Closed Crawl Spaces: From the Mississippi to the Ponderosa, Impacts on Humidity, Energy and Radon

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ABSTRACT

This paper presents a three-year research project on residential crawl space foundations, expanding on previous research by investigating the impact of closed crawl spaces on production homes in various climate zones. Researchers studied two sets of newly constructed homes: 15 modular homes in hot, humid Baton Rouge, La. and 12 stick-framed homes in cold, dry Flagstaff, Ariz. They divided the homes at each site into control and intervention groups. The control homes at each site had wall-vented crawl spaces built in compliance with local code. The intervention homes had air-sealed foundation vents, a sealed vapor retarder on the crawl space ground and walls, and insulation located either on the foundation wall or in the framed floor above. Researchers logged humidity and energy for 12 months in Baton Rouge. In Flagstaff, researchers logged humidity and energy data for 6 months, after which the intervention crawl spaces were re-vented due to elevated radon concentrations. In Baton Rouge, average daily relative humidity (RH) in the vented crawl spaces often exceeded 80 percent, while the closed crawl spaces barely exceeded 60 percent. In Flagstaff, RH in the vented crawl spaces remained less than 70 percent RH, but the closed crawl spaces never exceeded 50 percent RH. In hot, humid Baton Rouge, locating the HVAC ductwork in a wall-insulated closed crawl space provided energy savings, while in Flagstaff, only homes with a floor-insulated closed crawl space showed energy savings. Finally, closed crawl spaces proved to be similar to basement foundations with regard to radon impacts, exceeding action thresholds in Flagstaff. The findings support EPA recommendations to test all homes for radon.

Introduction

Research conducted throughout the last decade indicates that closed crawl spaces are a great moisture control strategy and can also save energy, depending on the placement of the insulation and location of the distribution ductwork.

An earlier demonstration project occurred in Princeville, N.C. where closed crawl spaces stayed substantially drier than wall-vented crawl spaces during humid seasons, with average daily RH controlled less than 70 percent. Additionally, homes built on closed crawl space foundations saved, on average, more than 15 percent of annual energy used for heating and cooling (Davis, Dastur & Warren 2005). The homes in Princeville were small, one-story Habitat for Humanity homes of simple design located in a mixed humid climate zone as defined by the Department of Energy Building America Program (USDOE 2007).

The current project described in this paper aimed to evaluate whether the same scale of energy and moisture performance improvements would result from the application of closed crawl spaces to larger, more complex homes typically built by production builders, and to assess that performance in two additional climate zones – hot, humid Baton Rouge, La.; and cold Flagstaff, Ariz.

The project's research hypotheses were:

1. Closed crawl space systems will control daily average RH 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.

As in the Princeville project, researchers also evaluated radon levels in all of the homes. Radon is an odorless, colorless gas that is the second leading cause of lung cancer in the United States, resulting in more than 20,000 deaths per year. For these reasons, the U.S. Surgeon General and the Environmental Protection Agency (EPA) recommend that all homes be tested for radon (EPA 2009). Similar to a short basement, the decreased ventilation inside a closed crawl space may cause radon levels to increase, requiring an appropriate mitigation system. The EPA recommends that all homes with radon concentrations of 4 picocuries per liter (pCi/L) or greater in the lowest lived-in level of the house be mitigated (EPA 2009).

Experimental Design

Researchers from Advanced Energy conducted the project at two sites: 15 new modular homes built in one neighborhood in Baton Rouge, La, and12 new stick-framed homes in one neighborhood in Flagstaff, Ariz. To reduce variability, all of the homes were built to meet ENERGY STAR® program standards, which included third-party quality assurance during construction and performance testing for envelope and duct leakage. Homes were assigned to control and intervention groups such that the groups had comparable above-grade wall areas, window areas and insulating features. In both Baton Rouge and Flagstaff, control groups consisting of code-compliant wall-vented crawl space homes were compared to homes with "closed" crawl spaces foundations. The closed crawl spaces included the following key design components:

1. A ground vapor retarder with sealed seams covering 100 percent of the crawl space floor.
2. A mechanically secured vapor retarder covering the interior of the 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 with a humid season.

Baton Rouge

Baton Rouge is located in a hot, humid climate as defined by the U.S. Department of Energy Building America Program (USDOE 2007). Moisture control is of particular concern, and the predominantly hot climate presents opportunities for energy savings.

The field site consisted of 15 single-story modular homes of similar size and footprint. The site was flat, with all crawl spaces approximately 2 feet high. Space conditioning for all homes was provided by the same make and model of package-unit heat pump. The heat pump was located outside of each home with the main supply and return trunks running into the crawl space. In 12 of the homes, the supply trunk turned up through a central chase, and the distribution ducts were installed in the attic. The remaining three homes had distribution ducts in the crawl space. In the closed crawl spaces, researchers installed a small supply duct that delivered conditioned air to the crawl space whenever the HVAC system was running. The closed crawl space systems for Baton Rouge were installed in the 11 intervention homes during the week of August 9 through August 16, 2007.

The control homes (CTL) in Baton Rouge consisted of four code-compliant wall-vented crawl spaces with R-19 subfloor insulation and standard 6-mil ground vapor retarder (seams not sealed), covering 100 percent of the earth floor.

The Baton Rouge site tested three configurations of closed crawl space:

- Four homes with R-19 fiberglass batts in the subfloor and ductwork in the attic (CCS-F).
- Four homes with R-8 polyisocyanurate foam board on the foundation walls and ductwork in the attic (CCS-W-A).
- Three homes with R-8 polyisocyanurate foam board on the foundation walls, and ductwork in the crawl space (CCS-W-C).

Homes were located in close proximity, on two adjacent streets in the same neighborhood. The homes were assigned to the control and intervention groups in order to balance the impact of differing floor area, glazing area and solar orientation (Table 1). The homes were performance tested to ensure there was no significant bias toward the research groups with regard to envelope leakage, duct leakage and mechanical ventilation rates (Table 2). As a whole, these characteristics indicated the research groups may be slightly biased toward using more energy for heating and cooling than the control group. This was 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.)
CTL	1144	9152	3456	183	78
CCS-F	1196 (4%)	9568 (5%)	3616 (5%)	186 (2%)	81 (5%)
CCS-W-A	1196 (4%)	9568 (5%)	3592 (4%)	183 (0%)	78 (0%)
CCS-W-C	1213 (6%)	9707 (6%)	3653 (6%)	185 (1%)	80 (3.2%)

Note: Numbers in ( ) indicate the percentage difference between the intervention groups and CTL group

Table 2. Baton Rouge building performance characteristics by group

Crawl Space Type	House Leakage Ratio (CFM50 per Sq. Ft. Envelope Area)	Duct Leakage Ratio (CFM25 per Sq. Ft. Floor Area)	Ventilation Rate (CFM)
CTL	0.26	10.1%	18
CCS-F	0.25 (-4%)	8.5% (-16%)	23 (30%)
CCS-W-A	0.27 (3%)	9.5% (-5%)	20 (16%)
CCS-W-C	0.25 (-4%)	12.7% (26%)	24 (37%)

Notes:
1. Numbers in ( ) indicate the percentage difference between the intervention groups and CTL group
2. Intentional outside-air ventilation was provided by a dampered, filtered six inch diameter intake duct connected from outside to the return duct of the air handler. The ventilation occurs only when the air handler is operating.

Flagstaff

Flagstaff is located in a cold climate as defined by the U.S. Department of Energy Building America Program (USDOE 2007). Flagstaff is also very dry, and except for the short "monsoon" season (July through September), 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 humid climates. However, the monsoon season presents short-term water impacts that are anecdotally reported to cause moisture problems in traditional vented crawl spaces in the region. In addition, the cold winters present the opportunity to achieve heating savings.

The Flagstaff site included 12 stick-framed homes of variable sizes and footprints. As in Baton Rouge, all homes were built to meet ENERGY STAR certification requirements, with additional requirements for outside air ventilation and combustion safety. Space conditioning for all homes was provided by a high-efficiency gas furnace (90+ AFUE, direct vented). The furnace was located inside the crawl space along with the air handler and distribution duct work. In Flagstaff's dry climate, researchers decided to test the closed crawl spaces with no active drying mechanism. Crawl space interior heights varied from approximately 3 feet to more than 8 feet in some cases. The closed crawl spaces were installed during construction, between August 2006 and October 2007.

In Flagstaff, the control group (CTL) consisted of four homes with code-compliant wall-vented crawl spaces, R-30 subfloor insulation, and no ground vapor retarder. At that time, local codes did not require foundation waterproofing or ground vapor retarders in vented crawl spaces. It may seem inappropriate to compare homes with and without ground vapor retarders. Our goal was not to compare the impacts of a ground vapor retarder alone, but instead to compare two different complete foundation systems. The reference system represents the common local building practice, which included a vented foundation with no ground vapor retarder. The comparison systems are represented by various closed crawl space designs as described below:

The closed crawl space groups in Flagstaff consisted of the following:

- Four homes with R-30 fiberglass batts in the subfloor. (CCS-F)
- Four homes with R-13 polyisocyanurate foam board on the foundation walls. (CCS-W)

The participating homes were located on three adjacent streets within the same neighborhood. Homes were assigned to the control and intervention groups in order to balance the impact of differing floor area, glazing area and solar orientation. 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 varied (Table 3).

The homes were performance tested to ensure there was no significant bias toward the research groups with regard to envelope leakage, duct leakage and mechanical ventilation rates (Table 4). Note the duct leakage to the 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.

Table 3. 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.)
CTL	2477	24225	6595	366	129
CCS-F	2184 (-12%)	20921 (-14%)	6016 (-9%)	318 (-13%)	141 (9%)
CCS-W	2277 (-8%)	21986 (-9%)	6349 (-4%)	320 (-13%)	121 (-7%)

Notes: Numbers in ( ) indicate the percentage difference between the intervention groups and CTL group

Table 4. Flagstaff Building Performance Characteristics by Group

Crawl Space Type	House Leakage Ratio (CFM50 per Sq. Ft. Envelope Area)	Duct Leakage to Outside Ratio (CFM25 per Sq. Ft. Floor Area)
CTL	0.18	1.2%
CCS-F	0.22 (19%)	1.32% (10.6%)
CCS-W	0.19 (7%)	1.52% (26.7%)

Notes:
1. Numbers in ( ) indicate the percentage difference between the intervention groups and CTL group
2. 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 toward 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. See Figure 5 and the discussion following in the Results section.

Data Collection

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.

Environmental Conditions

At the Baton Rouge site, the close proximity of the homes allowed researchers to use a wireless, Internet-based sensor network as the primary temperature and humidity data acquisition system, and to install HOBO Pros 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 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. Data was recorded for analysis by downloading from a web site. HOBO data served as a quality check.

At the Flagstaff site, researchers recorded indoor temperature and RH 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. Data was recorded by downloading data during quarterly field visits.

At both sites, loggers were set to download and log hourly data. Researchers recorded outside conditions from publicly available weather station data.

Energy

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 were 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. Flagstaff homes were conditioned 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. This design required up to 3 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 (if present), and a gas meter for the furnace. At both sites, energy data was collected on a monthly basis.

Radon

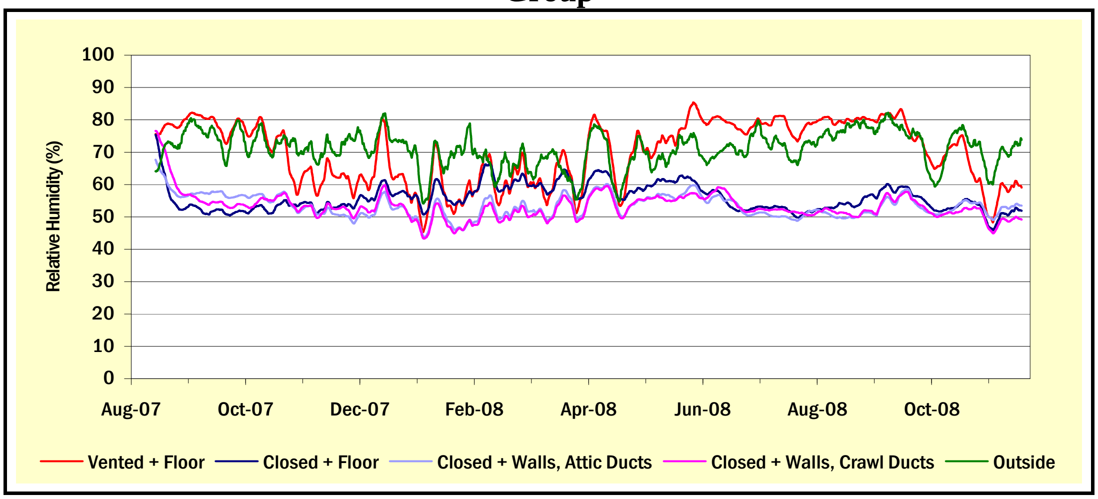
Researchers documented radon concentrations in the living space and crawl space of every home to identify potential radon hazards due to reduced crawl space ventilation. Short-term (vapor diffusion charcoal canister) and long-term (AT-100 alpha-track) radon testers from AccuStar Labs (www.accustarlabs.com) were used to measure radon concentrations. Note that the EPA does not recommend testing radon in crawl spaces, but instead testing in the lowest lived-in level of the home. Researchers decided to test all crawl spaces to assess the worst-case radon levels associated with reduced crawl space ventilation.

Results

Baton Rouge Moisture Performance

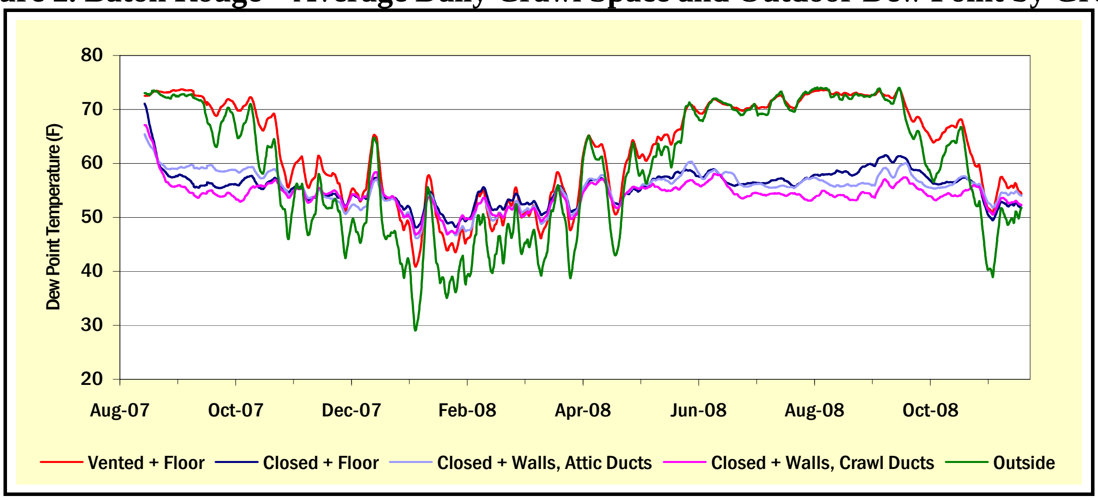
Figures 1 and 2 show, respectively, the RH and dew point temperatures in the crawl spaces during the data collection period. The impact of the initial installation of the closed crawl spaces is visible at the far left. The conditions in the control crawl spaces closely followed outdoor environmental conditions, while all three configurations of the closed crawl space system show a clear decline in dew point and RH. By August 17, RH had dropped to less than 70 percent in the intervention homes. Within a few days, RH dropped to less than 60 percent and remained at that level for the majority of the study.

Figure 1. Baton Rouge – Average Daily Crawl Space and Outdoor Relative Humidity by Group



Note: Key refers to vented or closed configuration, location of insulation (floor or wall), and location of ducts (attic or crawl space).

Figure 2. Baton Rouge – Average Daily Crawl Space and Outdoor Dew Point by Group



Note: Key refers to vented or closed configuration, location of insulation (floor or wall), and location of ducts (attic or crawl space).

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

Baton Rouge Energy

In Baton Rouge, all homes were sub-metered and monitored from June 2007 until August 2008. The closed crawl spaces were installed in August of 2007. During the pre-installation 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. Since the aim was to measure energy performance in occupied homes under real-world conditions, researchers did not ask homeowners to alter their home energy habits.

Upon review, researchers decided to present the heating and cooling energy use with summer and fall values adjusted based on differences in indoor temperatures. Winter and spring seasons were not adjusted, due to a lack of significant difference in indoor temperatures (Table 5). An expanded discussion can be referenced in the final technical report (Dastur, Mauceri & Hannas 2009). Table 5 shows adjusted values for sub-metered energy use for the duration of the data collection period from August 2007, after the closed crawl spaces were installed, to August 2008.

Table 5. Baton Rouge – Summer and Fall Adjusted Energy Use and Percent Differences from Control for Heating and Cooling Energy Use by Group

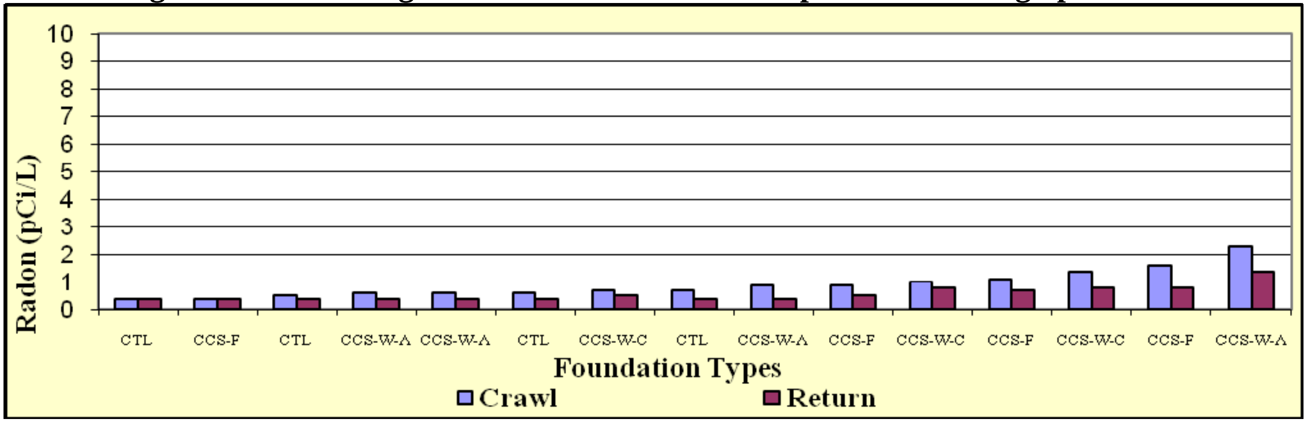
Period of Use	Heating and Cooling Energy (kWh/day)				Percent Differences from Control		
	CCS F	CCS W-A	CCS W-C	Control	CCS F	CCS W-A	CCS W-C
Annual comparison	13.7	12.8	10.0	10.6	**29.0%**	**20.4%**	**-6.2%**

Notes:
1. Summer and fall were adjusted based on indoor temperature differences, while winter and spring seasons were not adjusted. Annual comparison is an average spanning all seasons.
2. Outliers are excluded.
3. Positive percentage is energy penalty and negative percentage is energy savings.

Baton Rouge Radon Results

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, Mass. for analysis. The results in Figure 3 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 EPA has established a mitigation action level of 4.0 pCi/L, with a goal of reducing the concentration to 2.0 pCi/L or less, if mitigation is performed. According to the EPA, national estimates for average indoor radon levels are 1.3 pCi/L and average outdoor radon levels are 0.4 pCi/L (EPA 2009).

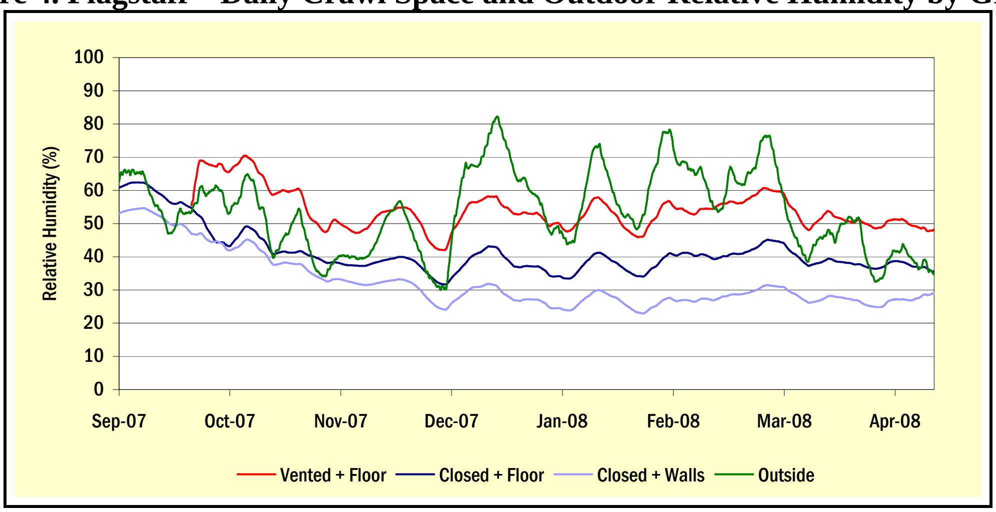
Figure 3. Baton Rouge – Radon Levels in Crawl Spaces and Living Spaces



Flagstaff Moisture Performance

Researchers collected RH data from September 2007 to April 2008 (Figure 4). In Flagstaff's dry climate, humidity levels in the crawl spaces were not a significant concern. The data verified that even in vented crawl spaces with no ground vapor retarder the RH remained less than70 percent; however, the closed crawl spaces performed even better, never exceeding 50 percent RH.

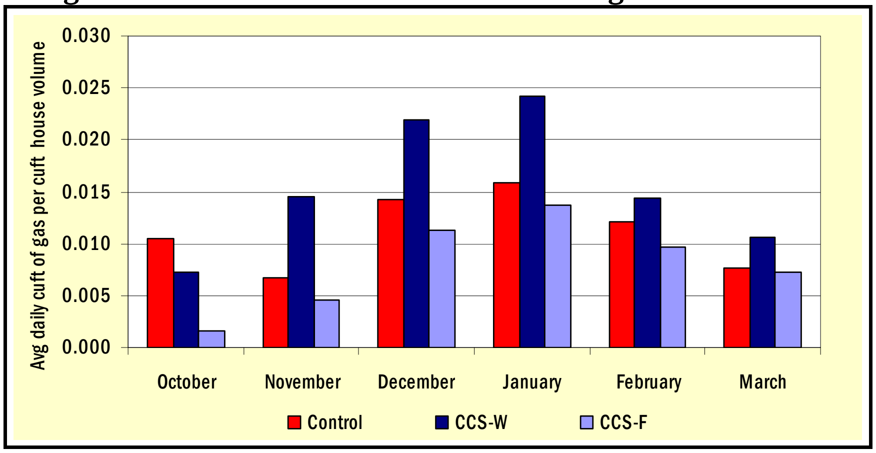
Figure 4. Flagstaff – Daily Crawl Space and Outdoor Relative Humidity by Group



Flagstaff Energy

Construction and occupancy schedules did not allow for pre-intervention energy use data to be gathered at the Flagstaff field site. Therefore, comparisons are made based on direct usage rates normalized by the volume of the home. (Figure 5)

Figure 5. Flagstaff – Gas Furnace Sub-Meter Readings Across the Three Groups



The data presented indicate the homes with floor-insulated closed crawl spaces used 20 percent less gas for space heating as compared to the gas usage for space heating in the control homes. In contrast, the homes with wall-insulated closed crawl spaces 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.

Flagstaff Radon Results

Due to anecdotal reports of elevated radon in Flagstaff, researchers analyzed the long-term testers at 90 days, as soon as valid results could be assessed. This initial radon analysis indicated elevated radon levels (greater than the EPA action level of 4.0 pCi/L) in eight of 12 crawl spaces, ranging from 4.0 to 22.2 pCi/L. The analysis also indicated elevated radon levels in four of the 12 conditioned spaces, ranging from 4.1 to 9.8 pCi/L (Figure 6). The radon levels in the living spaces indicated the need for mitigation. Adding radon mitigation systems was not feasible within the timeline and scope of the project, so researchers decided to discontinue the study and reverted the closed crawl spaces to vented crawl spaces.

After re-venting the crawl spaces and verifying the proper installation of subfloor insulation in homes that originally had wall insulation, radon levels were measured in the crawl spaces with short-term testers to ensure that levels dropped to below the EPA action thresholds. Radon levels dropped to below 2.0 pCi/L in all but one crawl space, which had a radon level of 3.0 pCi/L, still below the EPA action threshold (Figure 7). Homeowners had the option to receive results from long-term alpha-track radon testers installed in the crawl spaces and living spaces (behind the return grill) to confirm that radon levels were below the EPA action threshold. We obtained long-term test results for six of the crawl spaces and eight of the living spaces. The long-term results showed that the highest radon level in a living space was 1.4 pCi/L, with seven of the eight living spaces below 1.0 pCi/L."

Figure 6. Flagstaff: Initial Three-Month Radon Results in the Crawl Spaces and Living Spaces

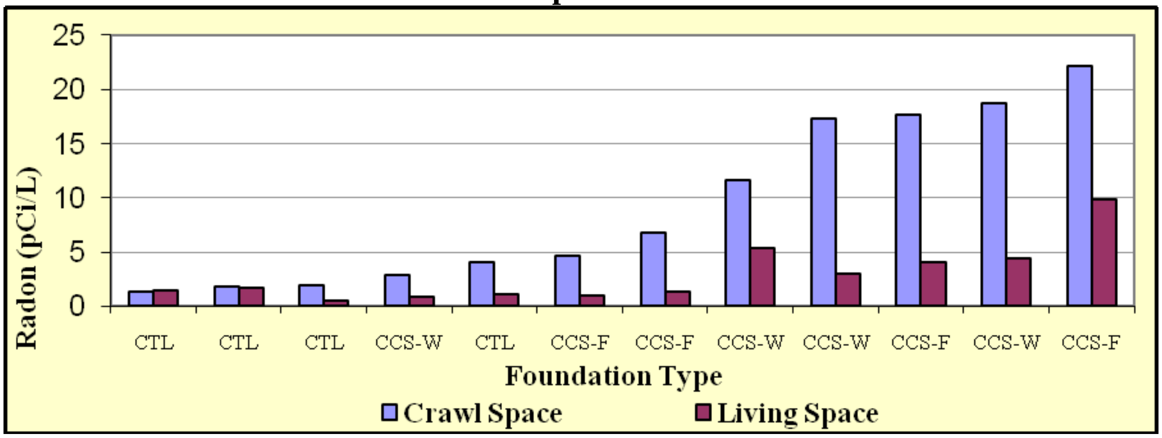
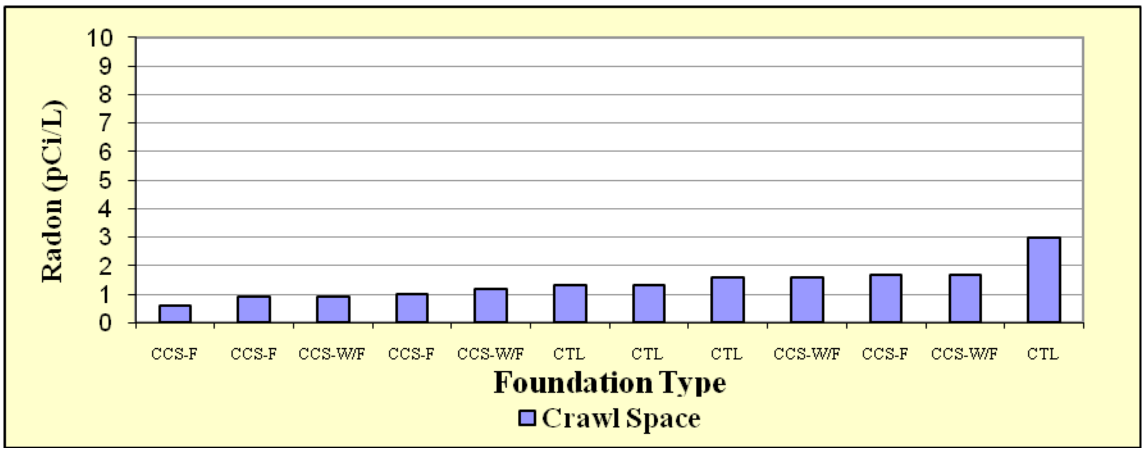


Figure 7. Flagstaff: Short-Term Radon Levels in Crawl Spaces After Opening Crawl Space Vents



Discussion

The project findings support researchers' hypothesis that closed crawl space systems will control daily average RH inside the crawl space to less than 70 percent regardless of climate zone or season.

- In the humid Baton Rouge climate, the closed crawl space systems were able to control crawl space RH 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. The improvement of humidity control in the Baton Rouge closed crawl spaces was robust and occurred very quickly after installation of the systems.
- In Flagstaff's dry climate even the RH in the control crawl spaces stayed less than 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. In the case of Flagstaff, remember we are comparing a code-compliant vented crawl space for the locality, at that time, which did not include a ground vapor retarder.

While moisture reduction was consistent, energy savings varied with climate, insulation and duct placement.

- In Baton Rouge, the performance of closed crawl space systems ranged from 6 percent savings to a 29 percent penalty across the three systems. Among homes with attic ducts, those with wall-insulated crawl spaces performed better in some months while those with floor-insulated crawls did better in other months. Homes with ducts in wall-insulated closed crawls used less energy all year. Based on the data, 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. Ideally, follow up research would add clarity to these results.
- In Flagstaff, the performance of the closed crawl space system varied widely depending on the placement of insulation. Floor-insulated closed crawl space homes showed a savings of 20 percent in heating season gas usage, while the performance of the closed crawl space system with wall insulation exhibited a large penalty of 53 percent.

Conclusions

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 location of ductwork inside 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. On the other hand, results indicate 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, even when the EPA radon map does not indicate a high risk level. 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 then homes on crawl space foundations. In crawl space research done in the Pacific Northwest, installing a radon mitigation system in a closed crawl space added an incremental cost of approximately $400 (Lubliner, Palmiter, Hales & Gordon 2007). Researchers recommend that builders consider “Radon-Resistant New Construction” techniques, for example, roughing-in a radon exhaust pipe during construction (EPA 2009). “Radon-ready” construction will make it easier to install a full radon mitigation system, when necessary.

See the final technical report, *Closed Crawl Space Performance: Proof of Concept in the Production Builder Marketplace*, at www.crawlspaces.org for complete research results.

Acknowledgements

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