Vented and Conditioned Crawlspace Performance in Marine and Cold Climates of the Pacific Northwest

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ABSTRACT

Vented and conditioned crawlspaces in the marine and cold climates of the Pacific Northwest are evaluated. Temperature, relative humidity, wood moisture content, dew point, radon levels, and air change rates were monitored for up to 2 years. Four new homes in each climate zone were constructed to International Residential Code standards. Homes were configured with vented and conditioned crawlspaces, with and without duct systems located in the crawlspaces.

Testing showed that roughly 40% of the house air entered from the vented crawlspace. Power-venting a conditioned crawlspace reversed the stack effect, to where less than 6% of the house air was entering from the crawlspace. Air change rates between the crawlspace and the outside were roughly 4 times higher in vented crawls, providing significantly higher dilution rates for potential pollutant sources.

Temperatures were higher and more stable in the conditioned crawls; wood moisture and relative humidity were lower. While more variable, conditions in the vented crawlspaces rarely reached dew point or exceeded acceptable levels. Radon levels in the conditioned crawlspaces were roughly three to ten times the level of the vented crawlspaces.

Implications for indoor air quality, duct placement in crawlspaces, and overall performance in heating-dominated climates are discussed.

BACKGROUND

Traditional vented crawlspaces dominate the new construction market in the maritime and cold-climate regions of Washington state and the Northwest. Interest from builders in the region in conditioned crawlspaces has been on the rise because of national publicity for systems built and evaluated primarily in the hot, humid climates of the Southeast. Research reports of both improved energy performance and indoor air quality have been published (Davis et. al. 2005). The Washington State Energy Code (WSEC) has emphasized insulating floors over vented crawlspaces, and only a few jurisdictions have allowed conditioned (unvented) crawlspaces with insulation at the perimeter wall.

There have also been concerns in the region about central forced-air system distribution losses with ductwork often located out side the conditioned envelope of the house. Conditioned crawlspaces were suggested as one pathway to reduce the impact of duct system losses by extending the conditioned envelope around ductwork in the crawlspace.

TECHNICAL APPROACH

Monitored data, including temperature, relative humidity, wood moisture content and radon levels, was collected over a period of about 18 months. Additional testing was done using the Brookhaven air infiltration measurement system, with equipment provided by and analysis performed by Brookhaven National Lab (Dietz 2000) (PFT testing) in the marine-climate homes during a 30 day period in November. The study was focused on both marine climate (IECC climate zone 4a) and cold climate (IECC climate zone 5). In each climate, four homes were built to Energy Star Northwest standards (NEEA 2010).

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Table 1. Crawlspace Configurations

House #	Climate	Crawlspace	Ducts in Crawl?
1	Marine	Conditioned*	Yes
2	Marine	Conditioned*	No
3	Marine	Vented	Yes
4	Marine	Vented	No
5	Cold	Conditioned*	Yes
6	Cold	Conditioned*	No
7	Cold	Vented	Yes
8	Cold	Vented	No

*All conditioned crawlspaces in this study were configured as power-vented crawlspaces with exhaust fans moving air from the crawlspace to the exterior at a continuous rate of 50 cfm (1.4 m^3/min) in accordance with *IRC Standard 408.3-2004*.

In each climate zone, two homes had conditioned crawlspaces; one with ducts in the crawl, one without. Two homes had traditional vented crawlspaces; one with ducts in the crawl, one without. In compliance with IRC 408.2 and WSEC 502.1.6.7, all vented crawlspaces had 1 to 150 ratio of net free vent area to crawlspace area and 6 mil poly vapor barriers (ICC 2006; SBCC 2007a). The builders varied in their approach to the conditioned crawls, as noted below. Long-term monitoring of temperature and relative humidity was conducted in the crawlspaces and living area of the homes. Moisture content of the structural wood was monitored in all eight crawlspaces. Monitoring started as the homes were completed before the homes were occupied and continued after occupancy. One of the marine-climate homes remained unoccupied during the entire monitoring period.

Marine-Climate Homes

New Tradition Homes, a Building America partner builder, built four spec homes in Vancouver (Clark County), Washington (US DOE 2007). The New Traditions homes are three-bedroom, two-story 2200 ft^2 (204 m^2) homes with a roughly 15% -window-to-floor area ratio.

Conditioned crawlspaces had R-15 (0.38 W/m^2K) interior extruded polystyrene perimeter insulation, were finished with concrete floor slabs, had passive radon vent stacks as required by the section 503 of the Washington State Ventilation and Indoor Air Quality Code (SBCC 2007b), and were power-vented according to IRC R408.3, except without an air pathway to common areas. During the study period, all the conditioned crawlspaces were continuously power-vented at a rate of 50 cfm (1.4 m^3/min) exhausted from the crawlspace to the exterior.

Cold-Climate Homes

Condict Homes built the four cold climate homes in Grant County Washington. The Condict homes are 1550 ft^2 (144 m^2) ranch-style models, with less than 10% glazing.

Table 2. House Characterizations

House #	Average Interior Temp. °F (°C)	Average Interior % RH	ACH50 House	Duct Leakage to Exterior CFM50*
1	69.5 (20.8)	41.1	4.7	130
2	70.7 (21.5)	38.9	3.3	32
3	69.7 (20.9)	43.6	3.4	95
4	67.5 (19.7)	39.0	3,7	45
5	68.4 (20.2)	42.4	3.7	25
6	68.6 (20.3)	39.8	4.3	25
7	70.5 (21.4)	39.8	3.7	65
8	69.9 (21.1)	38.4	4.6	25

*All systems were tested to be in compliance with the Energy Star Homes Northwest standard with less than 6% of the conditioned floor area of total duct leakage at 50 Pa.

The Condict insulated crawlspaces used batts with a vapor barrier on the inside; the crawlspace floor was dirt covered with 6 mil poly. This approach is similar to a retrofit effort undertaken by the local utility, Grant County PUD, where the perimeter vents were sealed while the perimeter was insulated with vinyl-faced batts known as metal building insulation (MBI). The conditioned crawlspaces in the cold climate houses were not power-vented.

The crawlspace configurations are characterized in Table 1. Additional house characterization is provided in Table 2.

DATA SUMMARY

Tracer Gas (PFT) Testing

Air change rates were determined between the crawlspace and the exterior, the crawlspace and the house, and the house to exterior for each marine site for the period from 11/7/2007 to 12/7/2007. During the PFT tracer gas testing, the two conditioned crawlspaces were power-vented to the exterior with the continuous operation of 50 cfm exhaust fans. The air pathway from the crawlspace to common areas (as stipulated in the IRC) was not provided in order to better decouple the crawlspace from the occupied areas of the house. Results of the PFT testing are shown in Table 3.

Radon

Radon monitoring was conducted in both the living areas and the crawlspaces. Clark County, where the marine test houses are located, is considered a high-risk radon area; as such, the crawlspaces had passive radon vent stacks installed in compliance with section 503.2.6 of the Washington State Ventilation and Indoor Air Quality Code (SBCC 2007b). Grant County is not considered a high-risk radon area, but passive radon vent stacks were installed. Short-term monitoring of the living areas showed no radon levels above the EPA action level

Table 3. Marine Climate Tracer Gas (PFT) Results

House	Crawlspace to House m^3/h (ft^3/h)	% of House Air from Crawl	House to Crawl m^3/h (ft^2/h)	% of Crawl-space Air from House	Total Flow Crawl m^3/h (ft^3/h)	ACH Crawl	Total Flow House m^3/h (ft^3/h)	ACH House
1	8.6 (304)	6.0	17.2 (607)	21.6	79.5 (2807)	1.26	142.5 (5032)	0.26
2	8.1 (286)	4.6	11.1 (392)	13.6	81.4 (2875)	0.87	175.4 (6194)	0.30
3	40.5 (1430)	39.3	1.7 (60)	0.7	230.9 (8154)	3.67	103.0 (3637)	0.18
4	38.4 (1356)	42.7	0.1 (3.5)	0.03	323.4 (11421)	3.45	89.9 (3175)	0.15

Table 4. Radon Levels in Crawlspace

House #	Climate	Crawlspace	Ducts in Crawl?	Radon Level, pCi/L
1	Marine	Conditioned	Yes	13.9
2	Marine	Conditioned	No	11.9
3	Marine	Vented	Yes	1.0
4	Marine	Vented	No	1.9
5	Cold	Conditioned	Yes	16.5
6	Cold	Conditioned	No	12.4
7	Cold	Vented	Yes	5.7
8	Cold	Vented	No	4.5

of 4 pCi/L (EPA 2010). Results of long-term monitoring (1-year test) in the crawlspaces are shown in Table 4.

Wood Moisture Content

Wood moisture content in the crawlspaces was monitored using 3/4 in. × 3 1/2 in. × 6 in. (19 mm × 89 mm × 152 mm) pine blocks. Multiple blocks were suspended in the crawl-spaces for the duration of the monitoring and periodically weighed. At the end of the monitoring period, the blocks were dried in an oven until they reached a steady-state weight (approximately 24 h at 220°F [104°C]). Results for the marine and cold-climate crawlspaces are shown in Figures 1 and 2, respectively.

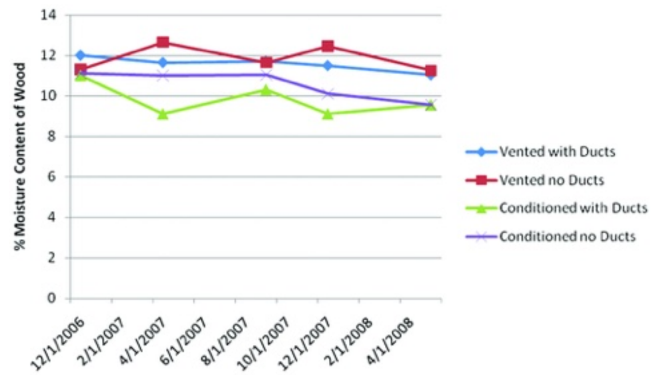


Figure 1 *Marine-climate crawlspace wood moisture content.*

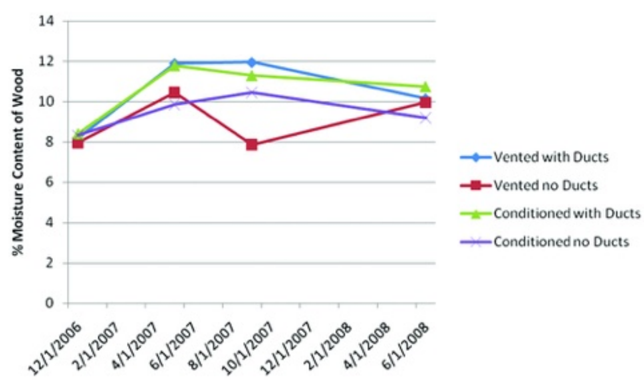


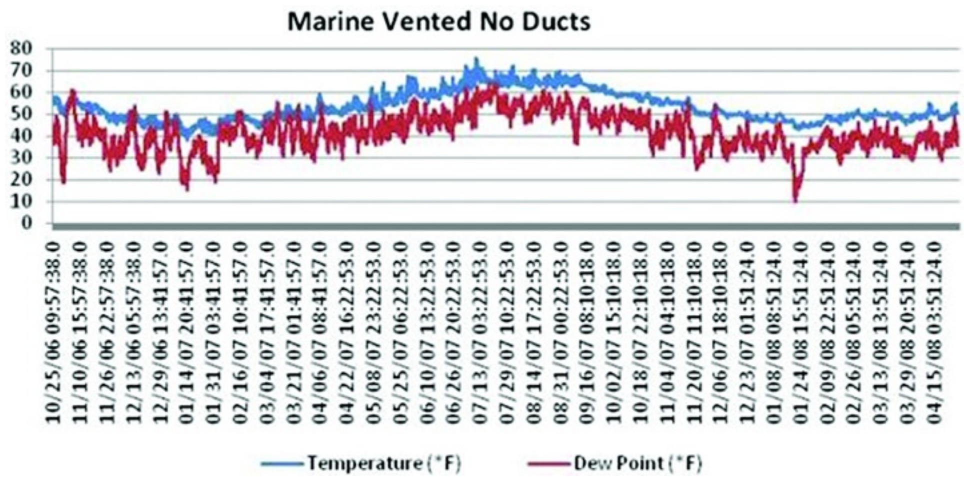
Figure 2 *Cold-climate crawlspace wood moisture content.*

Temperature and Relative Humidity

Continuous monitoring of temperatures and relative humidity took place for the crawlspaces, the occupied areas of the houses, and outside ambient conditions. Data were collected at 60-minute intervals with HOBO H8 series loggers. Overall, the conditioned crawlspaces showed more stable conditions, with higher average temperature and lower relative humidity than the vented crawlspaces. Dew-point conditions were never reached in the conditioned crawlspaces and were only seen rarely as a transient condition in the vented crawlspaces. Figures 3 through 6 are from the marine climate. Figures 7 through 11 are from the cold climate.

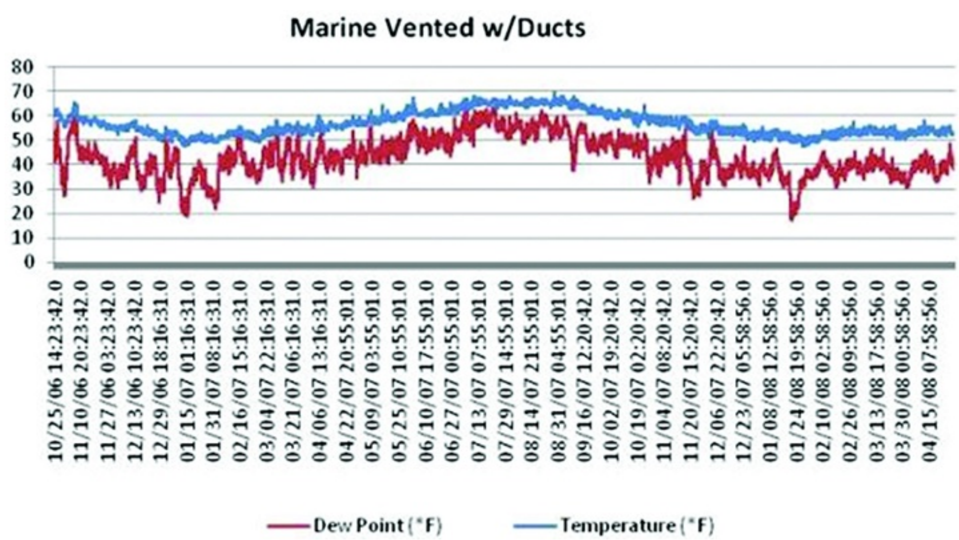
The figures for each crawlspace also include the average temperature; minimum and maximum temperature; average difference between crawlspace temperature and dew point; percentage of time crawlspace temperatures were at dew point; percentage of time crawlspace relative humidity was above 80%; and average relative humidity.

In the cold climate, additional temperature and relative humidity measurements were made in the crawlspace perim-eter wall insulation. Sensors were buried in the fiberglass batt insulation between the exterior concrete stem wall and the interior vapor retarder, about 16 in. above the footing and 16 in. below the top of the stem wall (see Figure 11).



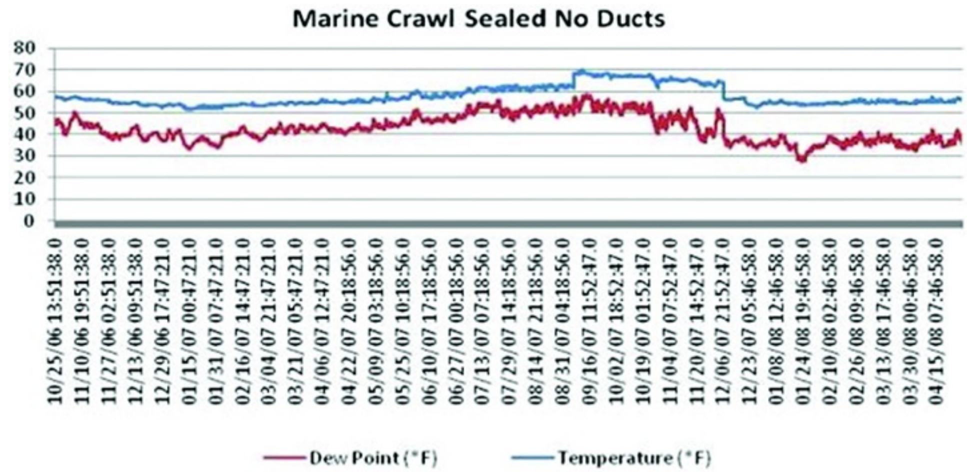
Avg. Temp., °F (°C)	Min. Temp., °F (°C)	Max. Temp., °F (°C)	Avg. Temp. Above DP, °F (°C)	%Time at DP	%Time Above 80%RH	Avg. %RH
53.4 (11.9)	38.0 (3.33)	75.9 (24.4)	11.7 (6.5)	0.58	9.0	65.3

Figure 3 *Temperature and relative humidity, marine vented crawlspace, no ducts in crawlspace.*



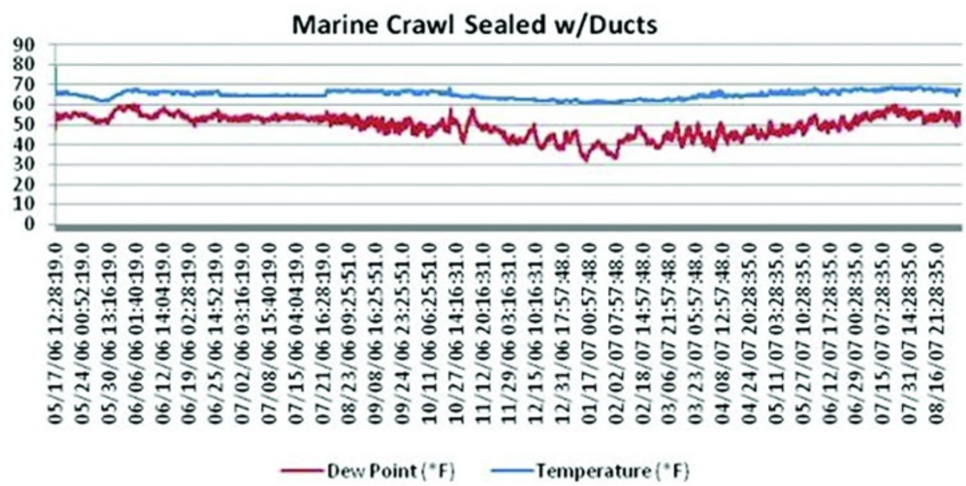
Avg. Temp., °F (°C)	Min. Temp., °F (°C)	Max. Temp., °F (°C)	Avg. Temp. Above DP, °F (°C)	%Time at DP	%Time Above 80%RH	Avg. %RH
56.7 (13.7)	47.5 (8.6)	69.7 (20.9)	13.7 (7.6)	0.015	3.5	60.8

Figure 4 *Temperature and relative humidity, marine vented crawlspace, ducts in crawlspace.*



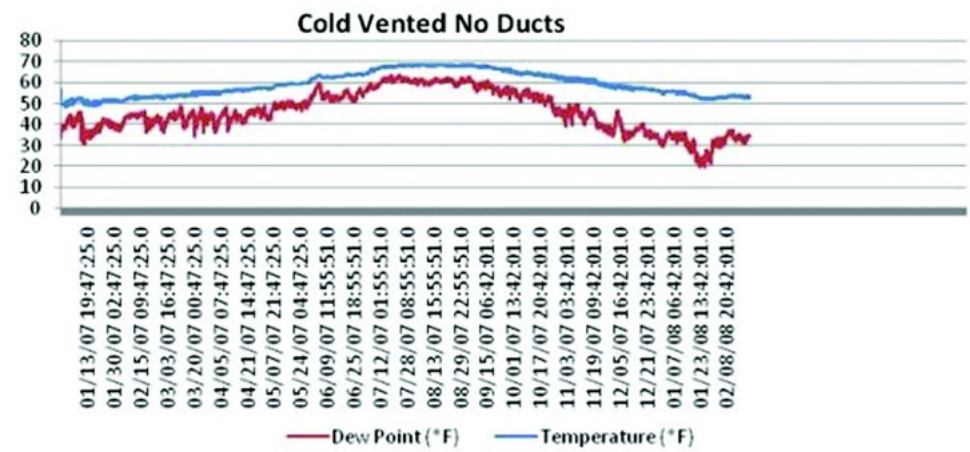
Avg. Temp., °F (°C)	Min. Temp., °F (°C)	Max. Temp., °F (°C)	Avg. Temp. Above DP, °F (°C)	%Time at DP	%Time Above 80%RH	Avg. %RH
57.9 (14.4)	51.8 (11.0)	70.4 (21.3)	15.1 (8.4)	0	0	57.6

Figure 5 *Temperature and relative humidity, marine sealed crawlspace, no ducts in crawlspace.*



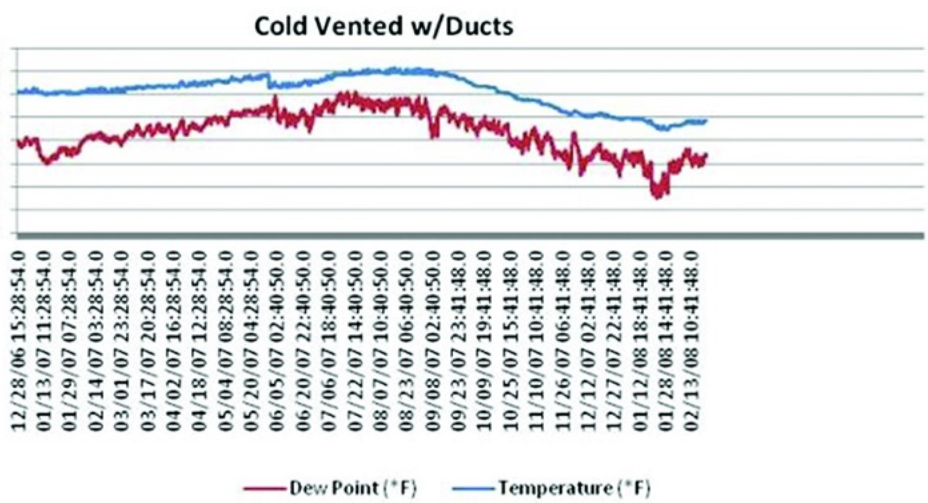
Avg. Temp., °F (°C)	Min. Temp., °F (°C)	Max. Temp., °F (°C)	Avg. Temp. Above DP °F(°C)	%Time at DP	%Time Above 80%RH	Avg. %RH
64.7 (18.2)	60.1 (15.6)	78.7 (25.9)	15.3 (8.5)	0	0	54.8

Figure 6 *Temperature and relative humidity, marine sealed crawlspace, ducts in crawlspace.*



Avg. Temp,. °F (°C)	Min. Temp., °F (°C)	Max. Temp., °F (°C)	Avg. Temp. Above DP, °F (°C)	%Time at DP	%Time Above 80%RH	Avg. %RH
59.1 (15.0)	48.3 (9.1)	68.3 (20.2)	12.8 (7.1)	0	4.2	63.9

Figure 7 *Temperature and relative humidity, cold vented crawlspace, no ducts in crawlspace.*

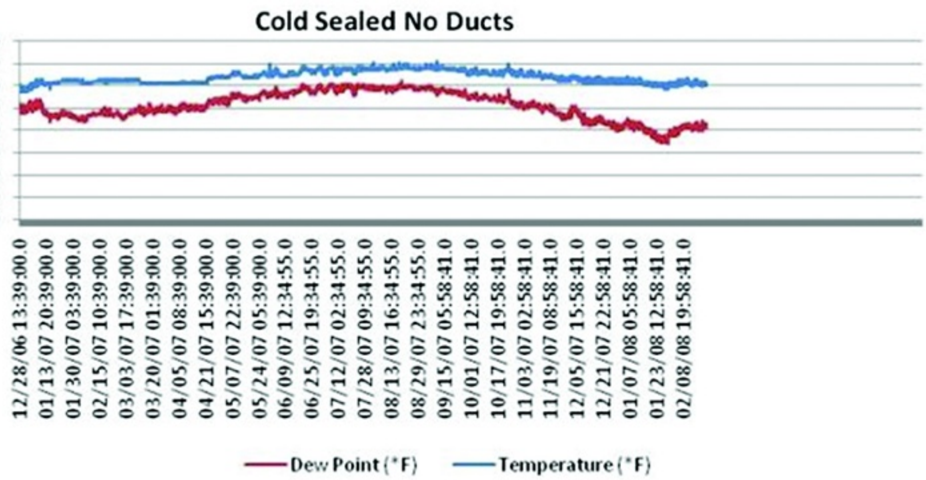


Avg. Temp., °F (°C)	Min. Temp., °F (°C)	Max. Temp., °F (°C)	Avg. Temp. Above DP °F (°C)	%Time at DP	%Time Above 80%RH	Avg. %RH
61.0 (16.1)	44.7 (7.1)	71.8 (22.1)	17.5 (9,7)	0	.09	53.0

Figure 8 *Temperature and relative humidity, cold vented crawlspace, with ducts in crawlspace.*

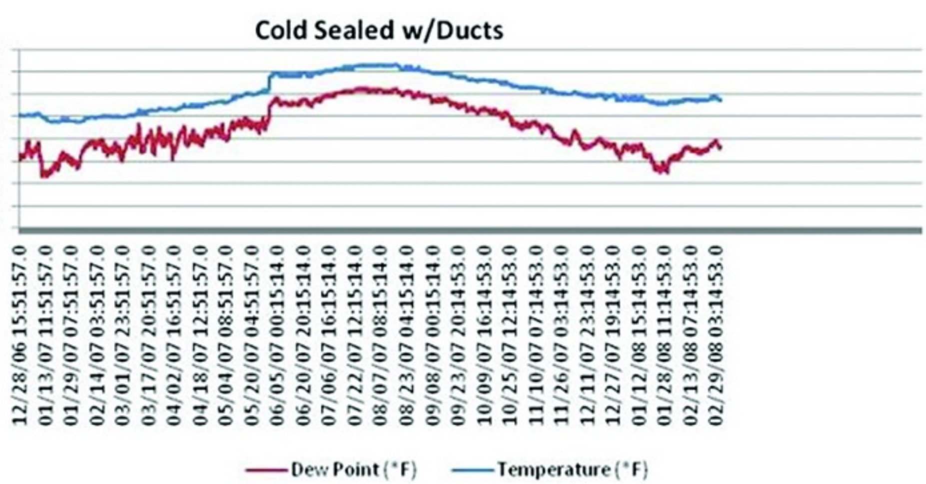
ANALYSIS

Air Change Pathways



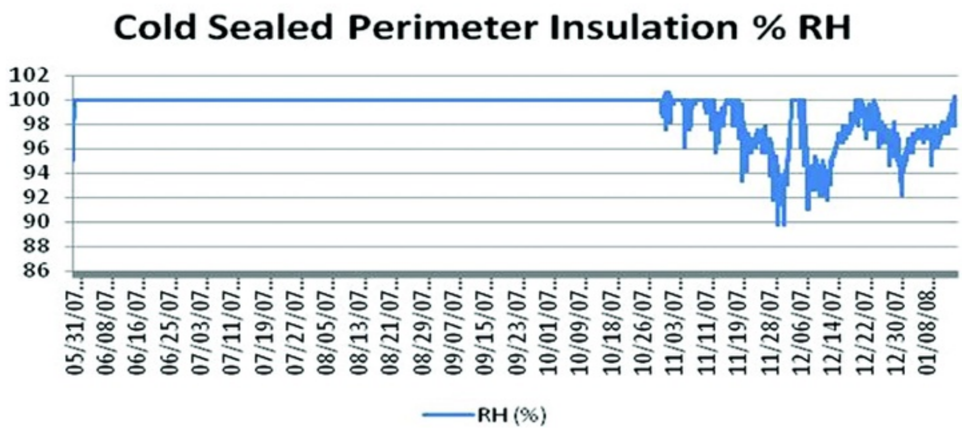
Avg. Temp., °F (°C)	Min. Temp., °F (°C)	Max. Temp., °F (°C)	Avg. Temp. Above DP, °F(°C)	%Time at DP	%Time Above 80%RH	Avg. %RH
64.0 (17.8)	57.4 (14.1)	71.1 (21.7)	12.8 (6.6)	0	.01	63.7

Figure 9 *Temperature and relative humidity, cold sealed crawlspace, no ducts in crawlspace.*



Avg. Temp., °F (°C)	Min. Temp., °F (°C)	Max. Temp., °F (°C)	Avg. Temp. Above DP, °F (°C)	%Time at DP	%Time Above 80%RH	Avg. %RH
60.6 (15.9)	47.5 (8.6)	73.8 (23.2)	16.1 (9.1)	0	0	56.1

Figure 10 *Temperature and relative humidity, cold sealed crawlspace, with ducts in crawlspace.*



Avg. Temp., °F (°C)	Min. Temp., °F (°C)	Max. Temp., °F (°C)	Avg. Temp. Above DP, °F (°C)	%Time at DP	%Time Above 80%RH	Avg. %RH
60.4 (15.8)	45.4 (7.4)	71.1 (21.7)	0.2 (0.11)	90.8	100	99.1

Figure 11 *Relative humidity, cold sealed crawlspace perimeter.*

The choice was made to power-vent the conditioned crawlspaces after preliminary analysis in the marine-climate homes indicated that this showed the greatest potential to decouple the house from the crawlspace. The marine-climate houses with conditioned crawlspaces were constructed with supply vents in the crawlspace and a passive return back to the house, in addition to the power vent fans. Modeling results indicated a possible energy penalty, which would be increased with added heat to the crawlspace (Lubliner et al. 2007). The passive return only made it more difficult to run the crawlspace at a negative pressure with respect to the house. Consequently, the supply vents to the crawlspace and the passive vents back to the house were sealed for the entire test period.

As indicated from the tracer gas results, the conditioned crawlspaces showed a significant reduction in air entering the living space from the crawlspace, as shown in Figure 12. With power-vented conditioned crawlspaces, about 5% of the house air originated in the crawlspace; with vented crawlspaces, the number climbed to roughly 40%.

This benefit is dependent on continuously operating a crawlspace exhaust fan, and is lost if the fan fails. Without power venting, there is a concern about increased pollutant concentrations because of reduced dilution. Radon levels in the conditioned marine crawlspaces averaged 12.9 pCi/L. This level is almost nine times the 1.45 pCi/L average in the vented crawlspaces, and more than three times the EPA action level for exposure in homes. The elevated radon levels in the conditioned crawlspaces appear to be attributable at least in part to two factors: (1) the lower dilution rate, around 1 ACH for the conditioned crawlspaces compared to around 3.5 ACH in the vented crawlspaces as seen in the tracer gas testing, and (2) a higher entrainment rate because the conditioned crawlspaces were power-vented and operated at a negative pressure (marine climate only). No tracer gas testing was conducted on the cold-climate homes, but the tested radon levels were roughly three times greater in the conditioned crawlspaces than the vented crawlspaces. The greater difference in the marine crawlspaces may be attributable to the power venting. When the crawlspace is put under negative pressure, one would expect to increase the rate of entrainment and at least partially negate the benefit of the passive radon vent.

None of the occupied areas of the houses showed elevated radon levels, but only short-term testing (one week) was done in the living areas at the beginning of the monitoring. The concern remains that, if the conditioned crawlspaces are constructed in an alternative manner or with a passive air path to the house as required by the IRC, then a power-venting failure may leave homes vulnerable to higher rates of entrainment of radon and other pollutants found within the crawlspaces.

Water Intrusion

An attempt was made to evaluate the drying potential after a moisture event in the crawlspaces. Small 5 ft diameter “kiddie” pools were set up and filled with 3 in. (76 mm) of water. Monitoring did not detect any changes in relative humidity even when 2 pools failed and spilled all the water onto the floor of the crawlspaces. Evaporation rates were low and apparently below the level needed to simulate a significant moisture event. Both the conditioned and vented crawlspaces appear to be able to absorb small water events with no observable consequences.

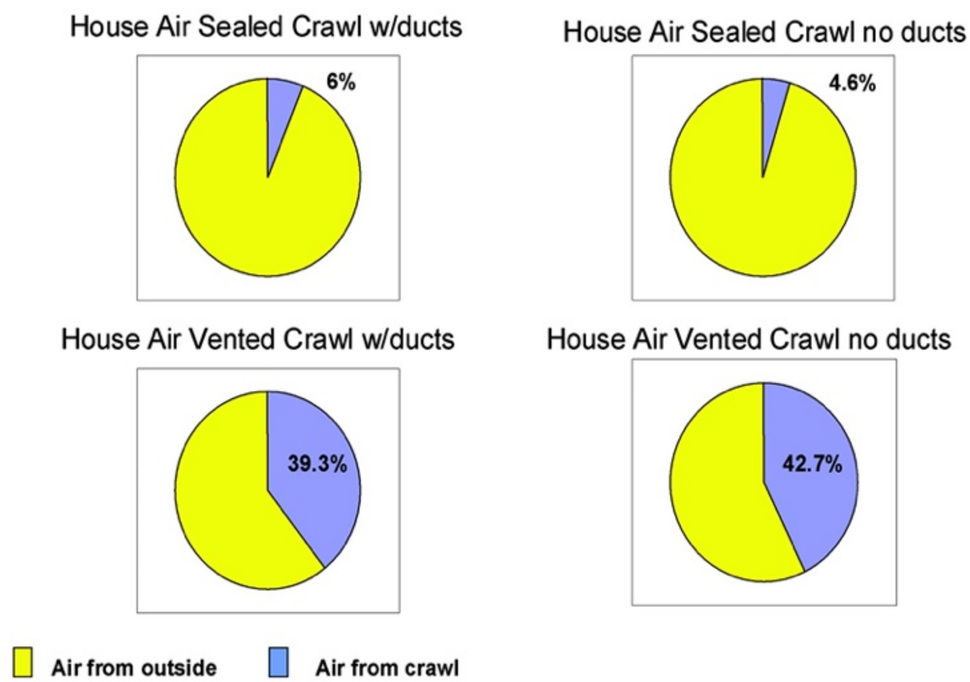


Figure 12 *Marine climate tracer gas result.*

Table 5. Comparison of All Vented to All Conditioned (Sealed) Crawlspaces

Crawlspace	Avg. Temp., °F (°C)	Min. Temp., °F (°C)	Max. Temp., °F (°C)	Avg. Temp. Above DP, °F (°C)	%Time Over DP	%Time Above 80%RH	Avg. %RH
All vented	57.6 (14.2)	44.6 (7.0)	71.4 (21.9)	13.9 (7.7)	0.1	4.2	60.8
All sealed	61.8 (16.6)	54.2 (12.3)	73.5 (23.1)	14.8 (8.2)	0.0	0.0025	58.1

Temperature and Relative Humidity

Comparing the averaged values for vented and conditioned (sealed) crawlspaces across climate zones in Table 5, there are generally only small differences. Overall, the conditioned crawlspaces are warmer, with more stable temperatures and almost no wetting potential from condensation or dangerous levels of sorbtion.

Wood Moisture Content

Over the course of 18 months, there was some variation in moisture content of the structural wood exposed to the crawlspaces, but no trend indicating an overall increase. Moisture content was below 13% in all cases, well below the 20%+ level normally needed to induce mold or decay.

Examining the averaged conditions in Table 5, there would appear to be a small wetting potential from condensation in the vented crawlspaces. Our analysis also calculated the percentage of time that the crawlspaces had over 80% RH. This was considered a critical point based on the sorbtion curve for wood (Hoadley 1980). Relative humidity over 80% is required to maintain wood moisture content of 20% or more. In the vented crawls, this condition existed from 3.5% to 9% of the time, but the measured moisture levels in the wood suggest that there is sufficient drying potential to offset any wetting. The averaged percentage relative humidity in all the crawlspaces (roughly 60%) is also consistent with the wood sorbtion curve and the reported wood moisture content levels.

Perimeter Crawlspace Insulation

The use of fiberglass batt insulation with a vapor retarder on the interior warm side is problematic. With no below-grade drying potential to the exterior and an interior warm-side vapor retarder, the system has little drying potential. This assembly was used only in the cold climate to evaluate current practice in the area of the test homes. The data in Figure 11 confirm the problem. The assembly temperature remained at the dew point 100% of the time during the summer and only rose above dew point in the winter while remaining above 80% RH 100% of the time. Prolonged exposure to these conditions poses a significant risk especially at the rim joist.

Interactive Affects of Duct System Location

The tracer gas data seem to confirm the intuitive idea that there is more air movement between the crawlspace and the house when ducts are located in the crawlspace. This could have a negative impact on indoor air quality by providing a pathway for pollutant sources in the crawlspace.

There also seems to be confirmation that the heat loss even from tight, well-insulated R-8 (0.71 W/m^2K) ducts has a warming affect on the crawlspace temperatures that helps to reduce the relative humidity. While one would expect an energy penalty from this heat loss from the ducts, eliminating the ducts from some crawlspaces could increase the wetting potential.

Modeling on these homes suggests that the energy performance impacts of conditioning the crawlspace (thereby bringing the ducts within conditioned space) is minimal, and only when supply ducts in the crawlspace are quite leaky (Lubliner et al. 2007).

CONCLUSIONS

- With proper site water management, both conditioned and vented crawlspaces can be built successfully in the marine and cold climates of the Northwest.
- The combination of relatively dry summers with low dew points (even in the marine climate) allows vented crawlspaces to perform adequately.
- Condensation did not appear a significant source of liquid water in any of the crawlspaces as tested.
- Sorbtion of water by structural wood exposed to the crawlspace conditions appeared to reach equilibrium at levels well below the critical range.
- Neither crawlspace configuration appeared to adversely affect wood moisture content.
- Neither crawlspace was adversely affected by a small moisture intrusion event.
- Power-venting conditioned crawlspaces significantly reduced the amount of house air originating from the crawlspace.
- There appears to be a possible benefit for improved IAQ associated with decoupling the conditioned crawlspace from the house by power venting. The benefit would only continue with continuous fan operation and would require elimination of the IRC requirement for a return pathway to the house. Continuous fan operation, however, could have a significant energy cost.
- Use of a vapor retarder on the warm side of below-grade perimeter insulation is a mistake. A drying potential to the interior must be maintained.
- Heating-season air change rates in the vented crawlspaces were around 3.5 ACH, providing a greater dilution factor for pollutant sources in the crawlspace. Conditioned crawlspaces were around 1 ACH (marine-climate tests only).

Recommendations for Conditioned Crawlspaces

- Use foam insulation products for perimeter insulation and never install a warm-side vapor retarder with perimeter batt insulation. Use of foam insulation can reduce the movement of moist air trapped in batts, with the vapor retarder reducing the risk of moisture exposure at the rim joist.
- Power-vent with a tightly sealed floor to decouple the house from the winter time stack effect.
- Require passive or active radon mitigation, depending on the risk for the site.
- Direct return or supply air to or from the crawlspace is unnecessary.

These recommendations are seen as climate specific and are based on the maritime climate in the Northwest and cold climates to about 7000 HDD (3889 HDD Celsius) with dry summers and average dew points below average ground temperatures.

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