Liabilities of Vented Crawl Spaces, Their Impacts on Indoor Air Quality in Southeastern U.S. Homes and One Intervention Strategy

Jonathan Coulter[1]

ABSTRACT

This paper documents the influences vented crawl space foundations have on indoor air quality in houses located in Central and Costal North Carolina and presents performance results of one intervention strategy from a Healthy Homes, Healthy Lives study in Central North Carolina. Researchers tested 45 houses with wall vented crawl spaces for mold species indoors, outdoors, and in the crawl space. A building science evaluation was performed on each house to characterize infiltration and exfiltration between the indoors, outdoors, crawl space, and the HVAC system located in the crawl space.

Findings supported that houses in the humid southeastern United States with HVAC equipment located in vented crawl spaces were found to possess these characteristics:

- Presence of high moisture
- Presence of fungal spores
- Measured holes between the crawl space and living space
- Natural and mechanical forces that drive crawl space air across the holes
- Measured transmission of fungal spores from the crawl space to the living space.

When these characteristics exist together, occupants might be exposed to potentially harmful crawl space contaminants. Because these results show that crawl spaces are important sources of mold in the home environment, a parallel field performance study was conducted to test an affordable closed crawl space configuration designed to reduce the detrimental characteristics of wall vented crawl spaces noted above. This closed crawl space intervention consisted of sealed foundation wall vents, a sealed polyethylene film liner and 0.5 L/s (1.0 ft^3/min) of air supplied by the heating, ventilation, and air conditioning (HVAC) system for each 2.8 m^2 (30 ft^2) of crawl space ground surface area. The findings from the performance study demonstrate that properly closed crawl spaces are a robust intervention that facilitates a crawl space with moisture readings below mold supporting levels while also significantly reducing space conditioning energy usage on an annual basis.

INTRODUCTION

Building codes often require foundation vents to allow air exchange between the crawl space and outdoors in order to provide a drying mechanism. Because approximately 20% of new homes in the United States are built on vented crawl space foundations and an estimated 26 million existing homes have vented crawl space

[1]Jonathan Coulter is Building Science Associate at Advanced Energy in Raleigh, North Carolina, USA.

foundations, the scale of this construction practice is quite large. In the Southeastern U.S., where the moisture content of outdoor air in the summer season often exceeds that of the crawl space air, this intention of having a drying mechanism for the crawl space has been found to be unsuccessful (Davis and Dastur 2004). As a result of these unintended outcomes, complaints of high moisture in crawl spaces have been voiced to builders, insulators and other contractors. Hardwood floor installers have also had dissatisfied customers when floors cup or buckle from elevated crawl space moisture levels (Davis and Dastur 2004). There is also growing evidence of these elevated moisture levels impacting the health of occupants. As literature suggests, there is a strong association between building moisture and detrimental health outcomes including asthma (Institute of Medicine 2004). This paper compares the findings of the vented crawl spaces characterization study with a field performance closed crawl space intervention study.

Characterization Study

The 45 homes in the characterization study were selected and measured during the summer of 2004. They ranged in age from two to 60 years, and averaged 27 years old. The homes were a subset of 187 homes sampled for bioaerosols under a related study that assessed residential allergens and asthma triggers (Thomann and Miranda 2004).

In order to document past or current moisture problems, we conducted a 100 point inspection which included house air temperature and relative humidity, crawl space air temperature and relative humidity, outside air temperature and relative humidity, crawl space surface temperatures, house framing wood moisture content, crawl space construction details, crawl space and exterior grading conditions, and the presence of a drainage systems. These data were collected using commercially available and calibrated wood moisture meters, spot radiometers, digital thermometers, and relative humidity meters.

12 Month Relative Humidity and Temperature Monitoring

Commercially available data loggers were installed to record hourly temperature and relative humidity readings in all the crawl spaces. For the characterization study, data was collected to make observations about long term trends for 12 months from October 2004.

Mold Species Sampling

In each home, at least two sets of air samples were taken using a matched-pairs signed rank test. Prior to mold species sampling, the homeowner was asked to keep the HVAC system off for four hours. Three samples were taken before the HVAC system fan was turned on. These sample locations were: 1) near the return grill for the HVAC system, 2) in the crawl space, and 3) outdoors.

The system fan was then turned on and allowed to run for at least five minutes before two additional samples were taken: one near the return grill and one at the closest supply air diffuser (or register) to the system fan. The air sampled from the

supply diffuser was isolated from the potential contaminant sources within the house, thus allowing characterization of the relative contribution of the HVAC system to the total fungal count inside the house.

The sampling used two-stage cascade impactors, which collect and separate both non-respirable and respirable size particles. The sampler was connected to a vacuum pump calibrated to collect air samples at the rate of 0.5 L/s (1.06 CFM). Equipment calibration was conducted at the beginning of sampling, at mid-day and at the end of the day. A sampling period of 3.5 minutes was used for the outdoor air sample and all samples collected within the houses. The sampling period for the crawl space samples was one minute. The collection medium used for impaction of mold spores was Malt Extract Agar and after sampling, the culture plates were incubated at ambient temperature for 96 hours. Mold identification was then accomplished by macroscopic examination of colony morphology and microscopic examination of fungal elements.

Characterizing Hole Locations

During the initial site visits, we conducted air leakage and zone pressure testing to quantify the cross-sectional area of airflow pathways, or "holes" between the conditioned space and unconditioned spaces. Air leakage could be in the form of infiltration or exfiltration depending on the pressures and locations in an individual house. Three leakage groupings were measured: total house air leakage, air leakage through the floor between the living space and the crawl space, and air leakage between the HVAC duct system and the crawl space. We used a multi-pressure testing system set up with two house depressurization systems and one duct depressurization system to arrive at the values. Software recorded the data generated by the multi-pressure testing system at each of three house systems:

- house envelope leakage measuring system
- crawl space to house leakage measuring system
- HVAC duct leakage measuring system.

DISCUSSION

The average number of crawl space vents per house was 13, with the maximum being 22 and the minimum being four vents. Sixty-seven percent of the vents were found all open, 26% were partially open, and seven percent were closed at the time of the data collection. The open crawl space vents demonstrate that houses were experiencing the ventilation intended by the building code.

Moisture

Overall, substantially high moisture levels were found in these vented crawl spaces. During the summer months, 99% of crawl space relative humidity readings were ≥70% RH, or above the commonly accepted threshold in which mold growth is supported (Building Air Quality). Sixty-seven percent of the crawl spaces recorded ≥90% RH during these summer months. These crawl space readings were also on

average higher than the outside relative humidity readings. During the remainder of the year and through winter, the crawl space relative humidity readings averaged 70%. Based on the house visits conducted between June and September, the following visual results were recorded. In 42% of the homes, the ground vapor retarder had visible puddles present. The duct and plumbing systems located in the crawl spaces were found to provide condensing surfaces and resulted in 27% having condensation on the exterior of the ducts and eight percent having moisture on the water pipes. Liquid water was found inside the inner liner of 15% of the duct systems. Seven percent of the homes had a leaking condensate drain for the HVAC system. Active plumbing leaks were also found in 31% of the houses. As a result, these moisture sources helped provide conditions conducive to mold growth and wood rot in 67% of the houses.

Although moisture was not always visible at the time of the testing, evidence of recent moisture accumulation in the crawl space was sometimes visible as shown in Table 1.

Table 1: Moisture Indications Found Inside Crawl Spaces and Percent Frequency.

Drip line visible on ground	22%
Absence of ground vapor retarder	27%
Absence of full coverage of ground vapor retarder	100%
Discoloration on walls	49%
Termite tunnels	4%
Animals and insects	36%
Dryer exhaust terminating in crawl space	16%
Visible mold growth	62%
Wood moisture readings at mold supporting levels (≥19 %)	67%
Wood moisture meter readings at wood rot supporting levels (≥ 25 %)	36%

Fungal Sampling

Fungal air sampling provided an evaluation of the total number of breathable mold spores, reported in colony forming units per cubic meter of air, of the most common species of mold in this region: Cladosporium, Aspergillus, and Penicillium. In the 45 homes, mold was detected in the house, outside, and in the vented crawl space. The mean value found inside the house was 825 CFU/m³ with the HVAC system off and 1061 CFU/m³ with the HVAC system on. Outside, a mean of 3027 CFU/m³ were present, and in the crawl space 19102 CFU/m³ were measured.

Measured Holes Between the Crawl Space and Living Space

To obtain these data reflecting the approximate holes between the crawl space and living space, we performed a series of leakage tests together and separately to determine the relative contribution component leakages had on the whole. Overall house leakage is reflected in Table 2. The measured leakage between the HVAC duct system and the crawl space are shown in Table 3. Five homes (or 4%) were not classified for the duct leakage to crawl space test because they were unable to reach their target pressure.

Table 2: Overall House Leakage.

Ft^3/min at 50 Pascals per ft^2 of Surface Area	**M^3/hr at 50 Pascals per m^2 of Surface Area**	**Classification**	**Percent of Houses Tested**
<0.25	<4.6	Minimal	0
0.26-0.45	4.7-8.2	Limited	25
0.46-0.60	8.3-10.9	Moderate	42
0.61-0.75	11-13.7	Excessive	20
>0.76	>13.8	Major	13

Table 3: Leakage Between Duct System and Crawl Space.

Ft^3/min at 25 Pascals per ft^2 of Conditioned Floor Area as a Percentage	**M^3/hr at 25 Pascals per m^2 of Conditioned Floor area as a Percentage**	**Classification**	**Percent of Houses Tested**
<3%	<0.55%	Minimal	0
3.1-5%	0.56-0.91%	Limited	4
5.1-8%	0.92-1.46%	Moderate	9
8.1-12%	1.47-2.19%	Excessive	18
>12%	>2.20%	Major	65
Unable to reach target pressures.			4

These findings in Tables 2 and 3 document pathway locations where contaminants could move from the crawl space to the living space. These flow readings were then converted to equivalent hole sizes to provide for a more understandable interpretation of the data. As shown in Table 4, the total hole size measured between the crawl space and the occupied parts of the house was 464 cm^2 (72 $inch^2$).

Table 4: Equivalent Hole Size by Location.

Location	Mean Equivalent Hole Size in cm^2
Total House to Crawl Space	464
Crawl Space Ducts	371
Through House Floor	93

Through the use of the series leakage tests, it was determined that the majority of these homes (69%) had 11% to 30% of the total house air leakage coming from the crawl space. This possible leakage is assisted by three driving forces: wind, stack effect, and mechanical fans. All of these forces have the potential to worsen infiltration or exfiltration.

Measured Fungal Transmission

To examine whether mold was being transmitted between the crawl space and living space through infiltration, mold counts were compared in the living space when the HVAC system was off and when it was in operation. The possibility of transmission was classified based on the answers to the following questions:

- Was the concentration of mold higher in the living space once the HVAC system was turned on compared to the concentration when the HVAC system was off?
- Was the concentration and makeup of indoor mold matched more closely with the concentration and makeup of the mold measured in the crawl space than that of the outdoors?

If these two conditions held true, it was determined that fungal contaminants from the crawl space were being transmitted into the living space. This is what is called “transmission possible”. If only one condition held, the house was classified as “transmission not detectable” and if neither condition held true, the house had “no transmission”.

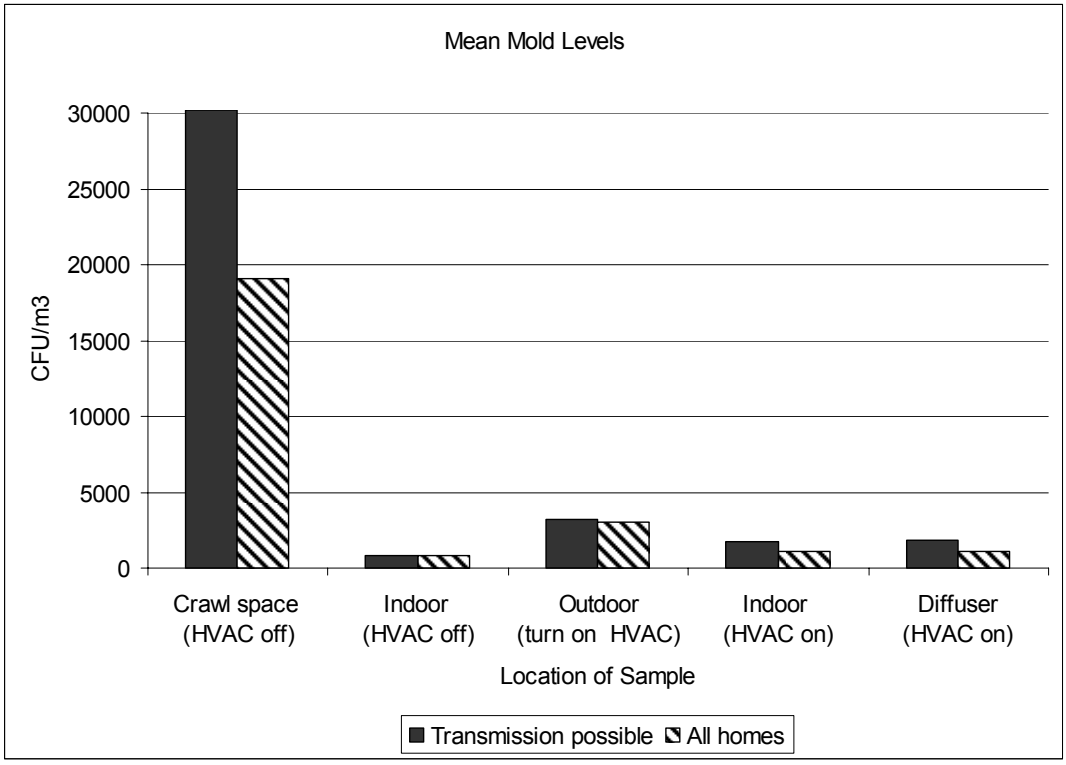
Both conditions held true in 47% (21) of the houses, showing definitive fungal transmission occuring from crawl space to living space. In 22% (10) of the houses, transmission was not detectable or only one of the two conditions held true. No transmission was found in 31% (14) of the houses.

Table 5 shows fungal results reported as colony forming units per cubic meter. The results are grouped according to whether the home had the possibility of transmission from the crawl space to the house. Figure 1 displays the mean mold levels for houses with the possibility of transmission compared to the mold levels for all houses based on sample location.

Table 5: Summary Mold Count Results.

Sample	% of Houses	Mean In CFU/m3
Transmission possible	**47%**	
Crawl space (HVAC off)		30163
Indoor (HVAC off)		861
Outdoor		3235
Indoor (HVAC on)		1761
Diffuser (HVAC on)		1822
Transmission not detectable	**22%**	
Crawl space (HVAC off)		161
Indoor (HVAC off)		55
Outdoor		2033
Indoor (HVAC on)		176
Diffuser (HVAC on)		1415
No transmission	**31%**	
Crawl space (HVAC off)		16041
Indoor (HVAC off)		1323
Outdoor		3427
Indoor (HVAC on)		645
Diffuser (HVAC on)		556
All homes	**100%**	
Crawl space (HVAC off)		19102
Indoor (HVAC off)		825
Outdoor		3027
Indoor (HVAC on)		1061
Diffuser (HVAC on)		1062

Figure 1. Mean Mold Levels for Houses Where Transmission Possible.



A Field Performance Intervention

In the performance study, a separate grouping of 36 newly built homes in Central North Carolina were selected to compare a closed crawl space protocol to a standard vented crawl space. These homes were built between 2002 and 2003 with 20 homes having the closed crawl space protocol and 16 control homes. The intention of the closed crawl space intervention was to limit overall mold counts in the living space by reducing: moisture levels and thus mold growth in crawl spaces, holes between the house and crawl space, the effects of driving forces. To eliminate mold supporting moisture sources in the crawl spaces, this space was physically separated from outside moisture sources as well as ground moisture sources. By sealing the HVAC duct system and house floor, the intervention attempts to first significantly minimize the hole sizes between the crawl space and house and second to substantially reduce infiltration and exfiltration caused by driving forces. These techniques would then in combination reduce the amount of air from the crawl space that contributes to air in the living space.

The closed crawl space detail of the protocol included a sealed polyethylene vapor retarder liner attached to the inside top of the crawl space wall while allowing for a termite inspection gap and covered 100 percent of the crawl space floor. See Figure 2. The crawl space door was weather stripped and locked.

In addition to the liner, foundation vents were properly sealed and a permanent crawl space drain installed at the lowest portion of the crawl space to remove liquid water from the crawl space.

Figure 2. Closed crawl space after installation is finished.

Relative humidity is tempered in all of the closed crawl spaces by virtue of a small amount of conditioned supply air. This air is delivered at a rate of 0.5 L/s (1.0 ft^3/min) per 2.8 m^2 (30 ft^2) of crawl space ground surface area via a duct outlet installed with a manual balancing damper and backflow prevention damper directly off the supply plenum of the HVAC system. This drying mechanism source in this geographical house location is advantageous because it requires no additional maintenance by the homeowner and, over time, will continue to function as designed because if the HVAC system malfunctions, the homeowner will most likely have it repaired. Other “add-on” systems might be easily ignored by homeowners—either through lack of notification of failure or lack of knowledge of the system—and therefore there is no motivation to fix the system.

Data for the performance study was collected for 18 months from March 2005. Measurements were taken in a variety of ways. Allergens were collected every six months during the study using a study approved vacuum and analyzed using an industry recognized protocol. Temperature, relative humidity and dew point were recorded hourly for the entire study period using the same data loggers. Airborne particulates were recorded during each allergen collection visit using a handheld particle counter. Fungal spore samples were collected on a free-standing air purifier collection grid once for seven days before being analyzed.

DISCUSSION

The closed crawl space intervention was successful in a number of ways. Not only did this protocol not exhibit any visible indications of liquid moisture inside the crawl space, but the moisture loads measured confirm that the closed crawl spaces had a lower quantity and variance of relative humidity readings across the year than the comparative houses with vented crawl spaces. These data showed 24 hour average winter relative humidity readings of 51% for the closed and 56% for the comparable

vented crawl spaces and 24 hour average summer relative humidity readings of 66% for the closed and 83% for the vented crawl spaces.

Total mold spore counts in the vented crawl spaces were substantially higher than outside which was also higher than the closed crawl spaces. The mold counts in the living spaces above the vented crawl spaces as well as the closed crawl spaces were not significantly different from the other. See Table 6 with the mold measurements.

Table 6: Summary Mold Count Results.

Sample	% of Houses	Mean In CFU/m3
Transmission not detected	**100%**	
Vented Crawl Space (HVAC off)	50	29858
Closed Crawl Space (HVAC off)	50	1227
Indoor Both Groups (HVAC on)	100	706
Outdoor	100	4233

There was no specific test to determine the relative contribution of crawl space originated air in house air. But, the mold count results described above suggest very little contribution of crawl space air in the living space.

All the houses (100%) had minimal house air leakage. Table 7 shows results of house leakage testing.

Table 7. Overall House Leakage.

Ft^3/min 50 Pascals per ft^2 of surface area	M^3/hr at 50 Pascals per m^2 of surface area	Classification	Percent of houses tested
≤0.25	<4.6	Minimal	100
0.26-0.45	4.7-8.2	Limited	0
0.46-0.60	8.3-10.9	Moderate	0
0.61-0.75	11-13.7	Excessive	0
≥0.76	>13.8	Major	0

The leakage found between the HVAC duct system and the crawl space were measured to be minimal at <3% CFM 25 per ft^2 of conditioned floor area as a percentage (<0.55% $M^3/h/m^2$ at 25 Pascals of conditioned floor area as a percentage). Series leakage testing was not performed on these houses to determine the estimated hole sizes between the house and crawl space through the floor or duct system. However, as a result of significantly lower overall house and duct system leakages, the effects of driving forces on infiltration and exfiltration in these houses were considerably reduced.

CONCLUSIONS

This study not only documents that typical southeastern U.S. houses built over wall-vented crawl spaces are reservoirs of moisture and mold, but holes exist between the living space and crawl space through the floor and HVAC duct system affording the delivery of mold species into the living space. Mold transmission was specifically measured in 47% of the houses thereby potentially compromising indoor air quality.

Therefore to reduce or counter act this potential harmful construction technique, a closed crawl space intervention protocol was tested. The data demonstrated that the closed crawl space protocol is a robust measure producing substantially drier crawl spaces thus reducing conditions that support mold growth, wood decay, and insect damage. In the summer seasons closed crawl spaces generally maintained below 60% relative humidity on 24 hour average. In the wall-vented crawl spaces the 24 hour average was often above 80% relative humidity.

Our hope was that not only would the closed crawl space protocol reliably maintain the desired relative humidity to below mold growth supporting levels in the crawl space, it would also significantly reduce relative humidity in the living space. This was not confirmed and further research is being conducted to further explore this area.

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