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Vented Crawl Spaces as Mold Amplification and Delivery Systems?

Measured Performance and a Dry Alternative

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Vented Crawl Spaces as Mold Amplification and Delivery Systems? Measured Performance and a Dry Alternative

ABSTRACT

Researchers tested hypotheses that traditional wall-vented crawl spaces in the southeastern United States contain moisture levels that support mold growth, insects and rot and contain adequate duct leakage to create pathways for transmission of mold from crawl spaces to the living space. Fungal air sampling was conducted indoors, outdoors and in the crawl spaces of forty-five vented crawl space houses. Air leakage testing determined the connections between the house, crawl space, and HVAC systems located in the crawl space. The relative contribution of crawl spaces mold species and species found outdoors and in the homes' living spaces were compared. The results indicate that typical wall vented crawl spaces contain liquid water, moisture vapor, and fungal spores. The houses also contain measureable holes between the crawl space and living space. They further contain natural and mechanical forces that drive air across the holes. Results comparing fungal species in the home, crawl space and outoors show transmission of fungal spores from the crawl space to the living space. High moisture levels in vented crawl spaces in the southeastern United States were linked to high mold counts inside the living space.

In parallel research, the study team tested a closed crawl space configuration designed to bring the crawl space moisture load to an acceptable level. The configuration included sealed foundation wall vents, a sealed polyethylene film liner and 1 CFM (0.5 L/s) of HVAC supply air for each 30 ft2 (2.8 m2) of ground surface. The study was conducted at 12 identical-floor plan houses co-located in the southeastern United States. Comparative moisture measurements for these crawl spaces and sub-metered heat pump kWh use demonstrated that the closed crawl space protocol produced substantially drier crawl spaces, reducing conditions for mold, wood decay and insects. It also reduced space conditioning energy use by 15 percent to 18 percent annually.

INTRODUCTION

Building codes often require foundation vents to allow air exchange between the crawlspace and outdoors in order to provide a drying mechanism for crawl spaces. However, in the southeastern United States, where moisture content of outdoor air in summer often exceeds that of crawl space air, the outdoor air does not act as drying mechanism when introduced into the crawl space. (Davis and Dastur, 2004). Builders, insulators and other contractors often receive complaints about moisture conditions in crawl spaces. Hardwood floor installers often experience dissatisfied customers when floors cup or buckle. (Davis and Dastur, 2004). Further, the literature suggests strong association between building mosture and detrimental health outcomes, including asthma (Institute of Medicine, 2004). Approximately 20% of new homes in the United States (200,000 per year) are built on vented crawl space foundations and an estimated 26 million existing homes have vented crawl space foundations.[*]

[*] Data provided by National Association of Homebuilders, Washington D.C., 2005.

CHARACTERIZING FUNGAL LEVELS AND TRANSMISSION PATHWAYS TO THE LIVING SPACE.

This research demonstrated that there are pathways and driving forces sufficient to cause the transmission of pollutants from the crawl space to the occupied space in a sample of forty five homes in North Carolina. Homes were selected for this study during the summer of 2004. They ranged in age from 2 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).

CHARACTERIZATION PROTOCOL

A characterization protocol was applied to each home to identify:

- pathways between the house and crawl space through which air contaminants could be transmitted
- driving forces to accomplish the transmission
- the thermal and moisture profile associated with each ventilated crawl space.

Each element of the protocol is described in the following sections of this paper.

Building pressure diagnostics

On initial site visits in summer 2004, we conducted air leakage and zone pressure testing to quantify the cross-sectional area of airflow pathways, or "holes". Air leakage consists of infiltration or exfiltration depending on the pressures in an individual house. 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. We used a multi-pressure testing system set up with two house depressurization systems and one duct depressurization system. Software recorded the data generated by the multi-pressure testing system at each of three house systems:

1) house envelope leakage measuring system
2) crawl space to house leakage measuring system
3) HVAC duct leakage measuring system.

We tested the following pressures in sequence:

Test 1) Baseline-HVAC system off, all windows and doors closed
Test 2) House envelope leakage test only
Test 3) House, crawl space and duct leakage measuring systems run together
Test 4) House and duct leakage measuring systems run together
Test 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. 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

During the crawl space characterization visit, data loggers were installed in each crawl space. These loggers record hourly temerature and relative humidity and calculate dew point. Data was collected to make observations about long term trends from October 15, 2004 through September 5, 2005.

Mold Species Sampling

In each home, at least two sets of air samples were taken during the test using a Wilcoxon 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 1.06 CFM (0.5 L/s). 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. After sampling, the culture plates were incubated at ambient temperature for 96 hours. Mold identification was accomplished by macroscopic examination of colony morphology and microscopic examination of fungal elements.

Discussion and 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. The open vents demonstrate that houses are experiencing the ventlation intended by the building code.

Moisture

The crawl spaces contained liquid water indicating current moisture load and also evidence of recent moisture accumulation. In 29% of the homes, the ground vapor retarder had visible condensation present. Duct and plumbing systems located in the crawl spaces provided cold surfaces for condensation: 27% had damp ducts and 8% had damp water pipes. 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. Wood moisture conditions conducive to mold growth and wood rot were found in 67% of houses studied.

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

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

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%

Measured holes between the crawl space and living space

We identified measurable holes between the crawl space and home, thus documenting a pathway for contaminants to move from the crawl space to the living space. The average equivalent hole size measured between the crawl space and the occupied parts of the house was 72 inch² (464 cm²) shown in Table 2. The average equivalent hole size was determined by recording the sequential pressure testing noted above in the Building Pressure Diagnostics section. After performing the baseline, we tested for house envelope leakage using Test 2, which provided us with the total leakage for the entire building envelope. Next**,** we performed Test 3 and then Test 4 to determine what percentage of the air flow of Test 2 came from each of these three components.

Table 2.
Equivalent hole size by location.

Equivalent hole size ($cm^{2)}$	**Mean**	**Median**	**High**	**Low**	**NA***
House to crawl space	73 (464)		288 (1858)	0.0	
Crawl space ducts	58 (371)		216 (1393)	14 (93)	2 houses

*NA indicates numerical data could not be calculated due to difficulty in reaching target pressure.

The majority of the homes (69%) had 11% to 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 3. Five homes were not classified for this test because they were unable to reach their target pressure.

Table 3.
Measured duct leakage and classification.

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

The majority of the houses (72 %) tested had moderate, excessive, or major air leakage. Table 4 shows results of house leakage testing.

Table 4.
Measured house leakage.

CFM 50 per ft2 of surface area*	M3/h/m2 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

One driving force for air leakage includes the mechanical force of the HVAC system moving air. Building physics is another driving force, in which warm air in the house rises and exits through holes in the ceiling and upper walls. Cool air is then drawn through holes in the floor and lower walls, bringing contaminants from the crawl space and outdoors.

Measured Fungal Transmission

To examine whether mold is being transmitted between crawl space and living space, we compared fungal counts in the living space with the HVAC system on and off. We then classified the relative levels as follows:

1) Was the concentration of the mold samples higher in the living space once the HVAC system was turned on compared to the level of spores with the HVAC system off?

2) Was 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 was the rank order of species different from the outdoor sample?

If these two conditions held true, we determined that fungal contaminants from the crawl space were being transmitted into the living space. 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 21 (47 %) of the houses characterized, showing fungal transmission occuring from crawl space to living space. In 10 (22 %) houses, transmission was not detectable or only one of the two conditions held true. No transmission was found in 14 (31 %) of the houses.

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 and the most common species of mold in this region: Cladosporium, Aspergillus, and Penicillium. An "other" grouping was also examined to ensure a complete picture of fungal levels.

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 house to crawl.

Table 5.
Summary Fungal Count Results.

Sample	# Houses	Mean	Std. Dev.	Max	Min
Transmission possible	**In CFU/m3**				
Crawl space (HVAC off)	21	30163	16230	41146	1348
Indoor (HVAC off)	21	861	1233	5802	146
Outdoor	21	3235	3862	11756	349
Indoor (HVAC on)	21	1761	2425	11756	373
Diffuser (HVAC on)	21	1822	2607	11756	166
Transmission not detectable	**In CFU/m3**				
Crawl space (HVAC off)	10	161	508	1607	0
Indoor (HVAC off)	10	55	173	548	0
Outdoor	10	2033	2524	8418	40
Indoor (HVAC on)	10	176	556	1759	0
Diffuser (HVAC on)	10	1415	2282	11756	0
No transmission	**In CFU/m3**				
Crawl space (HVAC off)	14	16041	15144	41146	105
Indoor (HVAC off)	14	1323	3045	11756	71
Outdoor	14	3427	4630	11756	146
Indoor (HVAC on)	14	645	765	3219	124
Diffuser (HVAC on)	14	556	1101	4326	71
All homes	**In CFU/m3**				
Crawl space (HVAC off)	45	19102	18179	41146	0
Indoor (HVAC off)	45	825	1911	11756	0
Outdoor	45	3027	3836	11756	40
Indoor (HVAC on)	45	1061	1837	11756	0
Diffuser (HVAC on)	45	1062	2011	11756	0

Figure 1 displays the bioaerosol levels for houses with the possibility of transmission. Figure 2 illustrates bioaerosol levels for all houses by location.

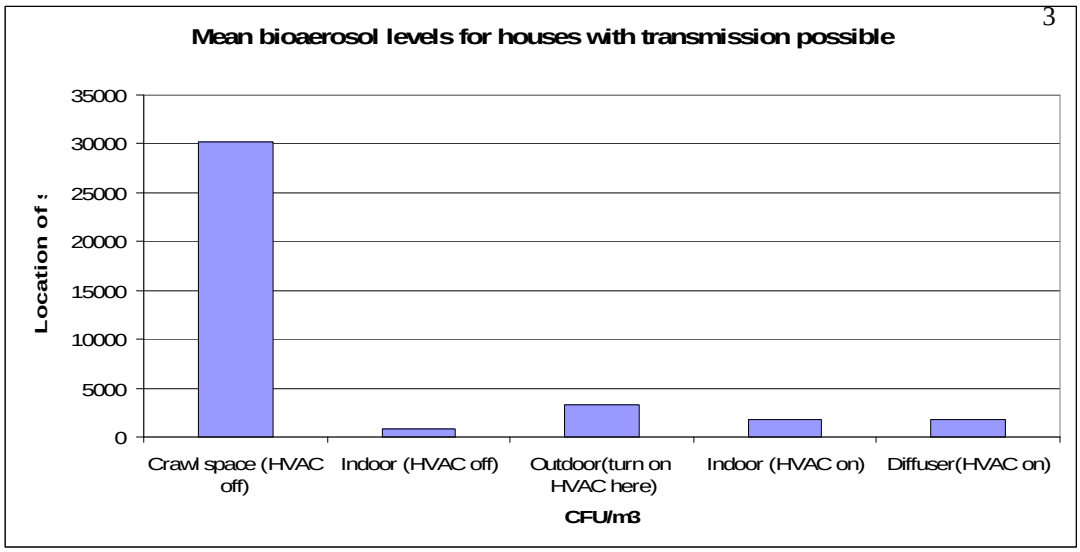
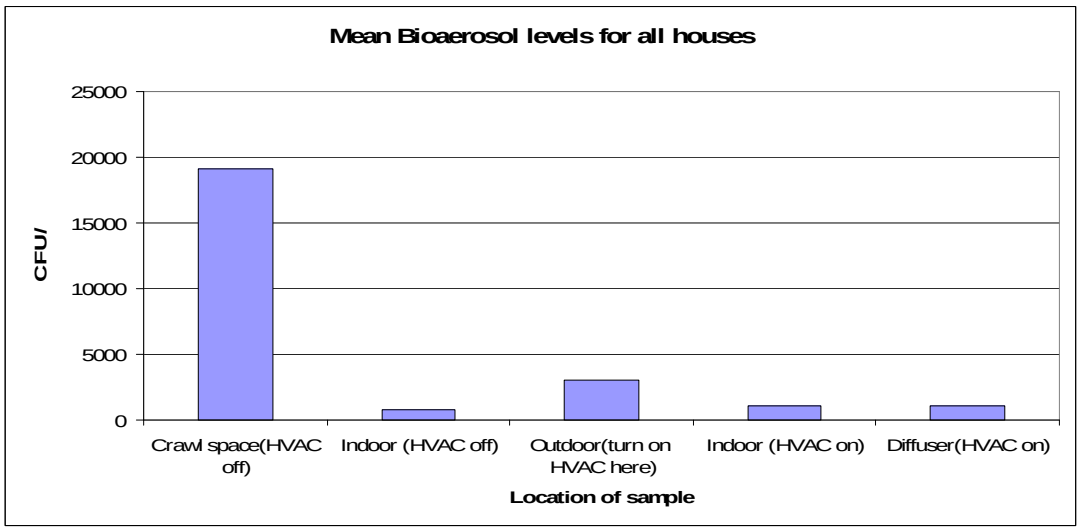


Figure 1 . Mean bioaerosol levels for houses where transmission possible.

Figure 2. Mean bioaerosol levels of all houses



THE CLOSED CRAWL SPACE SOLUTION

In previously published research, the authors have demonstrated a solution for dry crawl space construction techniques in the Southeast. (Davis and Dastur, 2004). The study demonstrated that houses built on what we refer to as "closed" crawl spaces will be notably drier, support less mold growth, and surprisingly are more energy efficient than houses built over vented crawl spaces. The intervention was tested on 12 similar sized homes in southeastern United States. It 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, and provided a source of conditioned air to the crawl space.

The data demonstrated that the closed crawl space protocol is a robust measure producing substantially drier crawl spaces thus reducing conditions for mold, wood decay, and insects. In the summer seasons closed crawl spaces generally maintained below 60% relative humidty on 24 hour average. In the wall-vented crawl sapces the 24 hour average was often above 80% relative humidity. For instance, during summer 2003, the closed crawl space houses spent 5% of their time above 70% relative humidity, while vented crawl spaces spent 98% of their time at that level. In that same summer, closed crawl spaces spent no time above 80% relative humidity, where the vented crawl spaces spend 86% of the time above 80% relative humidity.

The data also demonstrated reduced house space conditioning energy use by 15% to 18% annually as compared to the standard vented crawl space houses.

SUMMARY AND CONCLUSIONS

The 12 month study of typical southeastern US houses documents that wall-vented crawl spaces are a reservoir for mold and moisture.

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. While fungal transmission between house and crawl space was specifically measured in 47% of the houses in this study, pressure-driven airflow is a risk in all these houses because of its ability to transmit other pollutants such as moisture, carbon monoxide (from water heaters or furnaces), volatile organic compounds from lawn mowers, stored pesticides, and stored paint.

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. The closed crawl space solution provides both, and does so in an energy-efficient manner.

Utilizing the results of these studies, the authors designed a study of 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. While not yet published, the early results indicate similar energy savings, similar moisture control and durability in the crawl spaces. While closed crawl space technology reliably maintains the desired range of relative humidity in the crawl space, indications are that it has not significantly influenced the relative humidity in the home compared to homes in the same study built on vented crawl space foundations. Results from this study will be available in Fall of 2007.

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