High Performance Intervention Houses in North Carolina – An Attempt to Control Indoor Relative Humidity at 50% Year Round

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ABSTRACT

Exposure to damp indoor environments and the allergens that thrive in such environments has been associated with asthma development, exacerbation, wheeze and respiratory complications. This study tested whether a protocol for building a moisture-managed house with a closed crawl space could reliably maintain indoor relative humidity levels below allergen supporting levels of 50% relative humidity in a mixed-humid climate. The moisture management strategies included a closed crawl space, localized exhaust ventilation, and construction specifications used in a national high-performance homes program. The ventilation strategy included an outdoor air intake which operated every 20 minutes. The study results demonstrate that the strategies employed in these moisture-managed high-performance homes were able to control crawl space moisture to below 70% relative humidity, but the indoor relative humidity could not meet the desired target value, or be different from that achieved in the non-intervention comparison group.

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) and its Science Advisory Board have ranked indoor air pollution among the top environmental risks to public health (U.S. EPA 2005). Allergens that are important in the development of asthma correlate directly with levels of relative humidity in houses. Specifically, endotoxins, a part of bacteria cell walls have been identified as both a respiratory risk factor and positively associated with humidity in the home (Wikens 2003). House dust mites are another indoor allergen source that survive and thrive above 50% relative humidity and lead to potential respiratory ailments (Arlian 2001). Dampness in a house thus potentially increases allergen exposure to residents, increasing their risk of asthma (Billings 1998 and Institute of Medicine 2000).

Indoor environments may not be effected by allergens located in the vented crawl spaces as long as they stay in the crawl space. But previous research shows specific mold transmission from the crawl space into the living space via HVAC duct work located in the crawl space as well as penetrations through the floor between the house and crawl space (Malkin-Weber et al 2007).Throughout the building industry, controlled ventilation is a best practice recommendation for improved indoor air quality and moisture management. As a result, the ASHRAE 62.2 ventilation standard has been widely adopted by green building and healthy building programs with the aim to improve

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indoor air quality and health. Research shows the benefit of introducing outdoor air to dilute indoor pollutants such as formaldehyde (Offerman 2007). However, less is known about the interaction between allergen supporting indoor moisture levels and incorporating outdoor air as ventilation in homes located in the humid and mixed humid climates of the United States.

The goal of this study was to investigate whether or not a market-based high performance home specification in a mixed-humid climate could have an effect on maintaining an indoor relative humidity below an allergen supporting level of 50%. If typical moisture loads inside the house and crawl space were controlled and air communication between the crawl space and living space is limited, we hypothesized that the living space would exhibit a measurable decrease in the average relative humidity levels and reduced allergen concentrations compared to standard houses over vented crawl spaces.

Construction Intervention Protocol

The intervention protocol was based on the framework of a high performance housing program, which 1600 homes in North Carolina have demonstrated energy efficiency benefits compared to conventional code-built housing. Many of the features of this high performance homes program also relate to moisture control. These include:

- a right-sized heat pump
- ducts sealed to a total leakage rate of less than 3% of conditioned area
- performance tested kitchen exhaust fans to move 2.8 cubic meters per minute (100 cubic feet per minute) or greater of air flow
- performance tested bath exhaust fans to achieve 1.4 M^3/m (50 CFM) or greater air flow
- tight house envelope of 5.6 M^3/hr per m^2 (0.30 Ft^3/min per ft^2) of envelope area at 50 Pascals
- insulation installed in continuous contact with the air barrier
- room pressure-balanced to ± 3 Pascals with reference to outside.

The high performance housing program also mandates an outdoor air intake that brings in a measured amount of outdoor air whenever the air handler runs. The rate of outdoor air is based on residential industry standards and averaged 68 M^3/hr (40 Ft^2/min) for these study houses. The outdoor air intake in the study houses is on a timer which activates the air handler every 20 minutes if the thermostat has not called for heating or cooling. The objective is to dilute contaminants generated within the home (e.g., carbon dioxide, volatile organic compounds from building materials, furniture, and consumer products). This study was the first effort to measure the impact of the ventilation strategy in these high-performance program homes located in hot-humid North Carolina.

In addition to the program requirements above, the intervention included a closed crawl space, which has been shown to maintain crawl space relative humidity below 70% in North Carolina (Davis and Dastur 2004). The closed crawl space specifications included a sealed polyethylene film liner running up the sides of the walls and piers to within 3 inches of the band joist. A supplemental drying mechanism is provided by a measured amount of supply air provided through a vent in the supply plenum located in the crawl space and roughly equivalent to the volume of air coming in to the duct system through the outside air intake. The intervention upgrades also included a commercially available MERV 11 ducted filter upstream of the air handler.

Study Participants

The intervention group homes for the study were built by four non-profit builders in the Piedmont region of North Carolina between 2002 and 2003. They used a national high-performance homes program as the base and added ventilation, pressure balancing, filtration and a closed crawl space. The non-intervention group homes were built by local builders to North Carolina Building Code standards over a very short construction period. They were then partially randomized and assigned to the intervention or non-intervention group, though the construction schedules hindered a full randomization effort. As a result, this inability to maintain randomization in the home assignments hindered statistical valid results from these house groupings. There were 20 homes in the intervention group and 16 homes in the non-intervention group. Both groups consisted of one-story single family detached three-to-four bedroom homes with two bathrooms and averaged 1165 ± 124 square feet in total size.

We encountered process failures in the installation of the closed crawl spaces. Therefore, the closed crawl spaces did not fully meet specifications until March, 2005.

Data was then collected for 18 months. Temperature and relative humidity readings were recorded hourly for the entire study period. Allergens were collected every six months during the study using a one time use cellulose extraction thimble on the extension tube end of a high efficiency vacuum cleaner. Bedding was vacuumed for a total of five minutes, bedding layers for two and a half minutes, the top of the mattress for two minutes and a pillow for 30 seconds. Fully encased, impermeable mattress covers were not removed. For the floor samples, a one by two meter area of floor template was placed on the sample area and vacuumed for five minutes. For the sofa, the surface of the cushions, arms, seat back and pillows were vacuumed for five minutes. The collection material was then analyzed using industry standard assay methods.

RESULTS

Intervention homes had much more consistently tight ducts than non-intervention homes. With regard to house tightness, both sets of homes would be considered tight compared to average homes across the country, but the intervention homes were slightly tighter than non-intervention homes. Kitchen and bath exhaust fans performed better in intervention houses than in non-intervention houses. In particular, the non-intervention homes were all equipped with recirculating kitchen fans, which is standard practice in North Carolina, particularly in low and moderately priced homes. Table 1 shows these differences.

Table 1. Average House Performance Values

Status	% Duct Leakage in M^3/h per m^2 floor area (F^3/min per ft^2) at 25 Pascals	House Leakage in per M^3/h per m^2 envelope area (F^3/min per ft^2) at 50 Pascals	Kitchen exhaust M^3/min (F^3/min)	Bath 1 exhaust M^3/min (F^3/min)	Bath 2 exhaust M^3/min (F^3/min)
Intervention	55% (3%)	4.6 (0.25)	3.0 (106)	1.6 (58)	1.6 (56)
Non-Intervention	187% (10%)	5.8 (0.31)	0*	1.1 (38)	1.0 (37)
% Difference (I from N)	72% tighter	25% tighter	Recirc-ulating	53% higher	52% higher

The closed crawl spaces, once properly installed, managed relative humidity to stay below 70% relative humidity, even during the humid summer season. Figure 1 shows the relative humidity levels in intervention closed crawl spaces compared to the non-intervention houses using seven-day moving average. The summer and fall seasons of 2004 show excursions above 70% relative humidity in the intervention crawl spaces, demonstrating that the improperly closed crawl spaces did not manage moisture as intended. Figure 2 shows the seven-day moving average of outdoor relative humidity over time.

Once the houses were brought to specification, the relative humidity remained below 70% for the rest of the monitoring period. The relative humidity in the closed crawl spaces exhibited smaller swings from high to low during the course of the year compared to the wall-vented crawl spaces.

Figure 1. Crawl Space RH

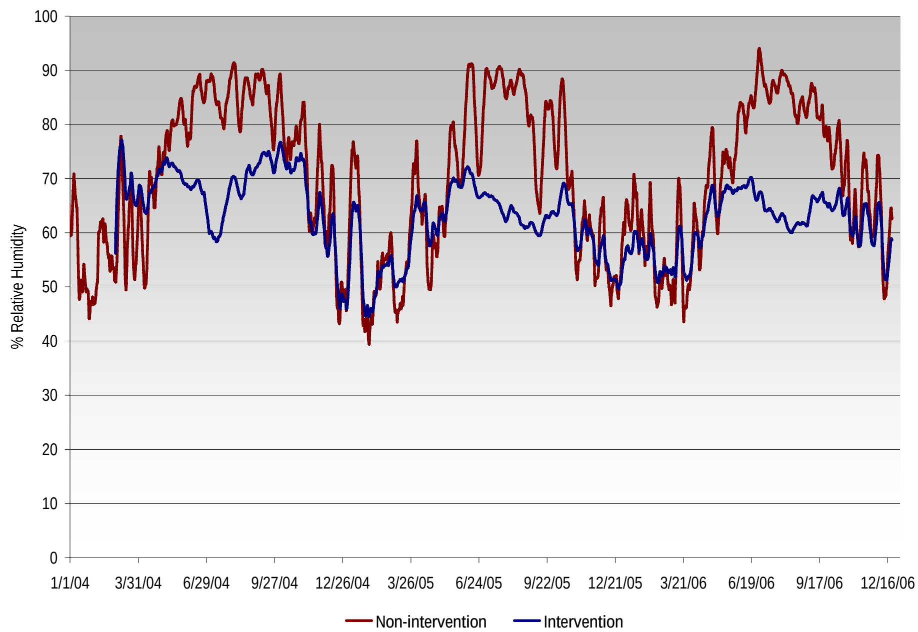

Figure 2. Outside RH

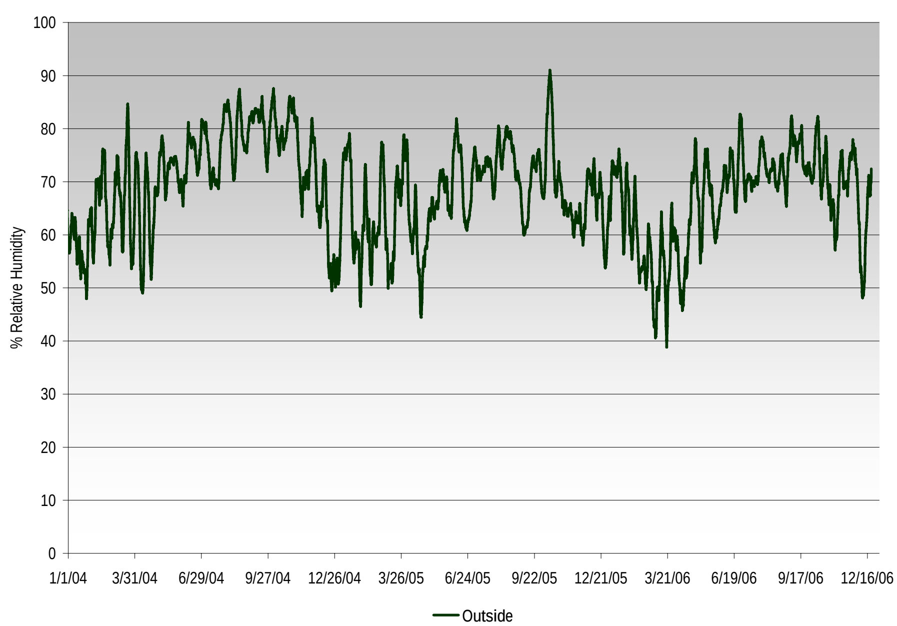

Table 2 shows the detail of crawlspace relative humidity levels during the humid season of May 15 through October 15 during the years 2005 and 2006.

Table 2. Crawl Space RH During Humid Season (May 15-October 15)

Status	Mean Crawl RH (%)	Standard Deviation Crawl RH (%)
Intervention	66.4	4.9
Non-Intervention	83.1	4.8

The crawl space moisture difference did not translate into a moisture difference in the living space. There was no statistically significant difference between the groups. The interior moisture load across all homes averaged 63 percent relative humidity during the summer months, 50 ± 5 percent during the spring and fall and 37 percent during the winter.

Figure 3 uses a 7-day rolling averages of relative humidity in the 2 housing groups to show how closely the relative humidity inside the living space tracked across the two groups houses.

Figure 3. Indoor RH Not Different Between Intervention and Control Groups

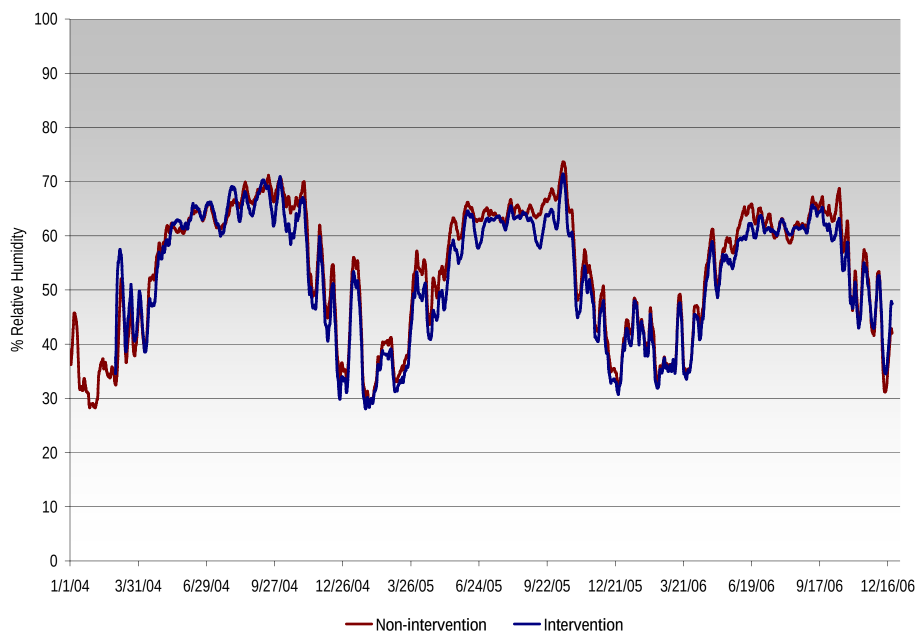

Table 3 shows the average indoor relative humidity levels inside the control and intervention homes during the humid seasons of May 15 through October 15 during 2004 and 2005.

Table 3. Indoor RH as a Percentage During Humid Season

Status	Mean Indoor RH (%)	Standard Deviation Indoor RH (%)
Intervention	62.3	4.4
Non-Intervention	64.3	4.4
All houses	63.8	4.5

Tables 4-6 show the details on average indoor relative humidity in the winter, spring and fall seasons.

Table 4. Indoor RH during winter (typically dry season)

Code	RH (%)	Std Dev (%)
Intervention	36.7	5.6
Non-Intervention	37.9	4.9
All houses	37.2	5.3

Table 5. Indoor RH during Spring shoulder season

Code	RH (%)	Std Dev (%)
Intervention	46.7	4.4
Non-Intervention	51.1	4.6
All Houses	48.7	5.0

Table 6. Indoor RH during Fall shoulder season

Code	RH (%)	Std Dev (%)
Intervention	48.4	5.4
Non-Intervention	53.8	4.6
All Houses	50.7	5.7

Since the closed crawl spaces were equipped with supplemental drying by way of a trickle of supply air, we found that the crawl space relative humidity tracked closely with the indoor relative humidity, while the relative humidity in the vented crawl spaces tracked with the outdoor relative humidity levels through the year.

Allergen Results

Since there was no significant difference in indoor moisture in these homes, we expect there to be no differences in moisture dependant allergens in these houses. Validated results, however, were unattainable. One critical detail led to failure of randomization: non-intervention homes were enrolled during an intensive building period in which all homes were completed during a week. Intervention homes were enrolled over time, and therefore came online over a much longer time period due to construction delays. Finally, results from all of these analyses show large variations due to a small sample size. Therefore analysis of the allergen results is therefore not reported here.

DISCUSSION

The crawl space moisture load data verified that the closed crawl spaces in the intervention homes had a lower variance of moisture across the year than the non-intervention homes with vented crawl spaces. The properly closed crawl spaces maintained relative humidity below the 70% threshold across the study period. This result shows that the closed crawl space eliminated a risk factor common in houses in this climate: namely the presence of mold-supporting moisture levels, standing water, and measurable mold levels inside the crawl space. (Malkin-Weber et al 2008). In addition, the tight ducts and tight house envelope eliminate a typical pathway in which mold enters the home through floor penetrations and duct leakage, driven by forces including stack effect, HVAC fans, and pressure differentials from wind (Malkin-Weber et al 2008).

However, the substantial relative humidity reductions in the closed crawl space relative to wall-vented crawl spaces did not translate into reduced relative humidity in the living space of the home. There was no statistical difference in the relative humidity levels inside the home of the intervention versus non-intervention groups.

The lack of relative humidity differences is a surprising result, since the intervention package contains many elements designed to reduce the building's moisture load, as described in the methods section, above. It raises several questions that bear further research.

It may be that the reduced moisture load in the crawl space simply offset the added moisture being introduced by the outdoor air intake and timer to the indoors of the intervention homes. The relative humidity inside the non-intervention homes might have been even higher if the outdoor air intake on a timer was used with wall-vented crawl spaces.

Another factor that may contribute to the unexpected result is that the intervention houses depended partly on the moisture-removal capabilities of a right-sized heat pump. However, the intervention heat pumps may have still been too large for this size home; therefore the heat pump may not have been removing adequate moisture from the indoor air. Anecdotal reports from practitioners report that it can be difficult to right-size the heat pump on a very small home, as the prescribed sizing may be below the smallest commercially available unit. Further, for purposes of seeing a difference in relative humidity between these groups of houses, we found that the non-intervention group had not significantly oversized their HVAC systems.

Energy use data will be published in future papers, validating that the intervention homes incurred energy savings comparable to those found in prior closed crawl space research (Dastur and Davis 2005).

Overall, the substantial moisture control improvements in the crawl space likely translated into lower risk of molds growing there and being transferred into the living space. The closed crawl space protocol as implemented here, however, did not have a large enough influence on the living space to maintain the home at levels that dust mites are suppressed, even in homes with other systematic moisture management strategies.

CONCLUSION

Even though this study was unable to verify that improved moisture control through guaranteed performance building standards plus a closed crawl space and supplemental HVAC filtration was capable of inhibiting dust mite life and growth, the lessons learned are very worthwhile. Those interested in creating an inherently healthy home to reduce asthma triggers via the modification of home components should be aided in the creation of interventions based on this study. Study results are still valuable in terms of what has not made an impact. This study has also been helpful to provide clarity on a follow up study that is currently underway. This and future research can still be used for builders, health care providers and consumers. Results on the impacts of the interventions on different indoor conditions and future parameters will be published to members of the public health sector and medical community, healthy homes networks, energy efficiency contractors, building scientists, state and federal agencies in the United States.

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