Movement and Sources of Basement Ventilation Air and Moisture During ASD Radon Control

Additional Analysis

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ABSTRACT

The original study in three Pennsylvania houses found that operation of active soil depressurization (ASD) radon control systems caused modest reductions in basement moisture levels. Additional, supplemental analysis has been conducted on the relationship between basement air and outdoor air moisture, and on the movement of airborne sources of basement air moisture under the influence of ASD systems. Results indicate that moisture levels in the air of the basement, first floor, soil, and outdoors are all strongly intercorrelated (correlation coefficients ranging from 0.6 to 0.9), with basement and outdoor air having correlation coefficients of approximately 0.77 and lagged responses for basement air of six to 12 hours, for all houses. Simple linear regression models found that moisture from the outdoor air directly, and indirectly from the other zones, explained approximately 70% of the overall variation in basement air moisture levels.

Examining the movement of airborne moisture sources and basement air moisture revealed that all houses experienced large variations in interzonal air flows and ventilation, and that ASD operation increased the flow of outdoor and upstairs air into the basement. ASD operation virtually eliminated the minor, pre-existing flow of air and moisture from the soil, which may be a more important source in houses with larger soil gas entry. Lower moisture levels in outdoor air in winter and the upstairs air in summer (due to dehumidification by the HAC systems) have the potential to help dry the basement or offset moisture entry from other sources. The ASD systems extracted and exhausted large quantities of moisture from the house and soil around the house, implying that the systems may cause long-term drying of the basements. For one house, direct block wall depressurization (BWD) more effectively reduced wall moisture than sub-slab ASD. Results again hint that ASD/BWD may have a much larger, beneficial impact on moisture levels and conditions for microbial growth in and around the microclimate of moisture-sensitive, finish materials applied to basement walls and floors. ASD for effective moisture control may require higher air flow and PFE than is necessary for effective radon control. Although additional ventilation from ASD operation may help IAQ, its lack of control and predictability can cause over- and under-ventilation, and may be detrimental in some cases.

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EXECUTIVE SUMMARY

An earlier, exploratory study in three Pennsylvania houses found that operation of active soil depressurization (ASD) radon control systems caused modest reductions in basement moisture levels (Turk and Hughes 2008). The reporting and analysis of data covered the theoretical framework; basic presentation of data on air movement, building air leakage, and moisture levels; and results showing that basement moisture levels were significantly reduced during non-summer periods. While extensive data was collected during the study, analysis of other, related topics was limited.

Therefore, additional analyses have been conducted on the relationship between basement air and outdoor air moisture, and on the movement of airborne sources of basement air moisture under the influence of ASD systems, and findings are reported here. This report is best considered as a supplement to the original study report, which contains detailed descriptions of experimental procedures and is frequently referenced throughout this document. Readers are encouraged to first become familiar with the original study report.

Relationship Between Basement and Outdoor Air Moisture

Review of original data from the three Pennsylvania houses indicate that moisture in the basement air (along with first floor air and soil air below the basement slab floor) tends to closely follow moisture changes in outdoor air. In fact, this linkage appears to dominate over the measureable, but smaller, changes in basement air moisture caused by cycling of the radon control systems. Basic statistical assessment were performed and findings include:

- Five variables were identified as most likely to have an impact on basement moisture: outdoor air moisture, first floor moisture, sub-slab soil air moisture, ASD on/off operation, and heating and air conditioning (HAC) equipment operation. The review also pointed out the many inter-relationships between the variables, and comparatively high correlations between them. Outdoor air entering the soil and the upper floors of the house likely has a strong influence on the air in those spaces, and indeed the correlation coefficients between them and outdoor air ranged from 0.6 to 0.9. In turn, the moisture levels of the air in those zones influenced the basement air. Therefore, the outdoor air had both direct and indirect (through the other zones) effects on the basement. The correlation coefficients for basement and outdoor air are consistent for all houses at approximately 0.77 with a delayed response, or lag, of approximately six to 12 hours.

- While correlation measures association between variables, least squares linear regression models were developed to examine the comparative causation of the dependent variables on basement moisture and their predictive ability. As with most regression models, the predictive ability increased as variables were added, explaining over 95% of the variation in basement air moisture when all five variables were included. However, because of the pass-through of outdoor air through the other two zones, the simplified models of one, two, and three variables (outdoor air, ASD and HAC operation) were evaluated in more detail.

- Regression with outdoor air moisture alone explained approximately 70% of the variation in the basement air moisture, while ASD and HAC added modest explanatory power (approximately 4%). These results were consistent for all houses and confirm that changes in outdoor air moisture are a large determinant for changes in indoor air moisture. Remaining variability in basement moisture appears to be largely explained by other source and removal processes in the basement, soil, and upstairs. These would include occupant activities (respiration, cooking, showers, laundry and cleaning, etc.), dehumidification by HAC equipment, storage effects, precipitation, water leaks, drying of new construction, and diffusion from the soil.

- Attempts to estimate the quantities of moisture contributed or removed by outdoor air (and the other factors) produced a broad range of seasonally-dependent responses that are not easily explained. In fact, the regression models estimate that summer season contributions of outdoor air moisture were less than during non-summer periods – which is not in line with expectations and calculations of short-term air flow and moisture during the summer for several of the houses (see below). It is probable that the large cross correlations between the key variables being studied and the underlying assumptions for linear regression models may have limited the ability to fully account for the non-linear relationships between the variables and the contributions of individuals variables to basement moisture.

- Autoregression models, using three variables (outdoor air, ASD and HAC operation) to account for the time series nature of the data, were very successful predictors of behavior (R^2 greater than 0.995). However, the ordering of the values imposed by the temporal factor, which is not addressed at all in linear regression, makes the relationships less clear.

Basement Moisture Sources and Movement, and ASD Moisture Considerations

As suggested in the Conceptual Model and data analysis of the original study report, ASD-induced air flows to and from outdoors, the first floor, and the soil were likely to significantly impact moisture levels in the house and basement. This additional, more detailed examination of moisture levels and air flows for the various air masses confirm that ASD, along with other factors (house structural characteristics, seasonally-variable weather and house mechanical operation, and ASD configuration and operating characteristics), can cause large changes in air flow and moisture.

It should be noted that most of the ASD operating periods were quite short, and the data frequently suggest that the full potential effect on moisture levels of a particular ASD operating mode may not have been realized by the end of an individual operating period.

It is likely that ASD remains the most cost-effective method of controlling soil gas entry, especially where entry potential is high (large effective soil-contact leakage area and high soil permeability). Since soil gas entry has the potential to inject large quantities of contaminants such as radon, landfill gases, chemical vapors, and moisture into buildings, ASD should always be considered as a control strategy.

More specific findings for the three Pennsylvania houses are:

- The houses experienced large variations in interzonal air flows and outdoor air infiltration, both seasonally and from house-to-house. However, by removing air from the basement through cracks and gaps in the foundation surfaces (and slightly depressurizing the basement), ASD operation generally increased outdoor air infiltration into the basement and upstairs, and the flow of upstairs air into the basement.

- As expected, ASD operation appears to have had little impact on the moisture level of the air streams from the outdoors and first floor that enter the basement, although some drying of the soil air may have occurred.

- Although soil gas consistently had high moisture levels, the convective flow of soil gas into these houses was generally small, and the moisture contribution to the basement air was typically less than that from other sources. Operation of the ASD systems dramatically reduced or eliminated this moisture contribution, but that reduction had a relatively small drying effect on the basement air. This finding in these houses is contrary to common assumptions about the generally dominant role of soil gas entry reduction in basement moisture control. However, for houses with larger soil gas entry, the ASD systems' control of soil gas entry might be a larger potential drying influence.

- Moisture levels in outdoor air exhibited very large variations, but tended to be higher in the Summer than Winter, by factors of three to five, or more. Because the ASD systems tended to increase the infiltration of outdoor air throughout the year, this incoming air has the potential to both enhance the drying of the basement when the outdoor air is drier than the basement (e.g., during the Winter) and to add significant moisture when the outdoor air is wetter (e.g., Summer).

- Upstairs air was usually drier than basement air, with the central air conditioning equipment acting to dehumidify this air during the Summer. The data suggest that the ASD systems significantly increased the flow of upstairs air into the basement which often accounted for drying observed in the basement, especially during the Summer and parts of the Spring and Fall. This mechanism appears to partially or completely offset the additional moisture added to the basement by the incoming outdoor air during warm, humid weather.

- In these houses, the ASD systems extracted and exhausted large quantities of moisture, some from within the house, the balance from other sources – presumably the soil around the foundation. The amount extracted generally varied seasonally with the moisture levels in the soil and outdoor air, ranging from approximately 1.2 to 1.5 times higher in the Summer.

- The ASD system in one house removed approximately five to 10 times the quantity of moisture as did a standard dehumidifier – implying that the systems may have the potential for more effective, long-term drying of the basements.

- In terms of standard ASD installations, radon control effectiveness may not be a good surrogate for moisture control effectiveness. It appears that systems designed and installed for good control of radon may not be optimal for moisture reduction, since greater moisture reductions were achieved from more robust systems with higher flow and PFE than in a typical installation.

- Although it is seldom necessary to install block wall depressurization (BWD) for radon control (in homes with open core block foundation walls), direct BWD was most effective at reducing moisture in the block walls of one basement, while sub-slab ASD alone had a smaller effect.

- Findings suggest that ASD/BWD systems may provide more effective control of moisture in the materials and small spaces of finished walls and floors. These regions are in closer proximity to the entry locations of moisture-laden soil gas, and would likely experience larger moisture reductions (than basement air) when the systems are operated. Because many finish materials are moisture sensitive and will easily support microbial growth, reduction in their moisture content might have greater beneficial impact on moldy odors and related biocontaminants. This phenomenon was not investigated during this study.

- While ASD systems tend to reduce moisture by modifying interzonal flows and boosting outdoor air ventilation rates, these changes are not controlled and are difficult to predict and quantify. Although adequate ventilation is desirable and recommended by ASHRAE, ASD as a ventilation technique often misses its mark: over-ventilating with attendant energy penalties, under-ventilating, and/or causing air flow in locations that may actually be harmful. To be a more reliable ventilation approach, ASD systems would need to be carefully, designed, engineered, installed, and operated – at present, an impractical objective. Proper ventilation is more appropriately achieved with techniques other than ASD.

INTRODUCTION

An earlier, exploratory study in three Pennsylvania houses found that operation of active soil depressurization (ASD) radon control systems caused modest reductions in basement moisture levels (Turk and Hughes 2008). The reporting and analysis of data covered the theoretical framework; basic presentation of data on air movement, building air leakage, and moisture levels; and results showing that basement moisture levels were significantly reduced during non-summer periods. While extensive data was collected during the study, analysis of other, related topics was limited.

Therefore, additional analyses have been conducted on the relationship between basement air and outdoor air moisture, and on the movement of airborne sources of basement air moisture under the influence of ASD systems, and findings are reported here. This report is best considered as a supplement to the original study report, which contains detailed descriptions of experimental procedures and is frequently referenced throughout this document. Readers are encouraged to first become familiar with the original study report.

A. RELATIONSHIP BETWEEN BASEMENT AND OUTDOOR AIR MOISTURE

While the original study showed that basement moisture levels could be significantly reduced, the data also appeared to show that, regardless of operation of the radon control system, changes in basement moisture tracked most closely with outdoor air moisture. To estimate the strength of this relationship, and the relationship among other factors that could alter basement air moisture levels, further statistical assessments have been performed.

A1. BACKGROUND

Review of the graphical data from the three Pennsylvania houses indicate that moisture in the basement air (along with first floor air and soil air below the basement slab floor) tends to closely follow moisture changes in outdoor air (Figure 1). In fact, this linkage appears to dominate over the measureable, but smaller, changes in basement air moisture caused by cycling of the radon control systems – active soil depressurization. Long-term, seasonal changes are due, in part, to coincident changes in the temperature of air and its subsequent ability to hold moisture. However, based on preliminary results from the study and additional analysis (Section B of this report), it is suspected that air flows between zones within the buildings, between outdoors and indoors, and between the surrounding soil and the indoors accounts for much of the moisture transport. Thus, the flows can either add or remove moisture, depending on the comparative moisture levels in the various air masses and the direction of air flows.

While indoor moisture sources, from occupant activities (e.g., respiration, cooking, showers, laundry and cleaning, etc.), water leaks, drying of new construction moisture, and diffusion from the soil, have the potential to add large amounts of moisture to the indoors, they don’t appear to be responsible for most of the changes in indoor moisture levels for these three houses. Figure 1 displays long-term tracking of outdoor air moisture suggesting that outdoor air is the common, underlying cause of indoor air wetting and drying, but that indoor sources and drying mechanisms (central air conditioning equipment) and perhaps precipitation are likely responsible for episodic changes and some observed divergence from the trend.

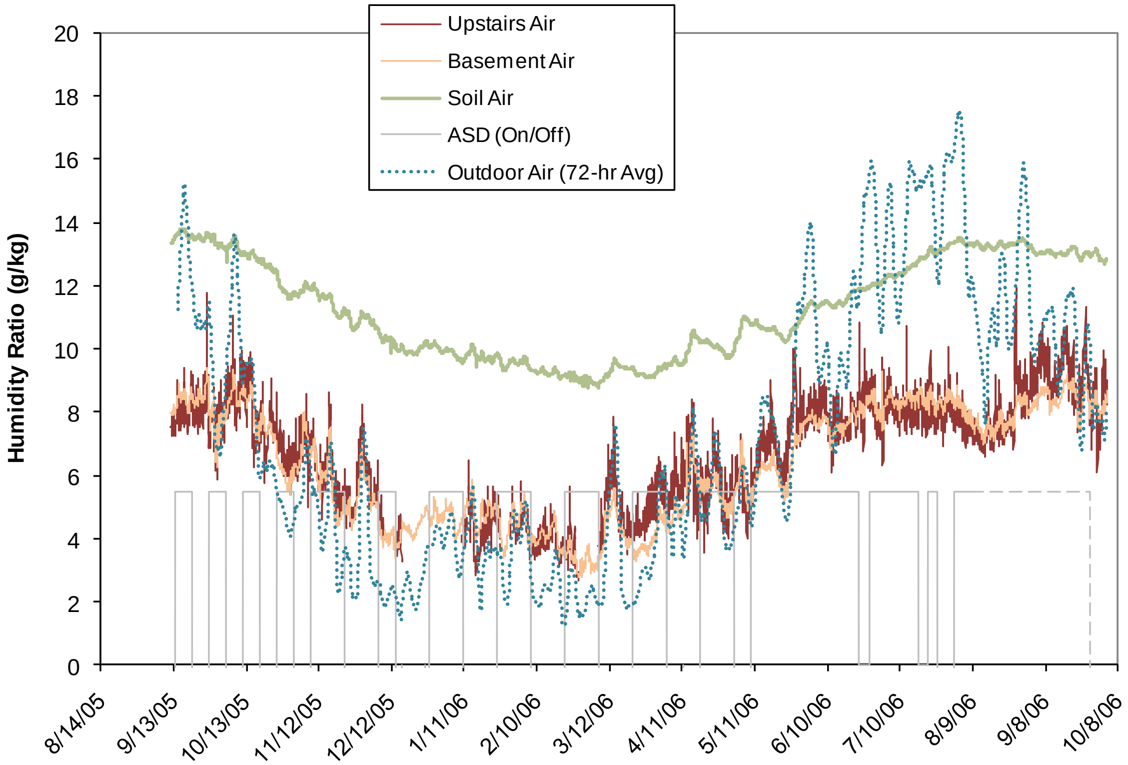

Figure 1. *Continuously measured and moving average (outdoor) data for variables considered to be important in contributing to moisture levels in the basement air (PA01).*

A2. ANALYTICAL APPROACHES AND RESULTS

To investigate the association between basement air moisture and outdoor air moisture, a physical model of the moisture mechanisms at work in the houses could be created. However, it would require much more comprehensive measurements of moisture, temperature, and air flow and was beyond the scope of this analysis. Instead, simpler statistical assessments, associative and predictive, were applied to test the dependence of changes in basement moisture on changes in outdoor air moisture. Evaluations of relationships were made using correlation coefficients and several variations of the common least squares regression, and different independent variables. Where correlation is useful for measuring association (interdependence) between variables, regression can be used to estimate dependence of one variable on another (causation and ability to predict one from another).

A2.1 Correlation

The selection of variables was based on a combination of variables that would be representative of the physical system in conjunction with the statistical concerns of sample size (not more than about 10% missing values) and correlations. Strong correlation between dependent variables (such as sub-slab soil air, first floor air, and outdoor air moisture) limits the statistical meaning of a regression model framework that incorporates these variables.

Five of the measured variables meeting these criteria were considered for the models. In Figure 2, the relationships connecting basement air with outdoor air, first floor air, sub-slab (soil) air, and operation of the ASD and heating and cooling (HAC) systems are shown. Other, undefined, sources of moisture/removal are also indicated (O_i).

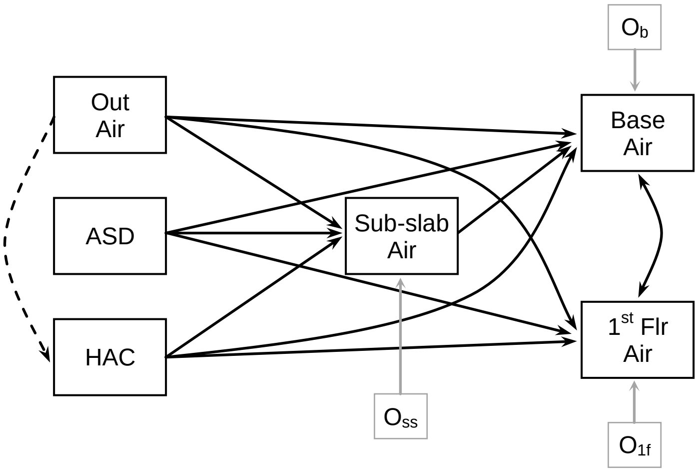

Figure 2. *Diagram of paths interconnecting primary sources and mechanisms that affect moisture levels in the basement air. Other, undefined sources (removal) of moisture that may play an important role are aggregated in* O_{ss}*,* O_{1f}*,* O_b*, and may include diffusion, occupants and occupant activities, precipitation, liquid water entry, mechanical dehumidification, storage, etc.*

The association between these variables is measured by the correlation coefficients in Appendix A, where many are shown to be cross-correlated, reflecting the paths diagrammed on Figure 2. The correlations of the five variables to basement air moisture are summarized in Table 1. For all houses, the strongest correlations occur for first floor air, sub-slab air, and outdoor air, in that order. Since outdoor air is drawn into the first floor and sub-slab, it is likely a large contributor to the correlation, and is augmented by the other factors mentioned above.

Table 1. Correlation Coefficients Associating Moisture in Basement Air with Key Dependent Variables.

	Basement Air		
Description	**PA01**	**PA02**	**PA03**
Outdoor Air	0.837	0.723	0.857
First Floor Air	0.932	0.952	0.969
Sub-slab Air	0.922	0.861	0.928
ASD On/Off	0.209	-0.246	-0.253
HAC	0.070	-0.447	0.163

ASD operation is modestly correlated with basement air moisture in all houses, with the negative correlation at PA02 and PA03 being consistent with observed reductions in basement air moisture levels. Interestingly, ASD operation is positively correlated with basement air moisture at PA01 (basement moisture levels and ASD [on] increase together), although subsequent regression analysis demonstrates the expected response when summer and non-summer periods are isolated.

Operation of the HAC equipment that moves heated, cooled, and dehumidified air around the house is controlled by a thermostat on the first floor. Besides dehumidifying the house air during humid summer periods and mixing the house air, the HAC systems are capable of indirectly drawing in outdoor and soil air, due to poor supply and return balance, and injecting it into the building. The correlation coefficients imply that these effects of HAC operation are not strongly associated with basement moisture levels in PA01 and PA03. The negative correlation at PA02 indicates that the basement air moisture is reduced when the HAC system is running, likely caused by the dehumidification and/or injection of drier air into the basement.

A2.2 Lag/Response Time of Selected Variables

A simple evaluation of the delay in response of basement air moisture levels as other factors change was conducted by watching correlations as lag times were introduced into the data (Table 2). Lags applied were hourly for up to 12 hours, then daily for up to 10 days. For basement air moisture, correlated to earlier basement values, correlations are quite high for the first hour declining slowly up to 24 hours – suggesting that basement moisture does not change rapidly over short intervals.

The response of basement air moisture to changes in outdoor air moisture was generally delayed approximately six to 12 hours in all three houses. The relationship between the ASD variable and basement air moisture was more difficult to assess. In house PA01, the correlation was positive but in the other two houses it was negative. In house PA03, the interpolation of missing values did not result in reliable data so those correlations are not reported. A single correlation for PA03 is reported to indicate that the correlations followed a pattern similar to that observed in house PA02.

The correlation between basement air moisture and HAC operation ranged in strength, but was generally small and initially negative in all three houses. The lag time for maximum correlation was from one hour (PA02 and PA03) to approximately 24 hours (PA01). HAC operation could impact basement moisture levels by creating pressure differences that would alter air (and moisture) movement within the buildings, from outdoors, and from the soil.

Table 2. Correlation Coefficients as Variables are Lagged (maximum correlation coefficients highlighted in bold italics)

Lag Time (hours)	PA01				PA02				PA03			
	Base	**Out**	**ASD**	**HAC**	**Base**	**Out**	**ASD**	**HAC**	**Base**	**Out**	**ASD**	**HAC**
0		0.756	0.134	-0.050		0.766	-0.149	-0.205		0.747	-0.180	-0.061
1	***0.998***	0.759	0.133	-0.056	***0.999***	0.769	-0.151	***-0.208***	***0.997***	0.750		***-0.066***
2	0.996	0.762	0.132	-0.061	0.997	0.771	-0.152	-0.205	0.992	0.754		-0.060
3	0.994	0.765	0.132	-0.065	0.996	0.773	-0.154	-0.201	0.987	0.756		-0.051
4	0.991	0.767	0.131	-0.068	0.995	0.775	-0.155	-0.198	0.982	0.759		-0.044
5	0.989	0.769	0.131	-0.070	0.993	0.776	-0.157	-0.195	0.977	0.761		-0.035
6	0.986	0.771	0.130	-0.072	0.992	***0.777***	-0.158	-0.192	0.972	0.763		-0.028
7	0.983	0.771	0.130	-0.072	0.990	***0.777***	-0.159	-0.190	0.968	0.765		-0.021
8	0.980	***0.772***	0.129	-0.072	0.989	***0.777***	-0.160	-0.188	0.964	0.766		-0.016
9	0.978	***0.772***	0.129	-0.071	0.987	***0.777***	-0.161	-0.186	0.960	0.767		-0.010
10		***0.772***				***0.777***				0.768		
11		0.771				***0.777***				***0.769***		
12		0.771				***0.777***				***0.769***		
24	0.940	0.755	0.131	***-0.077***	0.969	0.764	***-0.167***	-0.198	0.931	0.764		0.019
48	0.873	0.707	0.142	-0.075	0.935	0.737	***-0.167***	-0.191	0.873	0.738		0.049
72	0.819	0.678	0.167	-0.059	0.905	0.719	-0.150	-0.184	0.827	0.715		0.061
96	0.776	0.655	0.209	-0.042	0.875	0.697	-0.131	-0.172	0.790	0.694		0.072
120			0.253				-0.102					
144			0.291				-0.064					
168			0.334				-0.016					
240			***0.392***				0.089					

A2.3 Ordinary Least Squares Regression (OLS)

Multiple regression was performed by the least squares method for basement air moisture (y_{base}, humidity ratio, W) on dependent five variables initially: x_{out} – the moisture in outdoor air (humidity ratio, W, g/kg); x_{ff} – moisture in first floor air (W); x_{ss} – moisture in sub-slab soil air (W); x_{asd} – a discrete indicator of when the ASD system was on or off based on the semi-continuous measurement of air flow in one of the active suction pipes (PA01 and PA02) or on system status information (PA03); and x_{hac} – a measure of forced air heating and cooling (HAC) system operation that ranged in value between 0 and 100 (percent on-time for each hour). The basic form of the regression model is:

$$y_{base} = C + b_{out}x_{out} + b_{ff}x_{ff} + b_{ss}x_{ss} + b_{asd}x_{asd} + b_{hac}x_{hac}$$

where b_i are the corresponding regression coefficients, and C is the regression constant.

Although there is evidence that some variables elicit a delayed response in basement air moisture (Table 2), lagged values were not incorporated into the regression models for the sake of simplification. Regression results for coefficients, intercepts, and R^2 (coefficient of determination) are summarized in Table 3. These models successfully predict the basement air moisture, explaining over 95% of its variation in all three houses. Figure 3 graphically displays the predictive ability of the model for PA01, comparing the actual and predicted basement moisture over approximately 14 months of the study. More detailed information on the regressions for each house, along with plots of actual and predicted basement moisture levels are included in Appendix B.

Table 3. Parameters for Ordinary Least Squares Regression with Five Dependent Variables - All Seasons.

Description	PA01	PA02	PA03
Outdoor Air (x_{out})	0.064	0.077	0.028
First Floor Air (x_{1st})	0.452	0.678	0.686
Sub-Slab Air (x_{ss})	0.455	0.580	0.615
ASD (x_{asd} - binary)	-0.097	-0.445	-0.347
HAC (x_{hac})	0.002	0.000[‡]	-0.004
Intercept (C, g/kg))	-2.147	-5.491	-4.844
Number	8414	8545	7261
Multiple-R^2	0.951	0.968	0.969

[‡] All significant at p=.0001, except x_{hac} at PA02 where p=0.430

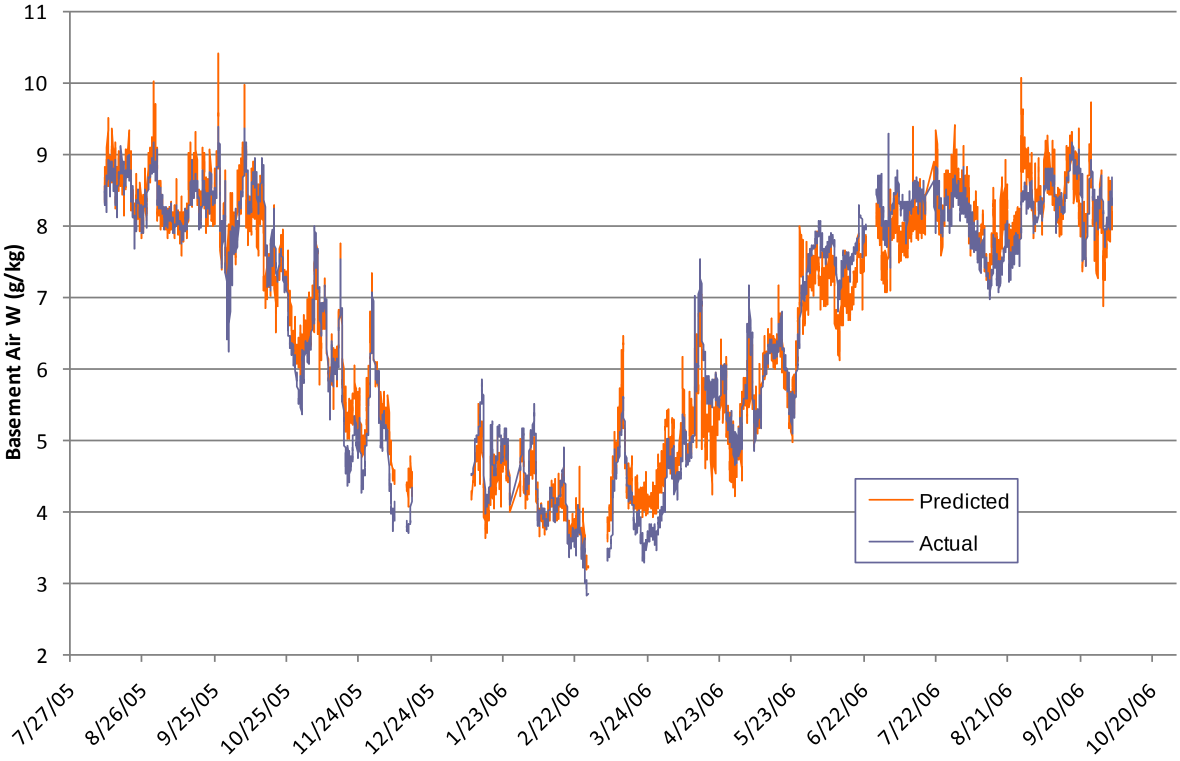

Figure 3. *Measured basement air humidity ratio (W) for PA01, along with predicted W using 5-variable regression model (outdoor air, first floor air, sub-slab air, ASD operation, and HAC operation).*

The regression coefficients in Table 3 for first floor and sub-slab soil air at all houses suggest a much larger contribution to basement air than from outdoor air. The regression coefficients for ASD and HAC are more difficult to interpret because these variable have different units than basement air. However, the regression coefficients for ASD are all negative indicating that when ASD is operating, basement moisture is lowered.

Since a better understanding of the relationship between outdoor air and basement air was one of the focuses of this extended analysis, and because it was expected that outdoor air effects would also be communicated through the first floor and sub-slab soil air, additional analysis of the effects of first floor and sub-slab soil air was conducted. In Figure 4, the coefficients of determination (R^2) for various combinations of dependent variables are shown. The R^2 is an estimation of the explained variation in basement air moisture by each regression model. Thus, regression on outdoor air alone explains approximately 70%, 73%, and 74% of the variation in basement air moisture for PA01, PA02, and PA03, respectively. These are not estimates of the quantity of moisture contributed by outdoor air.

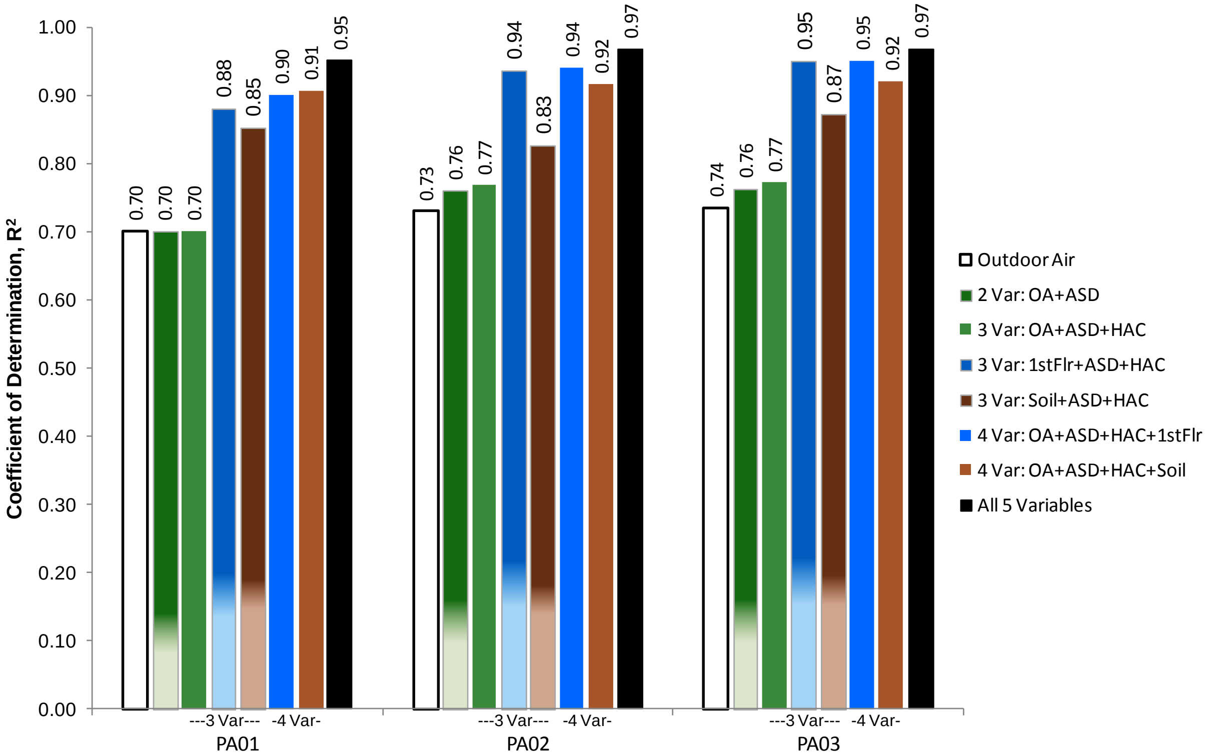

Figure 4. *Coefficients of determination (R^2) from regressions run for one (outdoor air) to five dependent variables. First floor and sub-slab soil air were substituted for outdoor air during the regressions on three variables.*

Addition of the ASD and HAC variables increase the explained variability by up to about 4%. Substituting the first floor or sub-slab air variables for outdoor air in the three-variable regressions results in larger improvements: 15% to 21%, with first floor air causing largest improvements in all houses. As mentioned earlier, a variety of other processes and activities can affect moisture levels in the first floor and sub-slab soil air, which in turn appear to have marked impact on basement air moisture. The four- and five-variable regressions resulted in only modest additional improvements.

To isolate the effects and relationships of outdoor air moisture on basement air, three-variable regression models containing outdoor air, and ASD and HAC operation were considered in more detail. The predicted (and observed) values from the regression for PA01 are shown in Figure 5. Inspection of Figure 5 and Figure 3 (five variable) indicates that the three-variable model deviates more from the observed values. Plots for PA02 and PA03 are similar, and the summarized regression data in Table 4 confirm these observations. The plots for other houses and more detailed regression information for the three-, two-, and single-variable models are included in Appendix B.

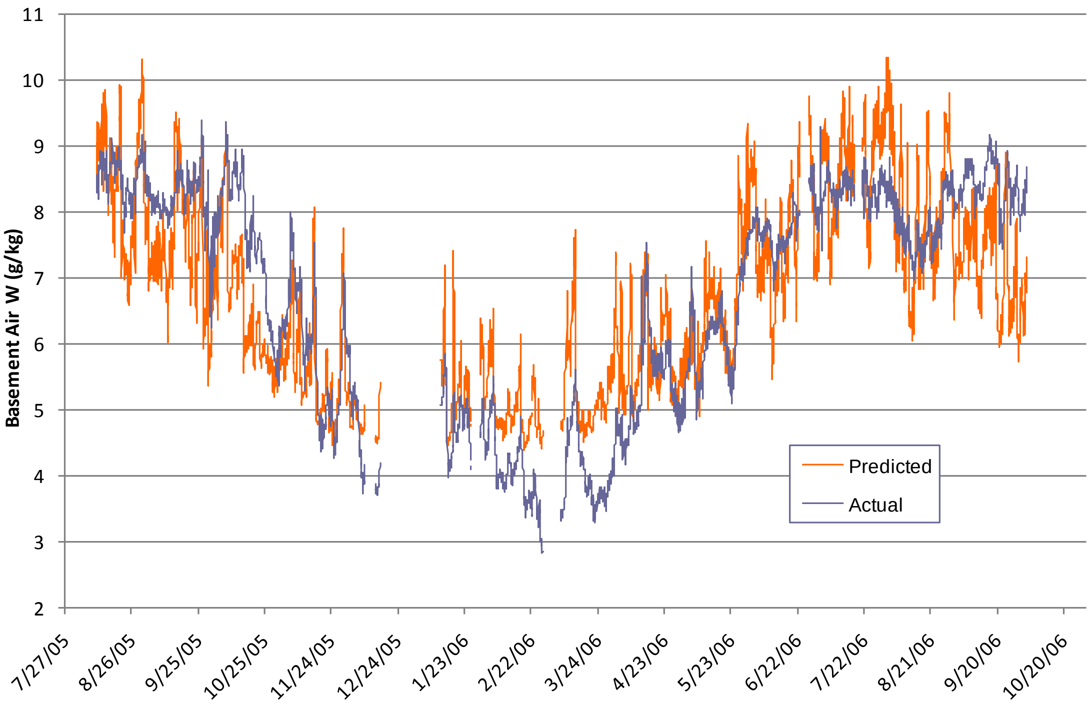

Figure 5. *Measured basement air humidity ratio (W) for PA01, along with predicted W using 3-variable regression model (outdoor air, ASD operation, and HAC operation – see Table 4).*

The earlier analysis and report found differences in basement moisture responses during the summer and non-summer periods, likely due to large summer increases in the outdoor air moisture load and possibly dehumidification by the central HAC system. Regressions were run separately for these two periods and for the combined periods, and the calculated regression factors are included in Table 4. While the R^2 for the combined summer and non-summer (All) data range from 0.70 to 0.77 for all three houses, the R^2 for separate summer and non-summer periods are much lower, possibly due to the fewer number of observed data used for the regressions.

As noted for Table 1, the correlation coefficient for basement air moisture vs. ASD at PA01 was positive, and contradicts the analyses in the earlier report showing reduced moisture during ASD operation – a similar result was found here for the ASD regression coefficient at PA01 for combined summer and non-summer (All) data. While this result is unexplained, the ASD regression coefficients for the separate summer and non-summer periods are negative, as expected.

Because the variables are not all in the same units of measurement, a standardized partial regression coefficient (SPRC), b'_y , was calculated that gives the rate of change in standard deviation units of *y* per one standard deviation unit of *x*, from

$$b'_y = b_y \frac{s_x}{s_y}$$

where s_x and s_y are the standard deviations of the dependent and independent variables, respectively.

The standard partial regression coefficients effectively eliminate the differences in measurement scale so they can be compared to show the relative effects of the independent variables on basement air moisture. Because of the binary (on/off) nature of the ASD data, the comparisons of SPRC for these data may not be meaningful – in fact, showing larger impacts than outdoor air, and the comparisons are not easily explained. For HAC, the SPRC consistently shows a very tiny impact on changes in basement air moisture compared with outdoor air in PA01 and PA02, while at PA03 the HAC effect ranges from one tenth to one third that of outdoor air.

To estimate the overall contribution (or removal) of absolute moisture quantities to the basement air, the regression coefficients were multiplied by the corresponding average of measured values for each independent variable (outdoor air and HAC on-time) to yield the average moisture gain/loss (W, g/kg). For ASD, the regression coefficient was multiplied by 0 (off) and 1 (on). Results of these calculations are shown in columns 4, 8, and 12 of Table 4. Extending this to estimates of gains/loss in basement air relative humidity (RH, %), the average basement air RH was proportioned (columns 5, 9, and 13) according to the calculated humidity ratios (W). These results indicate that the outdoor air can contribute moisture, ranging in average from 0.8 to 2.6 g/kg (5 to 19% RH) at PA01, 2.4 to 3.6 g/kg (15 to 24% RH) at PA02, and 1.1 to 2.9 g/kg (7 to 23% RH) at PA03. Although it is expected that outdoor air would add more moisture to the basements during the summer periods, these estimates point to the opposite. Estimated moisture reductions with the ASD in operation are smaller than, but approximately within the range of, reductions measured during ASD cycling as reported in Turk and Hughes 2008. For these three-variable regression models, the regression constants (*C*) typically accounted for more than 50% of the basement moisture. The constants lump all of the other moisture effects occurring in from upstairs, sub-slab soil, and from diffusion through the foundation materials, etc. Since there are many assumptions underlying the least squares linear regression, including that the moisture responses are linear, these estimates of actual moisture gains/losses should only be considered to be crude estimates intended to show ranges of effects.

Table 4. Regression Results and Estimated Contributions to Basement Air Moisture for Three Dependent Variables

Description	All Data				Summer Data				Non-Summer Data			
	Regress Fitted Factor	Std Partial Regress Coeff	Est Contrib Base W (g/kg)	Est Contrib Base RH (%)	Regress Fitted Factor	Std Partial Regress Coeff	Est Contrib Base W (g/kg)	Est Contrib Base RH (%)	Regress Fitted Factor	Std Partial Regress Coeff	Est Contrib Base W (g/kg)	Est Contrib Base RH (%)
PA01												
Outdoor (x_{out})	0.317	0.836	2.56	18.7	0.063	0.394	0.756	5.4	0.417	0.776	2.09	17.2
ASD (x_{asd})	0.024	0.064	off / on 0 / 0.024	off / on 0 / 0.18	-0.304	-1.892	0 / -0.304	0 / -2.2	-0.136	-0.253	0 / -0.136	0 / -1.1
HAC (x_{hac})	0.000	0.000	-0.003	-0.02	0.001	0.001	0.015	0.10	0.004	0.001	0.041	0.33
Intercept (C)	4.143		4.14	30.3	7.620		7.62	54.1	3.541		3.54	29.2
Number	8414				3734				4729			
Multiple-R^2	0.701				0.414				0.597			
Base Air Avg (act)[1]			6.72	49.1			8.15	57.8			5.60	46.1
PA02												
Outdoor (x_{out})	0.504	0.871	3.58	23.7	0.203	0.556	2.45	14.5	0.506	0.700	2.44	17.4
ASD (x_{asd})	-0.844	-1.458	off / on 0 / -0.844	off / on 0 / -5.6	-0.161	-0.441	0 / -0.161	0 / -0.95	-1.218	-1.686	0 / -1.22	0 / -8.7
HAC (x_{hac})	-0.011	-0.002	-0.153	-1.0	0.007	0.003	0.111	0.66	-0.015	-0.004	-0.189	-1.35
Intercept (C)	4.729		4.73	31.3	7.970		7.97	47.3	4.820		4.82	34.3
Number	8545				2691				5854			
Multiple-R^2	0.768				0.390				0.646			
Base Air Avg (act)[1]			7.71	51.0			10.44	62.0			6.45	45.9
PA03												
Outdoor (x_{out})	0.436	0.874	2.91	22.6	0.085	0.324	1.09	7.4	0.395	0.614	1.67	14.2
ASD (x_{asd})	-0.724	-0.155	off / on 0 / -0.724	off / on 0 / -5.6	-0.468	-0.280	0 / -0.468	0 / -3.2	-0.717	-0.247	0 / -0.717	0 / -6.1
HAC (x_{hac})	-0.006	-0.101	-0.154	-1.20	-0.002	-0.101	-0.098	-0.67	-0.007	-0.154	-0.107	-0.91
Intercept (C)	3.639		3.64	28.3	8.291		8.29	56.5	3.654		3.65	31.1
Number	7261				2060				5201			
Multiple-R^2	0.772				0.158				0.532			
Base Air Avg (act)[1]			6.08	47.3			9.12	62.1			4.88	41.5

[1] Average of actual, measured, basement moisture for all intervals included in regression

A2.4 Autoregression

Since the majority of data being analyzed were in time series, or automatically and semi-continuously collected on one-hour intervals throughout the study, autoregression was also evaluated. In autoregression, it is presumed that the dependent variable, basement air moisture, has a ‘memory’ of its preceding value – or is a function of itself and the independent variables at a previous moment of time.

The autoregressive component adds the following calculation to the structural equation (least squares):

$$\ldots + AR1e_{lag}$$

where $AR1$ is the autoregression coefficient, and e_{lag} is the lagged structural residual for the preceding period.

The autoregression model for basement air relative humidity (%RH) used the three independent variables as in the OLS, above. In house PA03, a stand-alone dehumidifier operated at some points in time – an independent variable for dehumidifier operation was added to the autoregression for this house ($x_{dehumid}$).

Data from after the start of cycling of the ASD systems was used in the analysis, while missing dependent variable data values were interpolated using an interpolation algorithm. Identifying the structure of the model itself involved a test for autocorrelation, followed by a test for the lag structure of the detected autocorrelation. Statistically significant autocorrelation was found in all three houses and a single lag was adequate to account for most of the autocorrelation. The final autoregressive models for all three houses, incorporating a single lag are shown in Table 5.

Table 5. Parameters for Autoregression Model

Descriptor	PA01	PA02	PA03
Outdoor (x_{out})	0.044 **	0.126 **	-0.011 **
ASD (x_{asd} - binary)	-0.3610 **	-0.3516 **	-0.8867 **
HAC (x_{hac})	0.0040 **	-0.0094 **	-0.0337 **
Dehumidifier	--	--	-1.55 **
AR1	-0.9985 **	-0.9990 **	-0.9976 **
Intercept (C)	48.8 **	50.7 **	50.2 **
Structural R^2	0.03	0.05	0.29
Total R^2	0.997	0.998	0.995

**p<.01

In terms of prediction, all independent variables are statistically significant in each house. The model is said to have a structural and an autoregressive component. The structural component is the usual regression model. Within the autoregressive framework, this actually doesn’t predict well yielding low structural R^2. The variables, however, are predictive as can be seen by the OLS regressions, above.

While the autoregessive model is a very successful predictor of behavior (R^2 greater than 0.995), the ordering of the values imposed by the temporal factor, which is not addressed at all in linear regression, makes the relationships less clear.

A3. SUMMARY OF FINDINGS – Relationship Between Basement and Outdoor Air Moisture

The extensive data collected during this project in three houses provided an opportunity to examine the relationship between moisture levels in the basement air and those in the outdoor air. Visual inspection of plotted data during the initial analysis suggested that basement air moisture tracked very closely with outdoor moisture. Over the long-term, some of this supposed tracking is due to coincident changes in air temperature, both indoors and outdoors, that enable air to hold more moisture at higher temperatures and less at lower temperatures. However, the data also show that without changes in temperature, basement air moisture levels can rise and fall in apparent response to outdoor air moisture. Following is a summary of the specific findings:

- After reviewing the correlation and physical dependencies of the many variables measured during the study, five variables were identified that were of interest and likely to have an impact on basement moisture: outdoor air moisture, first floor moisture, sub-slab soil air moisture, ASD on/off operation, and HAC operation. The review also pointed out the many inter-relationships between the variables, and comparatively high correlations between them. Outdoor air entering the soil and the upper floors of the house likely has a strong influence on the air in those spaces, and indeed the correlation coefficients between them and outdoor air ranged from 0.6 to 0.9. In turn, the moisture levels of the air in those zones influenced the basement air. Therefore, the outdoor air had both direct and indirect (through the other zones) effects on the basement. The correlation coefficients for basement and outdoor air are consistent for all houses at approximately 0.77 with a delayed response, or lag, of approximately six to 12 hours.

- While correlation measures association between variables, least squares linear regression models were developed to examine the comparative causation of the dependent variables on basement moisture and their predictive ability. As with most regression models, the predictive ability increased as variables were added, explaining over 95% of the variation in basement air moisture when all five variables were included. However, because of the pass-through of outdoor air through the other two zones, the simplified models of one, two, and three variables (outdoor air, ASD and HAC operation) were evaluated in more detail.

- Regression with outdoor air moisture alone explained approximately 70% of the variation in the basement air moisture, while ASD and HAC added modest explanatory power (approximately 4%). These results were consistent for all houses and confirm that changes in outdoor air moisture are a large determinant for changes in indoor air moisture. Remaining variability in basement moisture appears to be largely explained by other source and removal processes in the basement, soil, and upstairs. These would include occupant activities (respiration, cooking, showers, laundry and cleaning, etc.), dehumidification by HAC equipment, storage effects, precipitation, water leaks, drying of new construction, and diffusion from the soil.

- Attempts to estimate the quantities of moisture contributed or removed by outdoor air (and the other factors) produced a broad range of seasonally-dependent responses that are not easily explained. In fact, the regression models estimate that summer season contributions of outdoor air moisture were less than during non-summer periods – which is not in line with expectations and calculations of short-term air flow and moisture during the summer for several of the houses (Section B). It is probable that the large cross correlations between the key variables being studied and the underlying assumptions for linear regression models may have limited the ability to fully account for the non-linear relationships between the variables and the contributions of individuals variables to basement moisture.

- Autoregression models, using three variables (outdoor air, ASD and HAC operation) to account for the time series nature of the data, were very successful predictors of behavior (R^2 greater than 0.995). However, the ordering of the values imposed by the temporal factor, which is not addressed at all in linear regression, makes the relationships less clear.

B. BASEMENT MOISTURE SOURCES AND MOVEMENT, AND ASD MOISTURE CONSIDERATIONS

The final report of the radon/moisture study (Turk and Hughes) included a preliminary review of air flows, moisture movement, and moisture extraction by the radon mitigation systems. To better understand moisture movement and sources in the three houses participating in the ASD radon/moisture project, a more detailed examination of moisture levels and air flows for the various air masses has been conducted. The purpose was to better understand how ASD systems might impact indoor moisture levels and the variability in factors affecting moisture entry, and to consider implications for ASD system design and operation.

B1. BACKGROUND

The Conceptual Model, presented in the final report for this study, discusses the potential effects of air flows, including ASD-induced flows, on building moisture:

> *In all seven possible mechanisms described above the flow paths are generally complex, mostly accidental and unintended, and the pressures driving the flows are very small (that is, less than 10 Pa) and intermittent, depending on weather conditions. It is likely that many of these mechanisms work in combination, to varying degrees, depending on many house, soil, and meteorological conditions.*

The findings of this current analysis confirm that observation. Some general conclusions may be drawn from the data, and can be helpful in understanding the general effects of certain operational phenomena in these buildings. For example, the data strongly suggest that ASD operation typically increases the flow of air from the upstairs to the basement, and that there can be potential basement drying resulting from that air flow increase. However, the data even more strongly suggest that the degree of that air flow increase, and consequent moisture impacts, is heavily dependent on many factors, including house structural characteristics, seasonally-variable weather and house mechanical operation, and ASD configuration and operating characteristics. Further, as predicted in the Conceptual Model, the data show that ASD operation influences every air flow into, out of and within a structure, and that those influences and their consequences are also highly variable from house to house and season to season. In this regard, it is well to remember that this study examined three houses in one geographic location with ASD systems configured and operated in two different modes. Different house structural and operational characteristics, climatic factors and ASD systems would probably exhibit an even wider range of variability in operating characteristics and observed effects.

B2. DESCRIPTION OF MOISTURE AND AIR FLOW VARIABLES

Much of the moisture transport in these houses was due to the bulk flow of air moving between the outdoors, indoor, and soil. Therefore, data for temperature, humidity, radon, and barometric pressure were averaged over periods when valid interzonal flow tracer measurements were conducted. Following are brief descriptions of the measured and calculated data applied in this analysis.

B2.1 Air Flows

Interzonal air flows between the indoors-outdoors and basement-upstairs were determined using a constant injection, multi-tracer, ventilation measurement system (see Turk and Hughes for additional details). The time periods for these measurements typically included three, three-hour periods from 2:00 – 5:00 AM plus three, three-hour periods from 1:00 – 4:00 PM for each season. The median of the individual results for valid test periods is presented here.

B2.2 Absolute Humidity (AH, g/m^3)

Absolute humidity was calculated using standard psychrometric relationships (ASHRAE 2005) from temperature, relative humidity, and barometric pressure measurements in target air masses (Turk and Hughes 2008).

B2.3 Radon

Continuous radon monitors were used to sample air within the house (first floor and basement) and in the subgrade material beneath the slab floors at the following locations: PA01 – E3, PA02 – C4, and PA03 – C1. Radon within block walls and at the exterior of poured walls was also nmeasured.

B2.4 Soil Gas Entry

Soil gas entry was estimated from a steady-state mass balance calculation using estimated outdoor air radon levels (0.12 to 0.3 pCi/l), averages of measured radon concentrations in the soil gas and basement, and measured basement air flows for each three-hour period.

B2.5 Moisture Exhausted by ASD

Temperature and relative humidity of the air entering the bottom of the ASD pipes was used, along with the air flow in the pipes measured by center-located pitot tube, to determine the quantity of moisture being exhausted by the ASD pipes. During cool and cold weather some of this moisture may have condensed on sections of the pipe exposed to cold temperatures and drained back into the opening through the foundation wall or slab. Thus, the amount of moisture exhausted by the ASD systems may be overestimated, although the quantity of this returned moisture may have been small compared to the total exhausted.

B3. BASEMENT MOISTURE SOURCES AND FLOWS

Data from the three study houses were developed to illustrate the relationships between the moisture characteristics of basement air and of air moving into the basement from various sources, and the quantities of those flows. Of particular interest are the changes in air flow quantities due to ASD operation and the potential basement moisture consequences of those changes. Table 6, below, summarizes much of the data relevant to the following discussions. Appendix C contains additional measured and calculated data used to develop information in Table 6.

Table 6. Summary of Moisture, Radon, and Interzonal Flows under Different Seasons and ASD Operating Conditions

			Average AH (g/m^3)				Radon Concentrations (pCi/L)				Interzonal Flow/Ventilation							
											Upstairs to Bsmt		Outdoor to Bsmt					
House #	Season	ASD Config	Bsmt Air	Upstairs Air	Outdoor Air	Soil Gas	Outdoor Air (est)	Upstairs Air	Bsmt Air	Soil Gas	(cfm)	(ACH)	(cfm)	(ACH)	ASHRAE Bsmt (ACH)[1]	Outdoor to Upstair (ACH)	ASHRAE Upstairs (ACH)[1]	Soil Gas Entry (cfm)
PA01	Winter	Off	5.3	5.0	3.3	12	0.3	39	60	230	11	0.06	26	0.13	0.07	0.21	0.16	10.8
		On full	5.8	5.3	4.9	12	0.3	0.4	0.4	240	32	0.16	39	0.19		0.28		0.0
	Spring	Off	7.3	6.9	7.4	12	0.3	11	50	380	6.8	0.03	7.0	0.03		0.54		1.9
		On full	7.0	7.2	9.1	13	0.3	0.4	1.3	320	2.8	0.01	16	0.08		0.21		0.1
	Summer	Off	9.7	9.3	17	15	0.3	21	26	930	18	0.09	10	0.05		0.14		0.4
		On full	9.6	9.1	16	16	0.3	1.0	0.8	360	33	0.16	13	0.06		0.16		0.0
	Fall	Off	9.7	9.3	9.1	15	0.3	17	55	910	2.4	0.01	12	0.06		0.27		0.9
		On mod	10	11	13	15	0.3	0.5	0.7	470	4.4	0.02	9.1	0.04		0.28		0.0
PA02	Winter	Off	6.4	5.6	6.9	15	0.3	9.3	20	190	4.6	0.02	13	0.06	0.07	0.06	0.23	1.8
		On full	5.2	4.7	4.2	16	0.2	0.2	0.4	140	47	0.23	38	0.19		0.17		0.1
	Spring	Off	6.0	5.7	6.7	13	0.3	8.4	17	340	4.3	0.02	13	0.06		0.06		0.8
		On full	7.0	6.5	9.4	14	0.3	0.3	0.6	170	35	0.17	35	0.17		0.19		0.1
	Summer	Off	12	10	12	17	0.3	8.3	15	200	13	0.06	6.8	0.03		0.05		1.0
		On full	12	10	12	17	0.3	0.3	0.5	180	36	0.18	37	0.19		0.25		0.1
	Fall	Off	9.3	7.3	5	17	0.3	9.9	20	320	2.4	0.01	12	0.06		0.08		0.9
		On mod	8.2	6.8	3.8	16	0.1	0.1	0.6	230	19	0.09	30	0.15		0.16		0.1
PA03	Winter	Off	5.0	4.3	2.4	13	0.3	2.9	8.5	220	42	0.35	24	0.20	0.07	1.0	0.20	2.1
		On full	4.8	4.5	5.5	13	0.2	0.2	0.2	44	95	0.79	44	0.36		1.0		0.0
	Spring	Off	7.1	5.4	5.9	13	0.3	4.6	21	1400	3.7	0.03	7.3	0.06		0.56		0.1
		On full	5.7	4.7	4.3	13	0.1	0.1	0.2	64	73	0.60	25	0.20		1.2		0.1
	Summer	Off	11	10	17	15	0.3	2.2	3.8	1100	ND[2]	ND[2]	ND[2]	ND[2]		ND[2]		ND[2]
		On full	11	9.6	17	15	0.2	0.2	0.2	80	130	1.10	38	0.32		1.0		0.0
	Fall	Off	8.0	6.2	8.4	15	0.3	4.5	15	940	8.2	0.07	7.0	0.06		0.71		0.2
		On mod	7.2	6.1	7.8	15	0.3	0.4	0.3	92	67	0.56	8.0	0.07		1.1		0.0

[1] Ventilation rate for basement and upstairs as recommended by ASHRAE Std 62.2 (2007)

[2] Tracer gas-based values were suspect during Summer ASD Off period in PA03, and are therefore not included (ND, No Data).

B.3.1 Relative Source Moisture Index

A relative moisture index was created to compare the moisture levels in the air of different zones surrounding the basement (Figures 6 to 8). The figures show the index for air from each source, which is simply the difference between the absolute humidity (AH, g/m^3) of the basement air and the AH of the source air, normalized by the AH of the basement air.

Some clear, if not necessarily consistent, moisture relationships emerge from these data: 1) soil air was always much wetter than basement air; 2) upstairs air was almost always drier than basement air, but the difference is smaller than between soil air and basement air; 3) outdoor air varied from significantly drier to significantly wetter than basement air, including some periods when it had a higher relative moisture index than soil air; 4) during Summer, and parts of Spring and Fall, upstairs is the only potentially drying air source to the basement; and 5) ASD operation appears to have relatively little impact on moisture content of the into-basement air flows, although other data indicate some very limited drying of soil gas at a few locations.

Note that during the summer tracer gas study period in PA02, the outdoor air moisture content was considerably lower than the seasonal average. Outdoor air moisture conditions during summer tracer gas studies in PA01 and PA03 were more representative of that seasonal average (see Table 6).

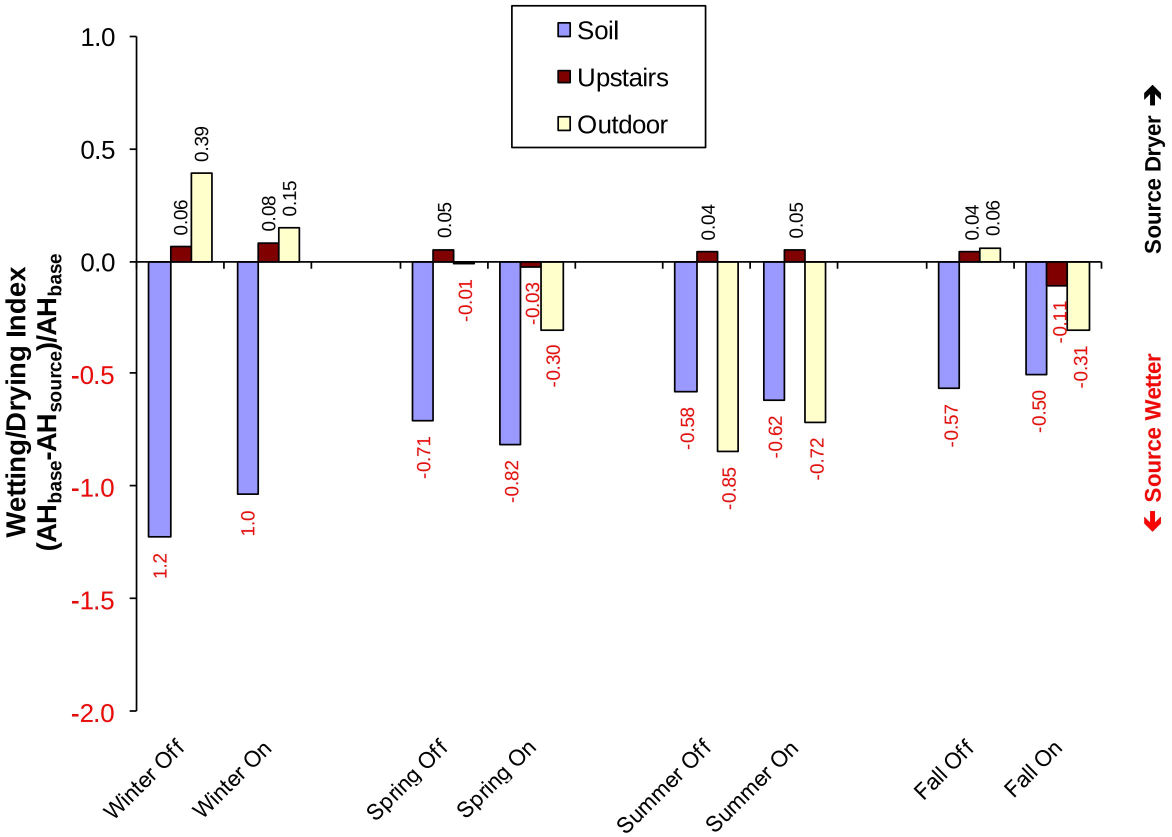

Figure 6. *Index comparing the moisture of air in the basement of house PA01 with that of sources of air in zones around the basement (soil, outdoors, upstairs), normalized by the basement air moisture. Values are shown for the periods during interzonal flow testing in the four seasons with the ASD system on and off. Zones with air dryer than that in the basement are represented as positive values.*

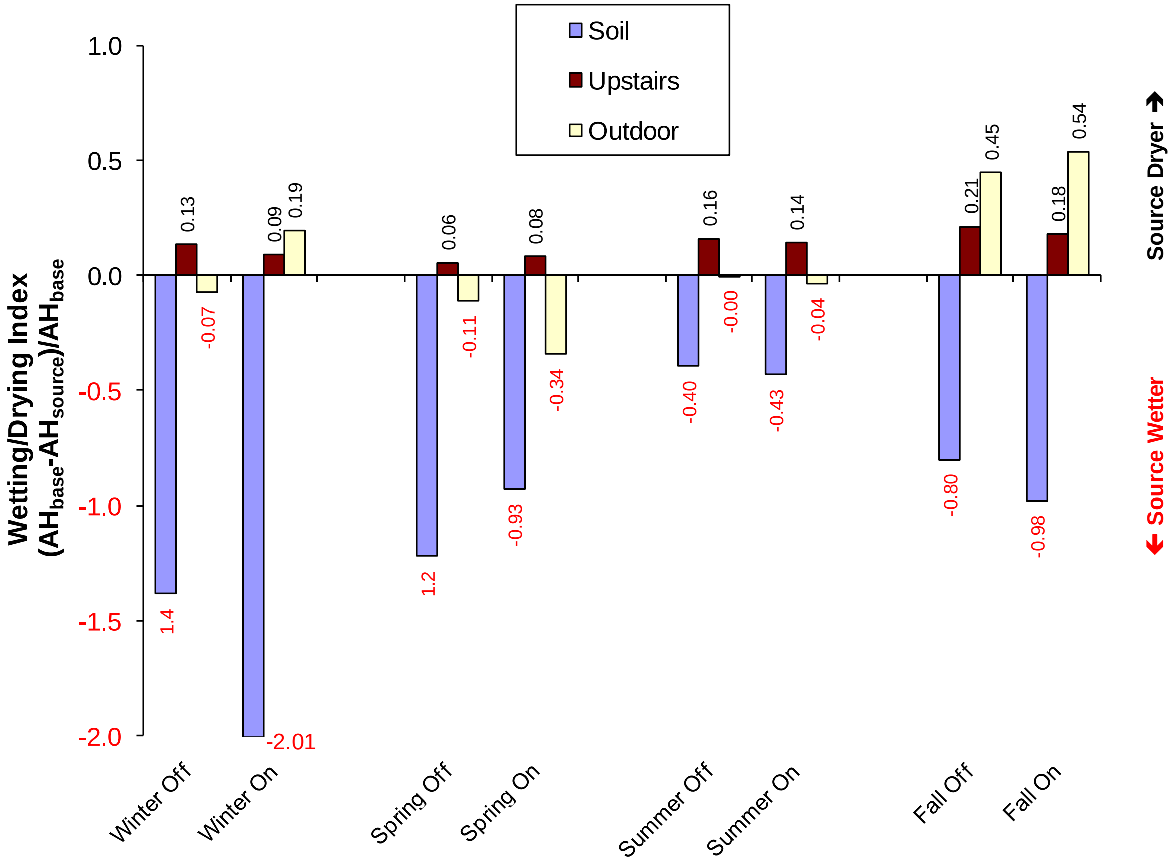

Figure 7. *Source moisture index for house PA02.*

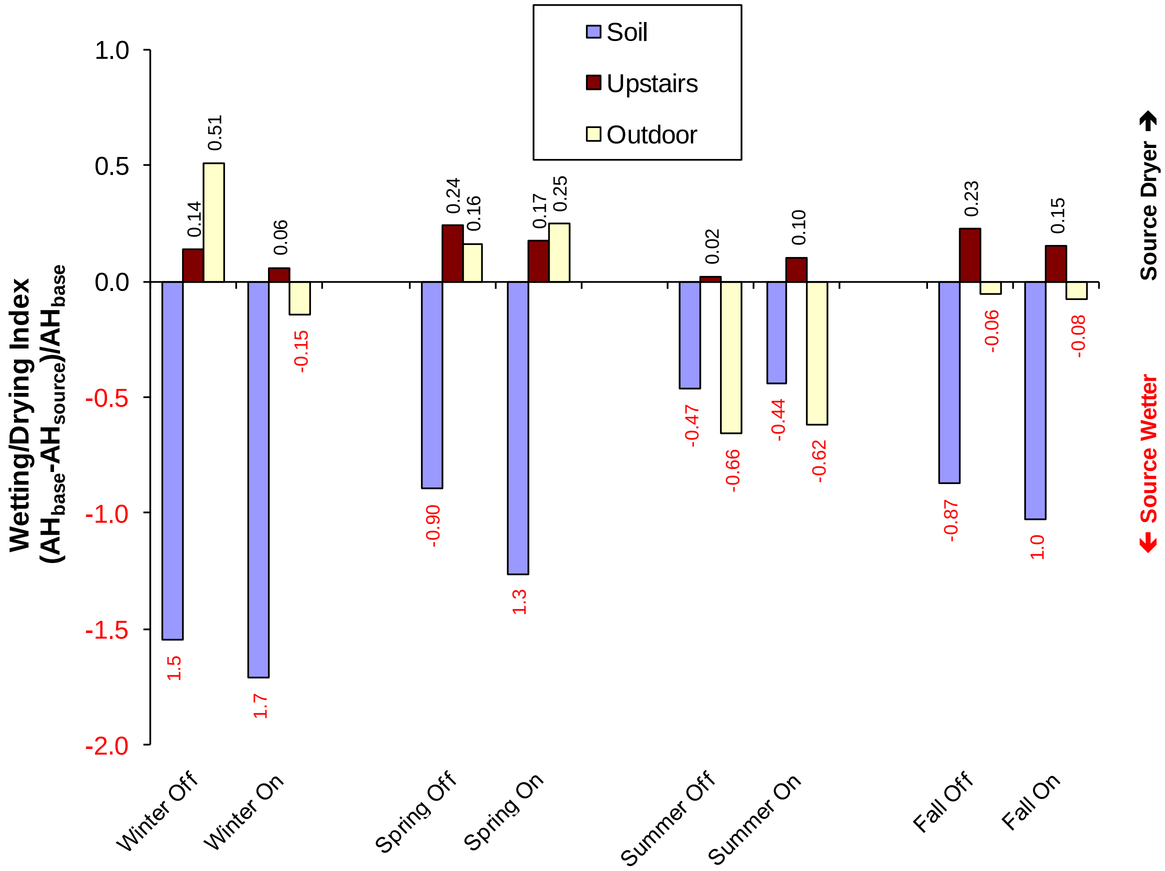

Figure 8. *Source moisture index for house PA03.*

B3.2 Air Flow Into the Basement

While the moisture content of the air entering the basement is a key factor in determining the contribution to, or removal of moisture from, the basement, the flow rates of air from these zones is also important. Figures 9 to 11 show the quantity of air flow into the basement from each source zone around the basement (soil, upstairs, and outdoors).

These plots show the extreme variability of air flows into the basements of the study houses, both seasonally and between houses. House to house differences might be inferred from the leakage characteristics of the building shells and the floor between the basement and first floor, as determined by blower door testing (see blower door test results, Turk and Hughes). However, the degree of overall air-tightness is only one of many influences on infiltration, exfiltration and in-house air flows. Other factors include weather, HAC operation and occupant activities. The net effect of these influences is not constant, as evidenced by the variance in flows between different ASD Off periods in each house. (Note: during ASD Off periods, gate valves in all suction pipes of the systems were closed.)

Of particular importance to considerations of ASD impact on basement moisture are the ASD-induced changes to these flows and the variability of those changes, even between the Winter, Spring and Summer periods when the ASD systems were configured identically in each

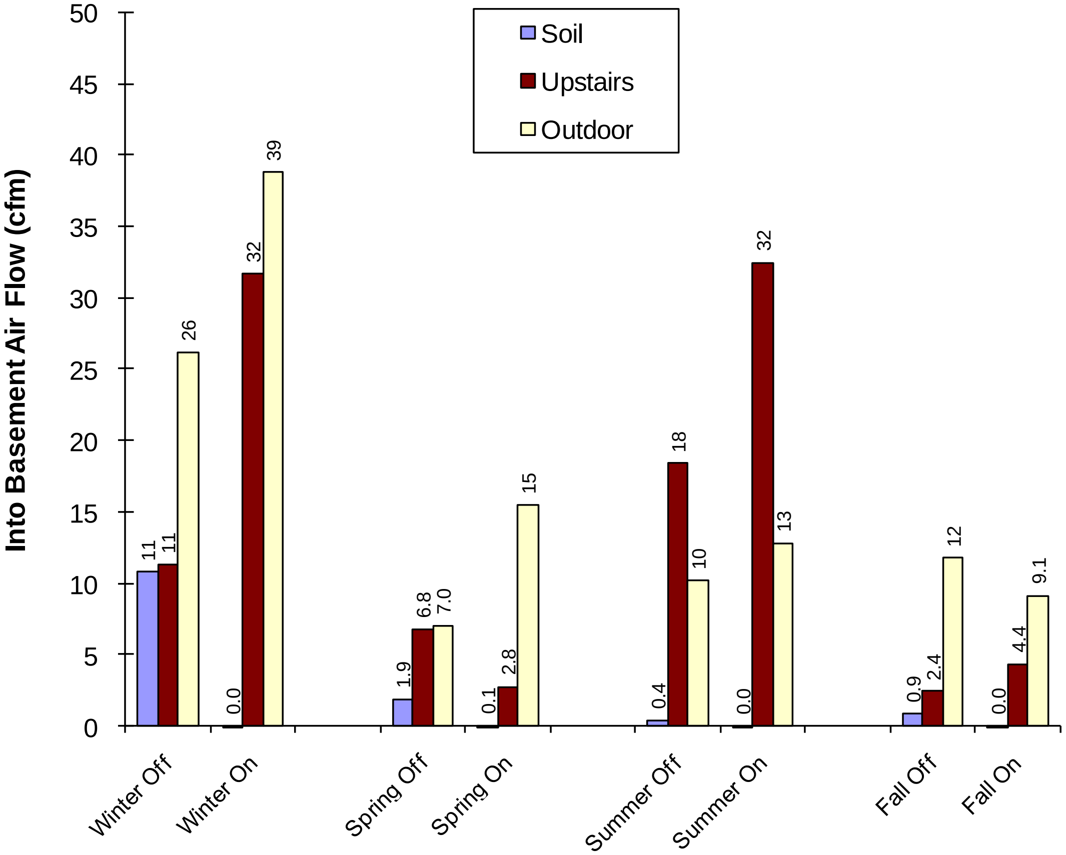

Figure 9. *Median of up to six measurements of air flow into the basement for each test period at house PA01 from the soil, upstairs, and outdoors during the interzonal flow test periods in the four seasons with the ASD system on and off.*

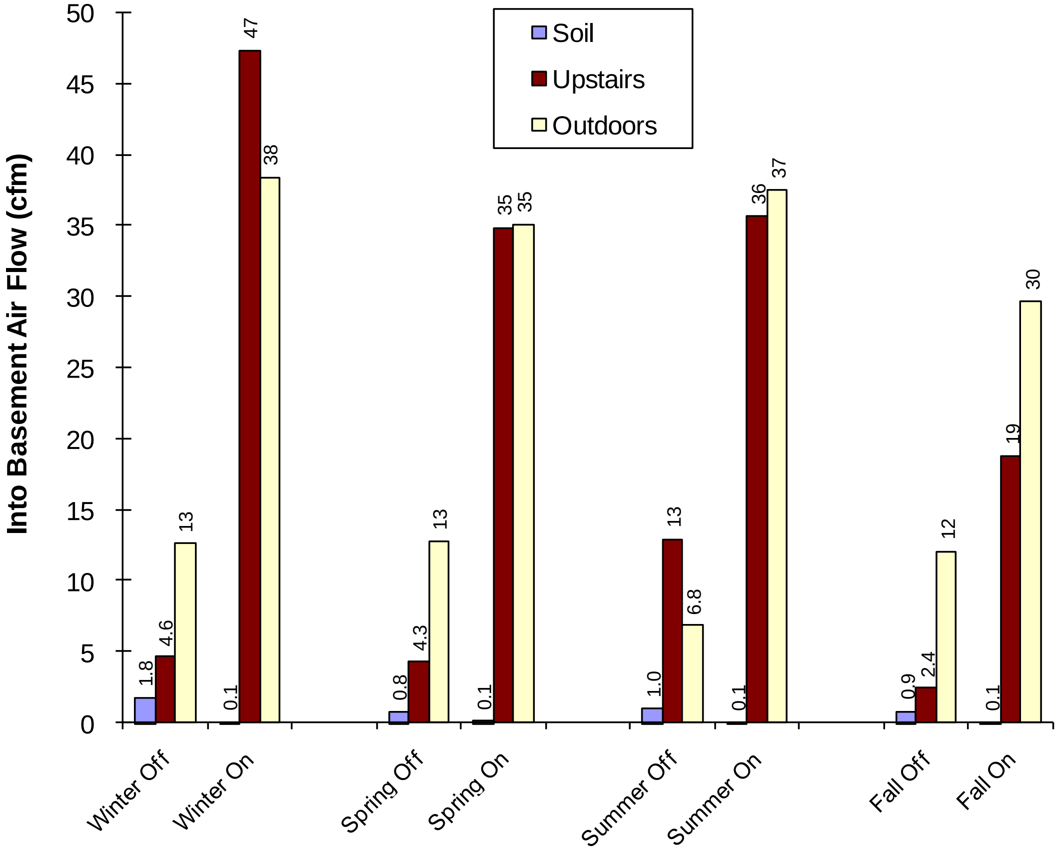

Figure 10. *Air flows into the basement of house PA02.*

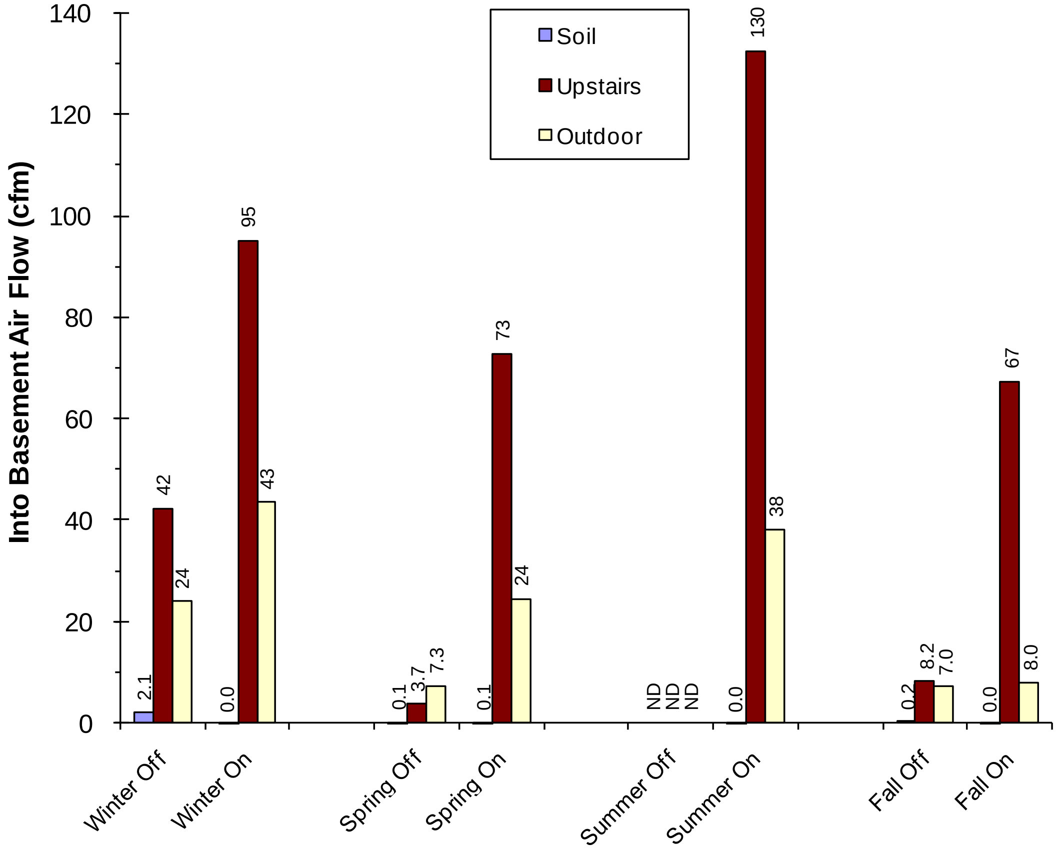

Figure 11. *Air flows into the basement of house PA03. Missing data is indicated by ND.*

house, and total system air flow remained virtually constant. During the Fall period in each house, the ASD systems were re-configured to a single slab suction point, and the system flows were reduced to produce air flows more representative of systems commonly installed for radon control (Table 7). This configuration produced yet another variation on air flows in each house.

Despite the marked variability of these air flows, there are some discernable patterns associated with ASD operation. Upstairs to basement flow increased in every house and every season except PA01 in the Spring. It is likely that these two exceptions to the general trends are related to the occupants' practice of employing natural ventilation during suitable weather, i.e., Spring and Fall. Outdoor to upstairs flow was also often increased (see discussion in Section B4, below). Soil gas entry was practically eliminated in every case, although ASD Off values for this flow were typically quite small. By far the largest, less than 11 cfm, was in PA01 in Winter, before the wall/floor joint was sealed. Increase in outdoor to basement flow was indicated except in PA01 in the Fall.

B3.3 Drying/Wetting Potential of Convective Moisture Sources

By combining the previous two sets of data (relative moisture index times the air flow quantity), a basement drying/wetting *potential* has been developed and presented in Figures 12 to 14 for the three houses. The potential does not imply actual drying or wetting of the air flows into the basement from the three sources.

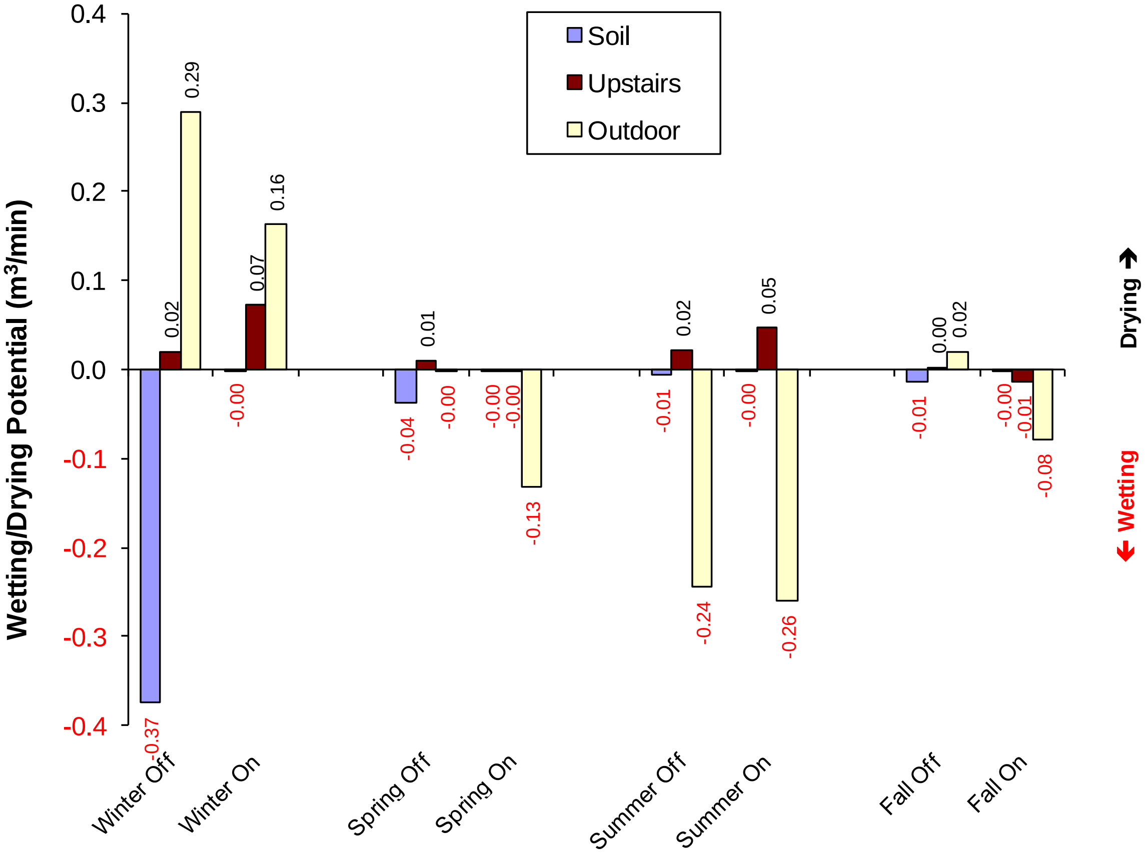

Figure 12. *The relative drying/wetting potential of into-basement air flows for house PA01. The values do not represent actual changes in basement moisture, rather are a comparison of the potential for air from different sources to add moisture to or remove moisture from the basement.*

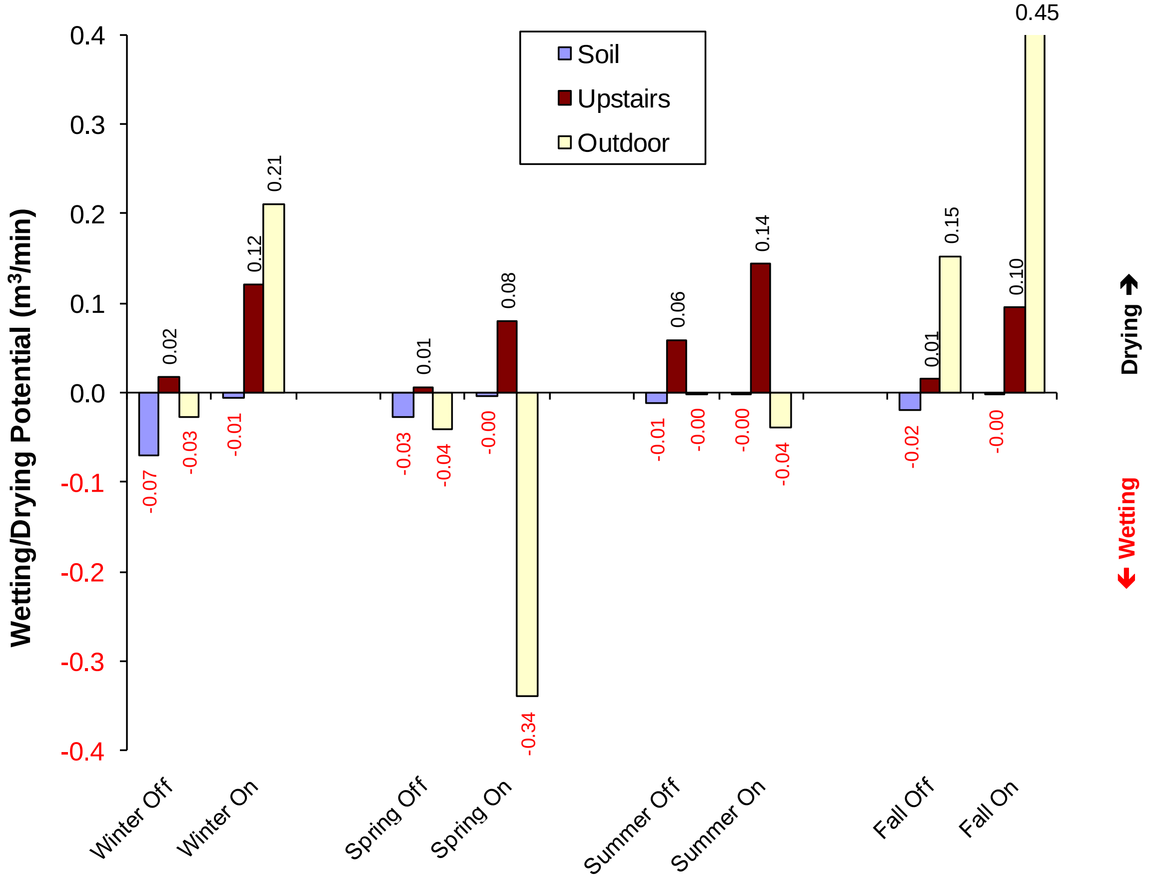

Figure 13. *The drying/wetting potential for house PA02.*

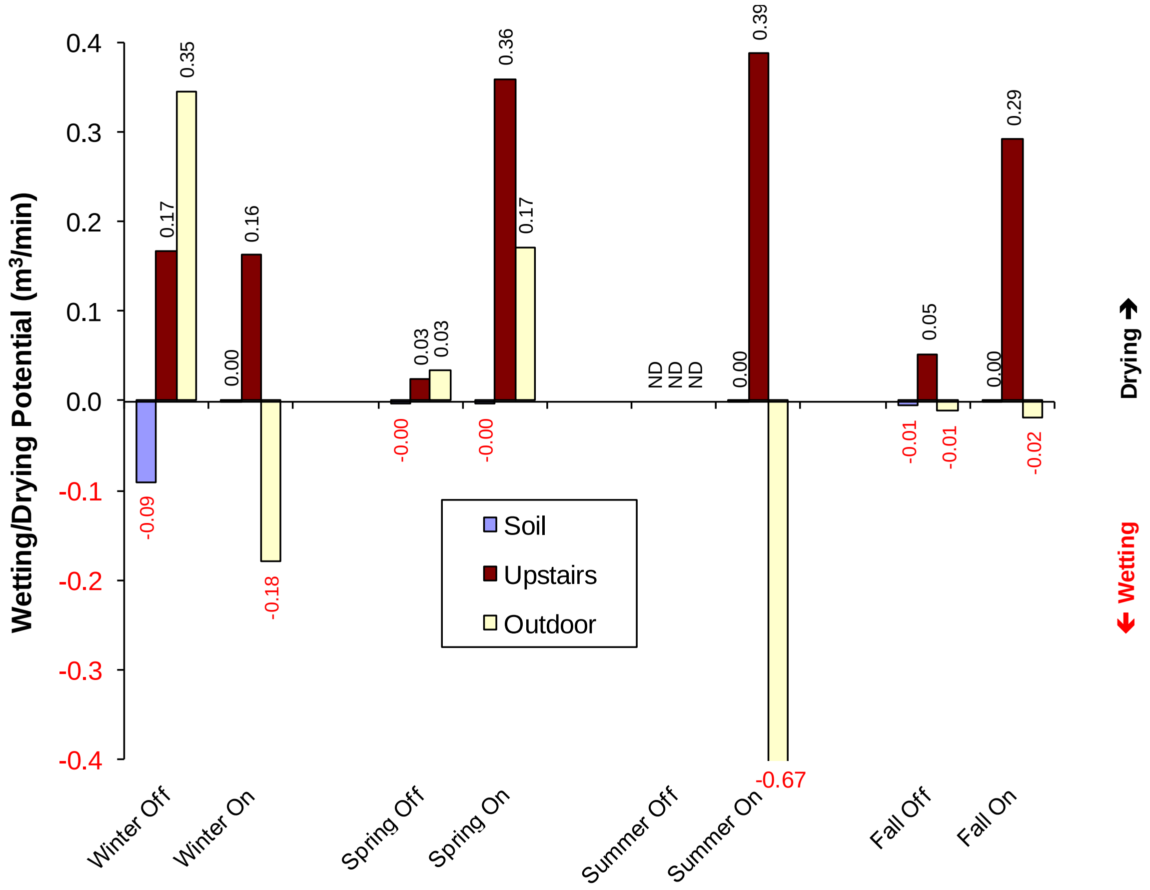

Figure 14. *The drying/wetting potential for house PA03*

Although at least the general *potential* drying or wetting influence of some of the flows could be deduced from the information in Figures 6 – 11, the magnitude and variability of the influences are clearly revealed here. As discussed in the final report of the study, ASD operation has the potential to increase moisture entry from outdoor air when outdoor moisture levels are high (especially Spring and Summer).

The increase in upstairs to basement air flow associated with ASD operation is the only consistently significant potential drying influence on the basement. As mentioned before, the Spring and Fall exceptions to this in PA01 are probably related to the use of natural ventilation during those seasons. In seven of the 12 ASD On periods, including Summer in all three houses, upstairs to basement air flow was the largest contributor to potential basement drying.

Reduction of soil gas entry is certainly a potential drying influence. In eight of 11 ASD Off periods (No Data for PA03, Summer), moisture contributions from soil gas entry had the largest wetting potential. However, with few exceptions, the ASD Off soil gas entry rates are typically so small that eliminating that moisture contribution usually provides a relatively small benefit compared to the increased upstairs to basement flow. Although the three houses in this study did not exhibit large soil gas entry volumes, it is probable that many houses do. For example, in contrast to this study, 15 houses in the Pacific Northwest were found to have soil gas entry rates ranging from one to 23 cfm (median of 8 cfm), accounting for one to 21% of total house ventilation (Turk et al 1990). In those cases, much greater moisture control benefit could be achieved by large reductions in that entry, in addition to radon control.

The less consistent general increase in outdoor to basement flow can be a very significant potential drying or wetting influence. With ASD Off, outdoor to basement flow was the largest contributor to potential basement wetting in three of 11 periods (No Data for PA03, Summer). That flow was the largest contributor to potential basement drying in four of 11 periods. With ASD On, that flow was the largest contributor to potential basement wetting in eight of the 12 periods, including Summer in all three houses. It was the largest contributor to basement drying in three of 12 periods. Further, the quantity of moisture entry and the increases produced by ASD operation were usually large compared to other contributing flows.

Infiltration of outdoor air to the upstairs also exhibited some large increases, but these were not as consistent as some other flow changes. Although not directly impacting the basement moisture, this infiltration does have implications for overall house moisture and mechanical system operation.

Table C-1 in Appendix C shows the potential drying/wetting influences of the various flows using a different, but proportional, index of relative moisture content of basement air and source air.

B3.4 Net Convective Flow of Moisture

Figures 15 to 17 summarize the net convective flow of moisture into and out of the basement relative to the surrounding zones. Supporting data are included in Table C-2 of Appendix C. The net convective flow takes into account the moisture content of the air in the basement, soil, upstairs, and outdoors, along with the net flow of air into and out of the basement. In contrast

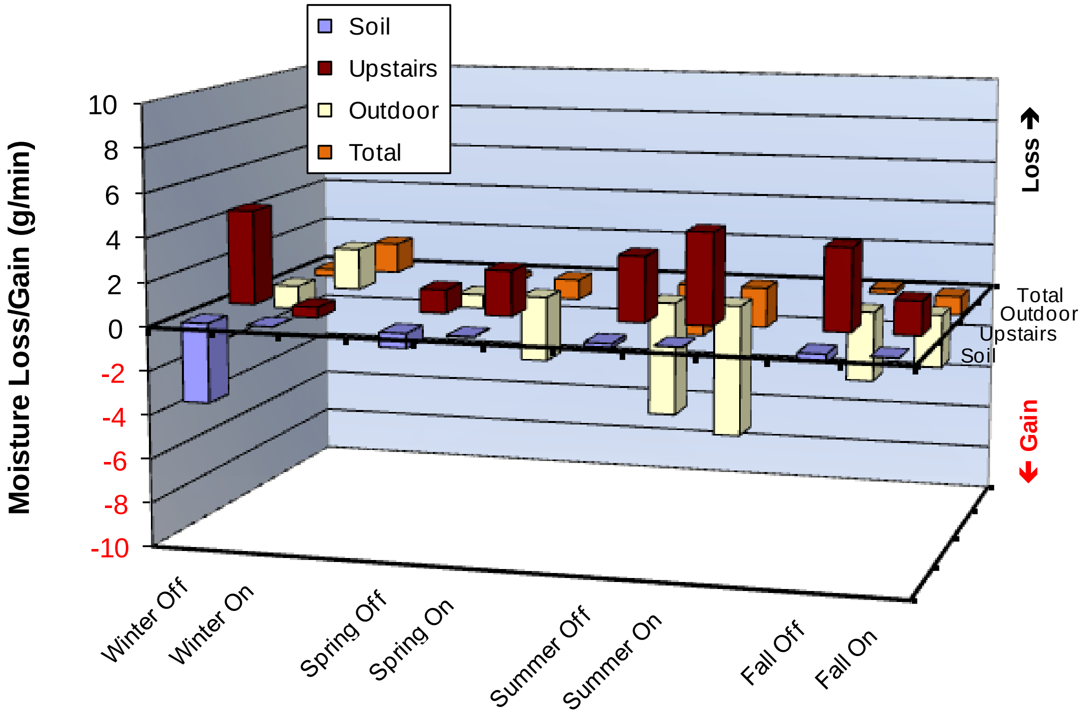

Figure 15. *The net convective flow of moisture, at house PA01, between the basement and soil, upstairs, and outdoors. 'Gain' indicates net moisture flow to the basement from a zone (soil, upstairs, outdoor), while 'loss' is net moisture flow out of the basement to a zone.*

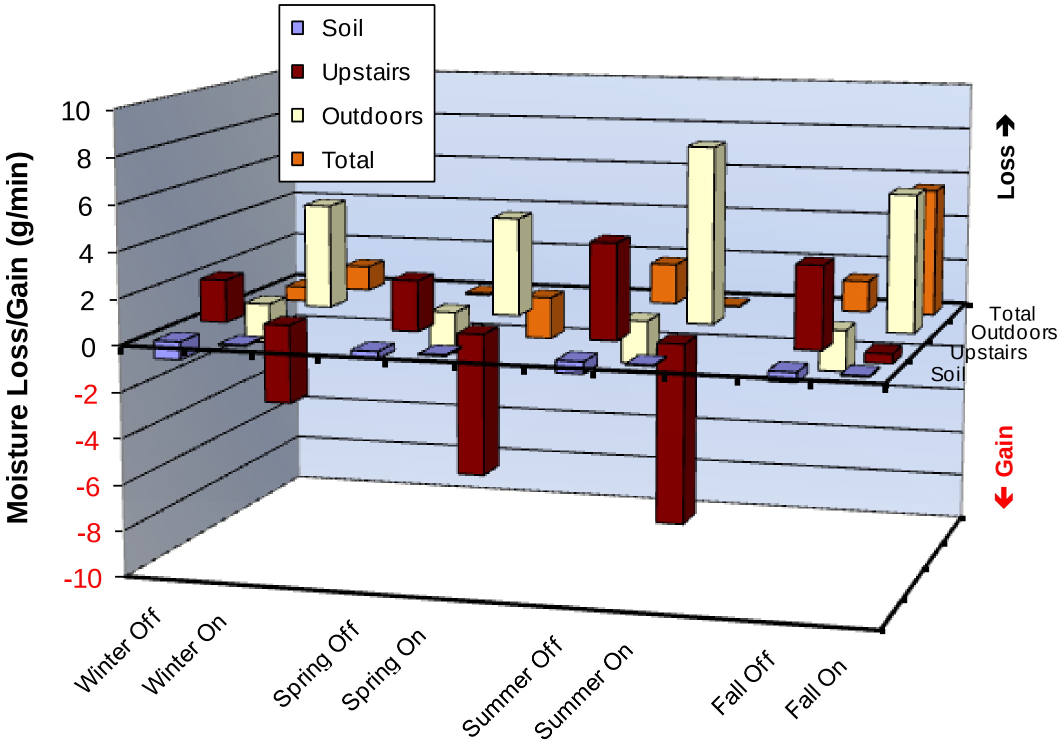

Figure 16. *The net convective flow of moisture for house PA02.*

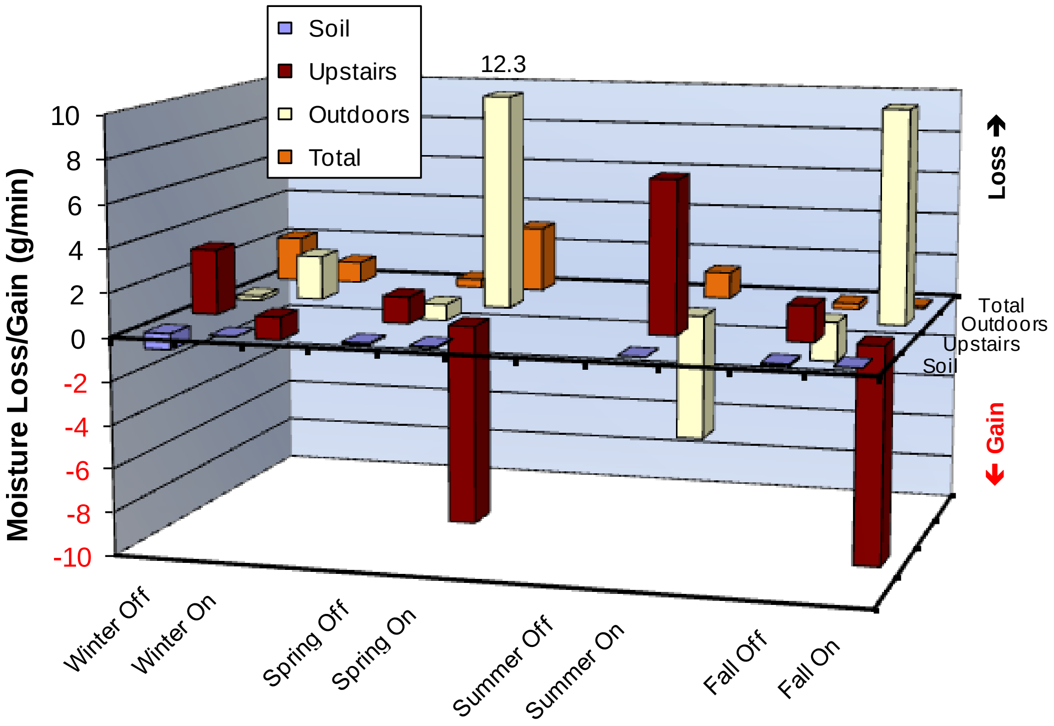

Figure 17. *The net convective flow of moisture for house PA03.*

with the drying/wetting *potentials* displayed in Figures 12 – 14, the net convective flow is a measure of the *actual* convective moisture exchange during the periods when the ventilation and interzonal flow rates were measured.

Interzonal flow measurements typically show that air often flows in both directions across floors and walls separating the zones. This occurs in most buildings as pressure fluctuations (as a result of HAC system and exhaust fan operation, wind, door and window openings, etc.) cause air flow to reverse directions, momentarily or for more extended periods. The tracer test method used for determining the interzonal flows detects and 'averages' these flow reversals. The calculation of data presented in Figures 15 to 17 was

$$m_{net} = q_{bn}c_b - q_{nb}c_n$$

where: m_{net} = net convective flow of moisture (g/min),
q_{bn} = median air flow from basement into zone n (m^3/min),
q_{nb} = median air flow from zone n to basement (m^3/min),
c_b = average absolute humidity of basement air (g/m^3), and
c_n = average absolute humidity of air in zone n (g/m^3).

The figures also show that while convective moisture entry from the soil is generally small, operation of the ASD system essentially stops the flow, consistent with the radon levels during ASD. The results for moisture movement involving the upstairs and outdoors, and total moisture movement, are more complicated and vary by house and season. For example in houses PA02 and PA03, ASD operation tends to cause an increase in moisture entry from the upstairs but at the same time offset that with moisture being lost to the outdoors (except in the Summer). Note again that outdoor air moisture during the summer testing at PA02 was lower than the seasonal average, likely causing the overall moisture loss to outdoor air. However at PA01, ASD operation tends to increase the net loss of moisture to upstairs (except Fall), while increasing the net gain from outdoor air during Spring and Summer. When the convective moisture movement for all zones is combined (Total), there is no consistent trend among the houses, with approximately one-half (five) of ASD On periods showing a total net moisture gain. In addition, the total net moisture movement into the basement does not appear to exhibit a substantial increase in the Summer.

As discussed in Section A, moisture levels in basement air of all houses appear to be strongly influenced by moisture in the outdoor air. This results in drier basement conditions during the Winter and more damp conditions in the Summer – dominating the impact of ASD system operation. Thus, it is interesting, and puzzling, that the total entry rates do not follow the same trend. This may be due, in part, to unrepresentative moisture conditions during the brief periods of the ventilation and interzonal flow measurements, and because the actual seasonal changes are small and difficult to detect in this analysis.

B3.5 Moisture Extraction by ASD Systems

Anecdotal reports by radon mitigation professionals have indicated that some systems collect large amounts of water over short periods of time. This water originates from water vapor that condenses inside cold sections of pipe, and then accumulates at low points of the pipe runs. The data from this study supports that contention, with large amounts of moisture being exhausted in the form of water vapor from the systems at all houses, regardless of the season (Figures 18 to 21, and Table 7). The maximum daily extraction rate was over 25 gallons/day (95 liters) during the Summer at PA03.

A sizeable portion of the exhausted air originates in the basement (Table 8), and it is presumed that the remainder is soil air. Therefore, it is not surprising that the graphs show the extracted moisture tracks with the moisture content in the outdoor air, basement air, and soil air. As discussed earlier, the outdoor air moisture appears to be a dominant factor affecting moisture in the basement and soil air for these houses.

In houses PA02 and PA03, the amount of moisture extracted dropped quickly after the ASD systems were activated, presumably as an initial reservoir of moisture was depleted. During many of the two-week cycle periods, the diminishing moisture did not stabilize. It was observed that when part of the system was shut off, the moisture extracted by the remaining system pipe increased – presumably because the air flow for the remaining single pipe generally increased (Table 7).

A standard efficiency dehumidifier was operated for three, two-week cycles (six weeks) during the Summer and early Fall at PA03. The moisture removed from the basement air by the dehumidifier is shown in Figure 21 and Table 7, and is significantly less than that extracted by the ASD system. These data strongly suggest the ASD systems remove moisture from sources other than the basement air, with the potential for more effective drying in the basement.

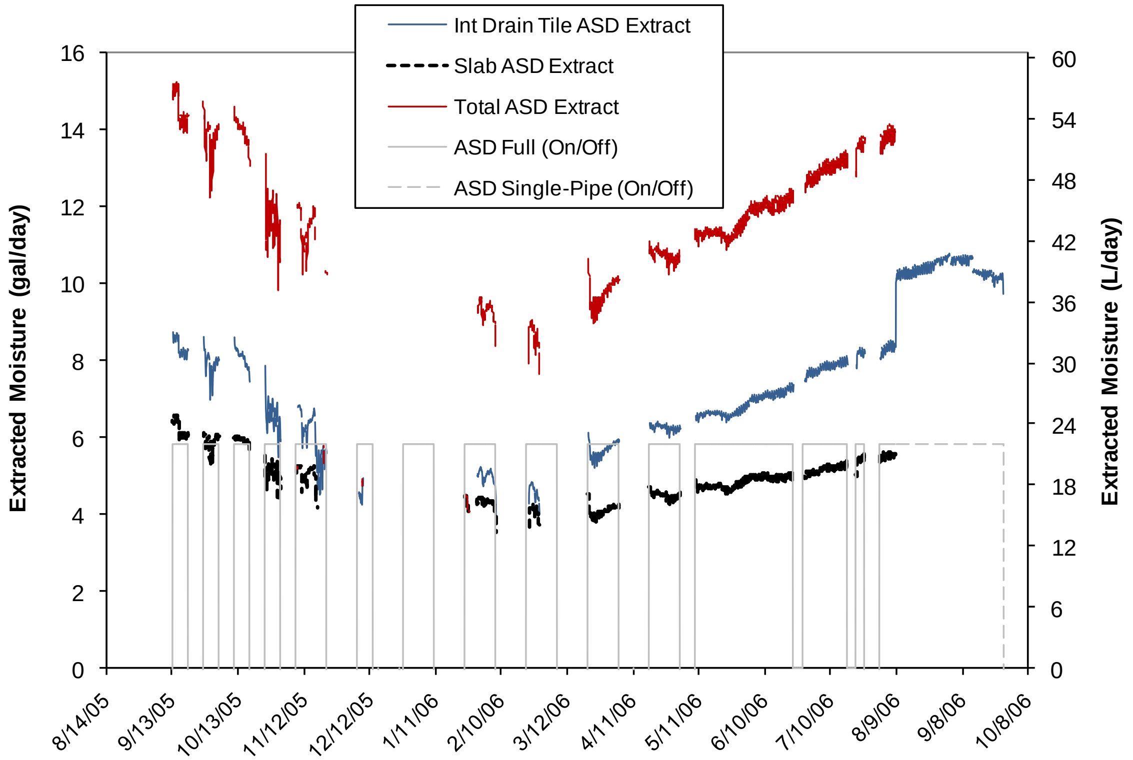

Figure 18. *The daily moisture extracted by the two ASD system pipes (and the combined total) at house PA01 over approximately 12 months of the study. Starting in August 2006, only the internal drain tile ASD pipe was open and operated.*

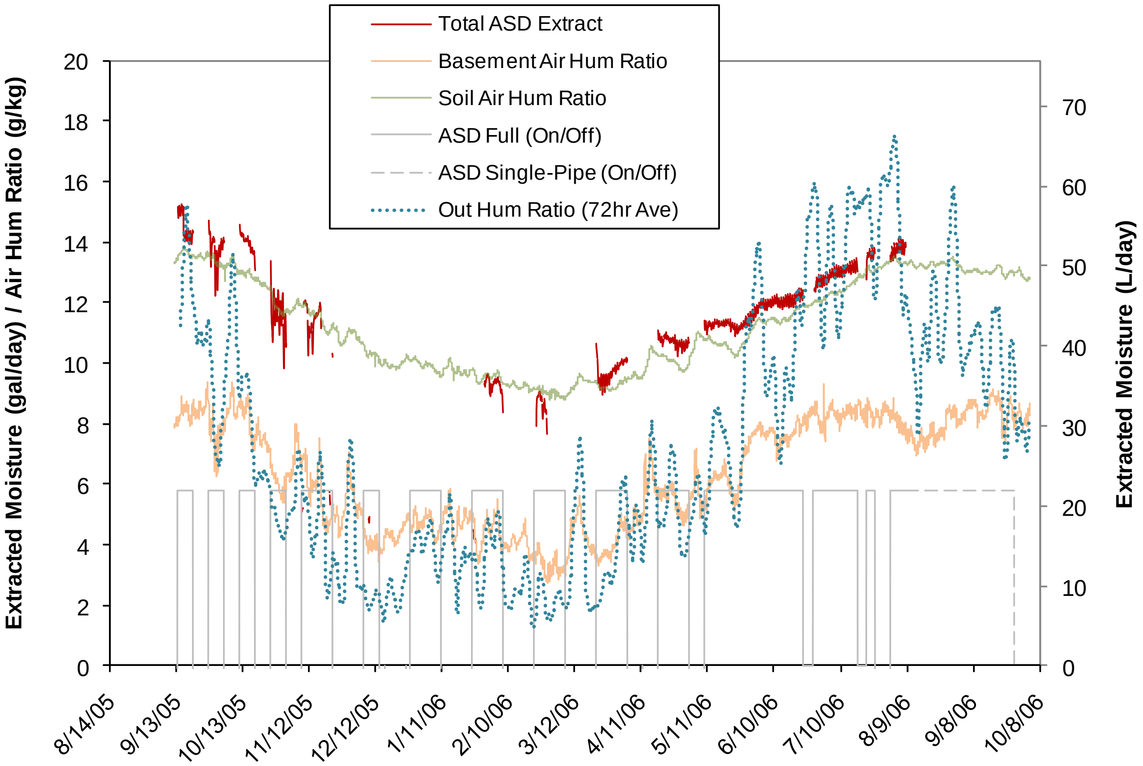

Figure 19. *The change in total moisture extracted by the ASD system at PA01 plotted with the 72-hour running average humidity ratios for the basement, soil, and outdoor air.*

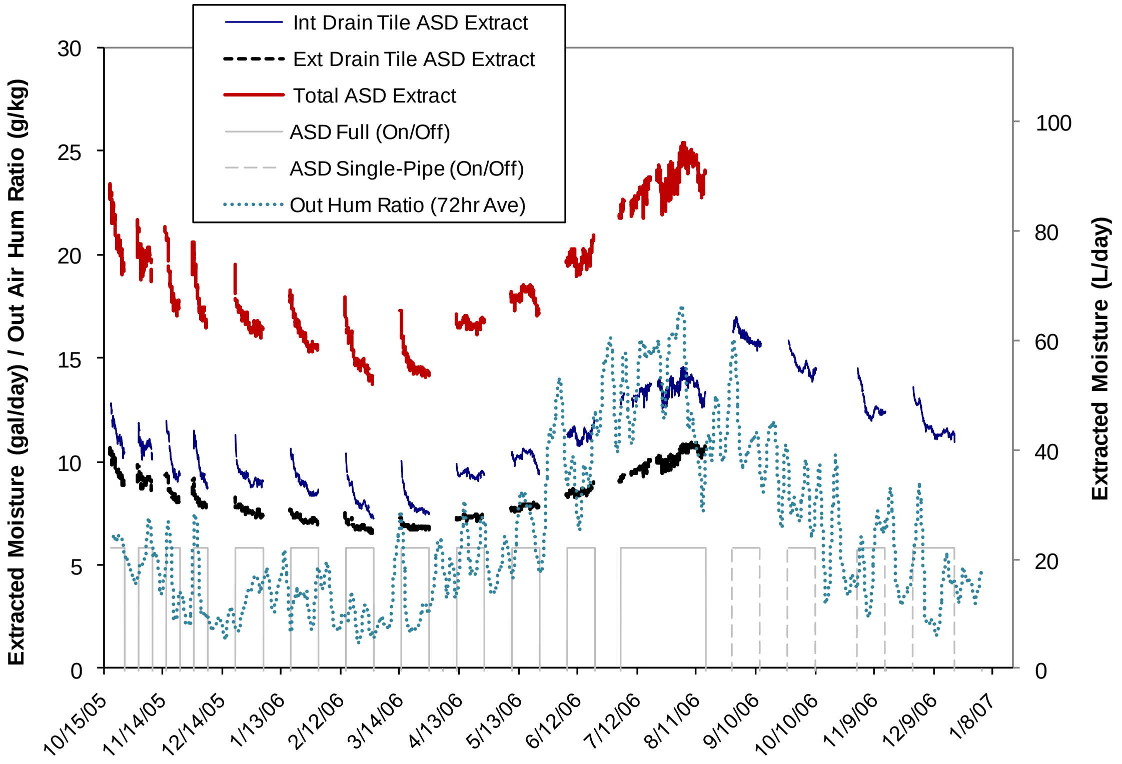

Figure 20. *The daily moisture extracted by the ASD system pipes (and combined total) at PA02, along with the outdoor air humidity ratio.*

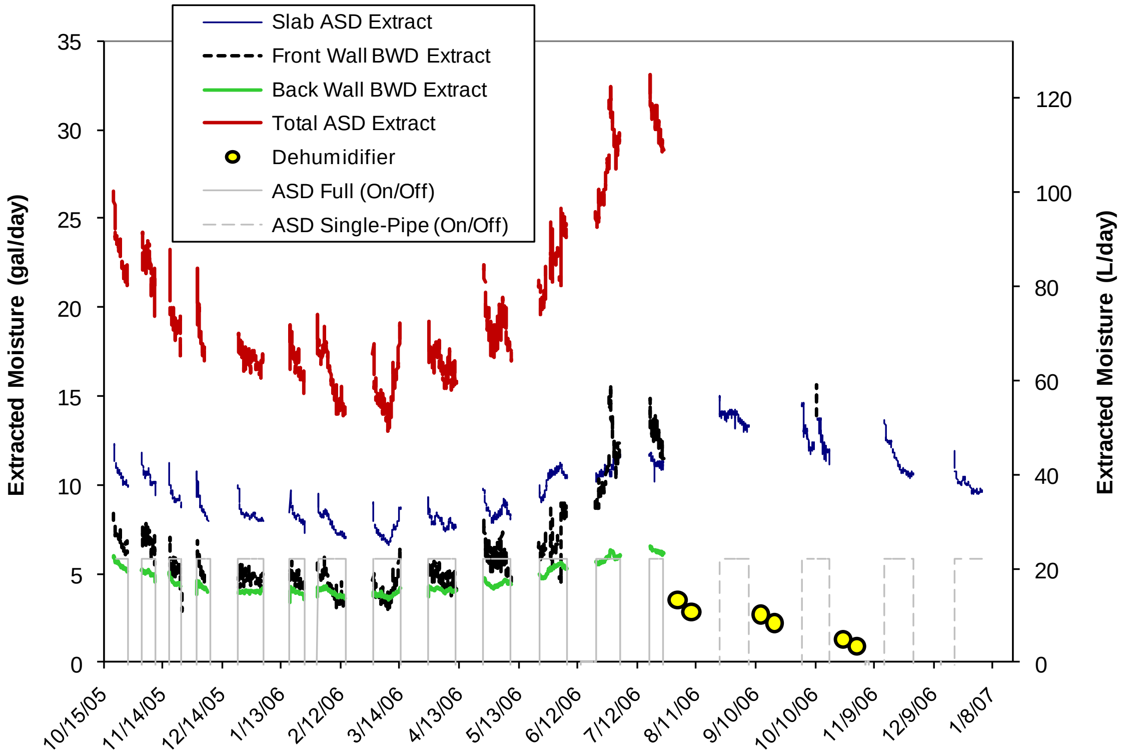

Figure 21. *The daily moisture extracted by the ASD system pipes, including the block wall depressurization pipes (BWD), and combined total, at PA03, along with the daily average moisture removed by the stand-alone dehumidifier for six weeks.*

Table 7. Summary of Daily Average Moisture Removed by Different System Configurations (gal/day / liter/day)

House ID/ System Description	Summer[1]		Non-Summer[1]	
	Full ASD	Single-Pipe	Full ASD	Single-Pipe
PA01				
Interior Drain Tile	7.8 / 30	10 / 38	5.4 / 20	--
Slab	5.4 / 20	--	4.1 / 16	--
Total ASD[2]	13 / 49	10 / 38	11 / 42	--
PA02				
Interior Drain Tile	13 / 49	16 / 61	9.4 / 36	13 / 49
Exterior Drain Tile	9.7 / 37	--	7.7 / 29	--
Total ASD[2]	23 / 87	16 / 61	17 / 64	13 / 49
PA03				
Slab	11 / 42	14 / 53	8.5 / 32	11 / 42
Front Wall BWD	11 / 42	--	5.1 / 19	--
Back Wall BWD	5.8 / 22	--	4.3 / 16	--
Total ASD[2]	27 / 102	14 / 53	18 / 68	11 / 42
Dehumidifier	2.8 / 10		1.1 / 4.2	

[1] Summer was defined as follows: when daily average outdoor air dew point changed to being above (Summer) or below (non-summer) 60°F (15.6°C) for five consecutive days. During the study this occurred between June 04, 2005 and September 27, 2005 and between May 26, 2006 and September 25, 2006).

[2] Total moisture extracted may not equal the sum of the average extracted for each pipe, due to periodic sensor or other failures in individual pipes.

B4. DRYING MECHANISMS

As observed in Table 6 and Figures 9 – 11, ASD operation often increased the infiltration of outdoor air to the basement, including in Summer, when this flow can have a significant wetting potential. Despite this, the basement air during the Summer sometimes exhibited lower relative humidity (RH) during ASD operation. (Turk and Hughes, Figures 9 – 11) The outdoor air flow into the basement would have a drying effect in Winter, due primarily to the low moisture content of the incoming air. But in Summer, basement drying is apparently mostly due to ASD-caused increases in flow of drier upstairs air to the basement. The movement of upstairs to the basement is caused by the ASD systems depressurizing the basement, with respect to upstairs, by removing basement air through cracks and gaps in the foundation. The only other potential basement drying influence, soil gas entry reduction, was not large enough to account for the observed drying.

ASD operation also often increased outdoor to upstairs flow, as is illustrated in Figures 22 – 24 and in Appendix C, Table C-1. In spite of this increase, the upstairs air remained at a low enough moisture content in Summer, not just to be a potential drying influence on the basement air but, in fact, to dry the basement air in spite of any increased outdoor air flow into the basement and upstairs. Increases in outdoor air entry into the upstairs during ASD operation occurred in three of four test periods at PA01 (increases of 3 to 13 cfm), in all test periods at PA02 (16 to 41 cfm), and in two of four test periods at PA03 (46 to 78 cfm).

Dehumidification caused by operation of the central air conditioning system (HAC) is probably the dominant mechanism drying the upstairs air during the Summer. The air conditioning was controlled by occupant-set thermostat in all three houses. The basements were not directly air conditioned by the HAC systems. However, conditioned air leaking from the basement ducts and HAC equipment and drawn into the basement from upstairs during many of the test periods was an indirect dehumidification mechanism. There was no evaluation of test periods during the Summer without air conditioning because of concern for maintaining occupant comfort. A better understanding of ASD-influenced drying in air conditioned houses is necessary before ASD systems are considered for widespread adoption to control basement moisture. It is left to future studies to evaluate the impact the impact of ASD moisture reductions in houses without air conditioning under various climatic conditions.

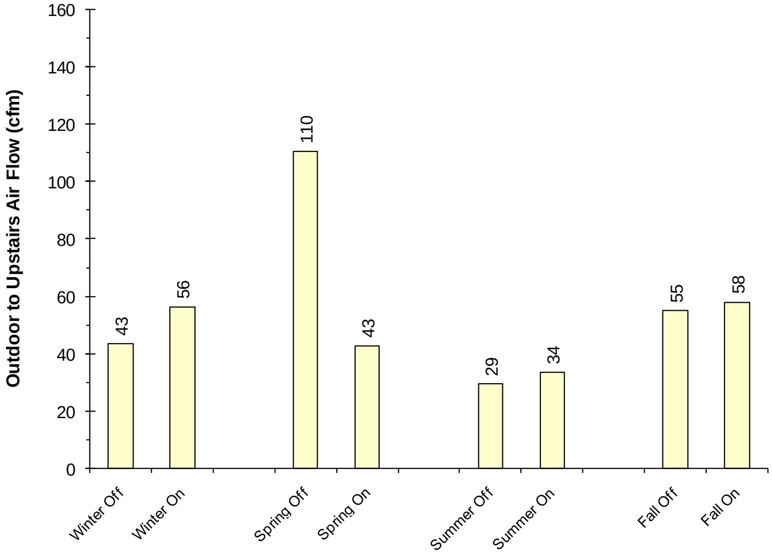

Figure 22. *Median outdoor air flows into the upstairs for interzonal flow test periods at house PA01 with ASD on/off.*

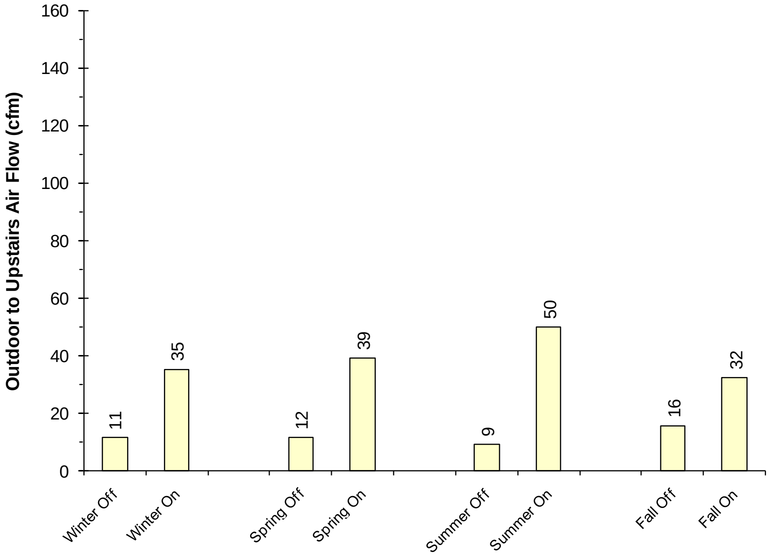

Figure 23. *Outdoor air flows into the upstairs of PA02.*

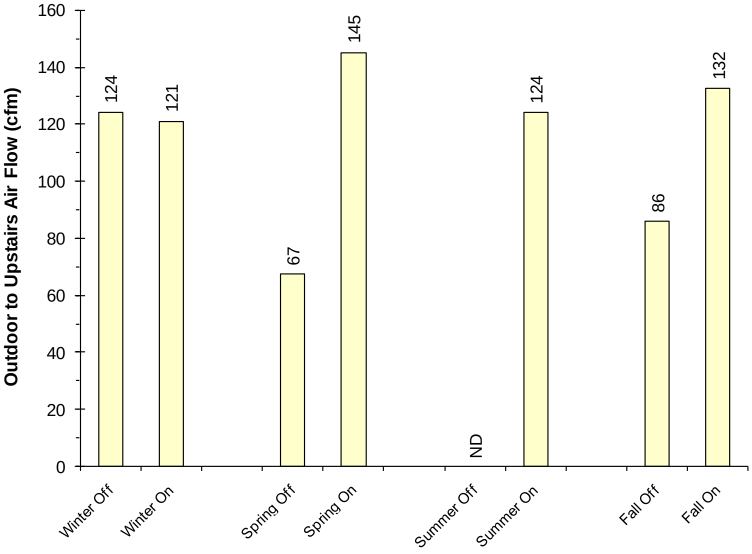

Figure 24. *Outdoor air flows into the upstairs of PA03.*

B5. ASD SYSTEM DESIGN ISSUES AND CONSIDERATIONS

The findings of this study, presented here and in Turk and Hughes, and the questions those findings raise, provide an opportunity to discuss and conjecture about ASD system design and consequent operating characteristics.

This discussion should be viewed as an attempt to examine the mechanisms by which ASD operation impacts moisture behavior in houses. That was, in fact, the central theme of this study. The focus here is from the system design perspective. The intent is to identify those aspects of ASD operation which favorably impact moisture in ways that are particularly cost-effective, and those which may produce favorable impacts, but do it in ways that might be more cost-effectively accomplished by other methods.

It is clear that, at least in the three study houses, the operation of the ASD systems had a generally favorable impact on basement air moisture. It is also clear that the more robust system operating configuration in each house usually had a more pronounced effect than the less robust mode, which was designed to be more representative of the operating characteristics of typical ASD systems installed for radon control. Those observations could be interpreted to indicate that: 1) standard design ASD systems should be regarded as a good method of reducing basement moisture, and 2) systems more robust than normal might be even better. These observations are not sufficient for conclusions about the specific effects and applicability of standard ASD systems for moisture control.

A closer examination of the study findings reveals that ASD effects were multiple and variable. Certain individual effects of ASD operation which might be tolerable or even desirable in one situation might be undesirable in another, including from one season to another in the same house. Classification of an individual or overall ASD-induced moisture effect as desirable does not necessarily imply that ASD is the most cost-effective method of achieving that effect. And it does not imply that systems, as they are commonly configured for radon control, would necessarily have the operating characteristics most appropriate for producing desired moisture reductions. It was not a stated purpose of this study to make those evaluations. Even so, the study results do raise some interesting questions concerning those issues, as follows.

B5.1 ASD System Air Flows

The ASD system design and operating objectives have been described in detail in the project final report (Turk and Hughes). Air flows in the ASD systems are recapped here (Table 8) and separated to show flow rates in the individual pipes. The systems installed in these three houses were intended to be more robust that typical systems under the initial, “On Full”, configuration – and the flow data show that they were. The single-pipe “On Modified” configurations were likely more representative of standard installations. Although increasing the structure’s overall outdoor air ventilation rate is not usually a design goal of ASD systems installed for radon control, the data on interzonal flow and basement air in ASD exhaust indicate that the systems did boost ventilation rates.

Table 8. ASD Configuration and Average Flow Characteristics

		Suction Points Active				System Air Flow (cfm)					
House ID	ASD Configuration	Slab	Interior Drain Tile	Exterior Drain Tile	Block Wall	Slab	Interior Drain Tile	Exterior Drain Tile	Block Wall	Total	Basement Air in ASD Exhaust (% / cfm)
PA01	On Full	x	x			34	52	--	--	86	--
	On Modified		x			--	62	--	--	62	46 / 29
PA02	On Full		x	x		--	79	60	--	140	--
	On Modified		x			--	90	--	--	90	72 / 65
PA03	On Full	x			x	78	--	--	Front 64 Rear 37	180	--
	On Modified	x				87	--	--	--	87	72 / 63

B5.2 Pressure Field Extension (PFE)

The sub-slab PFE values for the systems in the study houses (Table 9) are far in excess of the levels required to control soil gas entry from beneath the slab, assuming there are no soil gas entry points not under the influence of that pressure field. Also, the PFE values in all three houses are quite uniform, varying by less than a factor of three, usually much less, and even when generated from a single slab suction point in the On Modified ASD mode. This uniformity is largely the result of the highly permeable sub-slab material (good ‘communication’), connection to the drain tiles systems in PA01 and PA02, and the lack of large openings to the sub-slab area. In the On Full mode, sub-slab PFE was not enhanced by the block wall suction in PA03, possibly because the slab suction produced more air flow in the On Modified mode. In PA02, adding the exterior footer drain suction did significantly increase the sub-slab PFE, although even with the interior drain tile suction alone, the PFE was uniformly and strongly negative.

Table 9. Summary of ASD-Induced Pressure Field Extension Measurements

House ID	ASD Configuration	Least Negative / Most Negative (Pa, with respect to basement) [No. of locations: negative / neutral / positive]			
		HAC On		HAC Off[3]	
		Slab	Walls	Slab	Walls
PA01[1]	On Full	-40.1 / -55.9 [10/0/0]	2.6 / -24.5 [6/0/2]	-42.2 / -58.3 [10/0/0]	-1.3 / -24.6 [8/0/0]
	On Modified	-15.8 / -24.0 [10/0/0]	5.8 / -6.1 [3/2/3]	-15.5 / -30.6 [10/0/0]	1.2 / -10.8 [5/2/1]
PA02[2]	On Full	-31.3 / -61.9 [8/0/0]	0.0 / -6.1 [8/4/0]	-32.4 / -63.0 [8/0/0]	0.0 / -6.2 [11/1/0]
	On Modified	-17.9 / -42.6 [8/0/0]	0.7 / -4.8 [4/7/1]	-18.0 / -43.3 [8/0/0]	0.0 / -4.8 [7/5/0]
PA03[2]	On Full	-29.8 / -35.5 [8/0/0]	1.3 / -28.6 [8/0/2]	-30.8 / -36.0 [8/0/0]	-1.2 / -29.3 [10/0/0]
	On Modified	-32.5 / -38.4 [8/0/0]	2.4 / -9.1 [2/0/4]	-33.0 / -39.0 [8/0/0]	0.7 / -9.8 [5/3/2]

[1] At PA01, wall PFE measured outside poured wall

[2] At PA02 & PA03, wall PFE measured inside core of block wall.

[3] PFE values with HAC off were neutral to very slightly positive (typically < 1.0 Pa) in all houses. The basement depressurization effect of the HAC produced a small but significant increase in the PFE values (more positive) at many locations, sometimes approaching 4.0 Pa.

In these houses, the slab suction air flow and resultant PFE values could apparently be reduced substantially while still maintaining control of sub-slab soil gas entry, thus probably reducing the volume of basement air removed by the ASD operation. It should be noted, however, that the effects of this reduction on wall PFE and potential resultant changes in radon and moisture control are unknown. If sub-slab permeability were less uniformly high, and especially if there were large unsealed leaks, establishing a uniformly adequate and appropriate pressure field could be much more difficult, as discussed above.

The PFE picture in the block walls in PA02, and particularly in PA03, is more complicated. In contrast to the sub-slab PFE values, the values in the block walls exhibited very large variability, and rarely were they uniformly negative. However, even regarding the direct block wall suctions in PA03, there was no attempt to design systems which would produce uniform pressure fields in the block walls. Rather, the intent was to install systems which, at least in the On Modified mode, would be representative of commonly installed systems. Mitigators with extensive experience installing block wall depressurization systems report that they are able to produce more uniform wall PFE with lower system air flows by using multiple small wall penetrations rather than a few larger ones.

B5.3 Depressurization/Ventilation of Block Walls

The two houses with block wall basement construction (PA02 and PA03) offer a comparison between system designs for controlling radon only and those also intended to control moisture. House PA02 had partially filled block, with an ASD system that did not directly connect to the walls (separate suction points were connected to the interior and exterior drain tile). At house PA03, three suction points were attached directly to the hollow core block walls (block wall depressurization – BWD), while a fourth suction pipe penetrated the slab. In PA03, the two configurations (BWD + subslab, and subslab only) reduced the basement radon concentration to

0.3 and 0.5 pCi/L, respectively. In PA02, the radon levels for the two configurations (exterior + interior drain tile, and interior drain tile only) were 0.6 and 0.9 pCi/L. Since direct block wall suction is typically labor intensive and obtrusive, industry experience indicates that mitigators seldom install it unless it proves necessary to achieve adequate radon control. For the purpose of radon control in the two houses of this study, it is unlikely that block wall suction would have been installed initially, and there would have been little reason to add it later to the highly effective slab suction. This is probably true in many other structurally similar houses.

The discussion of varying ASD influence on block wall moisture in these two houses (see section B5.4 “Potential Drying Effects on Foundation and Near-Surface Materials”) shows the moisture control disparity between the different ASD configurations, all of which exhibited excellent radon control.

This example raises an important issue. The operational characteristics of ASD systems which may be highly effective in controlling convective entry of radon do not necessarily impact all aspects of basement moisture and their potential influence on living space conditions. It might be stated that radon control effectiveness may not be a good surrogate for moisture control effectiveness. Basement air moisture does not appear to be indicative of all relevant moisture conditions either. Figure 25 shows the effects of the two ASD system operating modes on basement air moisture in PA03. Sub-slab and block wall depressurization caused significant reductions in radon and moisture in basement air, while sub-slab depressurization alone had far less effect on block wall moisture.

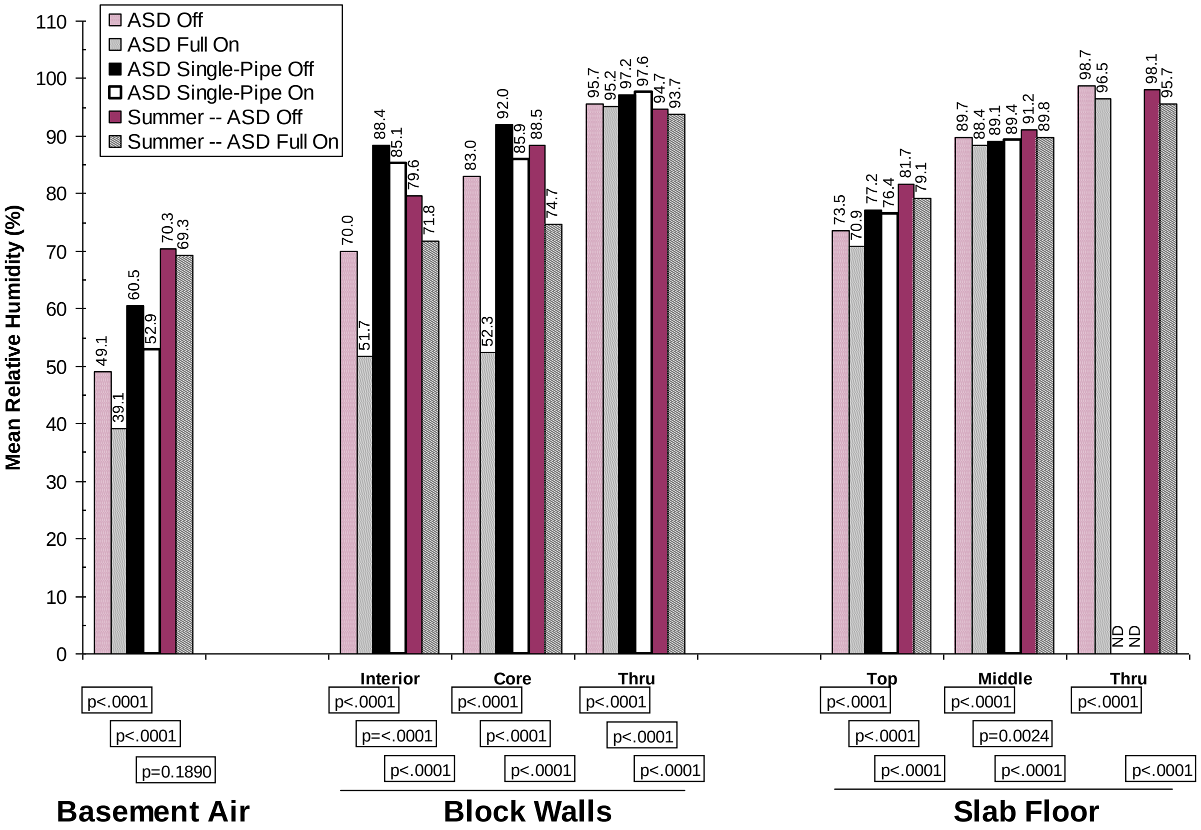

Figure 25. *Arithmetic mean RH for second 7 days of cycling periods at PA03. ‘Full’ is for combined BWD and sub-slab ASD operation, while ‘Single-Pipe’ is for single sub-slab pipe. ND = No data available.*

For house PA03, there appears to be a potential competition between designing an ASD system which would produce only the minimum air flow (and PFE) required for adequate reduction of soil gas entry; and designing to produce a greater air flow which might be required to achieve significant drying inside block walls. These disparate design goals may be confined to block wall structures with serious moisture problems in the walls.

B5.4 Potential Drying Effects on Foundation and Near-Surface Materials

Thus far, discussion has focused on the basement air moisture effects of ASD operation. Moisture influences on furnishings and stored items in basements are probably mostly dominated by basement air moisture. There are, however, other very significant aspects of basement moisture which may be impacted to varying degrees by ASD operation. An informative example of this is illustrated by the differing moisture impacts of the two ASD operating modes on block wall moisture in PA02 and PA03. Figures 13 and 14 of the final study report (Turk and Hughes), show the RH values from two sensors located in the block walls of those houses. In both houses, the sensor location referred to as ‘Interior’ was embedded in the block material approximately one inch from the basement-facing surface; the ‘Core’ sensor location was inside the interior cavity of the block. Refer to Table 8 for the ASD configurations and air flows; Table 9 shows the PFE values.

In PA02, the On Full ASD mode produced a much larger total air flow than the On Modified mode, but produced a relatively small increase in wall PFE compared to the difference between the two modes in PA03. There was no direct suction applied to the block walls at PA02. Also, the PA03 On Full (which included direct suction applied by pipes into the open cores of the block wall) overall PFE values were much greater than in PA02.

There are striking differences between these two houses in terms of the RH changes at the wall sensor locations under the influence of the two ASD configurations. In PA03, the On Full mode produced very significant reductions in RH at both wall sensor locations, reaching levels well below 60% in the Winter and reducing the RH to below 80% even in the Summer after a very short run time. Also, the RH reduction trends during ASD On Full operation show little indication of having reached a maximum, which might mean that the long-term drying effect of that operation could be greater. The On Modified mode (with wall suction pipes closed off) showed little impact on wall RH, which apparently reached a quasi-equilibrium at greater than 90% RH. In PA02, the data suggest that the On Modified mode may have had a lesser effect on wall RH, but it still produced significant reductions.

Microbial growth is generally assumed to occur at a ‘water activity’ of approximately 0.65 or higher. Water activity, simply defined, is an index of the water in a material which is available to microbes for incorporation into their body structures, allowing proliferation. For materials at moisture equilibrium with air at a particular RH, the water activity of the material may be calculated by dividing the RH of the air by 100. Thus, materials at moisture equilibrium with air at 90% RH level are considered to have a water activity of 0.90, which is sufficient to support proliferation of almost any species of mold and even many species of bacteria.

The moisture regime behind and within many moisture sensitive wall finishes (e.g., drywall or paneling) that are commonly installed over basement walls is likely to be dominated by block wall moisture unless the wall was extremely well protected against moisture transport. These conditions are highly conducive to material degradation from moisture and microbial growth, and real-world examples abound. Even if no wall finishes were installed, the nearly saturated walls could still be a strong potential moisture source to the basement air, and may even support microbial growth.

Therefore, although ASD systems can have an impact on reducing moisture in the basement air, they may be even more effective at controlling the microclimate and moisture in the materials on and within the foundation walls and floors – and that are vulnerable to microbial growth. While moisture entry with soil gas tends to be small and did not appear to be a large contributor to indoor moisture loads in these houses, it may have a much larger impact on the microclimate conditions around these vulnerable materials. This is because the common entry locations of soil gas (e.g., wall/floor joints) can inject this moist air directly into contact with, and into the small spaces around, the moisture sensitive materials. The data show that ASD and BWD have the potential to be an effective means of controlling this source of moisture.

B5.5 Unintended Ventilation Caused by ASD Operation

It is generally not recognized that ASD systems may increase the ventilation rate of a building, because it has rarely been investigated, quantified and reported. However, this study demonstrates this phenomenon, and that this air is usually drawn through cracks and other openings in the foundation walls and floor. While ventilation increases would be a *consequence* of ASD system design and operation, it may not appropriately be the system's design *purpose*.

If the whole house or parts of it are under-ventilated, increased ventilation is desirable, but only to the point where the ventilation rate is adequate. Beyond that point, increased ventilation creates an unnecessary energy penalty, and may contribute to other problems. Most residential structures do not have designed pathways for entry of outdoor ventilation air other than doors and windows, which most occupants do not use consistently for that purpose. Consequently, much infiltration of outdoor air occurs through 'unplanned air pathways' which may be inappropriate. For example, outdoor air migrating inward through the structure of an exterior wall during the cooling season in a humid climate may be cooled to its dew point upon contact with wall components such as insulation, drywall or wall coverings. Many moisture problems have been attributed to this and other 'leakage' phenomena. For these and other reasons, uncontrolled and undirected outdoor air ventilation may be undesirable.

During ASD operation, the amount of infiltration increase, and the associated change in upstairs to basement and other flows, is a function of the leakage characteristics of the house, the quantity of ASD-induced exhaust, outdoor environmental conditions, HAC and exhaust equipment operation, occupant activities, and other factors – all of which can be highly variable. Thus, ASD-induced ventilation changes would also be highly variable and largely unpredictable. Even the quantity of house air that is exhausted by the system, which is not easily determined, does not appear to be quantitatively predictive of the effects produced by that air removal.

For example, Table 6 shows the tracer gas-determined outdoor air ventilation rates (air changes per hour, ACH) of the basement and upstairs for the three study houses, as well as the recommended ventilation for those spaces based on ASHRAE Standard 62.2. The data indicate that the basements and upstairs were generally underventilated with the ASD systems off. Note that, in every case except PA01 in the Fall, ASD operation increased the infiltration of outdoor air to the basement, sometimes by several hundred percent. During some individual three-day test periods, even with the ASD-induced increase, the basement ventilation rates were less than recommended. Meanwhile, in other periods, the ASD-caused increase in ventilation was up to, or well in excess of the recommended level. And, in at least two other cases, the ASD-caused increases were in situations where the baseline (ASD off) ventilation rates were already above the recommended level.

Table 10 of the final report (Turk and Hughes) contains the ASD system (fan) operating costs and the projected energy penalty associated with the increased infiltration in the study houses. Note that most of the increase in energy consumption is due to the greater heating/cooling load from the increased infiltration of outdoor air, not to the ASD fan power consumption. While not shockingly large, these costs are calculated on the basis of current energy cost estimates and the climatic factors in the Harrisburg, PA area. In other houses in other climates the costs might be different, and increasing energy costs would certainly increase any penalty.

It is fairly straightforward to calculate the outdoor air ventilation needs for a particular structure. It is much more difficult to determine the current ventilation rate in an existing structure, and almost impossible to predict the ventilation rate increase which will be produced by an ASD system. The variable and unpredictable influences of ASD-induced exhaust ventilation might argue for system design procedures which minimize infiltration increases. At least, it should be recognized that ASD will very probably increase outdoor air infiltration by a practically unknowable amount.

To minimize undesirable increases in outdoor air infiltration caused by large basement exhaust volumes, ASD systems would need to be carefully designed, installed and possibly adjusted to optimize their function. Such systems might well need to be more complex (e.g., multiple suction points) in order to achieve uniformly adequate, but not excessive, pressure fields. This would require greater diagnostic and system performance prediction/evaluation capability than is currently employed by the mitigation industry generally. It would also require abandonment of the very common practice of installing systems which produce much greater air flow than is actually required to control soil gas/radon entry. This practice is driven by the understandable desire to minimize call-backs resulting from ineffective systems, and by the probably mostly mistaken belief that larger system air flows necessarily produce better radon control.

Besides the increased energy costs and potential moisture problems associated with infiltration increases, increasing the depressurization of the building also increases the probability of improper drafting of natural-draft combustion appliances.

B6. SUMMARY OF FINDINGS –
Basement Moisture Sources and Movement, and ASD Moisture Considerations

It is likely that ASD is the most cost-effective method of controlling soil gas entry, especially where entry potential is high (large effective soil-contact leakage area and high soil permeability). Since soil gas entry has the potential to inject large quantities of contaminants such as radon, landfill gases, chemical vapors, and moisture into buildings, ASD should always be considered as a control strategy.

This additional analysis of data from the study of ASD impact on basement moisture in three Pennsylvania houses has revealed some interesting additional findings, and amplified results presented in the original report. These findings for these houses are summarized below.

- The houses experienced large variations in interzonal air flows and outdoor air infiltration, both seasonally and from house-to-house. However, by removing air from the basement through cracks and gaps in the foundation surfaces (and slightly depressurizing the basement), ASD operation generally increased outdoor air infiltration into the basement and upstairs, and the flow of upstairs air into the basement.

- As expected, ASD operation appears to have had little impact on the moisture level of the air streams from the outdoors and first floor that enter the basement, although some drying of the soil air may have occurred.

- Although soil gas consistently had high moisture levels, the convective flow of soil gas into these houses was generally small, and the moisture contribution to the basement air was typically less than that from other sources. Operation of the ASD systems dramatically reduced or eliminated this moisture contribution, but that reduction had a relatively small drying effect on the basement air. This finding in these houses is contrary to common assumptions about the generally dominant role of soil gas entry reduction in basement moisture control. However, for houses with larger soil gas entry, the ASD systems' control of soil gas entry might be a larger potential drying influence.

- Moisture levels in outdoor air exhibited very large variations, but tended to be higher in the Summer than Winter, by factors of three to five, or more. Because the ASD systems tended to increase the infiltration of outdoor air throughout the year, this incoming air has the potential to both enhance the drying of the basement when the outdoor air is drier than the basement (e.g., during the Winter) and to add significant moisture when the outdoor air is wetter (e.g., Summer).

- Upstairs air was usually drier than basement air, with the central air conditioning equipment acting to dehumidify this air during the Summer. The data suggest that the ASD systems significantly increased the flow of upstairs air into the basement which often accounted for drying observed in the basement, especially during the Summer and parts of the Spring and Fall. This mechanism appears to partially or completely offset the additional moisture added to the basement by the incoming outdoor air during warm, humid weather.

- In these houses, the ASD systems extracted and exhausted large quantities of moisture, some from within the house, the balance from other sources – presumably the soil around the foundation. The amount extracted generally varied seasonally with the moisture levels in the soil and outdoor air, ranging from approximately 1.2 to 1.5 times higher in the Summer.

- The ASD system in one house removed approximately five to 10 times the quantity of moisture as did a standard dehumidifier – implying that the systems may have the potential for more effective, long-term drying of the basements.

- In terms of standard ASD installations, radon control effectiveness may not be a good surrogate for moisture control effectiveness. It appears that systems designed and installed for good control of radon may not be optimal for moisture reduction, since greater moisture reductions were achieved from more robust systems with higher flow and PFE than in a typical installation.

- Although it is seldom necessary to install BWD for radon control (in homes with open core block foundation walls), direct BWD was most effective at reducing moisture in the block walls of one basement, while sub-slab ASD alone had a smaller effect.

- Findings suggest that ASD/BWD systems may provide more effective control of moisture in the materials and small spaces of finished walls and floors. These regions are in closer proximity to the entry locations of moisture-laden soil gas, and would likely experience larger moisture reductions (than basement air) when the systems are operated. Because many finish materials are moisture sensitive and will easily support microbial growth, reduction in their moisture content might have greater beneficial impact on moldy odors and related biocontaminants. This phenomenon was not investigated during this study.

- While ASD systems tend to reduce moisture by modifying interzonal flows and boosting outdoor air ventilation rates, these changes are not controlled and are difficult to predict and quantify. Although adequate ventilation is desirable and recommended by ASHRAE, ASD as a ventilation technique often misses its mark: over-ventilating with attendant energy penalties, under-ventilating, and/or causing air flow in locations that may actually be harmful. To be a more reliable ventilation approach, ASD systems would need to be carefully, designed, engineered, installed, and operated – at present, an impractical objective. Proper ventilation is more appropriately achieved with techniques other than ASD.

It should be noted that most of the ASD operating periods were quite short, and the data frequently suggest that the full potential effect on moisture levels of a particular ASD operating mode may not have been realized by the end of an individual operating period.

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