LIABILITIES OF VENTED CRAWL SPACES AND THEIR IMPACTS ON INDOOR AIR QUALITY IN SOUTHEASTERN U.S. HOMES

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ABSTRACT

This study documented that houses in the southeastern United States built on typical wall-vented crawl spaces possess the following characteristics: 1) bulk water, water vapor and associated moisture issues, 2) mold spores, 3) measured holes between the crawl space and living space and 4) measured transmission of mold spores from the crawl space to the living space. When these characteristics exist together, the study indicates that contaminants (mold spores and moisture vapor) present in the crawl space are being transmitted through holes in the house floor and heating, ventilation and air conditioning (HVAC) system into the livable parts of the home, thereby exposing occupants to potentially harmful crawl space contaminants. These results confirm vented crawl spaces as important sources of mold species in the home environment. In order to reduce this exposure, closed crawl spaces in combination with thorough house and duct air sealing are recommended. Such a system was found to be a robust intervention that reduced the moisture and indoor air quality problems associated with typical wall-vented crawl spaces.

INTRODUCTION

Approximately 20% of new homes in the United States (200,000 per year) are built on vented crawl space foundations according to the U.S. National Association of Home Builders (NAHB). An estimated 26 million existing homes have vented crawl space foundations. Because adults and children today spend increasing amounts of time indoors, home environmental health is important for people's well being. Mounting evidence suggests that exposure to mold in damp buildings is an important risk factor for childhood asthma [1]. The strongest identifiable risk factor for the development of asthma appears to be exposure to environmental allergens, including indoor and outdoor pollutants [2].

Because vented crawl spaces in the mixed-humid climate of the southeast experience periodic high levels of moisture, they are very likely building areas where mold can be found. One remedy, in the form of properly closed crawl space standards, demonstrated houses will be notably drier, more energy efficient and support less mold growth compared to houses built over vented crawl spaces [3]. However, it was previously unclear whether the presence of crawl space

mold species resulted in exposure to occupants in houses. The overall purpose of this study was to evaluate the importance of typical wall-vented crawl spaces as sources of mold species in the livable parts of the home environment.

Forty-five homes in North Carolina were selected for mold species sampling and a building science evaluation to characterize the conditions of typical wall-vented crawl spaces. This report will explore the influences of this foundation construction technique on mold species growth, indoor air quality and house durability in houses located in the southeastern United States. From the results of these studies, we created a subsequent study of 36 new houses to validate the improved energy and moisture performance of the closed crawl space protocol established above compared to traditionally vented crawl spaces. Results from this study became available in June of 2007.

Methods

Mold species sampling

Prior to mold species sampling, the HVAC system was kept off for four hours. In each home, a minimum of two sets of samples were taken during the test using a Wilcoxon matched-pairs signed rank test. First, before the HVAC system fan was turned on, three samples were taken. One was taken near the return grill for the HVAC system, one in the crawl space and one outside the house. Then, the system fan was 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 supply diffuser sample air was isolated from the potential contaminant sources within the house, thus allowing characterization of the relative contribution of the HVAC system to the total bioburden within the house. The sampling was conducted by two trained indoor air quality technicians using Andersen two-stage cascade impactors, which collect and separate both non-respirable and respirable sized particles. The sampler was connected to a vacuum pump calibrated to collect air samples at the rate of 0.5 liters per second. 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, an aciduric mycologic medium designed for the collection of environmental fungi. After sampling, the culture plates were incubated at ambient temperature for 96 hours prior to enumeration and identification. Mold identification was accomplished by macroscopic examination of colony morphology and microscopic examination of fungal elements.

Characterization protocol

Data was collected to better understand the thermal, moisture and air leakage data associated with each ventilated crawl space:

- Homeowners interviews about how they operate in house and crawl spaces to determine any potential indoor air quality related health issues
- Air leakage and zone pressure testing was performed to quantify the "holes" between the house and outside, the crawl space and house and the HVAC system and crawl space

- House characteristics such as house measurements, topography, HVAC and other equipment and existing moisture control strategies
- Crawl space characteristics such as evidence of past moisture problems (wood rot, condensation, mold growth, puddles on vapor barrier, etc.), wood moisture content to evaluate the potential of wood for supporting current mold growth, temperature measurements of the ground, water pipes, ductwork, air handling cabinet and floor framing to assess surface condensation potential
- Long-term temperature and relative humidity data from the central area of the crawl space compared to outside between July 2004 and August 2005

Building pressure diagnostics

Detailed air leakage was measured using a multi-pressure testing system connected to three different systems – house envelope leakage measuring system, crawl space to house leakage measuring system and HVAC duct leakage measuring system. The testing order was as follows:

1) Baseline-HVAC system off, all windows and doors closed

2) House leakage test only

3) House, crawl space and duct leakage measuring systems run together

4) House and duct leakage measuring systems run together

5) Baseline-HVAC system on

House description and moisture history

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 drainage systems. Data was collected using commercially available and calibrated wood moisture meters, spot radiometers, digital thermometers and relative humidity meters.

RESULTS

The average number of vents per house was 13, with the maximum being 22 and the minimum being four vents. Sixty-seven percent of all vents were found open, 26% were partially open and 7% were closed at the time of the data collection.

Moisture

In 33% of the homes, moisture was present on the ground vapor retarder, duct and plumbing systems located in the crawl spaces. Seven percent of the homes had a leaking condensate drain for the HVAC system. Active plumbing leaks were found in 31% of the houses. Water was found inside 15% of the duct systems.

Although moisture was not always visible at the time of the testing, the presence of recent moisture accumulation in the crawl space was visible by the following means in Table 1.

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%

Table 1. Moisture indications and percent of frequency found inside crawl spaces.

Mold species

Mold species sampling provided an evaluation of the total number of breathable mold spores, reported in colony forming units per cubic meter of air and the most common species of mold growth found. Table 2 shows the summary of bioaerosol results (in colony forming units per cubic meter) by the possibility of transmission and sample location. Figure 1 displays the bioaerosol levels for houses with the possibility of transmission. Figure 2 illustrates bioaerosol levels for all houses by location.

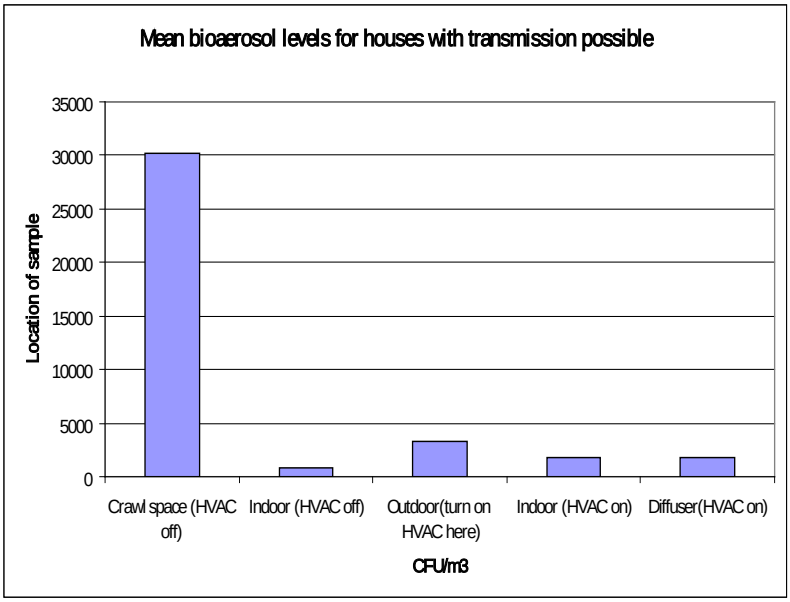

Figure 1. Mean bioaerosol levels for houses with transmission possible.

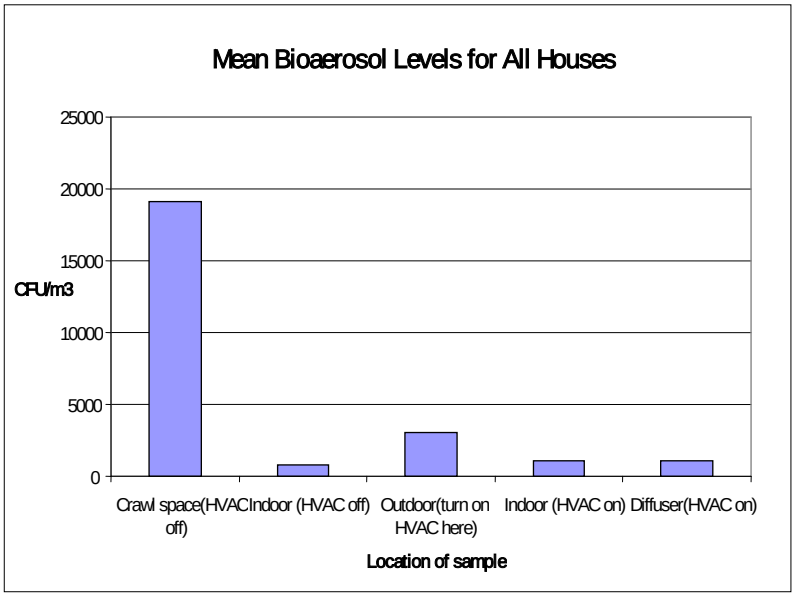

Figure 2. Mean bioaerosol levels for all houses.

Sample	# Houses	Mean	Std. Dev.	Max	Min
Transmission possible	In CFU/m3				
Crawl space (HVAC off)	21	30,163	16,230	41,146	1,348
Indoor (HVAC off)	21	861	1,233	5,802	146
Outdoor(turn on HVAC here)	21	3,235	3,862	11,756	349
Indoor (HVAC on)	21	1,761	2,425	11,756	373
Diffuser(HVAC on)	21	1,822	2,607	11,756	166
Transmission not detectable	In CFU/m3				
Crawl space(HVAC off)	10	161	508	1,607	0
Indoor (HVAC off)	10	55	173	548	0
Outdoor(turn on HVAC here)	10	2,033	2,524	8,418	40
Indoor (HVAC on)	10	176	556	1,759	0
Diffuser(HVAC on)	10	1,415	2,282	11,756	0
No transmission	In CFU/m3				
Crawl space(HVAC off)	14	16,041	15,144	41,146	105
Indoor (HVAC off)	14	1,323	3,045	11,756	71
Outdoor(turn on HVAC here)	14	3,427	4,630	11,756	146
Indoor (HVAC on)	14	645	765	3,219	124
Diffuser(HVAC on)	14	556	1,101	4,326	71
All homes	In CFU/m3				
Crawl space(HVAC off)	45	19,102	18,179	41,146	0
Indoor (HVAC off)	45	825	1,911	11,756	0
Outdoor(turn on HVAC here)	45	3,027	3,836	11,756	40
Indoor (HVAC on)	45	1,061	1,837	11,756	0
Diffuser(HVAC on)	45	1,062	2,011	11,756	0

Table 2. Summary bioaerosol results.

Measured transmission

Initial assessment of transmission of crawl space air and its contaminants, including mold spores and moisture vapor, into the living space was determined to be present if two conditions held true. First, the concentration of the mold samples had to be higher in the living space once the HVAC system was turned on compared to the level of spores with the HVAC system off. Second, the mix and rank order of the indoor samples with the HVAC system running shifted to reflect the dominant mold species present in the crawl space sample and the rank order of species was different from the outdoor sample. If only one condition held, the house was classified as "transmission not detectable", and if neither condition held true, the house had no transmission.

Transmission of air and its contaminants was possible in 21 (47%) of the houses characterized. In ten (22 %) houses, transmission was not detectable, or rather, only one of the two conditions held true. No transmission was found in 14 (31%) of the houses.

Measured holes between the crawl space and living space

Three leakage paths were measured: total house air leakage, air leakage between the living space and the crawl space and air leakage between the HVAC duct system and the crawl space. See Table 3 for total house leakage testing documented.

CFM 50 per ft^2 of surface area *	$M^3/h/m^2$ at 50 Pascals	Classification	Percent of houses tested
<0.25	<4.6	Minimal	0
0.26-0.45	4.7-8.2	Limited	24
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
* Cubic Feet per minute at 50 Pascals			

Table 3. Measured house leakage.

The majority of the homes (69%) had 11% and 30% of the total house air leakage coming from the crawl space. The measured leakage between the HVAC duct system and the crawl space are shown in Table 4. Five homes were not classified for this test because they were unable to reach their target pressure.

CFM 25 per ft^2 of conditioned floor area as a percentage	$M^3/h/m^2$ at 25 Pascals	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

Table 4. Classification of duct leakage.

See Table 5 for the mean equivalent hole size for air leakage across the floor between the house and crawl space and house duct system and crawl space.

Equivalent hole size in ft^2 (m^2)	Mean	High	Low	NA*
House to crawl space	0.5 (0.046)	2 (0.19)	0.0	
Crawl space ducts	0.4 (0.04)	1.5 (0.14)	0.1 (0.01)	2
*NA indicates numerical data could not be calculated due to difficulty in reaching target pressure.				

Table 5. Equivalent hole size by location.

CONCLUSION

This study, conducted during typical 12-month conditions, documents moisture characteristics of typical wall-vented crawl spaces in the southeastern United States and measures the impact on living space mold sources. In some situations, the use of foundation vents to dry a crawl space may cause additional moisture. Of the houses in this study:

- 49% had moisture-induced wall discoloration
- 62% had visible mold growth
- 67% had wood moisture meter readings at mold-supporting levels
- 36% had wood moisture meter readings at wood rot-supporting levels

Indoor air quality is compromised when moisture conditions exist in combination with air leakage between the house and crawl space and between the HVAC duct system and crawl space, as mold species can be delivered into the house through the air leaks. Therefore, both a moisture management strategy for the crawl space and an air sealing plan to reduce house and duct leakage should be incorporated into new and existing homes.

To demonstrate a protocol that will eliminate crawl space moisture problems and stop the total air leakage between the house and the crawl space, Advanced Energy also tested an intervention protocol on 12 similar-sized homes in southeastern United States. This intervention study compared the standard vented crawl space design with a closed crawl space design. The closed crawl space design included a sealed ground vapor retarder that extended up the perimeter walls of the crawl space, air-sealed the perimeter wall between the crawl space and outside, air-sealed penetrations between the house and the crawl space, provided a source of conditioned air to the crawl space and monitored the results [3]. The data from this study demonstrated that this closed crawl space protocol is a robust measure producing substantially drier crawl spaces (reducing conditions for mold, wood decay and insects). The data also demonstrated reduced house space conditioning energy use by 15% to 18% annually as compared to the standard vented crawl space houses. Utilizing the results of these studies, we then created a study with 36 new houses to validate the improved energy, moisture and indoor air quality performance of the closed crawl space protocol established above compared to traditionally vented crawl spaces. See conference paper entitled FORMALDEHYDE AND RELATIVE HUMIDITY IN HIGH-PERFORMANCE HOMES WITH OUTDOOR AIR INTAKES AND EXHAUST VENTILATION.

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