	74	86	Intervention
Summer 2007	17.6	17.6	17.0	17.7	-	-	-	-	83	Base/Inter
Fall	11.4	11.9	9.1	11.5	68	71	71	74	70	
Winter	11.1	8.9	8.3	8.2	70	71	71	70	56	Not adj.
Spring	14.3	11.2	8.8	7.1	69	71	72	71	69	Not adj.
Summer 2008	17.9	19.3	14.2	14.9	71	72	73	75	82	
Annual average	13.7	12.9	10.1	10.4						
Annual comparison	3.3	2.4	-0.3	n/a						

* Base = baseline month and Inter = intervention installed during first two weeks of August
 Not adj. = Winter and Spring seasons were not adjusted, only Summer and Fall based on indoor temperature differences

Table 10. Baton Rouge – Summer and fall adjusted heating and cooling percentage difference comparison. Positive percentage is energy penalty and negative percentage is energy savings.

Period of Use	Heating and Cooling Energy Percent Differences			Notes*
	CCS-F	CCS-W/A	CCS-W/C	
June 2007	4.4%	6.0%	5.3%	Baseline
July 2007	-4.4%	-6.0%	-5.3%	Baseline
August 2007	-0.2%	0.3%	-9.7%	Intervention
Summer 2007	-0.4%	-0.4%	-3.9%	Base/Inter
Fall 2007	-1.3%	3.7%	-20.5%	
Winter 2007-08	36.3%	9.7%	2.3%	Not adj.
Spring 2008	100.9%	57.0%	23.1%	Not adj.
Summer 2008	20.7%	29.8%	-4.3%	
Annual comparison	31.5%	23.4%	-2.8%	

* Base = baseline month and Inter = intervention installed during first two weeks of August
 Not adj. = Winter and Spring seasons were not adjusted, only Summer and Fall based on indoor temperature differences

For reference, the unadjusted values can be found in Appendix A on page 76.

4.3.3 Seasonally Adjusted Baton Rouge Energy Use With Possible Outliers Excluded

There appear to be some data that were outside the expected variation of the data set. With only three or four data points per group, it is difficult to determine whether a given datapoint is an outlier without other conclusive evidence. However, the study team wanted to assess the results with any likely outliers excluded, so Grubb's test for outliers was selected to determine which data to exclude.

Assuming normality of the data based on past experience, Grubb's test is used to calculate the probability of whether the tested data belong to the population. Due to the small sample size, only one iteration was conducted. The comparison test statistic was 1.48 for sample sets of four and 1.15 for sample sets of three. If the calculated test statistic for any data point was above this threshold, it was considered an

outlier. The method produced a sparse matrix of outliers with only the House 1 total energy use and base load energy use being fully suspect, as was predicted in the paragraph below Figure 34 on page 50 above.

Upon review, researchers decided to present the heating and cooling energy use with outliers excluded and summer and fall values adjusted, and to present the base load energy use with outliers excluded and all seasonal values adjusted. This is due to the measured differences in indoor temperature across the groups in different seasons, which affects the space conditioning energy use, while there were no measurements indicating seasonal differences between groups in the base load use. Therefore, Figure 35 below is adjusted in the summer and fall, while Figure 36 is adjusted in all seasons. The adjustment in all seasons for the base load also accounts for the obvious differences in base load energy use seen in Figure 32 above.

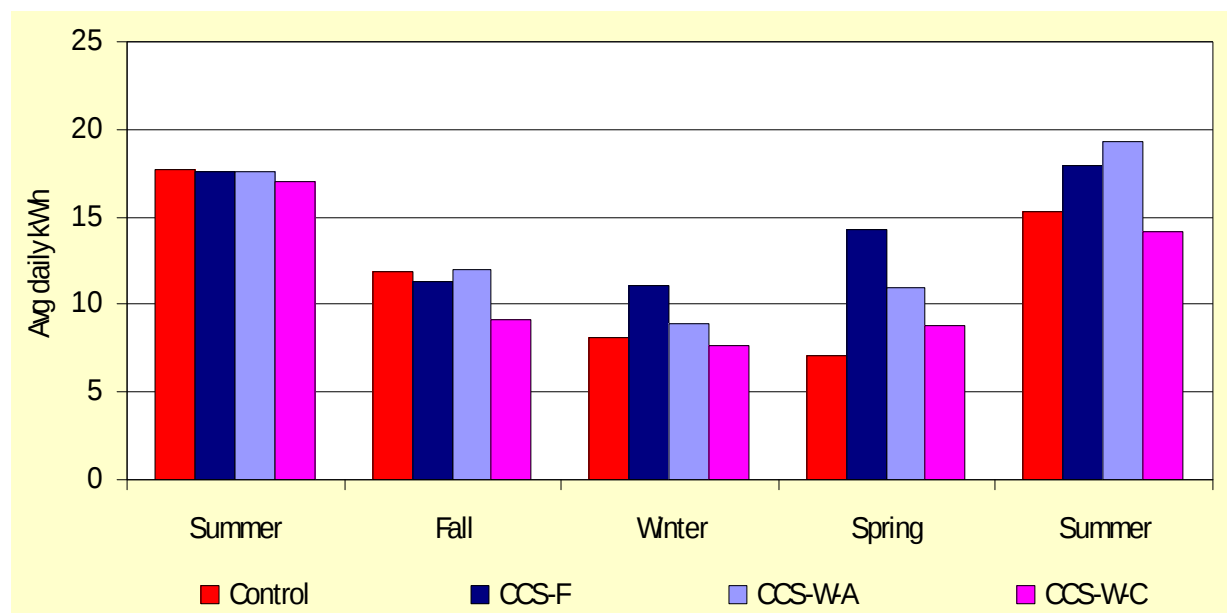


Figure 35. Baton Rouge – Seasonal heating and cooling energy use with outliers excluded and summer/fall adjustments.

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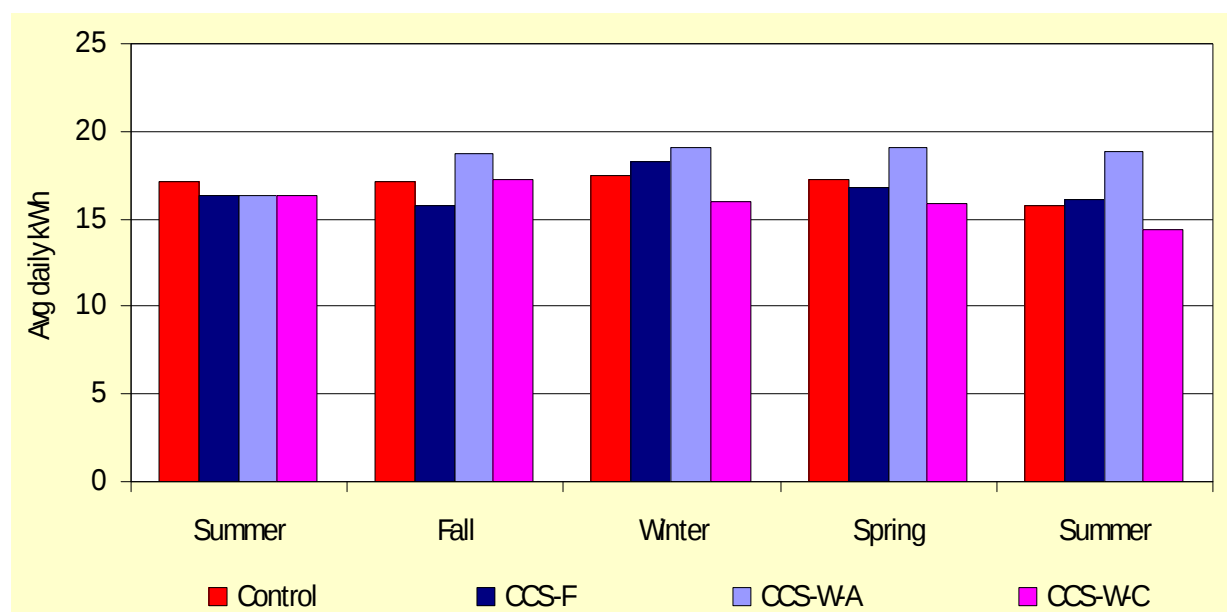


Figure 36. Baton Rouge – Seasonal baseload energy use with outliers excluded and adjustments made for all months.

Summaries for the data with outliers excluded are also given in tabular form below. Table 11 displays the adjusted base load energy use and percent differences, and Table 12 displays the summer/fall adjusted heating and cooling energy use and percent differences. For the most part, the values are not very different from the tables presented in earlier sections. In fact, the heating and cooling results are almost identical, but the baseload values across groups are closer together due to the one CCS-W-A outlier home.

Table 11 . Baton Rouge –All seasons adjusted energy use and percent differences from Control for base load energy use by group. Outliers are excluded. Positive percentage is energy penalty and negative percentage is energy savings.

Period of Use	Base Load Energy (kWh/day)				Percent Differences			Notes*
	CCS F	CCS W/A	CCS W/C	Control	CCS F	CCS W/A	CCS W/C	
June 2007	16.7	17.3	17.1	17.4	-3.9%	-0.8%	-1.7%	Baseline
July 2007	16.5	16.0	16.1	15.9	3.9%	0.8%	1.7%	Baseline
August 2007	15.8	15.9	15.8	18.2	-13.1%	-12.7%	-13.1%	Intervention
Summer 2007	16.3	16.4	16.3	17.1	-4.8%	-4.5%	-4.7%	Base/Inter
Fall 2007	15.7	18.7	17.2	17.1	-8.2%	9.2%	0.4%	
Winter 2007-08	18.3	19.1	16.0	17.4	5.0%	9.6%	-7.9%	
Spring 2008	16.8	19.1	15.9	17.2	-2.1%	11.1%	-7.5%	
Summer 2008	16.1	18.9	14.4	15.7	2.4%	20.0%	-8.8%	
Annual comparison	16.7	18.9	15.9	16.9	-0.8%	12.3%	-5.9%	
Annual difference	-0.1	2.1	-1.0	n/a				

* Base = baseline month and Inter = intervention installed during first two weeks of August

Not adj. = Winter and Spring seasons were not adjusted, only Summer and Fall based on indoor temperature differences

Table 12. Baton Rouge – Summer and fall adjusted energy use and percent differences from Control for heating and cooling energy use by group. Outliers are excluded. Positive percentage is energy penalty and negative percentage is energy savings.

Period of Use	Heating and Cooling Energy (kWh/day)				Percent Differences			Notes*
	CCS F	CCS W-A	CCS W-C	Control	CCS F	CCS W-A	CCS W-C	
June 2007	15.9	16.2	16.1	15.3	4.4%	6.0%	5.3%	Baseline
July 2007	18.3	18.0	18.1	19.1	-4.4%	-6.0%	-5.3%	Baseline
August 2007	18.5	18.6	16.8	18.6	-0.2%	0.3%	-9.7%	Intervention
Summer 2007	17.6	17.6	17.0	17.7	-0.4%	-0.4%	-3.9%	Base/Inter
Fall 2007	11.4	11.9	9.1	11.9	-4.4%	0.5%	-22.9%	
Winter 2007-08	11.1	8.9	7.7	8.2	36.3%	9.7%	-6.0%	Not adj.
Spring 2008	14.3	10.9	8.8	7.1	100.9%	52.9%	23.1%	Not adj.
Summer 2008	17.9	19.3	14.2	15.3	17.3%	26.1%	-7.1%	
Annual comparison	13.7	12.8	10.0	10.6	29.0%	20.4%	-6.2%	
Annual difference	3.1	2.2	-0.7	n/a				

* Base = baseline month and Inter = intervention installed during first two weeks of August
 Not adj. = Winter and Spring seasons were not adjusted, only Summer and Fall based on indoor temperature differences

Table 12 shows the estimated annual impact of the closed crawl space systems on energy used for heating and cooling (percentages in bold type), based only on the electric meter data:

- a 29 percent penalty for the floor-insulated closed crawl space with supply ducts in the attic (CCS-F),
- a 20 percent penalty for the wall-insulated closed crawl space with supply ducts in the attic (CCS-W-A), and
- a 6 percent savings for the wall-insulated closed crawl space with supply ducts in the crawl space (CCS-W-C).

These estimates create a conundrum for interpretation. If the 29 percent penalty can be taken as the accurate impact on heating and cooling energy use of the installation of the liner system with a crawl space supply duct (CCS-F), then the relocation of the insulation to the perimeter wall (CCS-W-A) would be responsible for an approximately 9 percent change (improvement from a 29 percent penalty to a 20 percent penalty). Then the relocation of the ducts from the attic to the crawl space (CCS-W-C, with significant additional duct leakage) would have to be responsible for another 26 percent change in annual heating and cooling energy savings (improvement from a 20 percent penalty to a 6 percent savings). This does not seem feasible, so the discussion section of this report explores other factors that may significantly affect the interpretation of the energy meter data.

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 in Medway, MA for analysis. The results are listed in Table 13 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 performed. Thus, no action is indicated by these test results.

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Table 13 . Baton Rouge – Group averages for Radon levels in crawl spaces and living spaces.

Foundation type	Crawl (pCi/L)	Return (pCi/L)
CTL	0.600	0.400
CCS (all)	1.045	0.700
CCS-WA	1.100	0.733
CCS -WC	1.033	0.700
CCS-F	1.000	1.000

4.5 FLAGSTAFF CRAWL SPACE TEMPERATURE AND HUMIDITY

For Flagstaff, Figure 37 below shows the effect of the crawl space intervention at the far left of the graph where the data are overlapping and then split. The last data collection of temperature and moisture conditions was downloaded on April 12, 2008. Figure 37 and Figure 38 show the moisture load in the crawl spaces during the entire study period. Figure 37 is a graph of the dew point group averages on a daily basis and Figure 38 is a graph of the relative humidity group averages on a daily basis. Figure 39 is a graph of the temperature group averages on a daily basis. As an explanatory variable, the outdoor dew point, relative humidity, and temperature are included in the graphs, respectively.

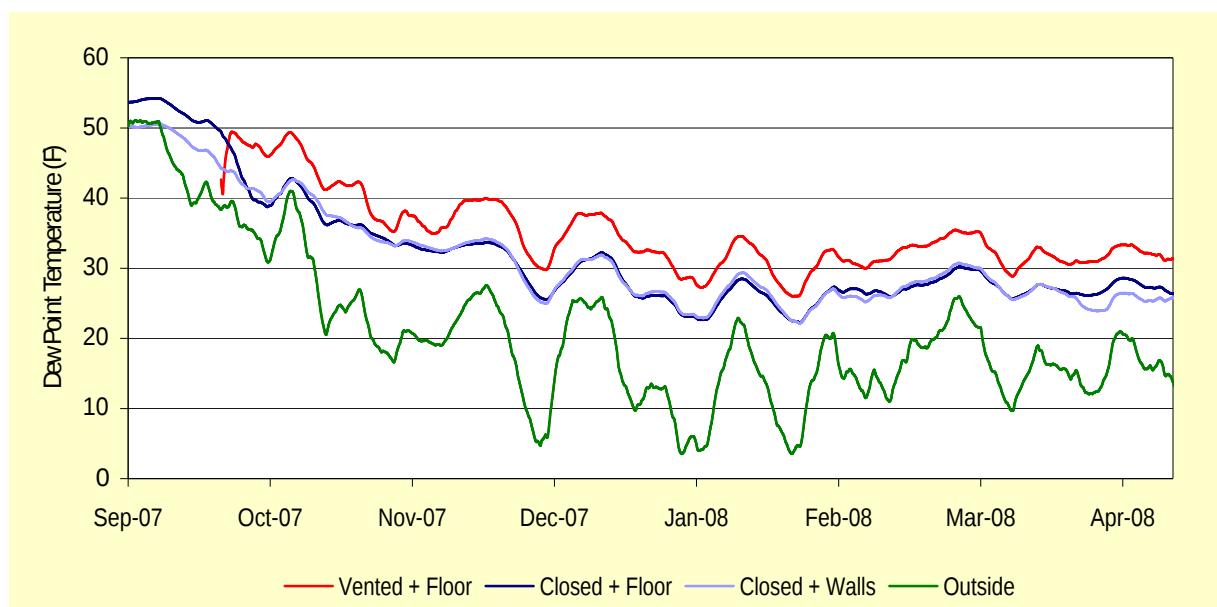


Figure 37 . Flagstaff – Daily crawl space and outdoor dew point by group.

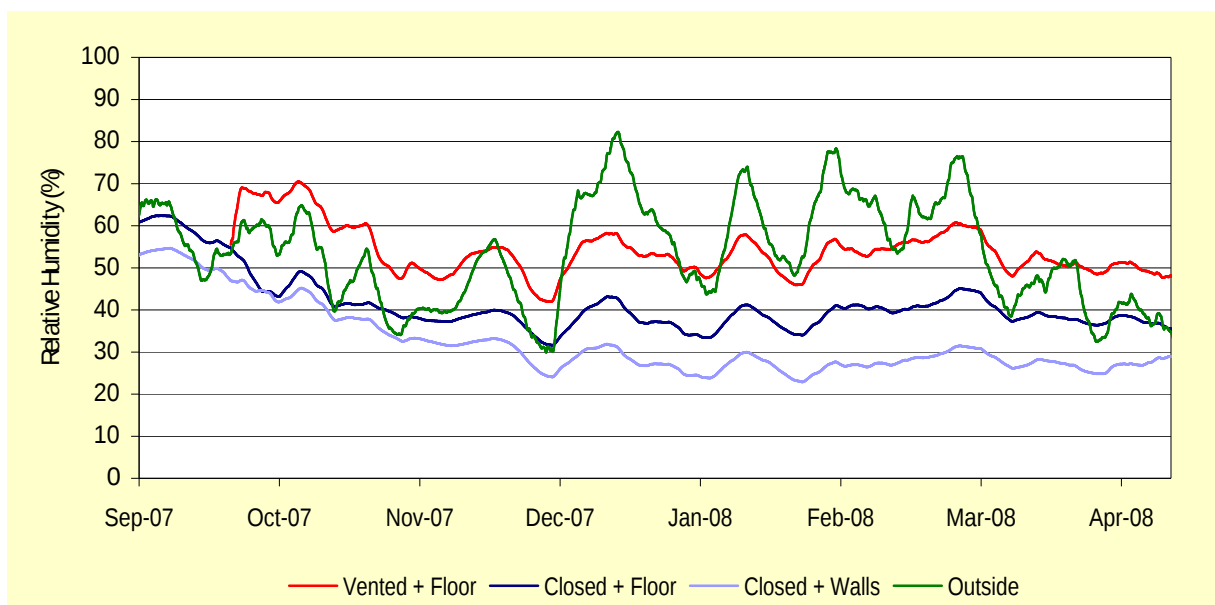


Figure 38. Flagstaff – Daily crawl space and outdoor relative humidity by group.

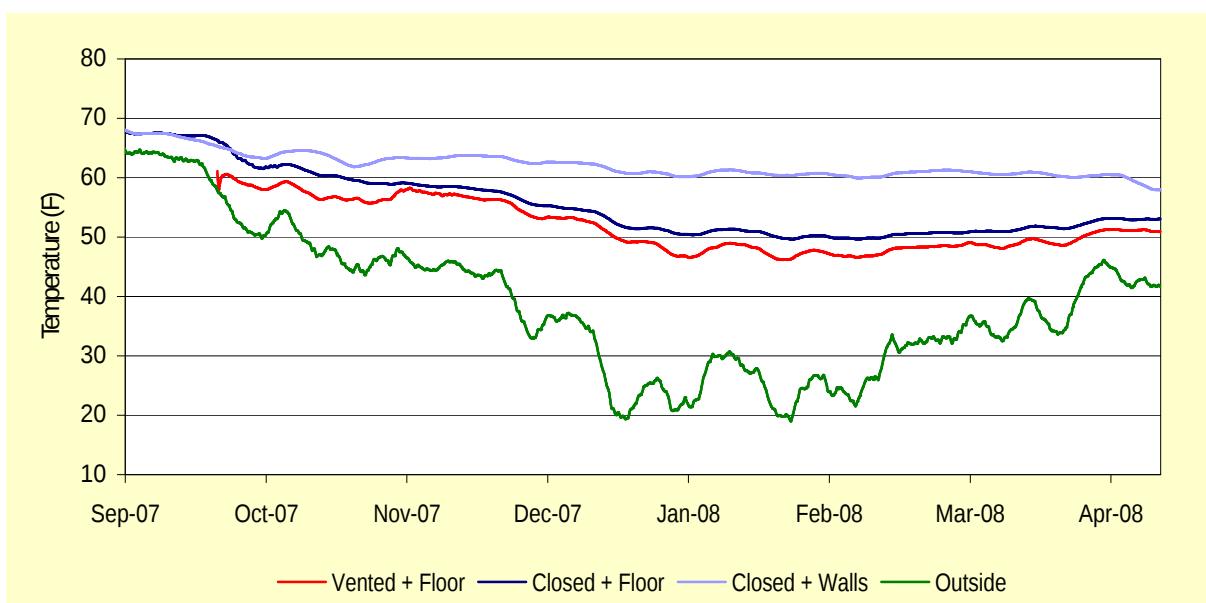


Figure 39. Flagstaff - Daily crawl space and outdoor temperature by group.

4.6 FLAGSTAFF LIVING SPACE TEMPERATURE AND HUMIDITY

Figure 40 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.

4. RESULTS

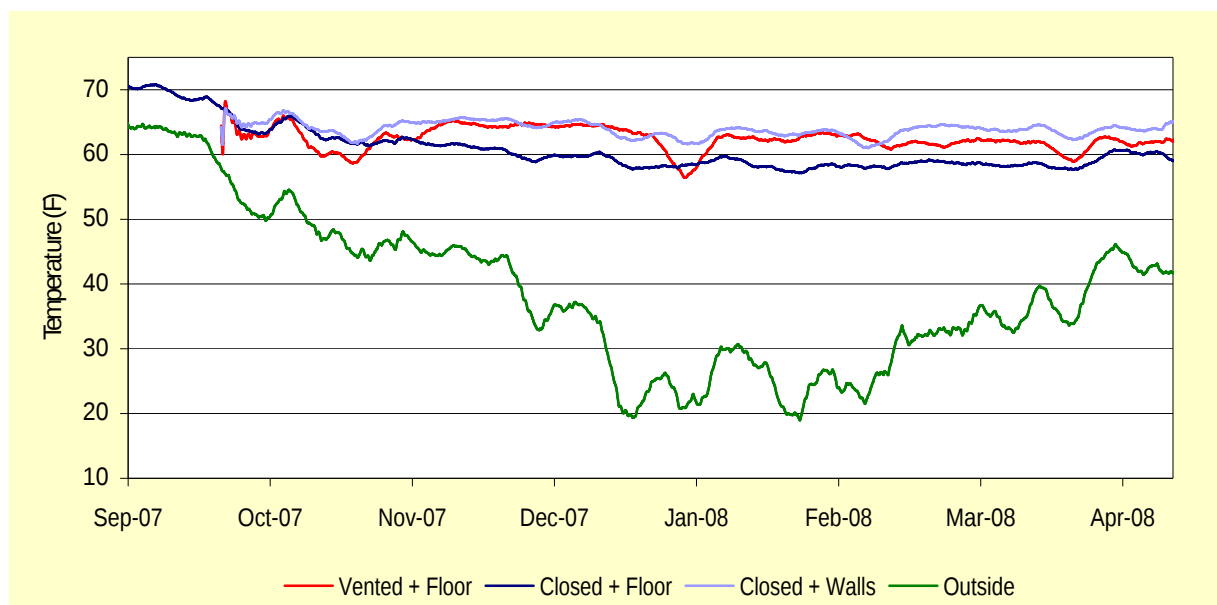


Figure 40. Flagstaff – Daily indoor temperature by group.

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 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 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 energy reading of the previous month is then subtracted from the interpolated cumulative reading to determine the energy use for a given month. 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 (one to two kWh per day max, which is roughly five percent of the total electric use of the homes). Figure 41 and Figure 42 show the main gas meter readings and furnace gas meter readings, respectively, for the groups.

The abbreviations listed in bold text below represent the corresponding system descriptions in the tables and figures below:

1. **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)
2. **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)
3. **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)

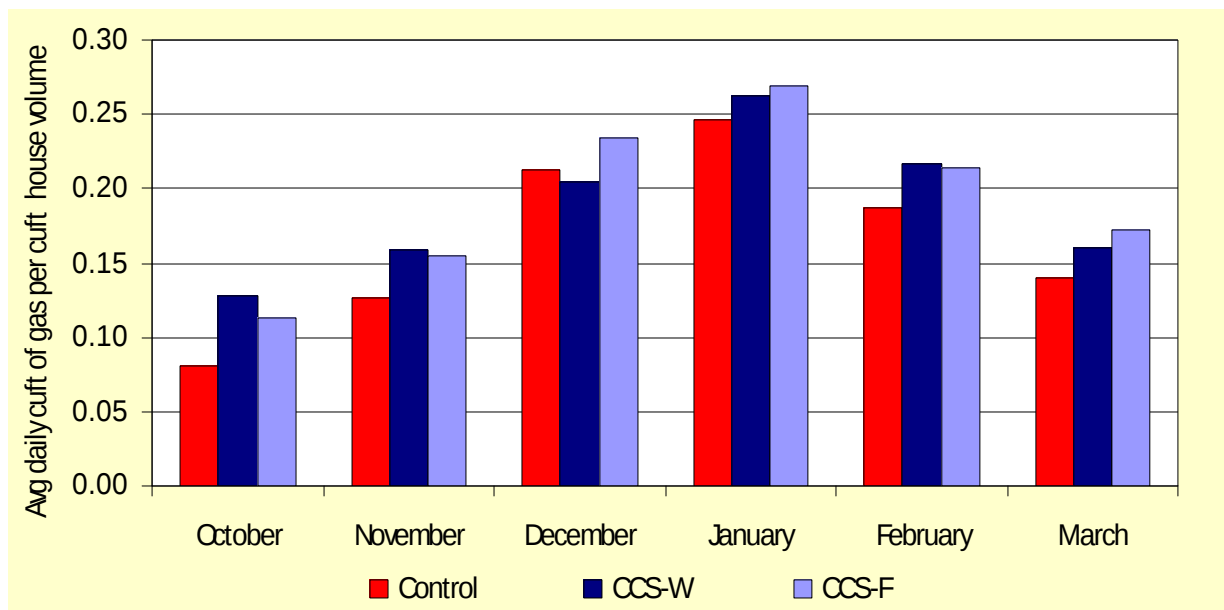


Figure 41. Flagstaff – Main gas meter readings across the three groups, October 2007 through March 2008.

4. RESULTS

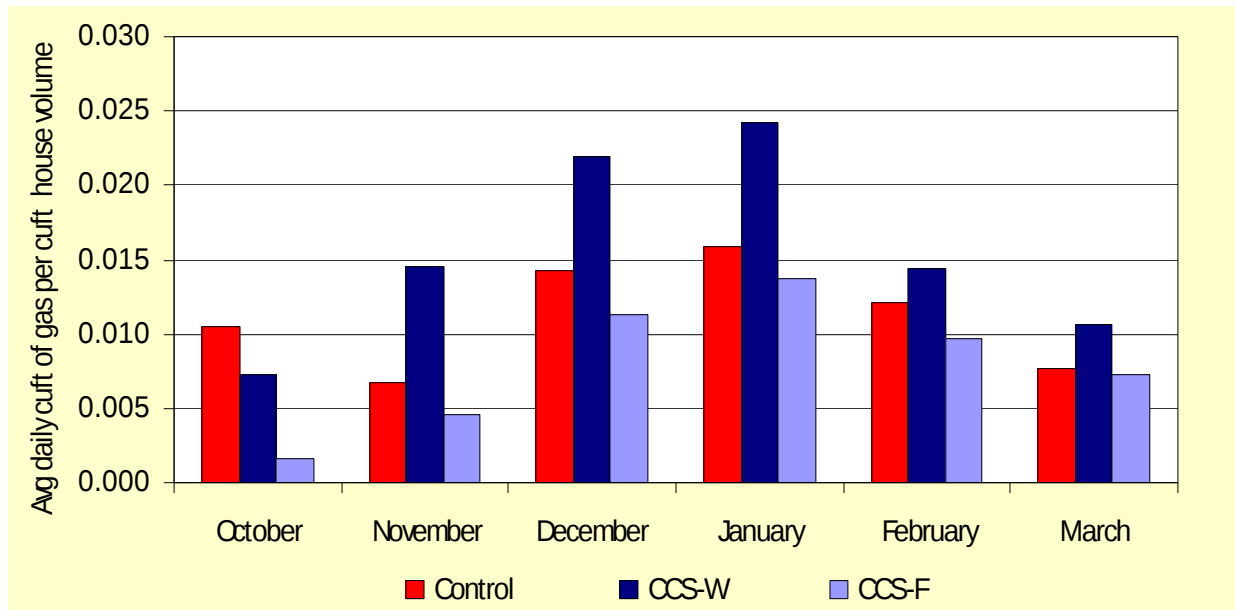


Figure 42. Flagstaff – Gas furnace sub-meter readings across the three groups, October 2007 through March 2008.

The data presented in Figure 42 indicate the closed crawl space systems with floor insulation appear to have used 20 percent less gas 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 53 percent more gas for heating as compared to that of the control homes. The analysis is more uncertain for the wall-insulated group due to the failure of several gas meters during the first two months of the monitoring period, but it is clear 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 43. 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 44. Both graphs are also adjusted for the volume of the homes.

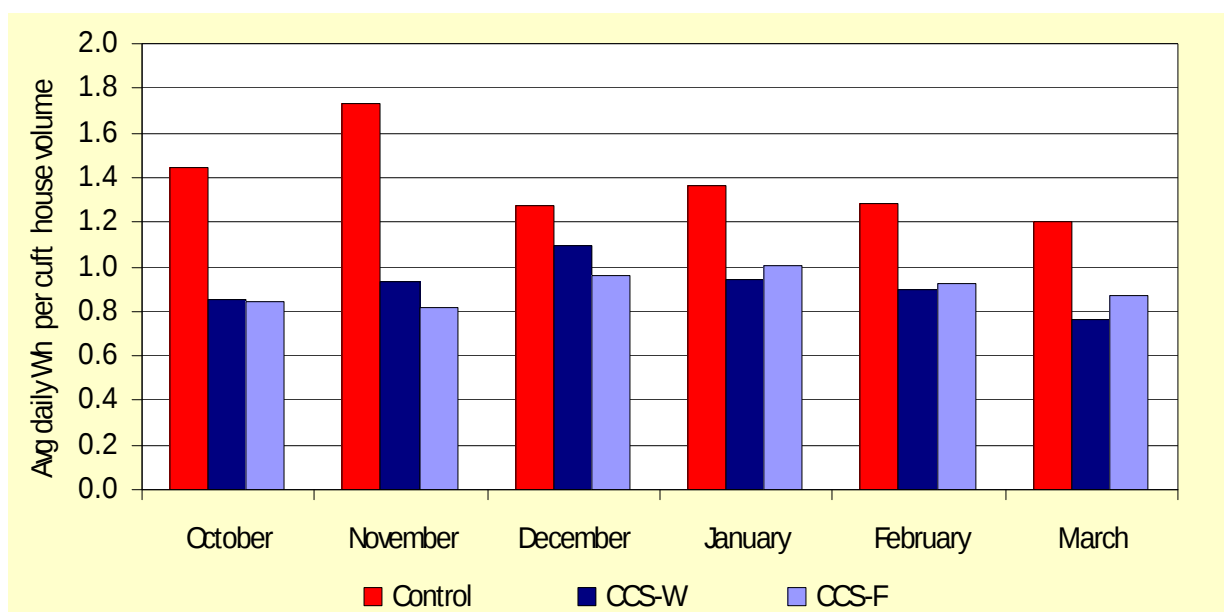


Figure 43. Flagstaff – Total average electricity use of homes in each group, October 2007 through March 2008.

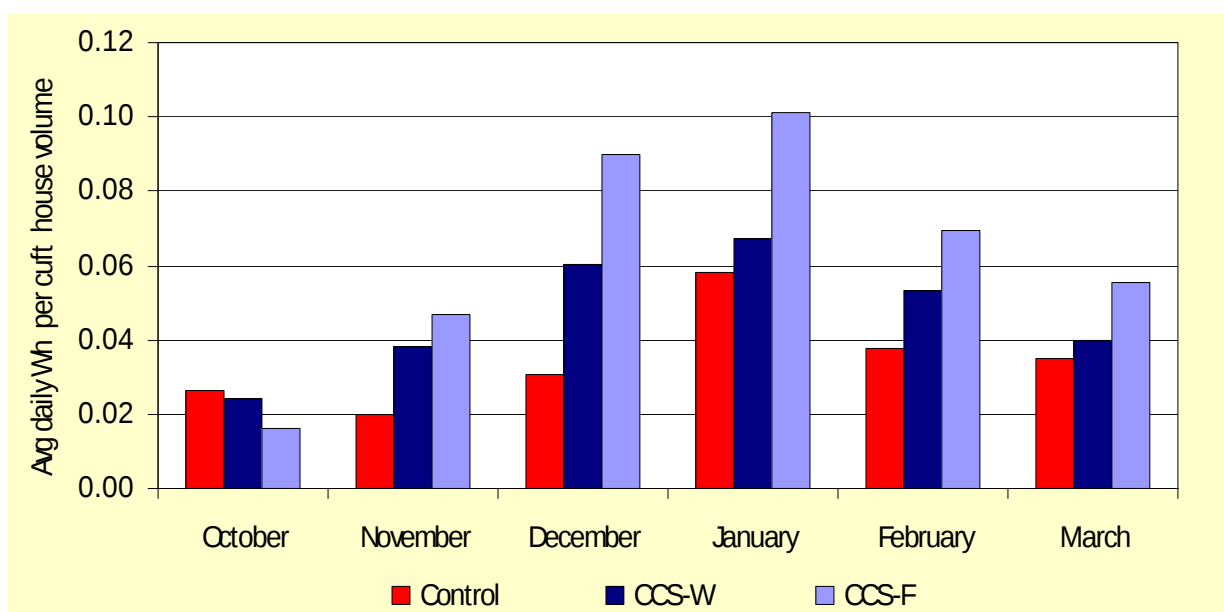


Figure 44. Flagstaff – Electricity used to run the heating distribution system, October 2007 through March 2008 (outliers removed due to potential faulty meters).

In Figure 44 above, three houses were excluded from the analysis because no electricity was registered for the entire study due to faulty meters. The houses excluded are lots 71 (CCS-F), 47 (Control), and 61 (Control). The significantly higher electrical usage of the air handlers in the floor-insulated closed crawl space group indicates excess fan usage by the occupants, given that the gas usage for those same homes was significantly lower than that of the control group homes. Due to these sources of error, conclusions on furnace electrical energy use in Flagstaff are not reliable.

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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 homeowner-controlled 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 14 and Table 15, respectively.

Table 14 . 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 15. 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	2.3	1.2
CCS-F	12.9	4.1
CCS-W	12.6	3.4

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 16. The crawl space foundations that were originally closed now have lower crawl space radon concentrations than the control foundations, as shown in Table 17. 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 Table 18 and Table 19 below. 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 16. 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 17. Flagstaff – Short-term group averages for radon levels in crawl spaces after opening crawl space vents.

Foundation Type	Crawl (pCi/L)
CTL (vented crawl space with no vapor retarder)	1.8
LINER (CCS-F* and CCS-W + F*)	1.2

4. RESULTS

Table 18. 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 19. 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)	1.5
LINER (CCS-F* and CCS-W + F*)	1.1

4.9 ENERGY MODELING PROGRAM ASSESSMENT

4.9.1 Baton Rouge

The Baton Rouge homes are more likely to have distinct differences between the research groups than the Flagstaff homes. This is due to the very consistent nature of the homes – having very slight variations between each of the simple floor plans.

Results from modeling the homes can be seen in Figure 45 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 programs (i.e., do the models predict a savings or penalty for the different designs?).

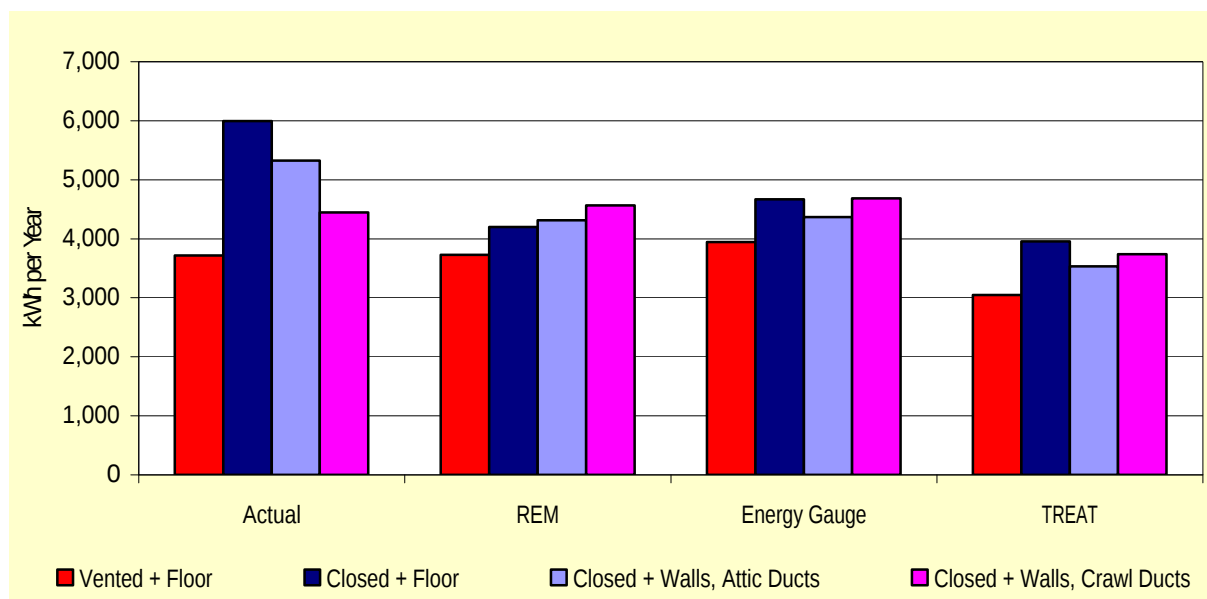


Figure 45. Modeled energy use versus actual energy use across the four groups in Baton Rouge.

Another way to view the same information is to combine the crawl space groups together for each of the energy use methods. Figure 46 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.

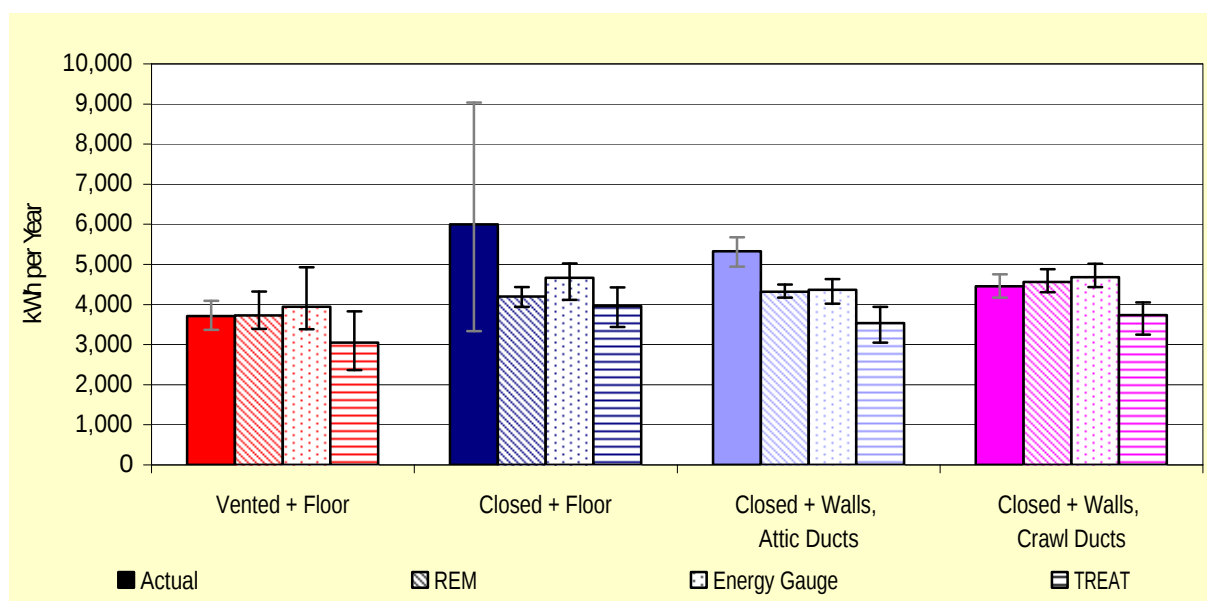


Figure 46. Actual versus predicted energy use for each of the crawl space design groups in Baton Rouge.

Table 20 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.

4. RESULTS

Table 20. Actual and Modeled energy use with percent differences between groups and modeling software.

Group	Software	Heating/Cooling			Total Energy		
		Energy (kWh/yr)	Difference from Vented	Difference from Actual	Energy (kWh/yr)	Difference from Vented	Difference from Actual
CTL	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%
CCS-F	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%
CCS-WA	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%
CCS-WC	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 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 intake in the return box. This may be the reason 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 47 and Figure 48 show the electricity and gas energy predictions from the modeling programs for space conditioning.

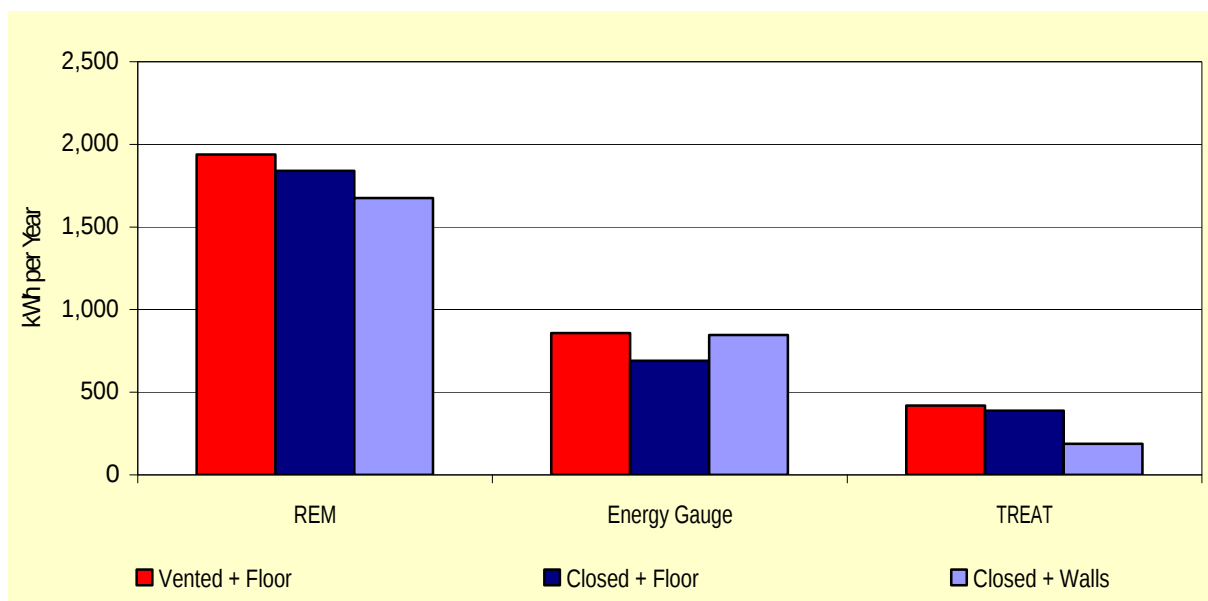


Figure 47. Predicted space conditioning electricity use for each of the modeling programs.

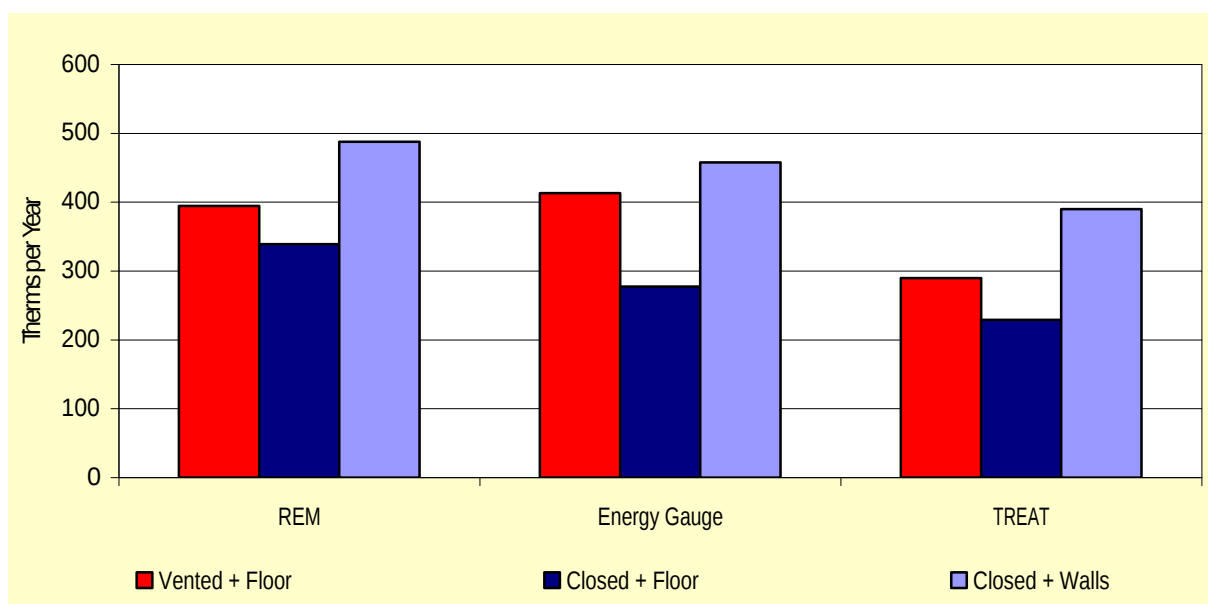


Figure 48. Predicted space conditioning gas use for each of the modeling programs.

5. DISCUSSION

5.1 BATON ROUGE FIELD STE

The improvement of humidity control in the Baton Rouge closed crawl spaces was robust and occurred very quickly after installation of the systems. 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. 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.

While humidity control in the closed crawl spaces was far better than in the vented crawl spaces, conditions in the living space were consistently good across all groups. Daily average relative humidity was roughly 60 percent from late spring through summer and into fall. From late fall, through winter and into spring, indoor daily average relative humidity ranged from 40-60 percent.

The estimated annual impact of the closed crawl space systems on energy used for heating and cooling, based only on the electric meter data, was as follows:

- a 29 percent penalty for the floor-insulated closed crawl space with supply ducts in the attic (CCS-F),
- a 20 percent penalty for the wall-insulated closed crawl space with supply ducts in the attic (CCS-W-A), and
- a 6 percent savings for the wall-insulated closed crawl space with supply ducts in the crawl space (CCS-W-C).

These estimates create a conundrum for interpretation. If the 29 percent penalty can be taken as the accurate impact on heating and cooling energy use of the installation of the liner system with a crawl space supply duct (CCS-F), then the relocation of the insulation to the perimeter wall (CCS-W-A) would be responsible for an approximately 9 percent change (improvement from a 29 percent penalty to a 20 percent penalty). Then the relocation of the ducts from the attic to the crawl space (CCS-W-C, with significant additional duct leakage) would have to be responsible for another 26 percent change in annual heating and cooling energy savings (improvement from a 20 percent penalty to a 6 percent savings). This does not seem feasible, so there should be exploration of other factors that may significantly affect the interpretation of the energy meter data.

First, consider the higher space-conditioning energy consumption of the homes with closed crawl space systems and mechanical supply ducts in the attic as compared to the control homes. Several observations from the temperature and humidity data indicate that these homes should decrease the energy needed for space conditioning, but that occupant behavior may be overwhelming those factors. The crawl space temperatures are 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. To some extent, these temperatures are also being influenced by the crawl space being air sealed and having a small supply duct installed for drying during the humid seasons. The drier conditions in the closed crawl spaces also means that any return duct leakage puts a lower latent load on the mechanical system during cooling periods, though again the drier conditions are partially due to the presence of the supply duct in the closed crawl space.

With regard to occupant behavior, researchers only monitored temperature and humidity in the central return as an indicator of conditions in the living space. 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. These variations would certainly increase the energy used for cooling compared to the control homes, and may only be partially accounted for by our data adjustment method. The variances in seasonal changes in heating and cooling usage from group to group also suggest significant operational differences that may skew the results. Finally, there were significant differences in other internal loads due to occupancy, lighting, and appliance operation that were not formally assessed in this project.

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 of equipment and, as package-unit systems, the factory-installed refrigerant 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 six percent greater floor area than the controls. Furthermore, in the summer of 2008, these homes outperformed the control homes despite having interior temperatures that were an average of two degrees F cooler than those of the control homes.

With 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 homes in flood-prone locations, upgrading to a closed crawl space may provide this additional benefit if applied to existing homes in such locations.

5.2 FLAGSTAFF FIELD STE

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 water intrusion into crawl space foundations is a problem. Although not intended to address liquid water problems, the closed crawl space liner offers a significant level of protection from any bulk water that would make its way past the foundation wall.

In contrast to the humidity performance pattern in Baton Rouge and in previous work in North Carolina, the moisture load inside the Flagstaff vented crawl spaces does not appear to follow the outside dew point. This is likely the result of the lack of ground vapor retarder in the vented crawl spaces 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. 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. In Flagstaff’s dry climate even the control crawl spaces stayed under 70 percent daily average relative humidity for all but a few days, but the closed crawl spaces were even drier, with levels around 50 percent under the same conditions.

Measurements from the floor-insulated closed crawl space group indicated significant energy savings, with a measured reduction in gas used for space heating of 20 percent. However, some uncertainty in this result must be acknowledged due to variables in the home characteristics. On average, the homes with

5. DISCUSSION

floor-insulated closed crawl spaces had lower total glazing area (48 square feet, or 13 percent) and greater east- and west-facing glazing area (13 square feet, or nine percent) than the homes in the control group. These variations would be expected to reduce the energy needed for heating, meaning that not all the 20 percent reduction in gas usage should be attributed to the closed crawl space configuration. On the other hand, the closed crawl space homes had lower performance with regard to envelope leakage (0.03 cubic feet per minute per square foot envelope area at 50 pascals, or 19 percent) and duct leakage (minimally higher) than the control homes. Those variations would be expected to increase the energy needed for heating. Furthermore, although interior temperatures were not used in energy calculations, there may be potential experimental bias due to occupant behavior. Interior temperature measurements were recorded by a sensor in the return grill, which may have allowed cool air from the outdoor air intake to create falsely low readings. Researchers also did not survey residents for potential fireplace use, which could offset some of the natural gas use for heating and yet not be detected by the indoor temperature sensor.

Measurements from the wall-insulated closed crawl space group indicated a large energy penalty, with a measured increase in gas used for space heating of 53 percent. While there is large uncertainty in this result due to a small data set, it is clear that closed crawl spaces in such a cold climate zone should have their thermal insulation located in the framed floor structure above the crawl space, not on the perimeter wall.

Besides the potential for energy savings, one benefit researchers expected from the closed crawl space systems in Flagstaff was warmer temperatures in the crawl space and thus improved freeze protection for plumbing. The data indicate warmer conditions, but only by approximately 10 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.

Finally, the radon measurements in the closed crawl space homes indicate the importance of testing for radon in homes, even when the US EPA radon map does not indicate a high risk level. With regard to closed crawl spaces, the reduction in crawl space ventilation is sufficient to allow radon to accumulate far in excess of the EPA action level. While the crawl space liner material itself can effectively block radon, the remaining penetrations in the liner (especially the exposed masonry areas at the top of the perimeter walls and support piers) provide paths for radon to continue entering the crawl space from the soil. The EPA does not recommend testing for radon in crawl spaces, but these study results show that testing for radon in a closed crawl space can expose an elevated risk of radon entering the living space.

5.3 ENERGY MODELING PROGRAM ASSESSMENT

5.3.1 Baton Rouge

From Figure 45 it can be seen that none of the modeling programs are able to predict the rank order 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 46 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 energy use in Figure 46, 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.

One way to interpret the percent differences in Table 20 is to convert the error term into a dollar amount. For a house using 5,000 kWh per year for heating and cooling (the approximate average used by the homes in this project), a 10 percent error in estimating the energy use will result in a \$50 change in annual energy cost to the homeowner (using \$0.10 per kWh, the 2008 average cost for electricity in LA reported by the U.S. Energy Information Administration).

5.3.2 Flagstaff

Without a full year of heating and cooling data, a comparison of the relative accuracies in the modeling programs is not possible. However, some of the shortcomings of the modeling programs 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 programs, 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 zero electricity load for heating. When looking at gas predictions for space conditioning, however, the estimates are fairly consistent across modeling programs. TREAT still has a pattern of having a lower estimate for energy use compared to the other two programs.

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 to the earth in the heating season. These predictions appear to indicate 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 RESEARCH HYPOTHESES

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

- In the very humid Baton Rouge climate, the closed crawl space systems were able to control crawl space relative humidity close to 60 percent on a daily average, while the control group humidity hovered around 80 percent for most of the spring and summer months.
- In Flagstaff's dry climate even the control crawl spaces stayed under 70 percent for all but a few days, but the closed crawl spaces were even drier, with levels around 50 percent 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 percent 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 does not support the hypothesis, indicating a range of performance from a 6 percent savings to a 29 percent penalty across the three systems. However, there is significant uncertainty in these estimates. Living space and crawl space temperature comparisons support a conclusion that thermal loads from the floor are lower in the homes with closed crawl space foundations, and it appears that confounding occupant behavior variables had a greater influence than the foundation system improvements.
- In Flagstaff, the performance of the closed crawl space system with floor insulation supports the hypothesis, showing a savings of 20 percent in heating season gas usage, while the performance of the closed crawl space system with wall insulation does not support the hypothesis, showing a large penalty of 53 percent.

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

- In Baton Rouge, REM/Rate and EnergyGauge do a very good job of predicting 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. TREAT consistently underestimates the energy usage across all study groups. The modeling results for the floor-insulated closed crawl space group have the most uncertainty.
- In Flagstaff, the even smaller data set due to meter failures and truncated study period raises too much uncertainty to draw any conclusions about the performance of the modeling programs.

6.2 IMPLICATIONS FOR FUTURE RECOMMENDATIONS AND REQUIREMENTS

The Baton Rouge study results provide strong support for the application of closed crawl space systems as a humidity control method for crawl spaces under homes in the hot-humid U.S. climate zone, and the results provide even stronger support for wall-insulated closed crawl spaces, which provide energy savings in addition to humidity control.

The Flagstaff results provide support for the application of floor-insulated closed crawl space foundations in cold climates, both as a moisture control and energy-saving home improvement, while indicating that wall-insulated closed crawl spaces should not be recommended in cold climates due to a significant energy penalty.

Regardless of climate zone, contractors or occupants who install closed crawl space systems should perform testing to confirm the absence of a radon hazard whenever crawl space ventilation to the outside is eliminated. Any recommendations or requirements to install closed crawl space foundations should include requirements for radon testing and, if indicated, mitigation.

In areas of elevated radon risk, it should 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 such homes, since homes with basement or slab foundations would likely be more expensive to remediate. Slab and basement foundations may also put the residents at higher risk due to supporting occupancy in the parts of the home where the radon is entering the structure.

6.3 RECOMMENDED FUTURE RESEARCH

The study team recommends 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 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 and code requirements.

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 generally lower first cost and crawl space (or “raised floor”) foundations which utilize renewable resources and can offer improved flood protection but which 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

6. CONCLUSIONS

accompanied by improved ventilation, residential radon exposure is an issue that deserves renewed attention.

7. REFERENCES

Davis, B., Dastur, C., Warren, W. "A Field Study Comparison of the Energy and Moisture Performance Characteristics of Ventilated Versus Sealed Crawl Spaces in the South." U.S. Department of Energy Instrument # DE-FC26-00NT40995. June 22, 2005.

Dastur, C., Carter, A., Hannas, B. "Closed Crawl Space Performance: Proof of Concept in the Production Builder Marketplace" Phase I Technical Report, U.S. Department of Energy Information Bridge: www.osti.gov/servlets/purl/924882-oSWYXy/

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APPENDIX A – UNADJUSTED ENERGY USE TABLES FOR BATON ROUGE

The following tables are the raw group averages for energy used in the homes. Due to homeowner behavior, an adjustment factor was calculated and incorporated into the tables found in Section “4.3 Baton Rouge Energy Consumption beginning” on page 47. For reference, the unadjusted tables are presented here. The correspondence between the original tables and the following tables are:

- Total energy use is Table 7 on page 51 and Table 21 below
- Base load energy use is Table 8 on page 51 and Table 22 below
- Heating/cooling energy use with indoor temperatures is Table 9 on page 52 and Table 23 below
- Heating/cooling percent differences of energy use is Table 10 on page 52 and Table 24 below

Table 21 . Baton Rouge – Unadjusted energy use and percent differences from Control for total energy use by group. Positive percentage is energy penalty and negative percentage is energy savings.

Period of Use	Total Energy (kWh/day)				Percent Differences			Notes*
	CCS F	CCS W/A	CCS W/C	Control	CCS F	CCS W/A	CCS W/C	
June 2007	44.7	40.8	42.9	31.3	42.9%	30.4%	37.1%	Baseline
July 2007	47.7	41.6	44.7	35.0	36.2%	18.7%	27.6%	Baseline
August 2007	47.0	42.2	42.3	35.2	33.5%	19.7%	20.0%	Intervention
Summer 2007	46.5	41.5	43.3	33.9	37.3%	22.6%	27.8%	Base/Inter
Fall 2007	37.9	37.1	33.2	28.6	32.3%	29.6%	15.8%	
Winter 2007-08	35.5	37.7	27.1	25.6	38.8%	47.6%	6.1%	
Spring 2008	36.7	44.9	28.1	23.9	53.9%	88.3%	17.9%	
Summer 2008	46.7	60.5	37.0	30.3	53.9%	99.3%	22.0%	
Annual comparison	39.2	45.1	31.4	27.1	44.7%	66.5%	15.8%	
Annual difference	12.1	18.0	4.3	n/a				

* Base = baseline month and Inter = intervention installed during first two weeks of August

APPENDIX A – Unadjusted energy use tables for Baton Rouge

Table 22. Baton Rouge – Unadjusted energy use and percent differences from Control for base load energy use by group. Positive percentage is energy penalty and negative percentage is energy savings.

Period of Use	Base Load Energy (kWh/day)				Percent Differences			Notes*
	CCS F	CCS W/A	CCS W/C	Control	CCS F	CCS W/A	CCS W/C	
June 2007	22.3	20.4	20.1	16.0	39.3%	27.3%	25.3%	Baseline
July 2007	22.0	18.8	18.9	15.9	38.4%	18.9%	19.2%	Baseline
August 2007	21.0	18.7	18.5	16.7	26.1%	12.2%	10.9%	Intervention
Summer 2007	21.8	19.3	19.1	16.2	34.4%	19.3%	18.3%	Base/Inter
Fall 2007	21.9	22.1	20.2	17.1	28.1%	28.8%	17.7%	
Winter 2007-08	24.4	28.8	18.8	17.4	39.9%	65.4%	7.9%	
Spring 2008	22.4	33.8	19.4	16.7	33.8%	101.6%	15.7%	
Summer 2008	21.5	36.1	16.8	15.5	38.8%	133.5%	8.7%	
Annual comparison	22.5	30.2	18.8	16.7	35.1%	81.1%	12.6%	
Annual difference	5.9	13.5	2.1	n/a				

* Base = baseline month and Inter = intervention installed during first two weeks of August

Table 23. Baton Rouge – Unadjusted heating and cooling energy use (average kWh per day) with average indoor temperatures per group.

Period	Heating and Cooling Energy (kWh/day)				Indoor Temperature (degree F)				Avg Out. Temp	Notes*
	CCS F	CCS W/A	CCS W/C	Cont	CCS F	CCS W/A	CCS W/C	Cont		
June	22.4	20.4	22.8	15.3	-	-	-	-	82	Baseline
July	25.7	22.7	25.8	19.1	-	-	-	-	82	Baseline
August	26.0	23.5	23.8	18.6	68	71	71	74	86	Intervention
Summer 2007	24.7	22.2	24.1	17.7	-	-	-	-	83	Base/Inter
Fall	16.0	15.0	13.0	11.5	68	71	71	74	70	
Winter	11.1	8.9	8.3	8.2	70	71	71	70	56	
Spring	14.3	11.2	8.8	7.1	69	71	72	71	69	
Summer 2008	25.2	24.3	20.2	14.9	71	72	73	75	82	
Annual average	16.7	14.9	12.6	10.4						
Annual comparison	6.3	4.5	2.2	n/a						

* Base = baseline month and Inter = intervention installed during first two weeks of August

APPENDIX A – Unadjusted energy use tables for Baton Rouge

Table 24. Baton Rouge – Unadjusted heating and cooling percentage difference comparison. Positive percentage is energy penalty and negative percentage is energy savings.

Period of Use	Heating and Cooling Energy Percent Differences			Notes*
	CCS-F	CCS-WA	CCS-WC	
June 2007	46.7%	33.6%	49.5%	Baseline
July 2007	34.3%	18.6%	34.6%	Baseline
August 2007	40.2%	26.5%	28.3%	Intervention
Summer 2007	39.9%	25.6%	36.5%	Base/Inter
Fall 2007	38.6%	30.8%	12.9%	
Winter 2007-08	36.3%	9.7%	2.3%	
Spring 2008	100.9%	57.0%	23.1%	
Summer 2008	69.6%	63.7%	35.9%	
Annual comparison	60.1%	43.1%	20.9%	
* Base = baseline month and Inter = intervention installed during first two weeks of August				

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