Exploratory Study of Basement Moisture During Operation of ASD Radon Control Systems

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ABSTRACT

The technique most commonly used to control radon in buildings, active soil depressurization (ASD), has been investigated for its impact on basement moisture levels and ventilation. As part of an exploratory study, three houses near Harrisburg, Pennsylvania have been intensively monitored over an 18-month period for moisture indicators, radon levels, building operations, and other environmental parameters while ASD systems were cycled on and off. To implement this intensive monitoring program, novel protocols and study design were developed. A conceptual model suggested that the ASD systems can cause important changes in basement ventilation and interzonal air flows – therefore these parameters were periodically measured. Moisture levels were measured in walls and slab floors, indoor and outdoor air, surrounding soil, and wood framing members in the basement. The participating houses have unfinished basements: one having poured foundation walls, and the others having foundation walls of open and partially-filled concrete block. Results from these three houses indicate that ASD operation can produce significant moisture reductions in the basement air and walls, especially during non-summer months, and caused the predicted changes in air flow patterns. Both high and more typical flow and pressure configurations show this effect, although moisture reductions tend to be greater at higher system flows and pressures. Moisture reductions were diminished somewhat during the warm and humid summer months. Due to the long response time of moisture levels in foundation and soil materials, continuous operation of the ASD systems may cause greater reductions. The findings are consistent with anecdotal reports of drying and odor improvement in basements during ASD operation, and suggest that microbial growth may also be reduced. These effects may be different in other climates and house construction types.

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EXECUTIVE SUMMARY

Background

For years, those involved with radon mitigation in buildings have reported that operation of active soil depressurization (ASD) radon control systems appears to reduce moisture levels in the basements of some houses. These systems inhibit advective radon entry by reversing the air pressure gradient between the soil and house substructure. Reductions in musty and moldy odors, drying and shrinkage of materials in the basement, and less dampness in the basement have all been reported. Because of a demonstrated link between dampness in houses and respiratory problems, the ability to control indoor moisture as well as radon and other soil gas pollutants has important public health ramifications.

Although it has been speculated that ASD systems interfere with air movement that can carry moisture into substructures, and with capillarity and diffusion from the soil, there is little relevant information on ASD-caused moisture changes in buildings. To fill the research void, an exploratory project was initiated to investigate this phenomenon and to determine if ASD may be a beneficial multi-pollutant control technique. This approach was also evaluated as an energy efficient alternative or adjunct to dehumidifier use.

Study Design

A panel of experts was convened to formulate recommendations for the study design, experimental protocols, and measurement and testing techniques. These recommendations led to the development and implementation of innovative approaches to long-term monitoring of moisture and air movement in the project houses.

The panel also recommended development of a simple conceptual model for understanding moisture movement and the flow paths of water vapor-laden air within a building, between the building and outdoors, and through the soil near a building under the influence of an ASD system. This conceptual model identified the importance of drying that is caused by ASD operation altering three classes of increased air flows in and around a basement, including:

1) Air from outdoors enters the basement by several pathways and is then exhausted by ASD.
2) Basement air is pulled into the surrounding soil, then is exhausted by the ASD.
3) Outdoor air is pulled directly to the ASD suction point through the surrounding soil and is then exhausted by the ASD.

In order for drying of the basement air and materials to occur, the entering air must be drier than the materials or basement air that it replaces.

Using data representative of houses and outdoor conditions near Harrisburg, PA (with or without an ASD system operating), it was estimated that moisture contributions from air flows from outdoors, first floor, and soil (approximately 50 ft^3/min, 0.024 m^3/s) to the basement could be greater than 25 kg/day. It was also estimated that less than 2 kg/day is due to diffusion through 1500 ft^2 (139.5 m^2) of poured concrete walls and floors. Diffusion becomes more important when the ventilation rates are low and when permeability of the materials is higher (e.g., block walls). It is likely that these mechanisms work in combination, to varying degrees, depending on many house, soil, and meteorological conditions.

From a large number of candidates, three homes near Harrisburg, PA were selected for the field study. The homes were required to meet a number of criteria, including elevated basement radon levels, occupant-reported dampness problems, and basements that were mostly unoccupied, unfinished, and had concrete slab floors. During the house selection process, it was noted that the majority of the houses with occupant complaints of moisture problems in the basement also had block wall foundations. Therefore, two of the three study houses had open, or partially-filled, concrete block foundation walls, while one house had poured concrete walls. All houses had central forced air heating and cooling (HAC) equipment located in the basement.

ASD Systems

Following baseline testing and monitoring, ASD radon mitigation systems were installed in each house. Each system was constructed of an in-line exhaust fan connected to 3 or 4 inch PVC pipe that 1) penetrated the slab floor, 2) was attached to pre-existing passive radon control systems, or 3) penetrated into the open core of the block walls (house PA03 only, and is commonly referred to as block wall ventilation – BWV). When the systems are activated, the exhaust fan depressurizes and draws air from the soil and materials surrounding the basements, thereby limiting radon entry. To accentuate changes in moisture levels, the ASD systems were designed for research purposes with more options for changes in flow/pressure and configuration, compared with typical radon mitigation systems. Several configurations of the systems were cycled on and off over 1- to 14-day periods for 12 to 18 months.

The operating characteristics of the ASD systems were continuously monitored throughout the study, including during the 'full' system and single-pipe configurations. Static pressures developed by the 'full' systems ranged from 46 to 210 Pascal (Pa). Single-pipe pressures ranged from 74 to 210 Pa. Total system flows were from 85 cfm to 180 cfm for the 'full' system, and 62 cfm to 90 cfm for the single-pipe configurations. Time constraints did not allow for evaluation of other configurations of suction pipes and even lower operating pressures and flows.

Pressure Field Extension – To determine the extent of the depressurization caused by the ASD systems, the air pressure difference (ΔP) between the basement air and the exterior of the foundation walls and floor was measured several times throughout the study. Measurements made at 14 to 20 test holes showed that operation of the ASD systems caused robust ΔP that extended to all areas of the slab floor: typically ranging from -18 to -60 Pa for full ASD operation, and -15 to -44 Pa when ASD was in single-pipe configuration. The ΔP across the walls was not as uniform as the sub-floor PFE, with ΔP generally less than -1 Pa at many locations. Operation of the HVAC equipment appeared to have minimal impact (less than 1 Pa) on wall and floor ΔP during the pressure field measurements.

Air Leakage, Interzonal Flows and Ventilation

Air movement between the basement and outdoors, upstairs, and soil was periodically measured using a constant-injection, automated collection, perfluorocarbon tracer (PFT) gas system. Results indicate that the ASD systems tend to increase the air flow from all sources (outdoors, upstairs, and soil) into the basements. This is likely caused by basement air being pulled into the ASD pipes through cracks and openings in the foundation, thereby slightly depressurizing the basement, and being replaced with air from upstairs and outdoors. However, other than in house PA02, this additional depressurization of the basement was not measurable with ASD systems on. Outdoor air ventilation rates (infiltration) tended to be much lower in the basements than upstairs for two of the houses, while ASD operation caused large increases (60% to over 200%) in the ventilation rates – for both the basement and upstairs at two houses. Tracer measurements also determined that between 46% and 72% of the air in the ASD discharge originated in the basement, presumably, as described above, through openings in the foundation materials.

Air leakage of various portions of the building envelope was measured with a blower door. The calculated normalized leakage areas (NL) for all three houses are atypically low (0.113 to 0.543) when compared to other, similar houses. Determinations of the basement ceiling equivalent leakage areas (ELA_c) show the presence of potential pathways between the upstairs and basement for air to flow (0.027 m^2 to 0.088 m^2).

Continuous, Multi-parameter Monitoring

In order to evaluate the untried testing and measurement techniques employed in this study, and to be assured that important changes in building moisture and other characteristics were observed, a comprehensive and novel monitoring and testing protocol was developed and implemented. Over 115 parameters in and around each house were semi-continuously monitored using an array of sensors. These included temperature, humidity air pressure differentials, radon concentrations, and meteorological conditions.

To characterize moisture movement and storage in foundation walls and floors, measurement clusters were installed at four wall and two slab locations of each house. Each cluster consisted of temperature/relative humidity (RH) sensors embedded at three depths in the material, and calibrated wood moisture sensors installed at two depths.

Indoor Radon Concentrations

All houses experienced large reductions in indoor radon levels, regardless of system configuration – even approaching levels in the outdoor air. Radon concentrations, with ASD off, on the 1st floor of these houses were approximately 25 to 50% of the basement concentrations, which is typical for houses with HAC systems. These data indicate that the primary source of radon for these houses was pressure-driven entry from the soil.

Basement Moisture

Over the 10- to 15-month duration of system cycling, the dominant trend in the basement air RH tracks the outdoor air moisture levels. Closer inspection of the time series data suggests that the basement RH does change in response to many of the periods of ASD operation, but that this response is superimposed on the larger and longer seasonal changes in outdoor air moisture. These data also hint that ASD-caused moisture responses are more muted and less predictable in the summer months.

Analysis of changes in moisture included 1) comparison of mean RH and 2) autoregression to determine the daily rate of change in RH as the ASD systems were cycled on and off. Mean RH data were from Day 7 – 14 from the 14-day, and longer, cycle periods. The data indicate that, for many of the foundation materials, a much longer ASD on or off period will be required before quasi-equilibrium is reached. The autoregression was performed on the first seven days (and in a subsequent analysis, 14 days) of seven day and longer periods.

The mean RH reduction in basement air ranged from 4% (PA01) to 10% (PA03) during full ASD cycling in the non-summer periods. Reductions during the warm and humid summer months, when moisture control was most needed in these houses, were much smaller or negligible. Operation of the single-pipe ASD systems with more typical flows and pressures caused smaller, but still significant, reductions in basement air RH as compared to full system operation.

In contrast to the basement air RH, the equilibrium RH for most locations within the block cores and within approximately two cm of the interior surface of the blocks display large and dramatic changes as the ASD is cycled during the non-summer months, ranging from 18% to 30% RH. This drying effect is likely due to greater air flow induced by the ASD systems through the open cavities and porous block materials. It is not clear that the Interior and Core locations of the block walls reached steady state conditions even after two weeks of operation. Although the ASD system causes reductions of almost 30% RH in block walls when outdoor moisture levels are low, the response is dampened during the more humid summer months. Comparison with the single-pipe, sub-slab configuration at one house clearly shows that block wall ventilation component of the ASD system had a large impact on wall moisture at this house.

Poured wall locations exhibit behavior more like that of the slab floors, where moisture levels at all houses experienced much smaller responses to changes in ASD operation – generally less than 3% RH. The trend for most wall and floor locations is for the equilibrium RH to increase with depth into the wall or floor material. While the shallower test locations are often more responsive to ASD cycling and track with changes in basement air moisture, there are exceptions. For example, although some block wall cores have high baseline (ASD off) moisture levels, they show larger reductions than the Interior locations when the ASD is on. And several “Thru-slab” locations also have large reductions on equilibrium RH during when the ASD is running. These results indicate that the ASD systems are causing comparatively large changes in flow of air with low water vapor pressure, at these locations. The locations on the exterior surface of the walls are often very wet or saturated (causing the failure of many moisture sensors), and typically do not have an observable response to the ASD operation.

Hand-held Instrument Measurements of Surface Moisture

At the same time that the intensive moisture monitoring protocol was being conducted, another simpler method using hand-held instruments was also being performed on four to five occasions throughout the study. The purpose of these measurements was to evaluate and compare the measurement approaches.

To conduct these measurements, variable-spacing grids were laid out and marked with removable tape on both the floor and the walls. This resulted in between 51 and 55 floor measurement locations, and 80 to 120 wall locations for the each of the three houses, depending on size, layout, and obstructions.

The hand-held device used for determining surface moisture on the basement floors and walls would measure moisture within approximately the first ½” of the material. Moisture in the wood joists of the basement ceiling was measured using a hand-held, pin-type meter that detected the electrical resistance between the two sharp prongs inserted into the joists parallel to the grain.

Measurements of the moisture content in the joists of the basement ceiling and at the surface of the walls and floors tend to track the moisture in the basement air and within the basement-facing foundation surfaces.

The surface measurements also indicate that the moisture content of the slab floors tends to be higher than that for the walls, with the slab floor at PA01 having the highest overall moisture levels (Table 8). This is surprising given that conditions in the basement of PA01 tended to be the driest of all houses throughout the study.

Dehumidifier

Dehumidifiers are the most common method used by homeowners for removing moisture from basements, however, they can be large energy consumers. To compare the performance of the ASD technique to dehumidifier use, a medium efficiency dehumidifier was added to the cycling protocol at one house for three cycling periods from July to October 2006. Condensate production, energy use, and unit on-time were recorded during their operation. The unit was operated on demand by a built-in humidistat set to 50% RH. The dehumidifier showed dependable and stable moisture reductions in the basement air for all three cycles, but did not reduce the basement air RH to 50% during the first cycle (and neither did the ASD system during a contiguous time period). It appeared to have no impact on the moisture in the block wall core, nor, of course, did it affect indoor radon levels. Conversely, the full ASD configuration with wall extraction pipes had a larger impact on air within the block than the air in basement. The dehumidifier operated approximately 70% of the time during the first cycle, declining to 47% of the time during the last cycle

The quantity of water extracted from the air by the dehumidifier steadily declined from 3.5 gal/day (13.4 L/day) during the first cycle to 0.9 gal/day (3.6 L/day) during the last cycle. Using the flow rate and moisture concentration in the ASD pipes for the corresponding ASD on periods, calculations determined that the water extracted by the ASD system declined from 13.8 gal/day (52.2 L/day) to 12.7 gal/day (48.1 L/day). These results indicate that the ASD systems are probably mining moisture from sources other than the basement air alone. The most likely source is the wet/damp soil surrounding the foundation that is constantly being replenished due to poor drainage conditions.

Moisture Extraction by ASD

The average moisture extracted by the full ASD system configuration ranged from approximately 13 to 19 gal/day, while the single-pipe systems extracted approximately 10 to 13 gal/day. These data are averages of one or more seasons. A preliminary inspection of the data indicates that moisture removal during the summer is higher than for winter, for the same configuration.

ASD Energy Use

Estimates of energy to operate the ASD system fan and condition additional outdoor air ranged from $79 to $164 per year for these houses, while energy for a typical dehumidifier would cost approximately $193. This energy will be required for ASD systems installed to control indoor radon, and the extra benefit of moisture reduction piggybacks on the energy necessary for radon control. While the ASD systems in these houses may not eliminate the need for dehumidification during warm and humid periods of summer, they may reduce the moisture load in the basement and usage of the dehumidifier.

Summary and Conclusions

As the first systematic and intensive study of moisture changes in buildings caused by operation of ASD systems, normally used for indoor radon control, this project broke new ground by developing novel design and monitoring protocols and applying them over 12 – 18 months in a group of three homes. The project has also created a large data set on how ASD systems function and their impact on moisture in homes.

The primary finding of this project has been that ASD systems caused statistically significant and beneficial reductions in moisture levels and dampness in the basements of three Pennsylvania houses in the non-summer months. During the warm and humid summer months, when dehumidifiers are typically needed in these homes, overall changes in building moisture with the ASD operating were much smaller or negligible, and of less practical importance. ASD-caused moisture responses in the basement air were observed to be secondary to and superimposed on the larger trend of the basement air moisture to track outdoor air moisture levels. Block wall surfaces facing the basement, and especially block cores, showed the largest moisture reductions during ASD operation – possibly because the porous blocks permit greater air flow that dries the materials. Moisture changes in slab floors and poured walls were smaller and occurred more slowly than in porous block walls, and may require longer cycle periods to show a significant change. Since the foundation walls and floors of these homes were generally not finished, moisture changes in the micro-environments of furred wall cavities and beneath carpet were not examined. However, it is possible that ASD operation could have a relatively larger impact on moisture levels and microbial growth in these moisture sensitive materials, by increasing the flow of drying air, and reducing moisture ingress from diffusion and convective air movement. Robust system configurations, with more suction points and higher air flows and pressures than typical installations, produced larger moisture reductions. When configured for more typical flows and pressures, the systems caused smaller, but encouraging, moisture reductions. The effects were apparent in the basement air and walls of all three houses, and in the slab floor of two houses.

A number of innovative measurement protocols and techniques were evaluated and employed to monitor moisture and ventilation flows in houses. These included a novel adaptation of the constant injection, multi-PFT ventilation measurement technique, and long-term continuous monitoring of many environmental parameters, including moisture in the basement walls and floors and ASD exhaust. To evaluate the value of simpler and less-costly measurements techniques, handheld instrument measurements of moisture were conducted periodically over an extensive grid of locations in the basements, These handheld measurements within the interior surfaces of foundation materials track continuous measurements with sensors embedded within approximately the first two centimeters of the surface, and with measurements of moisture in the basement air. This approach may be an effective replacement in future studies for the intensive monitoring protocols used in these three houses. Additional work is required to study the relationship between these surface measurements and moisture stored at depth within the foundation materials.

Consistent with the guidance of the conceptual model, interzonal flow testing and results suggest that quantity of air drawn into the basement from upstairs and outdoors increases during ASD operation. In the non-summer months, this comparatively low moisture air can cause drying of the basement air and foundation materials. Under these conditions, it may be possible to reach a minimum moisture level, below which little additional drying will take place. Conversely, in the summer, the systems have the potential to add moisture to the basement by drawing in warm humid air from outdoors – while at the same time pulling in dry conditioned air from upstairs (in buildings with air conditioning). The ratio of the air leakage from outdoors to air leakage from the upstairs may be an important factor in determining the success of ASD moisture reduction in humid climates during the summer. The amount of air leakage from the soil through openings in the foundation surfaces is probably another important factor that influences the moisture-reducing performance of ASD systems.

With the ASD systems operating, outdoor air ventilation rates were boosted both in the basement and upstairs. When the systems were off, basement ventilation rates at all houses often fell below the requirements of ASHRAE Standard 62.2 (2007), while the upstairs ventilation rates often did not meet the minimum at PA01 and PA02. Therefore, the ASD systems tend to act as whole house exhaust ventilation in these three houses and could provide additional indoor air quality benefits, albeit at the cost of conditioning the incoming, outdoor air. Care must be taken with exhaust ventilation systems not to depressurize the building, causing combustion appliances to backdraft or other contaminants to be drawn into the occupied spaces. All of the houses participating in this study had sealed-combustion furnaces and hot water heaters with power-vented draft inducers, and wouldn't be vulnerable to backdrafting. As mentioned above, exhaust ventilation systems can also draw in humid outdoor, that may add unwanted moisture to the building air and materials.

In houses with bulk water entry (as in the case of PA03), ASD systems are probably not well-suited to control the resulting dampness and moisture accumulation. However, few remedial techniques can successfully address this issue. The best solution is to correct the source of water.

Portable dehumidifiers are currently one of the most common methods for seasonal control of moisture in basements and crawlspaces. A dehumidifier used for three months in one study house produced stable reductions in basement air RH, but had little impact on moisture in the block walls and slab floor. This may be an important consideration for finished walls, since, by contrast, the ASD system tended to reduce moisture in block walls. The dehumidifier extracted approximately 8% to 25% of the moisture removed by the ASD system. Presumably, the dehumidifier removed moisture primarily from basement air, while the ASD system pulled moisture from the air as well as from the foundation and materials surrounding the foundation.

Estimates of additional energy usage during ASD operation show increases from $79 to $164 per year for these houses. These costs may be representative of many ASD systems installed to control indoor radon. However, the data suggest that ASD operation may also reduce dehumidifier usage during the warm, humid summer months and may reduce the overall energy bill in houses with a radon problem and where a dehumidifier is being used at least 5 months out of the year.

Concerns over drying, and subsequent shrinkage and settling, of materials around the foundation were not addressed in this study.

Recommendations

It is not known whether the moisture and ventilation findings for these three houses apply to other houses in other regions. There appear to be many factors that could affect the effectiveness of ASD in reducing substructure moisture, and additional investigation is necessary to address these issues. This study was a good investment for future research. Some recommendations for this further work include:

- Conduct national survey of moisture in houses to identify vulnerable house construction and climates
- Examine the relationship between outdoor conditions (RH and precipitation) and ASD system effectiveness.
- Using information from this study, enhance and refine the conceptual model to forecast ASD moisture performance in other climates, house construction and soil types, incorporating air leakage areas and locations, house construction features and HAC systems, and climate characteristics

- Design and conduct investigation of ASD impact on building moisture in other climates, soil types, house foundation types, and mechanical cooling.
- Further explore less-intensive testing and measurement protocols so that evaluations of moisture control by ASD can be more easily and economically conducted in other houses.
- Monitor moisture levels during longer periods of ASD operation.
- Conduct extended, four season evaluation of additional configurations of ASD systems, with a wider range of operating flows and pressures and suction point placement.
- Consider what, if any, design and installation changes would improve moisture control capabilities of ASD systems.
- Examine the ASD-caused moisture changes in moisture sensitive materials and assemblies that are commonly installed to finish basement floors and walls: wood framing, gypsum board, paneling, carpet, etc.

1. INTRODUCTION

For years, those involved with radon mitigation in buildings have reported that operation of active soil depressurization (ASD) radon control systems appears to reduce moisture levels in the basements of some houses (Turk and Harrison 1987; Brodhead 1996). These systems inhibit advective radon entry by reversing the air pressure gradient between the soil and house substructure. Reductions in musty and moldy odors, drying and shrinkage of materials in the basement, and less dampness in the basement have all been reported.

The development and exacerbation of asthma, along with other respiratory ailments, has been related to damp indoor environments and dampness-dependent exposures to fungi and house dust mites (Fisk et al 2007; IOM 2000; IOM 2004; Mannino et al 1998). Mudarri and Fisk (2007) estimate that approximately 21% of all asthma cases in the U.S are attributable to dampness and mold exposure in homes. Other studies have specifically shown an association between damp basements and respiratory health symptoms (Brunekreef et al 1989; Dales et al 1991; Spengler et al 1994), and respiratory symptoms in children with dampness in housing (Jaakola et al 1993; Williamson et al 1997). Because of this link between dampness in houses and respiratory problems, the ability to control indoor moisture as well as radon and other soil gas pollutants has important public health ramifications.

The U.S. EPA Environmental Protection Agency (U.S. EPA) Indoor Environments Division conducted a literature review, but found little, relevant, published information on systematic studies of ASD-caused moisture changes in buildings. Although there can be many sources of dampness in basements, it has been speculated that ASD systems interfere with air movement that can carry moisture into basements (and other substructures), and with capillarity and diffusion from the soil. Therefore, the U.S. EPA funded an exploratory project through Auburn University to investigate this phenomenon and to determine if ASD may be a beneficial multi-pollutant control technique. This approach may also be more energy efficient than the use of dehumidifiers. Preliminary results on this project have been reported earlier (Turk et al 2007), but expanded findings of this work are presented here.

2. METHODOLOGY

Only limited, pre-existing information was available on study design, experimental protocols, and measurement and testing techniques for investigating the impact of ASD operation on moisture in buildings. Therefore, a panel of experts in moisture control, radon entry and mitigation, and building science was convened by the U.S. EPA to draft a research plan for this project. A majority of their recommendations were incorporated into the experimental design. Their overall recommendations were for the development of a conceptual model, evaluation of test and measurement methods, and a focused field test and measurement study in a small number of houses. A report on the guidance and recommendations is found in Appendix A. Primary forms, logs, and checklists that were used during the study are included in Appendix B.

2.1 House Selection and Description

Funding limits precluded designing and constructing a research house that would allow control over many of the parameters expected to influence moisture entry, accumulation, and removal. As a result, occupied houses with full basements were solicited, surveyed, and screened as candidates for study. To enhance the possibility that moisture changes could be detected in the resulting data, the houses had to meet a number of criteria. Critical criteria included:

- owner-occupied (or unoccupied) single-family, detached residence
- full-depth basement beneath the entire house
- expected residency of 18 months
- evidence of persistent moisture entry (dampness) into the basement
- no liquid water entry or unusual moisture sources
- unoccupied and mostly unfinished basement
- at least one house with poured basement walls
- no subsurface, karst-like features (water-formed cavities in rock) affecting basement floors or walls

With some exceptions, most of these criteria were met by the study homes. Additional criteria were also considered in selection of the houses, but were not essential for participation. The complete listing of criteria and rationale for applying the criteria are included in Appendix C.

The house selection process involved contacting prospective participants through newspaper advertisements, state and local building code departments, developers and builders, and word of mouth. The following steps were then taken to screen for suitable study candidates.

- Conduct a phone interview with the homeowners, using one of several versions of a phone interview checklist
- During a house visit to gather additional information on prospective homes, the following activities were conducted:
    - Meet with and interview occupants
    - Sketch floor plan with overall dimensions
    - Complete house characteristics checklist
    - Photograph house interior and exterior
    - Conduct moisture meter survey of basement (walls, floor, joists and framing)
    - Measure indoor and outdoor temperature/relative humidity
    - Conduct short-term measurement of radon concentrations in the house

The final selection was based on a number of factors, including interest of homeowners, access to house and lifestyle factors, compliance with critical criteria, and evidence of measurable moisture levels.

Three homes near Harrisburg, PA were finally selected. The homes had elevated basement radon levels, occupant-reported dampness problems, and basements that were mostly unoccupied, unfinished, and had concrete slab floors. During the house selection process, it was noted that the majority of the houses with occupant complaints of moisture problems in the basement also had block wall foundations. Therefore, two of the three study houses had open, or partially-filled, concrete block foundation walls (PA02 and PA03), while one house had poured concrete walls (PA01). Although the houses were selected so as not to have bulk water entry, two of the houses were later discovered to have minor water leaks through basement walls (PA02 and PA03), and drainage problems around the outside of building (PA03). All houses had central forced air heating and cooling (HAC) equipment located in the basement. House ages at the beginning of the study were 3 years (PA01), 8 years (PA02), and 35 years with a 31 year-old addition (PA03). Humidification equipment attached to the HAC was disabled during the study, although room-sized dehumidifiers were permitted in the bedrooms on the first or second floor. The upstairs of the houses were one story (PA02) or two stories (PA01 and PA03) in height and of frame construction.

2.2 Radon Mitigation Systems and Cycling

To establish pre-mitigation conditions and operating characteristics in each house, a two- to three-month period of baseline testing and monitoring was conducted. The tests and measurements during baseline were identical to those performed in the remainder of the study, and are described below. After the baseline period, ASD radon mitigation systems were installed in each house. Flow and pressure were predicted for each system through a systematic evaluation of the flow and pressure characteristics of the materials surrounding the foundation walls and below the slab floors. These ‘diagnostic’ protocols and results were used to design the ASD systems.

Each system was constructed of an in-line exhaust fan connected to 3 or 4 inch PVC pipe that 1) penetrated the slab floor, 2) was attached to pre-existing passive radon control systems, or 3) penetrated into the open core of the block walls (house PA03 only, and is commonly referred to as block wall ventilation – BWV). When the systems are activated, the exhaust fan depressurizes and draws air from the soil and materials surrounding the basements, thereby limiting radon entry. To accentuate changes in moisture levels, the ASD systems were designed for research purposes with more options for changes in flow/pressure and configuration, compared with typical radon mitigation systems. Since this project was intended as a ‘proof-of-concept’, the systems were initially operated at higher flows and pressures than in commonly installed systems. To evaluate the moisture response time of the house and surrounding materials, and to provide ‘control’ conditions for evaluating system performance, the systems were cycled on and off over 1- to 14-day periods over four seasons as multi-parameter testing and monitoring was conducted. Several longer, non-cycled, periods of operation were also evaluated during the 12- to 18-month field study. After approximately twelve months, the ASD systems were modified to be more representative of a typical system installation. This usually involved disabling one or more suction points/pipes, and reducing flow in the remaining single pipe that pulled air from below the slab floor. The reduced flows in the single pipes at PA02 and PA03 were still higher than for most installations. However, this would have occurred even with standard system fans because of the low resistance to air flow for these systems. These modified, or reduced operation, systems were also cycled on and off. Holes, large cracks, and joints in the foundation walls and floor were sealed as part of the mitigation process – and in house PA01, the wall/floor joint was sealed as a staged element of mitigation approximately six months after mitigation systems were installed. A more complete description of the diagnostic protocols and installed ASD systems is included in Appendix D.

2.3 Dehumidifier

During the house selection process, most of the homeowners who reported moisture problems in their basements used portable dehumidifiers to control that moisture during the summer. However, dehumidifiers can be large energy consumers depending on their efficiency and the amount of moisture in the space where they are located. To compare the performance of the ASD technique to dehumidifier use, a dehumidifier was added to the cycling protocol at house PA03 from July to October 2006. A medium efficiency dehumidifier (an energy factor of 1.6L/kWh) was purchased from a major home retailer and installed on an elevated platform so that condensate produced by the unit could be captured and measured during the weekly house visits. Energy use and unit on-time were monitored with a current transformer connected to the dehumidifier power cord and to one of the on-site data loggers.

2.4 Tests and Measurements

In order to evaluate the untried testing and measurement techniques employed in this study, and to be assured that important changes in building moisture and other characteristics were observed, a comprehensive monitoring and testing protocol was developed and implemented. Over 115 parameters at each house were semi-continuously monitored using an array of sensors. These sensors were scanned every 30 seconds and measurements recorded hourly by on-site data loggers (Campbell Scientific, models 21X and 10X). The houses were visited at least once per week to conduct tests, adjust ASD system operation, and download data. Monitoring and testing instruments and techniques are summarized in Appendix E. Results from a subset of the parameters monitored are reported here.

Data collected by the data loggers were subsequently processed to 1) remove erroneous values caused by sensor failure, power outages, or other acquisition system failure, 2) converted to engineering units, and 3) compiled into single, large Microsoft Excel spreadsheets. Where appropriate, data from measurements using hand-held instruments was also coded into spreadsheet formats. These data files are briefly listed and described in Appendix F.

2.4.1 Instrumented Clusters. To characterize moisture movement and storage in foundation walls and floors, measurement clusters were installed at four wall and two slab locations of each house. Each cluster consisted of temperature/relative humidity (RH) sensors embedded at three depths in the material, and experimental moisture sensors, made from calibrated wood dowel blocks, installed at two depths. Figures 1 and 2 show the typical layout and sectional views of the clusters for poured walls and slab floors. Sensor placement in block walls was altered so that the ‘Interior’ sensor (embedded in the block wall approximately 2 cm from the basement-facing surface) was placed in the block webbing, and the ‘Middle’ sensor was in the open block cores.

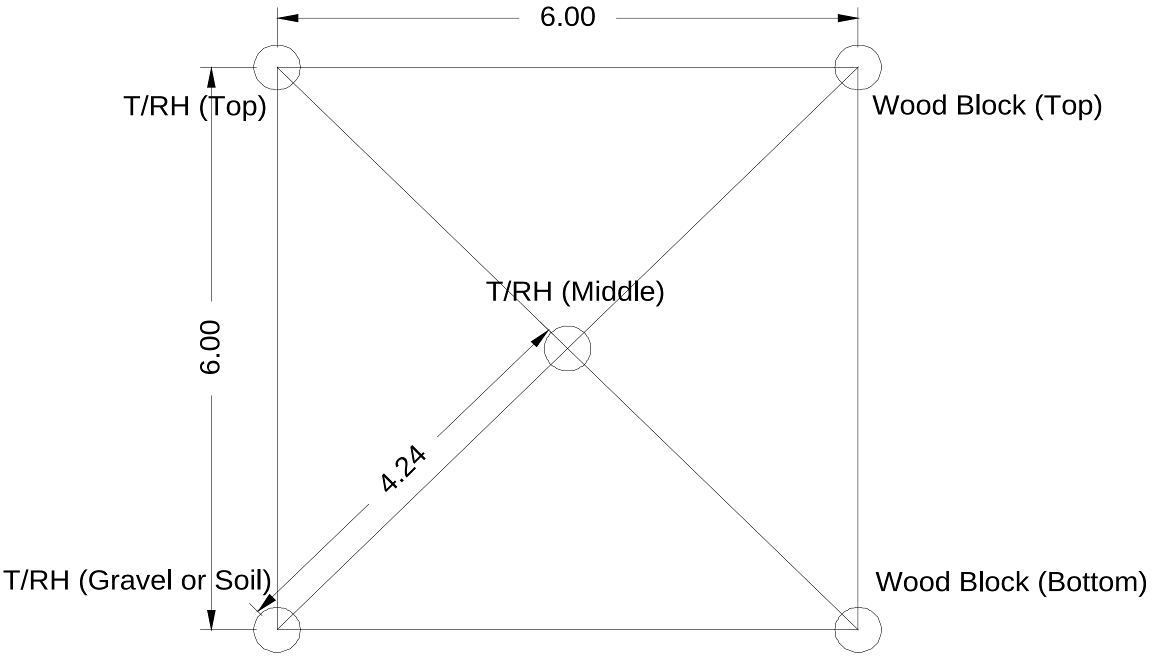

***Figure 1**. Plan view of the typical pattern of sensor placement for instrumented clusters in poured walls and slab floors (dimensions are in inches). See Figure 2 for sectional view of sensor placement.*

Temperature was measured with a thermistor, while RH was measured with a heated, variable-capacitance sensor. Temperature and RH sensors were packaged together in a sleeve of spunbonded polyethylene fabric that is water resistant, but vapor permeable. The wood probes sense changes in electrical resistance between two metal pins in the wood as moisture levels change. Basement-soil air pressure differences were also measured at each cluster with a transducer employing a variable-capacitance diaphragm (Setra, model 264). Radon levels were monitored semi-continuously by alpha scintillation cell technology (Pylon, model AB-5) through the foundation material at one floor and one wall cluster as an indicator of soil gas movement.

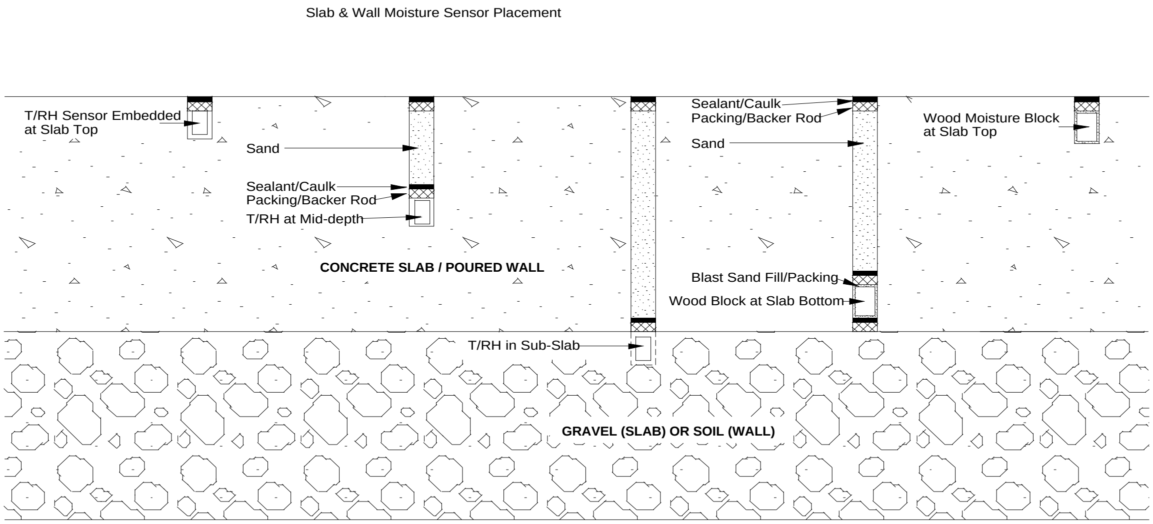

Figure 2. *Sectional view of typical sensor placement in poured wall and slab floor clusters. Placement in block walls is similar, but modified for open cores and web.*

2.4.2 General Building Conditions. Temperature and RH in the air of the basement, first floor, outdoors, and ASD system exhaust were also monitored. Differences in air pressure between the basement and upstairs and the basement and outdoors were measured, and HAC fan operation and ASD system flows and static pressure were monitored with the pressure transducers mentioned above. Indoor air radon levels in the basement and first floor were measured using pulsed ion chamber devices (Femto-Tech, model R210F). Moisture changes in wood framing (usually joists in the basement ceiling) were detected by measuring electrical resistance between two metal pins inserted into the wood.

2.4.3 Interzonal Flows and Ventilation. Air movement between the basement and outdoors, upstairs, and soil was periodically measured using a constant-injection perfluorocarbon tracer (PFT) gas system. Separate PFTs were used to label the basement and upstairs air. The permeation vials of tracer were placed in small, precision, temperature-controlled heaters to maintain a constant injection rate of the tracer. Air samples from the basement and upstairs were collected with an unattended, automated system over two, three-hour periods on each of three consecutive days for each of the four seasons. Samples were submitted to the laboratory for analysis by gas chromatography. The six air flows between the two house zones and the outdoor/soil air were then determined by solving the six equations describing the mass balance of PFT.

2.4.4 Outdoor Conditions. Outdoor temperature, RH, precipitation, wind speed and direction were monitored at only one house. Moisture content in the soil next to the foundation was monitored at three locations at each house using wood block sensors, and time domain reflectometers (Campbell Scientific, model CS616) at one house. These soil measurements were made at approximately 1.1 m in depth and 0.5 m away from the foundation walls.

2.4.5 Periodic Testing and Measurements. Other, periodic measurements using hand-held instruments were made of: house air leakage using a blower door, pressure field extensions

(PFE) developed by the ASD systems, and near-surface moisture over a 1- to 2-meter grid on the basement floor and walls, and wood joists of the basement ceiling.

2.4.5.1 House Air Leakage – A set of three blower door procedures was employed at each house. Each procedure was a multi-point depressurization test, with house pressures ranging from -60 Pa (where achievable) to -15 Pa or less, in 5 Pa increments. At each house pressure, fan pressure was recorded and converted to flow using the tables in the blower door manual. A power curve was fitted to house pressure and blower flow data, and the curve formula utilized to predict flow at 4 Pa (and in the case of PA03, the flow at 50 Pa). The 4 Pa and 50 Pa flow values were used to calculate the air changes per hour ($ACH_{50\text{ and }4}$) and effective leakage area (ELA_4). The normalized leakage (NL) was also calculated, using ELA, gross floor area, building height, and a reference height of 2.5 m (8 ft).

Blower location, house configuration and depressurized area for the three procedures were:

- Blower installed in ground-floor exterior door; all exterior doors and windows closed; door from ground floor to basement open. Represents whole house leakage (ELA_w).
- Blower installed in ground-floor exterior door; basement windows open, all other exterior doors and windows closed; door from ground floor to basement closed. Represents leakage of upstairs plus basement ceiling (ELA_u).
- Blower installed in door from ground floor to basement; basement windows closed, all other exterior doors and several windows open. Represents basement leakage plus basement ceiling leakage (ELA_b).

By utilizing the following relationships from Turk et al. (1987), it is possible to make estimates of the leakage areas of the basement ceiling and other portions of the building shell whose leakage cannot be measured directly:

$$ELA_w = ELA_u + ELA_b - 2ELA_c \tag{1}$$

Rearranging equation (1) gives

$$ELA_c = (ELA_u + ELA_b - ELA_w)/2 \tag{2}$$

In addition,

$$ELA_{bwf} = ELA_b - ELA_c, \tag{3}$$

Where:
ELA_w = whole building ELA,
ELA_u = upstairs ELA,
ELA_b = basement ELA,
ELA_c = basement ceiling ELA, and
ELA_{bwf} = basement walls/floor ELA

2.4.5.2 Pressure Field Extension (PFE) – The air pressure difference between the basement air and the exterior of the foundation walls and floor was measured several times throughout the study. A digital micromanometer was used while the ASD system and HAC equipment were turned on and off. The measurements were made at 14 to 20 test holes drilled through the floors and walls at each house. Pressure differentials were also measured between the basement and first floor and basement and outdoors.

2.4.5.3 Hand-held Instrument Measurements of Surface Moisture – At the same time that the intensive moisture monitoring protocol was being conducted, as described above, another simpler method using hand-held instruments was also being periodically performed. The purpose of these measurements was to evaluate and compare the measurement approaches.

To conduct these measurements, variable-spacing grids were laid out and marked with removable tape on both the floor and the walls. Measurements were made at the intersections of the grid lines. To improve resolution of the floor measurements, the grid spacing was smaller near the perimeter of the floors (1 ft / 0.31 m), and expanded to 8 ft (2.4 m) toward the center. The grid for the basement foundation walls included four locations in vertical lines (approximately 3 inches/0.08 m, 33 inches/0.84 m, 63 inches/1.6 m, and 93 inches/2.4 m from the top of the foundation wall) that were on a horizontally spacing of approximately six feet (1.8 m) around the entire wall perimeter. This resulted in between 51 and 55 floor measurement locations, and 80 to 120 wall locations for the each of the three houses, depending on size, layout, and obstructions.

The measurements were conducted on four (PA01) to five (PA02 and PA03) occasions throughout the study. The hand-held device used for measuring surface moisture on the basement floors and walls employs co-planar electrodes that emit a low frequency signal approximately ½" into the concrete (Tramex, model CME4). The instrument measures the change in the impedance of the signal, due to moisture in the material, as compared with a well-characterized dry concrete sample, and computes moisture content.

Moisture in the wood joists of the basement ceiling was also measured by transferring the floor grid to the ceiling. A hand-held, pin-type moisture meter (Delmhorst, model BD2100) was used to measure the electrical resistance between the two sharp prongs inserted into the joists parallel to the grain, and then determine moisture content.

3. RESULTS AND DISCUSSION

3.1 Conceptual Model

A simple conceptual model or framework was developed to describe the flow paths of water vapor-laden air within a building, between the building and outdoors, and through the soil near a building under the influence of an ASD system. The modeling exercise considered that moisture is transported by four primary mechanisms: 1) liquid flow driven by gravity, 2) capillary flow driven by suction gradients, 3) vapor diffusion driven by vapor pressure gradients, and 4) vapor carried along with convective air flow driven by air pressure differences.

The model identified the importance of drying that is caused by ASD operation altering convective flows (Figure 3). Three classes of increased air flows in and around a basement are described:

1) Air from outdoors enters the basement by several pathways and is then exhausted by ASD.
2) Basement air is pulled into the surrounding soil, then is exhausted by the ASD.
3) Outdoor air is pulled directly to the ASD suction point through the surrounding soil and is then exhausted by the ASD.

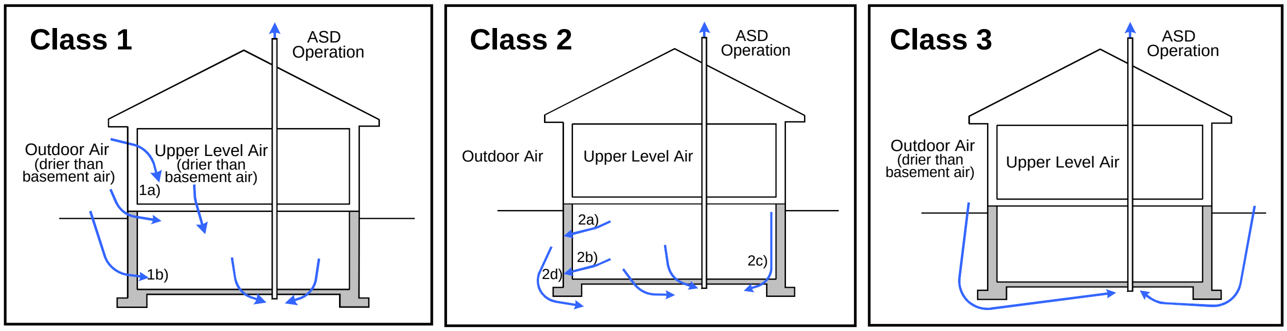

Figure 3. *Three classes of air flows within and around a basement that can be affected by soil depressurization caused by an ASD system, and that could account for drying of the basement. Sub-classes of flows are indicated.*

In order for drying of the basement air and materials to occur, the entering air must be drier than the materials or basement air that it replaces. In the case of Class 2 and 3 flows, the basement air (Class 2) and outdoor air (Class 3) must have a sufficiently low water vapor pressure to dry the foundation materials and surrounding soils, reducing diffusion and capillary flow. It is possible, under some circumstances, that these identified air flows could contribute moisture to the basement rather than extract moisture (e.g., periods of high outdoor air humidity). Since the temperature of the air is altered along many of these pathways, psychrometric analysis of moisture content is often required to determine if this entering air is actually 'drier'.

Using data representative of houses and outdoor conditions near Harrisburg, PA (with or without an ASD system operating), it was estimated that moisture contributions to the basement from air flows from outdoors, first floor, and soil (approximately 50 ft^3/min, 0.024 m^3/s) could be greater than 25 kg/day. It was also estimated that less than 2 kg/day is due to diffusion through 1500 ft^2 (139.5 m^2) of poured concrete walls and floors. Diffusion becomes more important when the ventilation rates are low and when permeability of the materials is higher (e.g., block walls). It is likely that these mechanisms work in combination, to varying degrees, depending on many house, soil, and meteorological conditions.

The complete document describing the model is included as Appendix G.

3.2 House Air Leakage

Results from blower door testing and subsequent calculations of house leakage are presented in Table 1.

Table 1. Summary of Blower Door Air Leakage Measurements and Calculations

House ID	Blower Door Test Results								
	Leakage @ 4 Pa		Leakage @ 50 Pa		ACH		ELA (4 Pa)		NL
	cfm	m^3/s	cfm	m^3/s	4 Pa	50 Pa	in^2	m^2	
PA01									
Whole House (ELA$_w$)	317	0.150	1907	0.900	0.52	3.14	90.3	0.058	0.206
Upstairs - Basement Ceiling (ELA$_u$-ELA$_c$)	177	0.084							
Basement - Basement Ceiling (ELA$_{bwf}$)	139	0.066							
Basement Ceiling (ELA$_c$)	485	0.229					136.22	0.088	
PA02									
Whole House (ELA$_w$)	132	0.062	808	0.381	0.34	2.06	37.6	0.024	0.113
Upstairs - Basement Ceiling (ELA$_u$-ELA$_c$)	131	0.062							
Basement - Basement Ceiling (ELA$_{bwf}$)	1	<0.001							
Basement Ceiling (ELA$_c$)	144	0.068					41.01	0.027	
PA03									
Whole House (ELA$_w$)	632	0.298	3541	1.671	1.49	8.33	180.0	0.116	0.543
Upstairs - Basement Ceiling (ELA$_u$-ELA$_c$)	457	0.216							
Basement - Basement Ceiling (ELA$_{bwf}$)	175	0.083							
Basement Ceiling (ELA$_c$)	376	0.177					107.07	0.069	

Notes:
ELA (Effective Leakage Area) from equation (33), page 27.12, ASHRAE Fundamentals, I-P Edition, 2005 (ASHRAE 2005).
NL (Normalized Leakage) from equation (38), page 27.13, ASHRAE Fundamentals, I-P Edition, 2005 (ASHRAE 2005)

For comparison, the mean normalized leakage (NL) for the Lawrence Berkeley National Laboratory (LBNL) database of 22,000 houses in 2002 was 1.18, with a standard deviation of 0.81 (Sherman and Matson 2002). For conventional houses built after 1996, the NL is less than 0.5 (mean of approximately 0.38 to 0.53), and for energy-efficient houses (those built according to some set of energy saving construction guidelines) the NL was about 0.30. Based on these data, the three houses in this study are rather atypical. All have a NL considerably below the mean for their general category, although there is a rather wide distribution of values in most categories. Both PA01 and PA02 have a NL which is less than the mean for a group of more than 4,000 energy efficient (AKWarm Program) houses built in Alaska between 1993 and 1999 and reported on by Sherman (mean of 0.23 with a standard deviation of 0.10).

3.2.1 Internal leakage. The air leakage area between the upstairs and basement is generally not of primary importance to most residential energy researchers. However, this leakage may influence not only pressure-driven soil gas (along with radon, moisture, and other soil gas pollutants) entry and attempts to manage basement-soil pressure differentials, but can also impact moist and dry air movement between the two zones and the subsequent removal or addition of moisture. This leakage may be quite significant, and can be caused by utility penetrations, door openings and undercuts, HAC supply and return ducts and plenums, and poorly-fitted floor and wall materials. Two of the three houses in this study have a basement ceiling leakage (ELA$_c$) which is greater than the whole house leakage (ELA$_w$). Another set of five houses in New Jersey (Turk et al. 1990) showed higher ELA_c, although the mean ELA_w was greater than the mean ELA_c (0.126 m^2 and 0.108 m^2, respectively).

3.3 ASD System Operating Performance

Table 2 summarizes the system descriptions and operating characteristics in the initial and modified configurations. As indicated elsewhere, these systems were designed to be capable if producing more robust performance than would commonly be installed for radon control alone. The governing system operational parameter was pressure field extension (PFE). The higher static pressures and air flows are simply consequences of requiring strong PFE. While the performance of commercially-installed ASD systems covers a wide range of flows and pressure, the full system (multiple suction pipes) air flows of 140 and 180 cfm, at PA02 and PA03, respectively, are approximately double that of typical systems (often with only one pipe). House PA01 had the lowest air flow of the three houses, largely due to poured walls and tight slab. However, the full system flow of 85 cfm (82 with wall/floor joint sealed) is also higher than a normal radon mitigation installation. Houses with complete passive systems and tight foundations like PA01 typically require only small fans (air flows) to be successfully mitigated for radon. Even in the reduced configuration (single-pipe), the systems would be considered fairly robust in terms of air flow, because of the relatively low resistance characteristics of the system, especially the sub-slab material. Time constraints did not allow for evaluation of other configurations of suction pipes and even lower operating pressures and flows.

Table 2. Summary of ASD System Characteristics

House ID/ System Description	**Initial (Full) Configuration**		**Wall/Floor Joint Sealed**		**Single-Pipe Configuration**	
	Static Pressure (Pa\std.dev)	Total Exhaust Flow (cfm \std.dev) *(m^3/s \std.dev)*	Static Pressure (Pa\std.dev)	Total Exhaust Flow (cfm \std.dev) *(m^3/s \std.dev)*	Static Pressure (Pa\std.dev)	Total Exhaust Flow (cfm \std.dev) *(m^3/s \std.dev)*
PA01						
1- interior drain tile loop*	69 \ 8.88	85 \ 17.2 *0.040 \ 0.0081*	100 \ 4.99	82 \ 17.3 *0.039 \ 0.0082*	110 \ 8.88	62 \ 1.55 *0.029 \ 0.0007*
1- center of slab	51 \ 26.8		84 \ 12.2		34 \ 30.9	
PA02						
1- interior drain tile loop*	190 \ 5.75	140 \ 3.44 *0.066 \ 0.0016*	--	--	210 \ 7.34	90 \ 1.50 *0.042 \ 0.0007*
1- sump\exterior drain tile loop	210 \ 6.14		--		24 \ 1.72	
PA03						
1- slab*	ND	180 \ 17.8 *0.037 \ 0.0012*	--	--	74 \ 30.2	87 \ 2.83 *0.041 \ 0.0013*
2- block wall	46 \ 2.12		--		0-9 \ 0.4-0.9	

* Indicates portion of system included as part of modified/reduced operation
ND = No Data

3.4 Pressure Field Extension Measurements

The pressure fields caused by operation of the ASD systems were generally robust and extended to all areas of the slab floor – and probably explain the very successful reduction of radon concentrations in these houses (below). Pressure differentials across the floor typically ranged from -18 to -60 Pa for full ASD operation, and from -15 to -44 Pa when ASD was in reduced, single-pipe configuration.

By contrast, ΔP across the walls was not as uniform as the sub-floor PFE, with ΔP generally less than -1 Pa at many locations. At PA02, a strong perimeter sub-slab pressure field extended into unsealed block walls at several locations. The block walls at PA03 were coated, but the sealing material was deteriorating, and there was some cracking at head and bed joints (horizontal and vertical mortar joints). Direct depressurization/ventilation of the block walls by the ASD system at PA03 was likely the reason for the pressure field extending along the exterior of these walls. As a result, the ΔP at one wall test hole at this house exceeded -20 Pa. Operation of the HVAC equipment appeared to have minimal impact (less than 1 Pa) on wall and floor ΔP during the pressure field measurements at all three houses. Detailed PFE data and information can be found in Appendix F.

3.5 Ventilation and Interzonal Flow Measurements

As suggested by the conceptual model, the changes in ventilation and interzonal flow are key to understanding the moisture behavior during ASD operation. An example of interzonal flow measurements for house PA02 during ASD cycling is shown in Figure 4. While many factors can cause large variations in ventilation and air flow, the data show a distinct change when the full ASD system was operated. The arrow indicating air entering from outdoors also includes outdoor air passing through the soil and below-grade cracks and holes in the foundation (soil air). These air flow patterns are consistent with the system withdrawing air from the basement, through cracks and leaks in the floor and walls, which is replaced in turn by increased flow from the outdoors (38 cfm) and upstairs (47 cfm). The ASD system in PA02 increases depressurization in the basement (Table 6) and, therefore, the amount of air entering and leaving (62 cfm) the basement – presumably, most of the latter is exhausted by the ASD pipe. The overall ventilation rate for this house also increased when the ASD was run during this winter test period, from approximately 0.1 to 0.2 ach in both the basement and upstairs.

The arrows across the floor between the basement and upstairs indicate that during the three-hour, measurement periods, air flowed both from the basement to the upstairs and vice versa. This can occur due to normal fluctuations in air pressure across the floor (caused by wind, door and window openings, exhaust fan and combustion appliance use, etc.), and by cycling of the forced-air, HAC system (that can mix upstairs and basement air).

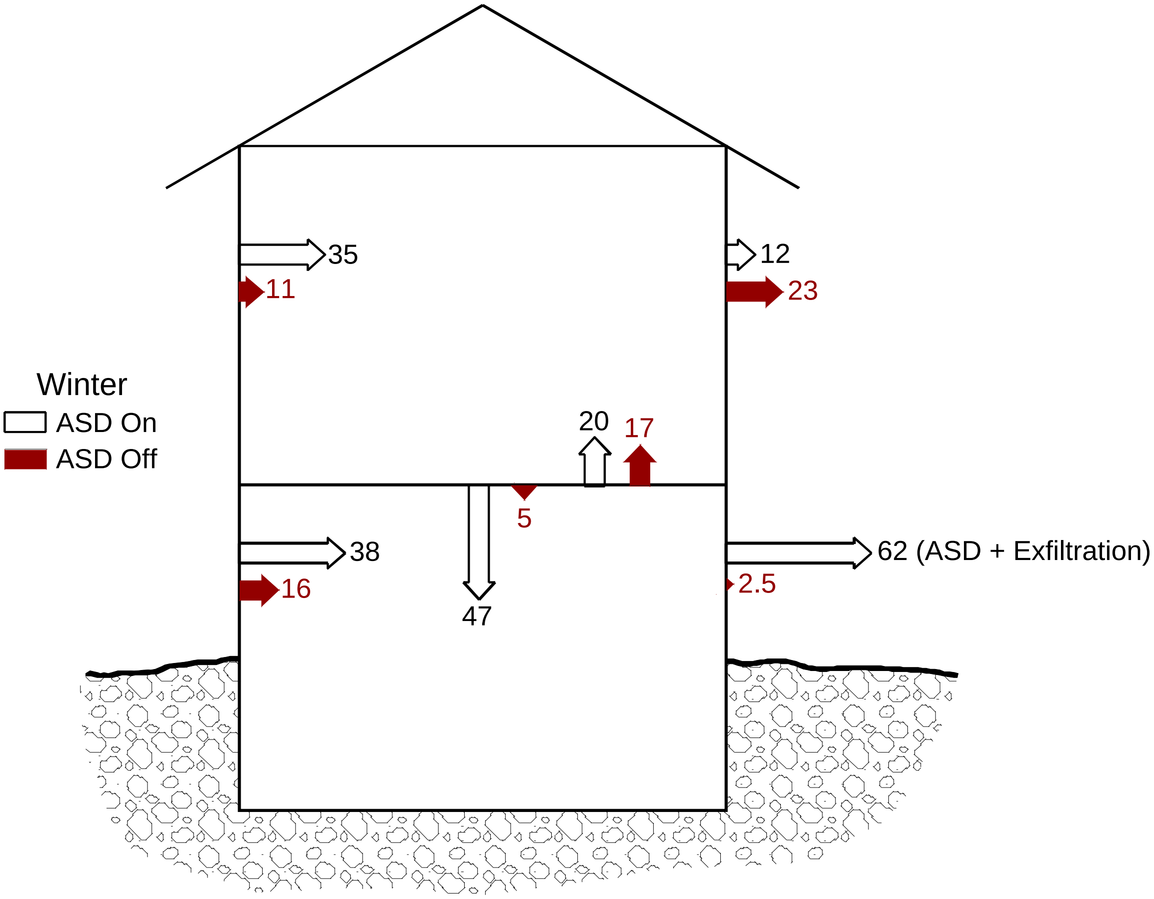

Figure 4. *Representative results of interzonal air flows with ASD system on and off during the winter at house PA02. Flows (in cfm) are the average of six, 3-hour measurements over three days.*

Data for air flow into and out of the basements are summarized for all houses and all four seasons in Figure 5. The ASD systems were in the full configuration for the Winter – Summer measurements, while the systems were configured with one pipe during the fall measurements. Except for large variations in results for house PA01, the findings show that air flow into the basement from all sources (outdoors, upstairs, and soil) consistently increases during ASD operation. The third bar in each series is the change in basement-to-outdoor air flow from ASD off to ASD on conditions. When this change is positive, it likely indicates that the ASD system is exhausting air from the basement (the second set of flow pathways, Class 2, described in the conceptual model), suggesting that a significant portion of the air in the ASD exhaust originates in the basement. These results again support the speculation that ASD systems can increase air flow through the basement, with most of this increase being fresh outdoor air and conditioned air from the upstairs. While it is assumed that the increased air flow out of the basement during ASD operation is going up the ASD exhaust pipe, direct pitot tube measurements of flow in these pipes (Table 2) tend to be higher than estimated here by the tracer measurements. The additional flow may be due to measurement error, or to the ASD systems pulling air from other locations (e.g., soil or short circuits to outdoors).

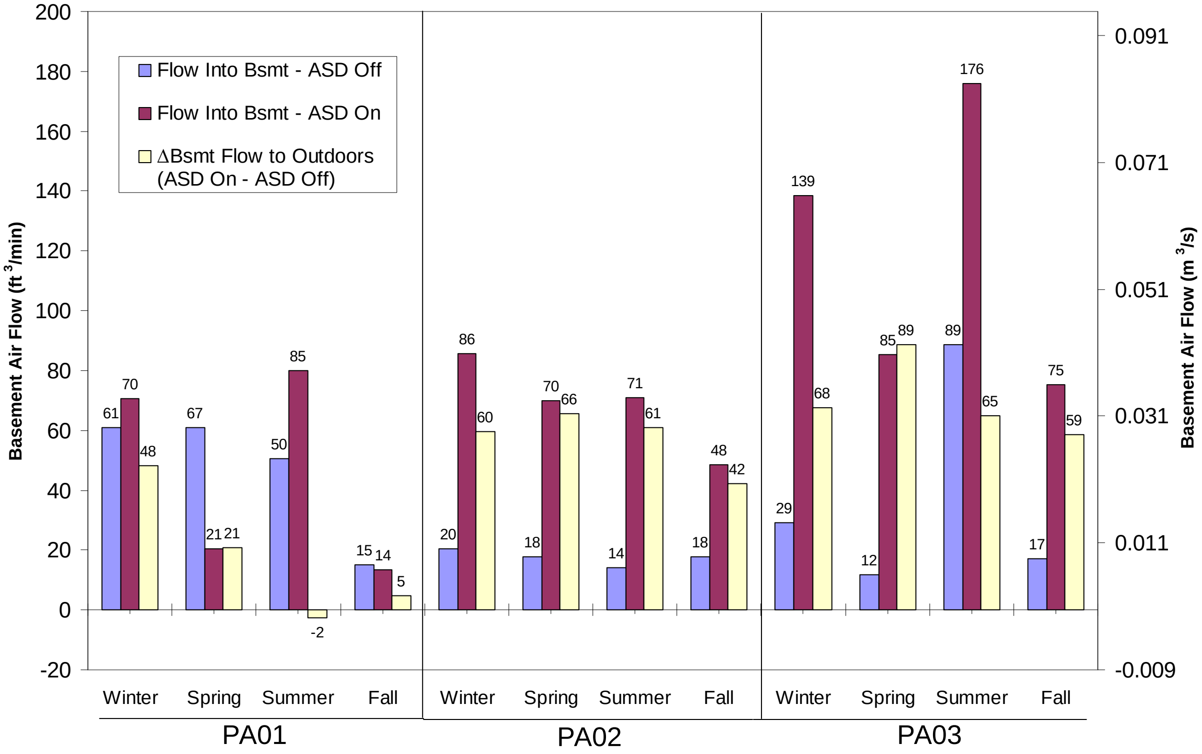

Figure 5. *Summary of air flow into the basement (from outdoors, soil, and upstairs), and change in flow from the basement to outdoors (ASD On – ASD Off) during ASD cycling over four seasons. Each bar represents the median of from four to six measurements over three days. Fall measurements were made with the one-pipe ASD configuration, while other season measurements were with the full ASD. A positive change in basement flow to outdoors indicates that flow was higher during ASD operation.*

Figure 6 summarizes the fraction of air entering the basements that originated upstairs. It highlights the large house-to-house differences in air flow patterns, and suggests that, when the ASD system was running, larger fractions of air from upstairs were being pulled into the basement. This condition is more likely to occur during the summer in the air conditioning mode, when the HAC system tends to operate for longer periods, and is reflected in the greater upstairs fractions at PA01 and PA03. In most houses, air can easily move between the upstairs and basements through oversized openings for utilities, door undercuts, poorly fitted building materials, and ducts connected to HAC equipment installed in the basement. Although all HAC return grilles and supply diffusers in the basements of these houses were closed throughout the study, large gaps and leaks in the ducts and plenums can still be the source of significant air flow, especially during HAC operation. Outdoor air can enter basements from leaky windows, rim joists, and sill plates, as well as through attic bypasses. The variations at PA01 may be due to unbalanced HAC flows, an unusual number of door and window openings, or to measurement errors.

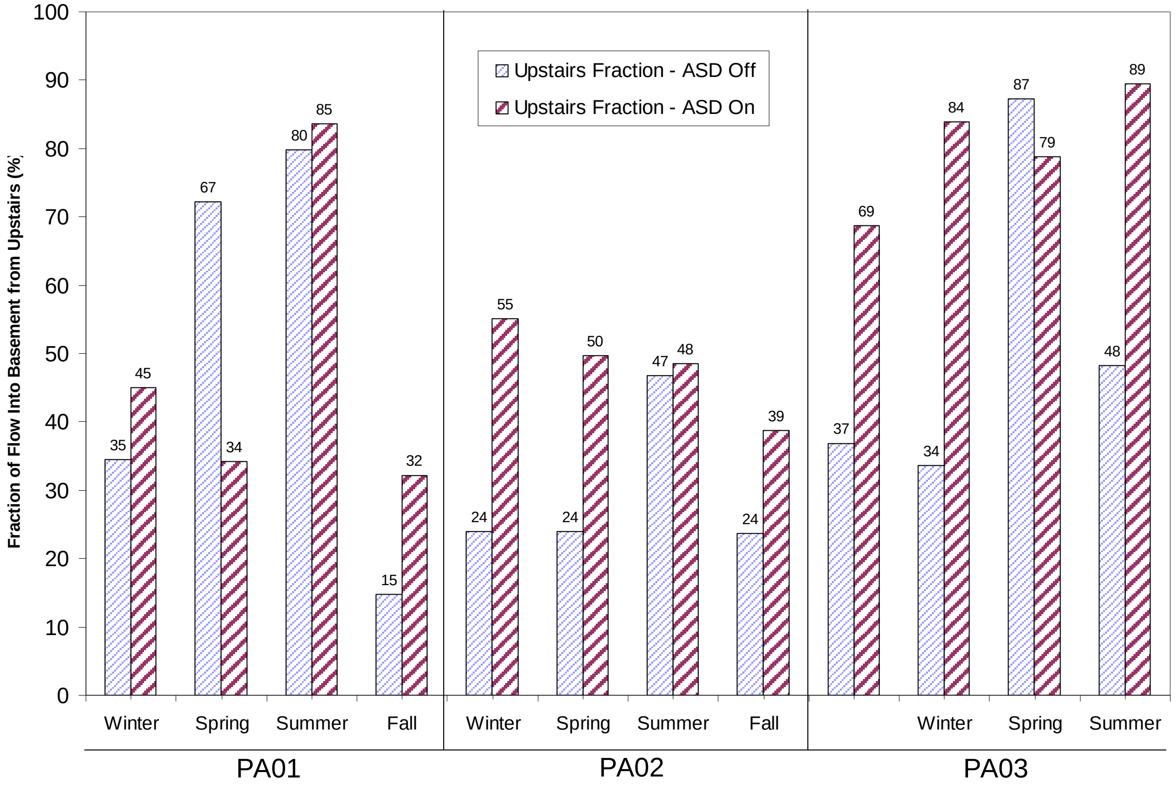

Figure 6. *Summary of the fraction of air flow into the basement that originated from upstairs. The balance is assumed to be from outdoors or the soil. As in Figure 5, each bar represents the median of multiple measurements during each period.*

Outdoor air ventilation rates (infiltration) for the basements and upstairs zones are summarized in Table 3 according to ASD On and Off periods. Data from the four to six test periods for each of the four seasons have been aggregated. Because of the large range in measured ventilation rates for some of the houses, the median infiltration is presented along with the arithmetic mean and standard deviation. For PA01 and PA03, ventilation rates in the basements tend to be much lower than for the upstairs, with basement ventilation in PA03 being almost a factor of 5 to 8 lower. At PA02 and PA03, ASD operation caused large increases (60% to over 200%) in the ventilation rates when the ASD was on for both the basement and upstairs.

The median ventilation rate for the basements of these houses with ASD off was just adequate to meet the ventilation required by ASHRAE Standard 62.2 (2007). With ASD on, the basement ventilation increased to well over the requirement for PA02 and PA03, but was unchanged for PA01. The median baseline (ASD off) ventilation rate for the upstairs of PA01 and PA03 exceeded the ASHRAE requirement, while even with the system operating at PA02, the median upstairs ventilation was below the minimum.

Both of these block wall houses also had the largest fraction of basement air in the ASD exhaust (Table 4, below), and the highest ASD exhaust flow rates. The complete ventilation and interzonal flow data are found in Appendix F.

Table 3. Summary of Outdoor Air Ventilation in the Basement and Upstairs

		Outdoor to Basement Infiltration (ach)				**Outdoor to Upstairs Infiltration (ach)**			
House ID	**ASD Status**	Mean/Std.Dev	Mean ΔOff/On[1] (%)	Median	Mean ΔOff/On[1] (%)	Mean/Std.Dev	Mean ΔOff/On[1] (%)	Median	Mean ΔOff/On[1] (%)
PA01 – 4 Seasons									
	Off	0.11 / 0.062	--	0.07	--	0.47 / 0.474	--	0.20	--
	On	0.10 / 0.065	-10	0.07	-11	0.22 / 0.092	-12	0.28	18
	ASHRAE[2]			0.07				0.16	
PA02 – 4 Seasons									
	Off	0.05 / 0.048	--	0.07	--	0.07 / 0.019	--	0.06	--
	On	0.16 / 0.032	280	0.18	150	0.22 / 0.084	200	0.18	220
	ASHRAE			0.07				0.23	
PA03 – 4 Seasons									
	Off	0.09 / 0.056	--	0.08	--	0.82 / 0.122	--	0.69	--
	On	0.22 / 0.125	180	0.21	110	1.11 / 0.100	39	1.08	66
	ASHRAE			0.07				0.20	
All House Totals – 4 Seasons									
	Off	0.08 / 0.056	--	0.07	--	0.45 / 0.408	--	0.20	--
	On	0.16 / 0.093	150	0.16	97	0.52 / 0.445	76	0.28	67

[1] The arithmetic mean and median of the individual seasonal changes (ΔASD Off/ASD On) in the ventilation rates was calculated, and may be different than the change in the summarized 4-season ventilation rate.

[2] ASHRAE ventilation required for each house is based on floor area and number of bedrooms (ASHRAE Std. 62.2, 2007)

3.5.1 Basement Air in ASD Exhaust. The tracer gas measurements were also used to determine the make-up or source of ASD discharge air. Table 4 shows the percentage of ASD discharge air that originated in the basement, based on tracer found in samples of discharge and basement air taken within a few minutes of each other. These measurements were performed during operation of the modified ASD systems (single pipe through the slab). The basement air can enter the ASD system through multiple pathways, such as cracks and holes in the foundation walls and floor (discussed in the conceptual model).

Table 4. Basement Air in ASD Exhaust

House ID	**Fraction of Air in ASD Exhaust Originating in the Basement (%)**
PA01	46
PA02	72
PA03	72

House PA01, with poured walls, sealed sump, sealed wall/floor joint, sealed utility penetrations and limited visible cracks in the walls or slab, apparently had the least leakage between the basement interior and the region around the foundation depressurized by the ASD systems. Even so, the tracer gas measurement indicates that approximately 46% of the ASD discharge air came from the basement. In PA02 and PA03, approximately 72% of the discharge air is from the basement. Block walls under direct or indirect depressurization would seem a likely pathway for additional loss of basement air to the ASD system in those two structures. These data are consistent with other studies (of seven houses) that reported between 40 and 90% of the air in ASD exhaust originated in the basement (Turk et al 1991).

3.6 Indoor Radon Concentrations

Active soil depressurization systems for radon control are the workhorse technique for reliably reducing indoor radon levels. A plot of typical changes in basement air radon concentrations as the ASD system was cycled on and off at PA02 is displayed in Figure 7, which shows large reductions regardless of system configuration. As seen in Figure 8, all of the systems installed in this project were very successful at reducing basement concentrations well below the US EPA's mitigation action level of 4 pCi/L (148 Bq/m^3) – even approaching levels in the outdoor air. The modified ASD configurations also demonstrate robust reductions.

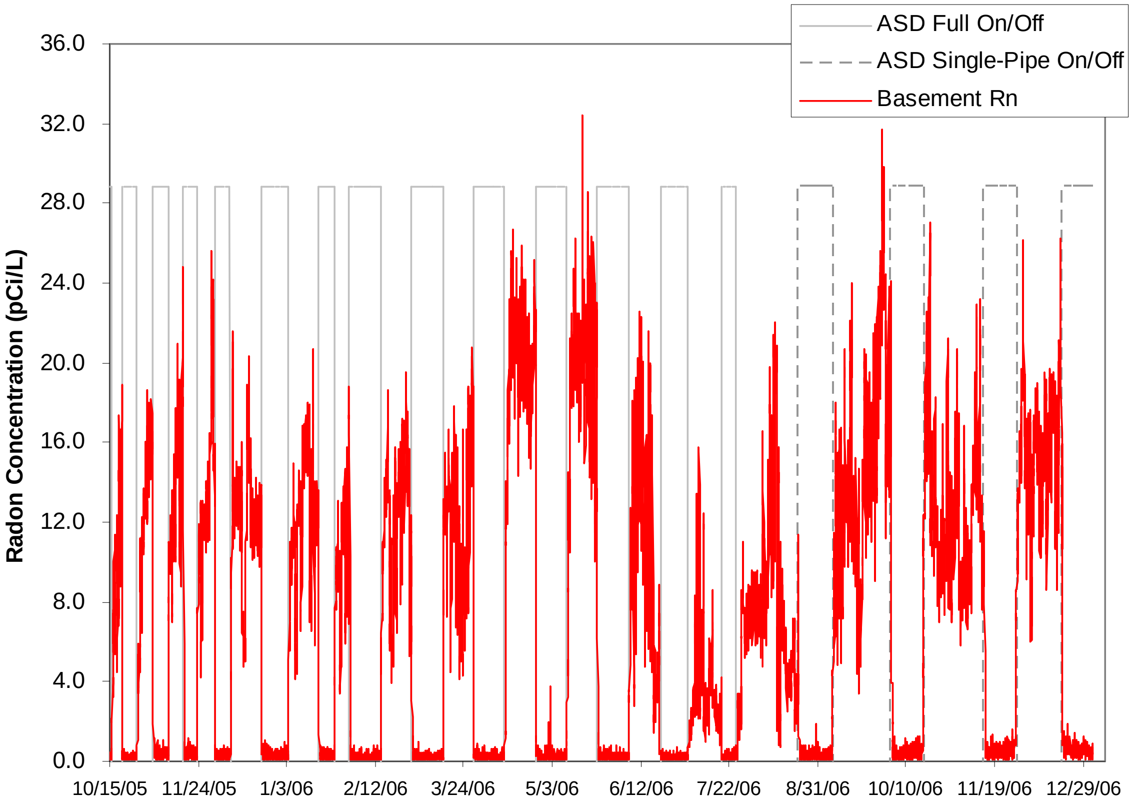

Figure 7. *Radon levels in the basement air of PA03 during ASD cycling, for periods of full ASD(multiple pipe) and single-pipe operation.*

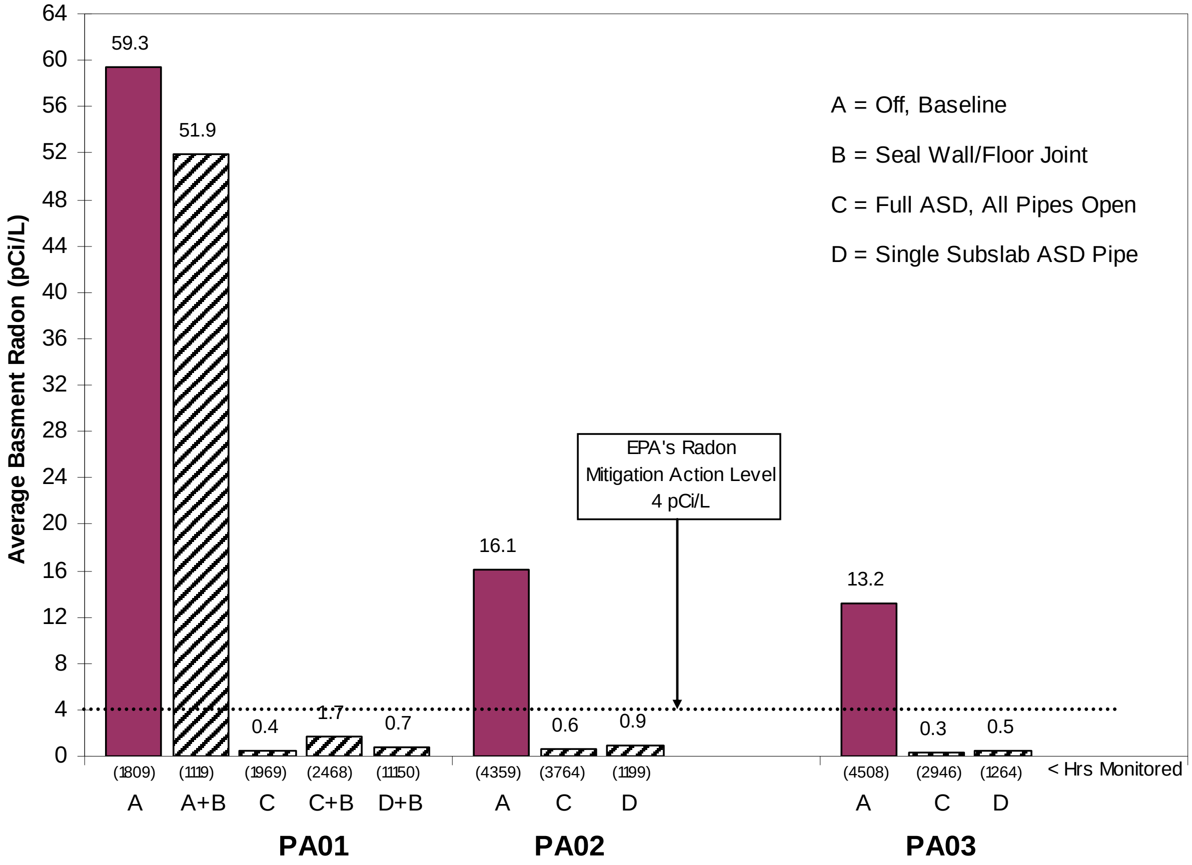

Figure 8. *Average basement air radon concentrations during ASD cycling (≥7-day cycle periods) for September 2005 through January 2007. Various mitigation configurations are identified by the letter codes, and the accumulated hours of monitoring for each configuration are shown below the data bars.*

As summarized in Tables 5 - 7, radon concentrations, with ASD off, on the 1st floor of these houses were approximately 25 to 50% of the basement concentrations, which is typical for houses with HAC systems. Radon concentrations below the slab floor and on the exterior side of the walls had large reductions during ASD operation, presumably because radon was being diluted with ventilation air from outdoors or the basement (through cracks and openings). The smallest reduction in wall radon levels occurred at PA01, the house with poured concrete walls. Single ASD pipe operation tended to cause slightly smaller reductions in radon levels at most locations. These results also indicate that the primary source of radon for these houses was pressure-driven entry from the soil.

Other than in house PA02, additional depressurization of the basement is not measurable with ASD systems on. At PA02, the house with the smallest air leakage area, it is likely that the ASD systems are increasing the basement depressurization with respect to upstairs and to outdoors. The additional depressurization is probably the result of basement air being extracted by the ASD system through cracks and openings in the basement walls and floor (see Figure 3).

Table 5. Summary of Radon and House ΔP Measurements at PA01

Measurement Location	**ASD Condition**				
	Off	**Off + Seal**	**Full On[1]**	**Full On + Seal[2]**	**Single Pipe[3] + Seal[2]**
Radon Mean (pCi/L) *Std Dev (pCi/L) # Hours*					
Basement Air	59 *12.3 1809*	52 *23.0 1119*	0.4 *0.27 1969*	1.7 *3.72 2468*	0.7 *0.49 1150*
1st Floor Air	33 *9.09 1809*	21 *12.4 1119*	0.4 *0.29 1969*	0.5 *0.35 2468*	0.7 *0.42 1150*
Basement Wall	280 *205.0 1809*	410 *173 1040*	200 *65.7 1969*	210 *36.6 2468*	160 *69.9 1150*
Basement Floor	520 *534.7 1809*	990 *286 1040*	19 *11.1 1969*	120 *28.4 2468*	230 *19.5 1150*
Differential Pressure Mean (Pa)[4] *Std Dev (Pa) # Hours*					
Basement-1st Flr	-0.2 *1.77 1733*	-0.1 *1.81 996*	-0.4 *2.7 1881*	-0.0 *1.50 2275*	-0.7 *1.85 1102*
Basement-Outdoor	-3.2 *1.66 1722*	-2.0 *1.61 978*	-4.1 *1.91 1873*	-1.6 *1.20 2359*	-1.3 *0.92 1102*

[1] Two suction pipes
[2] Perimeter wall/floor joint sealed
[3] One suction pipe at reduced flow
[4] Differential pressures are referenced to the 1st floor and outdoors

Table 6. Summary of Radon and House ΔP Measurements at PA02

Measurement Location	**ASD Condition**		
	Off	**Full On[1]**	**Single Pipe[2]**
Radon Mean (pCi/L) *Std Dev (pCi/L) # Hours*			
Basement Air	16 *5.24 4359*	0.6 *0.35 3764*	0.9 *0.84 1199*
1st Floor Air	7.1 *2.80 4601*	0.3 *0.33 2949*	0.3 *0.39 946*
Basement Wall	210 *117 3815*	30 *11.2 2975*	65 *8.30 1414*
Basement Floor	230 *82.0 4600*	3.7 *3.15 3621*	4.0 *0.89 1414*
Differential Pressure Mean (Pa)[3] *Std Dev (Pa) # Hours*			
Basement-1st Flr	-0.2 *0.19 4411*	-1.0 *0.53 3606*	-0.6 *0.36 1355*
Basement-Outdoor	-1.2 *0.97 4410*	-5.0 *1.13 3605*	-3.1 *1.44 1352*

[1] Two suction pipes
[2] One suction pipe at reduced flow
[3] Differential pressures are referenced to the 1st floor and outdoors

Table 7. Summary of Radon and House ΔP Measurements at PA03

Measurement Location	**ASD Condition**			
	Off	**Dehumid**	**Full On**[1]	**Single Pipe**[2]
Radon Mean (pCi/L) *Std Dev (pCi/L) # Hours*				
Basement Air	13 *5.75 4508*	11 *4.42 909*	0.3 *0.19 2946*	0.5 *0.27 1264*
1st Floor Air	4.4 *2.09 4514*	5.1 *1.91 911*	0.2 *0.17 2947*	0.3 *0.22 1264*
Basement Wall	130 *295 4514*	87 *32.3 911*	33 *3.47 2947*	28 *5.78 1264*
Basement Floor	650 *388 4514*	620 *232 911*	35 *13.4 2947*	29 *2.96 1264*
Differential Pressure Mean (Pa)[3] *Std Dev (Pa) # Hours*				
Basement-1st Flr	-0.1 *0.32 4135*	-0.8 *0.83 872*	-0.8 *0.72 2820*	-0.5 *0.67 1211*
Basement-Outdoor	-1.9 *1.18 4132*	-1.5 *0.88 872*	-3.2 *1.61 2820*	-2.1 *0.96 1210*

[1] Three suction pipes – two into the block wall, and one below the slab
[2] One sub-slab suction pipe at reduced flow
[3] Differential pressures are referenced to the 1st floor and outdoors

3.7 Basement Moisture

Time series plots of the basement air RH at PA01 – PA03 and outdoor air humidity ratio are presented in Figures 9 - 11. Because changes in outdoor air temperature add to other large and rapid variations in outdoor air RH, humidity ratios were computed to negate some of the temperature effects. While the plots cover a 10- to 15-month period when the ASD system was being cycled on and off, the dominant trend in the basement air RH tracks with the outdoor air moisture levels. Closer inspection of the plots suggests that the basement RH does change in response to many of the periods of ASD operation, but that this response is superimposed on the larger and longer seasonal changes in outdoor air moisture. These data also hint that moisture responses are more muted and less predictable in the summer months.

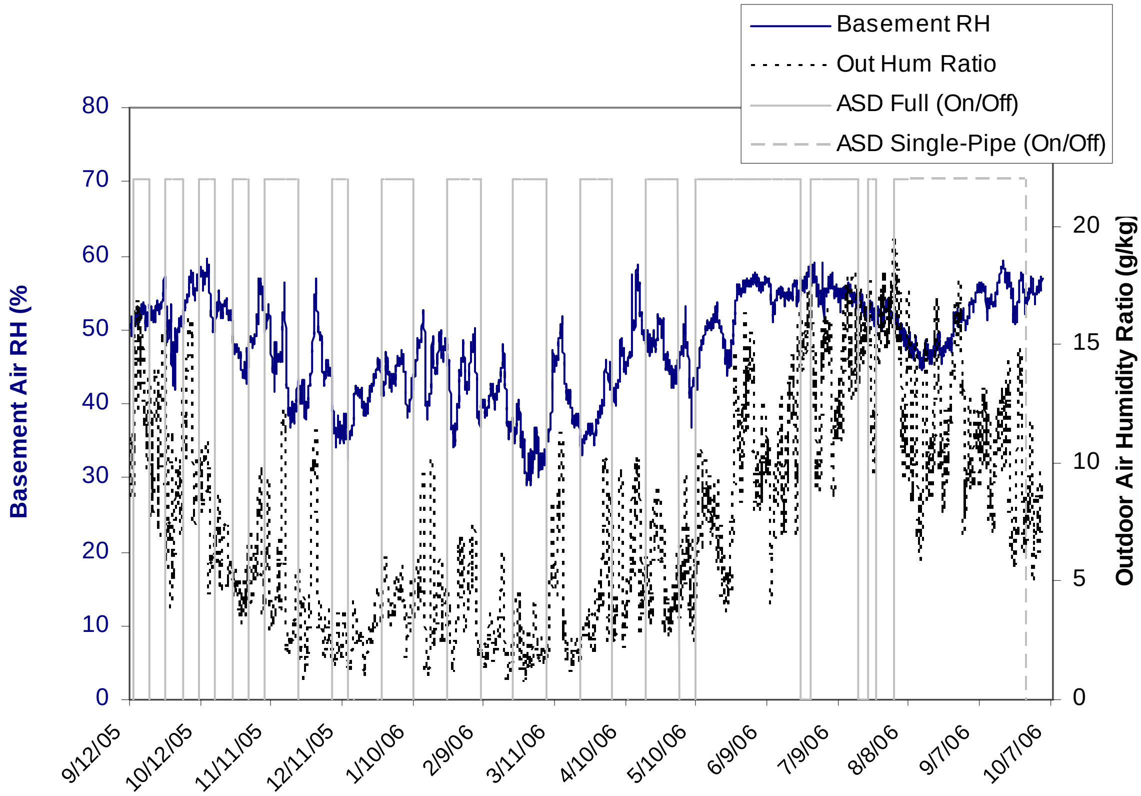

Figure 9. *Moisture levels in basement air (RH) and outdoor air (humidity ratio, W) over a 13-month period at PA01, during ASD system cycling. ASD 'on' periods are indicated by the rectangular bars near the top of the plot.*

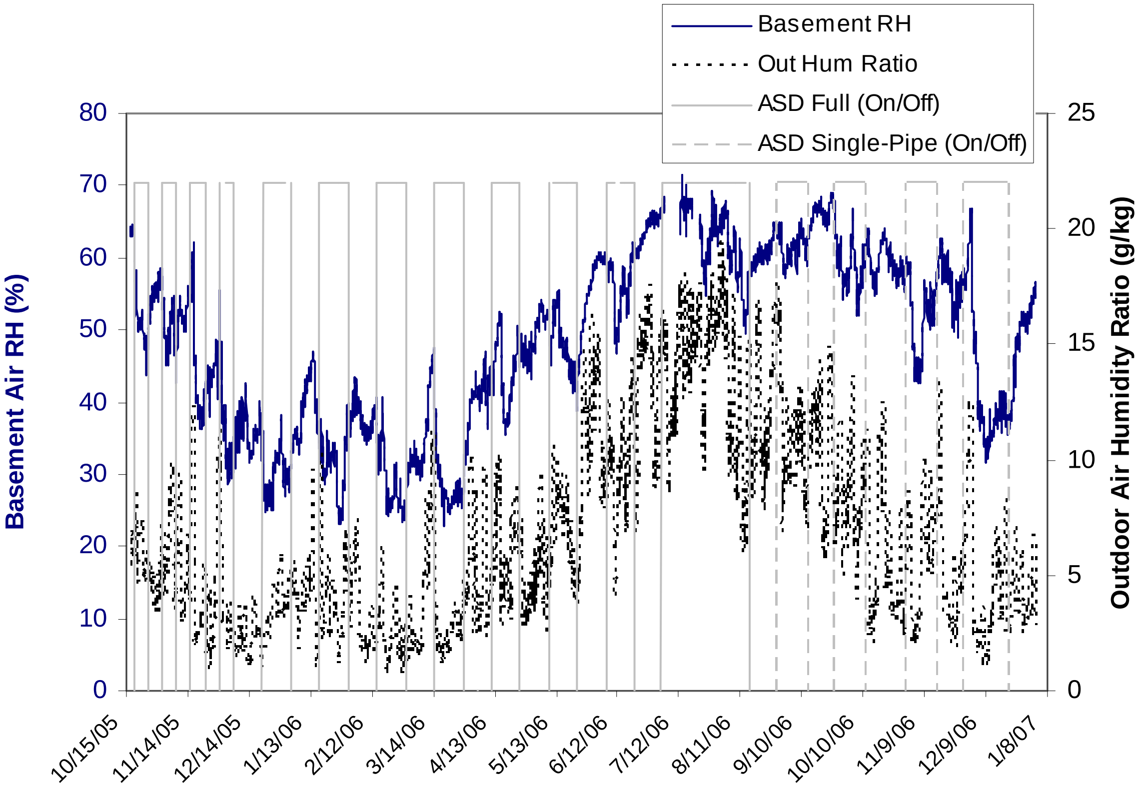

Figure 10. *Moisture levels in basement air (RH) and outdoor air (humidity ratio, W) over a 15-month period at PA02, during ASD system cycling.*

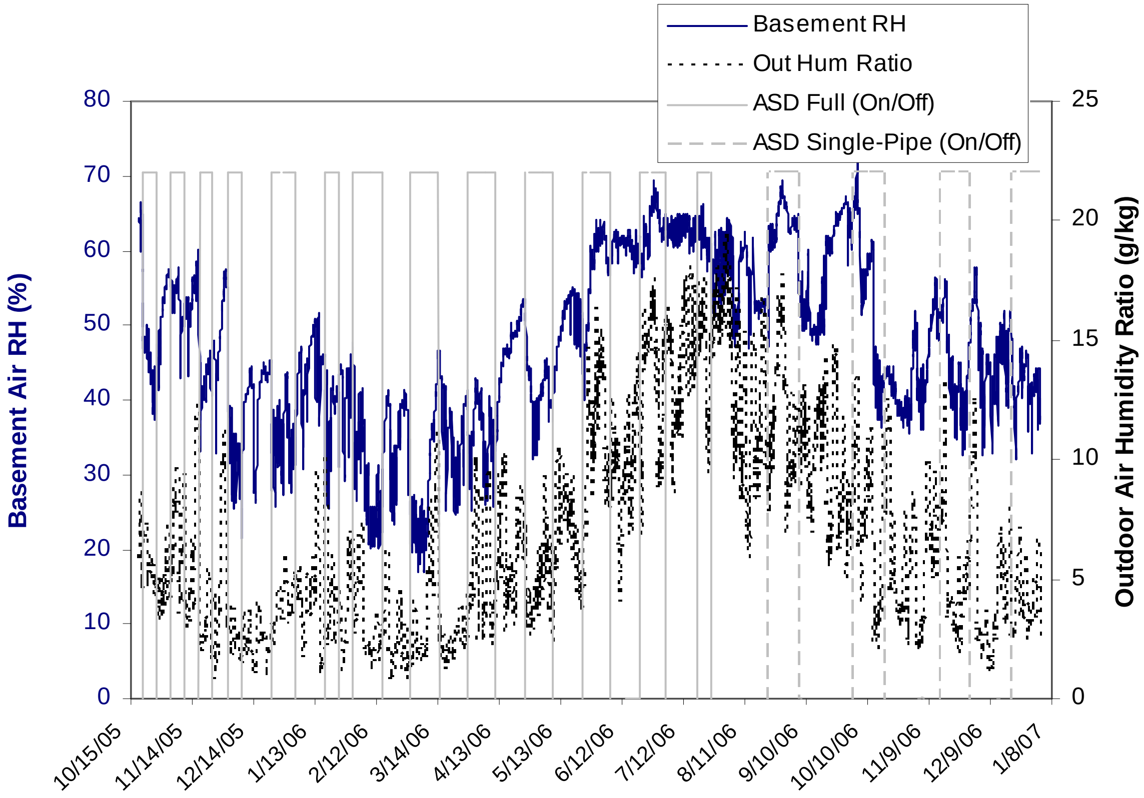

Figure 11. *Moisture levels in basement air (RH) and outdoor air (humidity ratio, W) over a 15-month period at PA03, during ASD system cycling.*

The equilibrium RH data from one sensor cluster in the walls at each of the three houses are shown for the same time periods in Figures 12 - 14. These data are representative of that from other wall locations, with poured wall locations (PA01) exhibiting behavior more like that of the slab floors (Figures 15 – 17). In contrast to the basement air RH, the data for many of the sensors embedded within the block cores (‘Core’) and within approximately two cm of the interior surface of the block (‘Interior’) display large and dramatic changes as the ASD is cycled (block wall houses PA02 and PA03, Figures 13 and 14). The sensors mounted on the exterior surface of the walls (‘Thru Wall’) typically do not have an observable response to the ASD operation, and after remaining in saturated conditions, many eventually failed. However, the plot of the Thru-wall moisture at W9 in PA03 (Figure 14) suggests that it too is responding as expected to ASD operation. It is not clear that the Interior and Core locations of the block walls (PA02 and PA03) reached steady state conditions even after two weeks of operation. Additional analysis of these responses is required. Although the ASD system causes reductions of almost 30% RH when outdoor moisture levels are low, the response is dampened somewhat during the more humid summer months. When the ASD system at house PA03 was operated with only the sub-slab pipe (”Single pipe”), reductions in wall moisture are greatly diminished (Figure 14). Clearly, the block wall ventilation component of the ASD system had a large impact on wall moisture at this house.

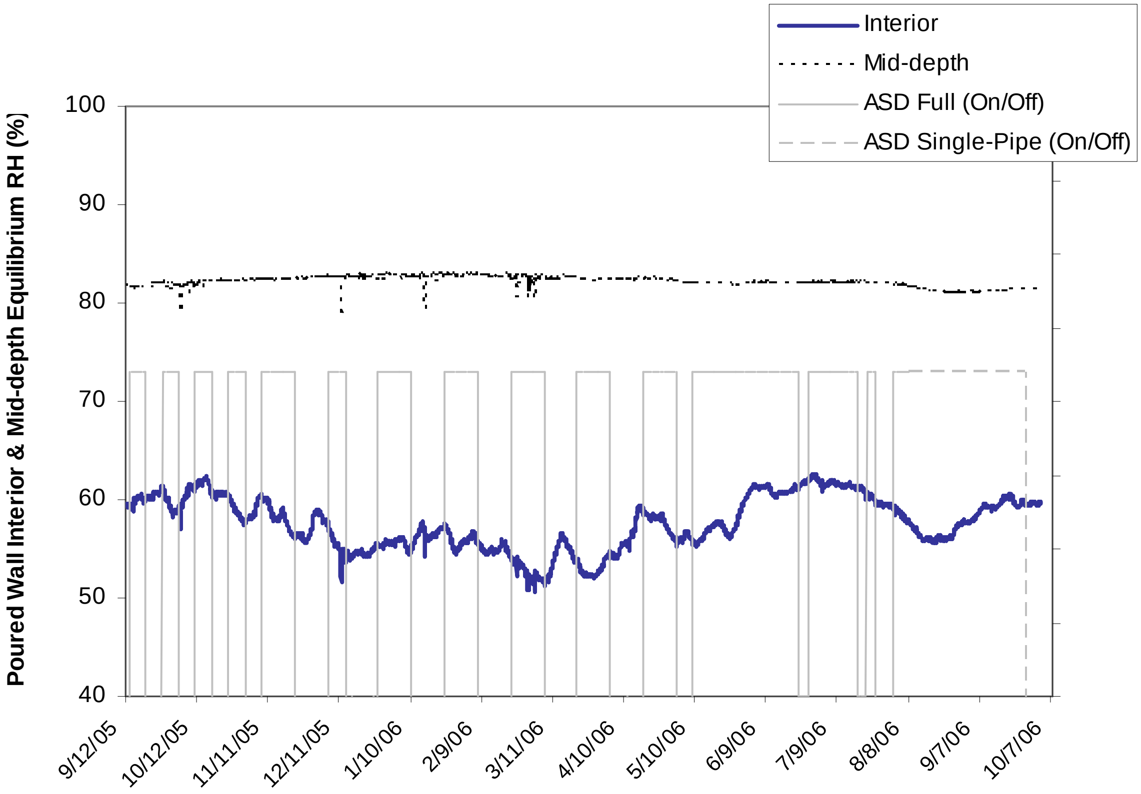

Figure 12. *Plot of equilibrium RH at two depths in poured wall location W26 at house PA01 while ASD systems were cycled. 'Interior' refers to the sensor embedded in the poured wall approximately 2 cm from the basement-facing surface. The 'Thru' wall (exterior) sensor failed due to prolonged exposure to saturated conditions, as did other RH sensors in similar conditions.*

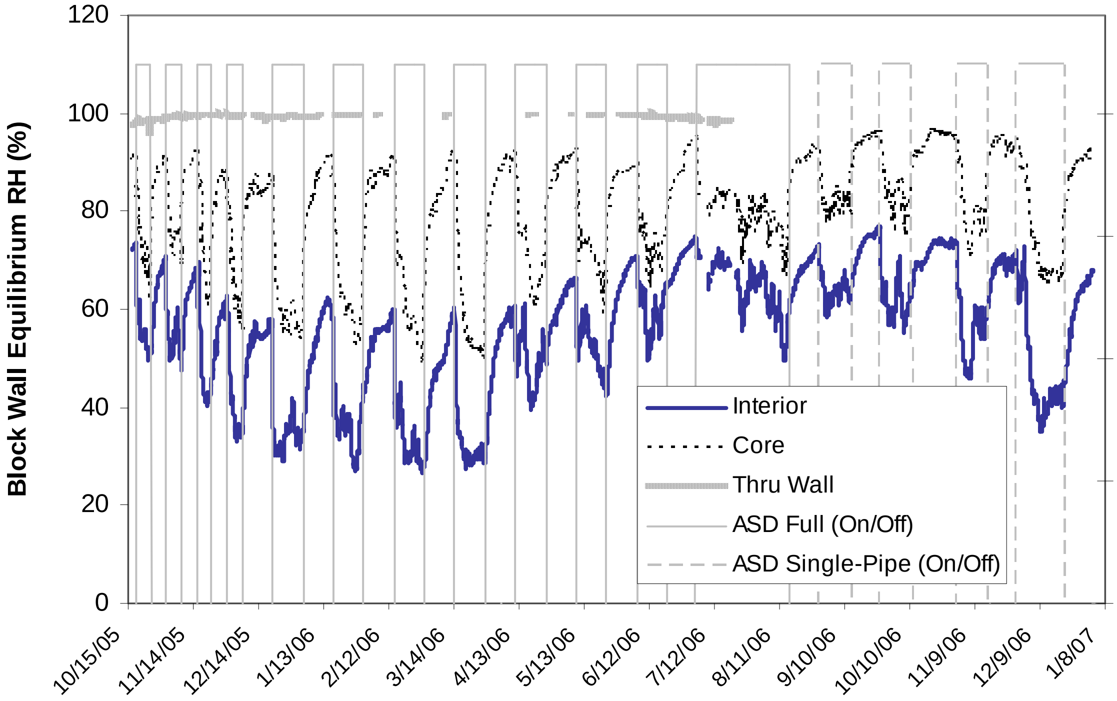

Figure 13. *Plot of equilibrium RH at three depths in block wall location W27 at house PA02 while ASD systems were cycled. 'Interior' refers to the sensor embedded in the block web approximately 2 cm from the basement-facing surface.*

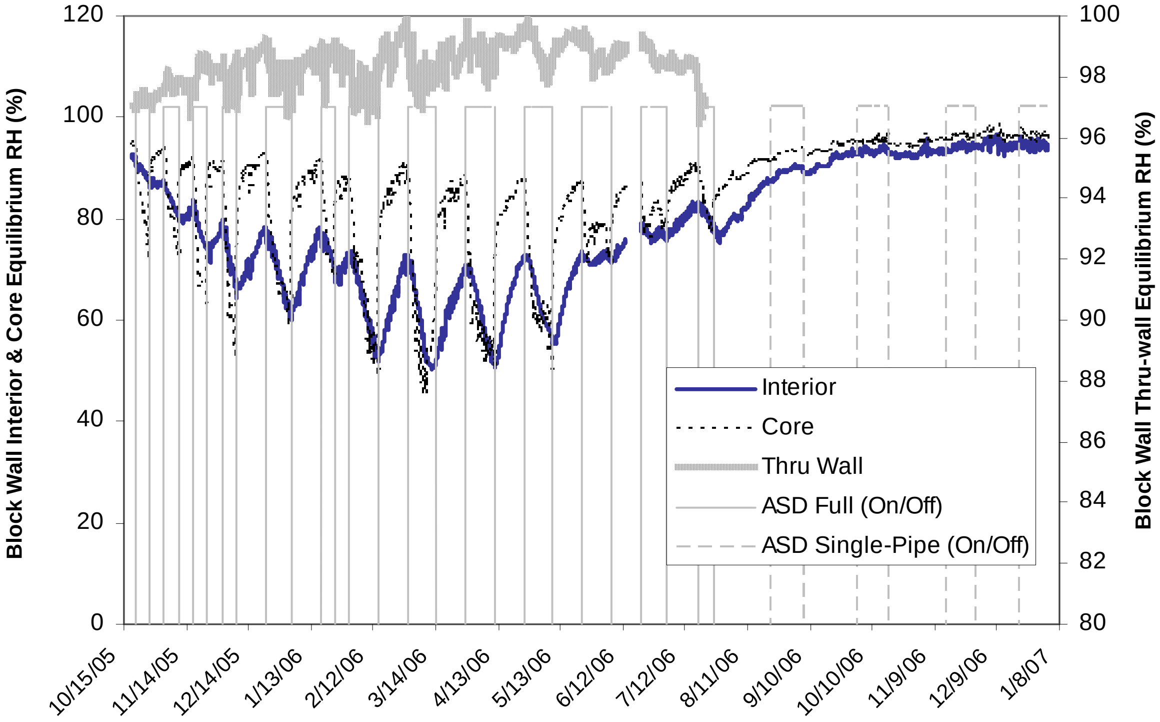

Figure 14. *Plot of equilibrium RH at three depths in block wall location W9 at house PA03 while ASD systems were cycled. Block wall ventilation pipes were disabled during ASD single-pipe cycling.*

The plot for the poured walls at house PA01 (Figure 12) and the slab floors at all houses (Figures 15 – 17) tend to demonstrate much smaller responses to changes in ASD operation. The trend for most wall and floor locations is for the equilibrium RH to increase with depth into the wall or floor material. While the shallower test locations (walls – “Interior”, floors – “Top”) are often more responsive to ASD cycling and track with changes in basement air moisture (Figure 12), there are exceptions. For example, although some block wall cores have high baseline (ASD off) moisture levels, they show larger reductions than the “Interior” locations when the ASD is on (Figures 13 and 14). And several “Thru-slab” floor locations also have large reductions in equilibrium RH when the ASD is running (for example, D1 at PA01 -- Figure 15). These results indicate that the ASD systems are causing comparatively large changes in flow of air with low water vapor pressure, in the gas-permeable sub-slab aggregate.

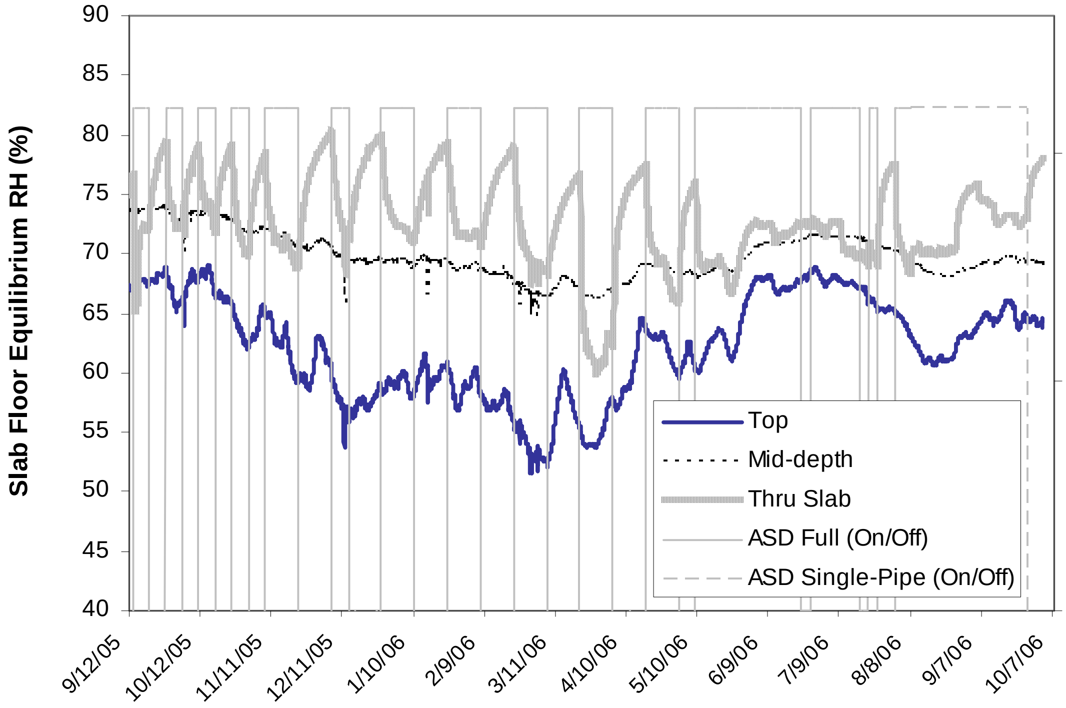

Figure 15. *Plot of equilibrium RH at three depths for slab floor location D1 at house PA01 while ASD systems were cycled. 'Top' refers to the sensor embedded in the slab approximately 2 cm from the top surface. Thru-slab sensors were generally in the aggregate below the concrete slab.*

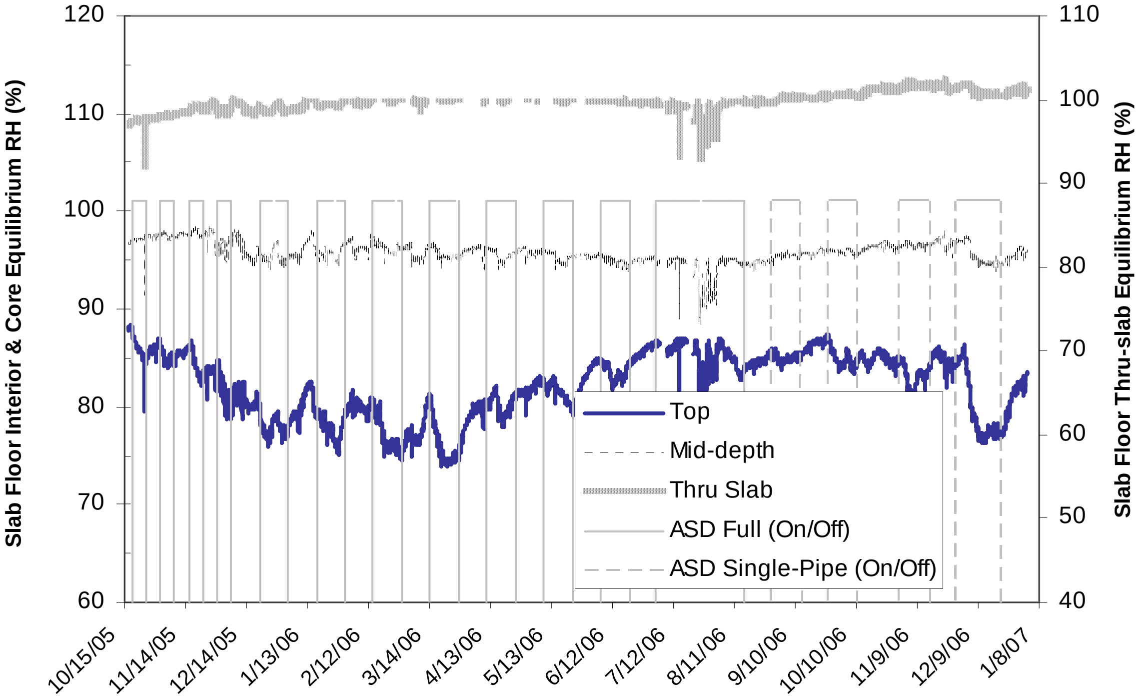

Figure 16. *Plot of equilibrium RH at three depths for slab floor location C4 at house PA02 while ASD systems were cycled. 'Top' refers to the sensor embedded in the slab approximately 2 cm from the top surface. Thru-slab sensors were generally in the aggregate below the concrete slab.*

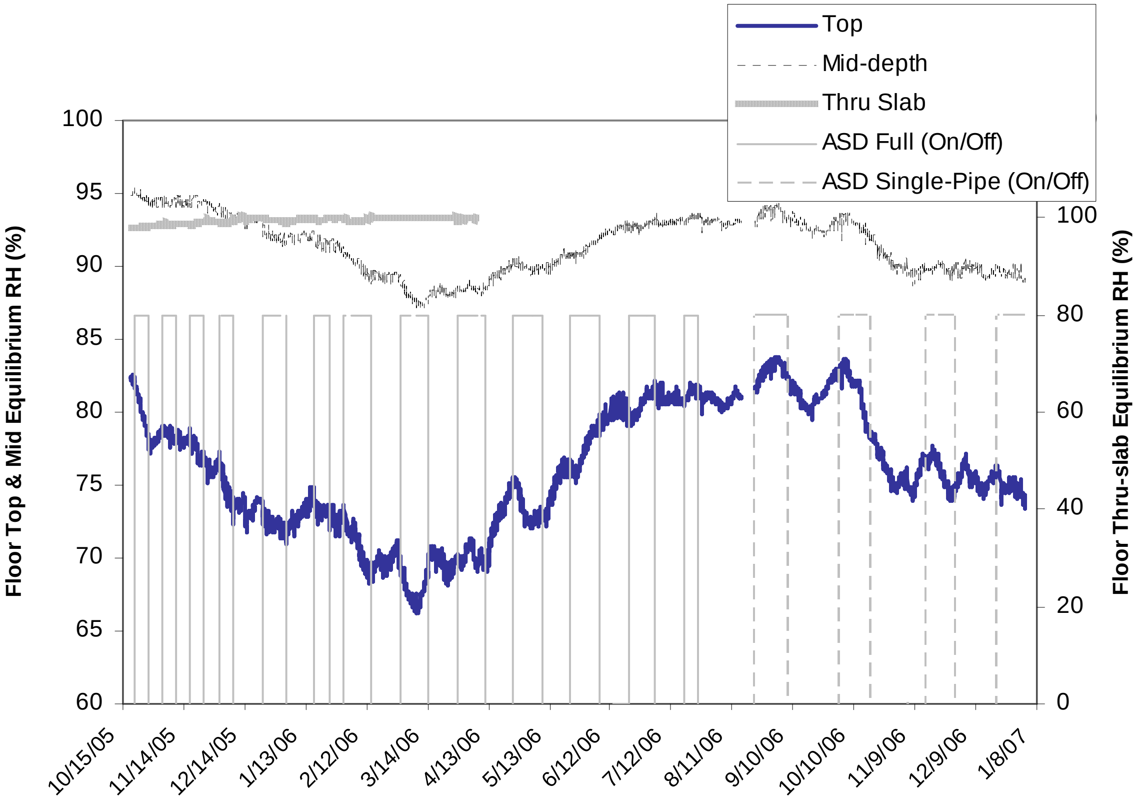

Figure 17. *Plot of equilibrium RH at three depths for slab floor location D3.5 at house PA03 while ASD systems were cycled. As with the Thru-wall sensors, many of the Thru-slab sensors also failed.*

To show the comparative changes in moisture levels in the air, wall, and floor during ASD cycling in house PA02, data from three figures (10, 13, and 16) are combined in Figure 18. Moisture changes in the air and foundation materials track together, but with different response characteristics.

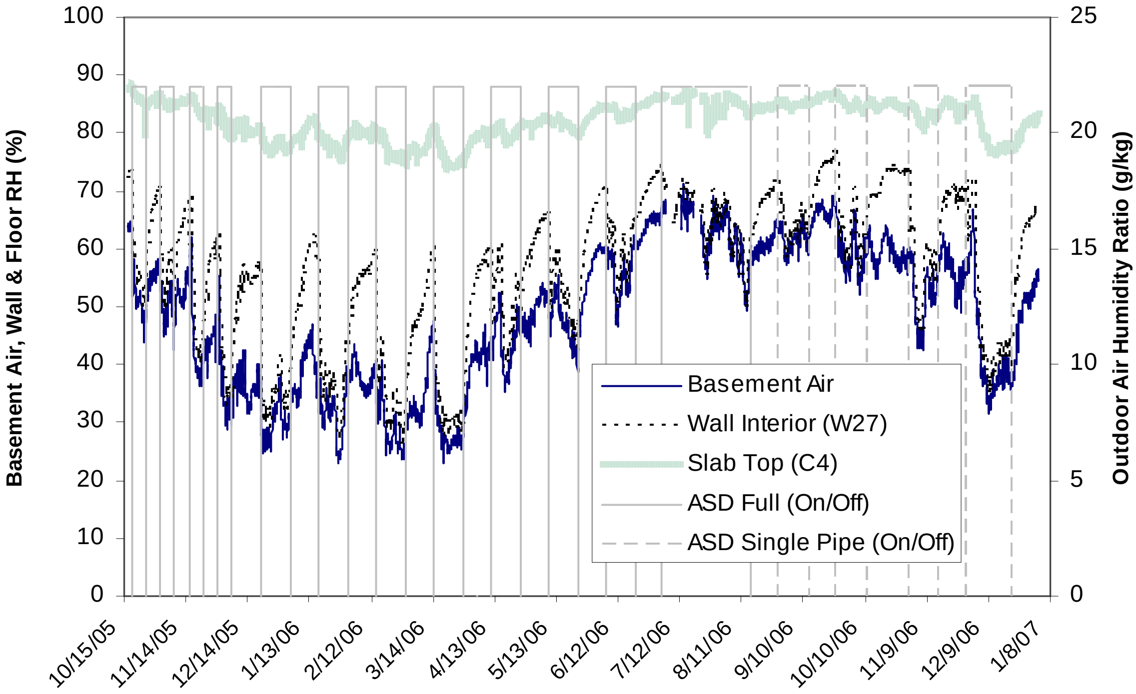

Figure 18. *Tracking moisture levels in the basement air along with one near-surface location for the wall and slab floor at PA02.*

The aggregated mean RH for most of the air, wall, and floor locations are compared for the ASD on and off periods during various configurations of the mitigation systems in Figures 19 – 21. The data are from Day 7 – 14 from the 14-day, and longer, cycle periods. This one week lag was used so that moisture conditions had more time to equilibrate before data were averaged. However, the data indicate that, for many of the foundation materials, a much longer ASD on or off period will be required before quasi-equilibrium is reached. Consequently, these data likely do not represent steady state moisture levels for extended ASD operation. For walls and floors, results from all sensors at all clusters were grouped. The data are also grouped by summer and non-summer conditions. The beginning and end of summer was arbitrarily defined for the purposes of this analysis as occurring when the daily average outdoor air dew point changed to being above (summer) or below (non-summer) 60°F (15.6°C) for five consecutive days. For the study site, this occurred in late-May/early June and September. Many of the differences (both increases and decreases) between mean RH for On and Off periods are statistically significant ($p<0.05$, value shown in figures), yet the magnitude of the differences are so slight as to indicate there was little practical change in moisture levels. Comparison of changes in indoor moisture levels with those in the outdoor air will be reported separately after analyses, and possible development of a statistical model, investigating the relationship of indoor moisture to many other factors.

The data for PA01 (with poured walls) show the trend of increasing moisture the deeper into the wall or floor, and the closer to the surrounding soil (Figure 19). The soil side of the slab floors appears to benefit from the presence of the gravel layer, acting as a capillary break. Full ASD system operation (ASD On/ASD Off) produced a modest reduction of approximately 4% RH in basement air and Thru-slab locations (before crack sealing), possibly due to the system's direct impact on air flow in those areas. Moisture changes in the remaining wall and slab locations are usually less than 1% RH. It is interesting to observe that after sealing of the wall/floor joint, average moisture levels at some locations increased slightly during baseline and ASD on periods. Sealing the crack may have reduced the amount or pattern of air flowing in and around these materials. Cycling data for the reduced, single-pipe and summer operation at this house are very limited and not presented here.

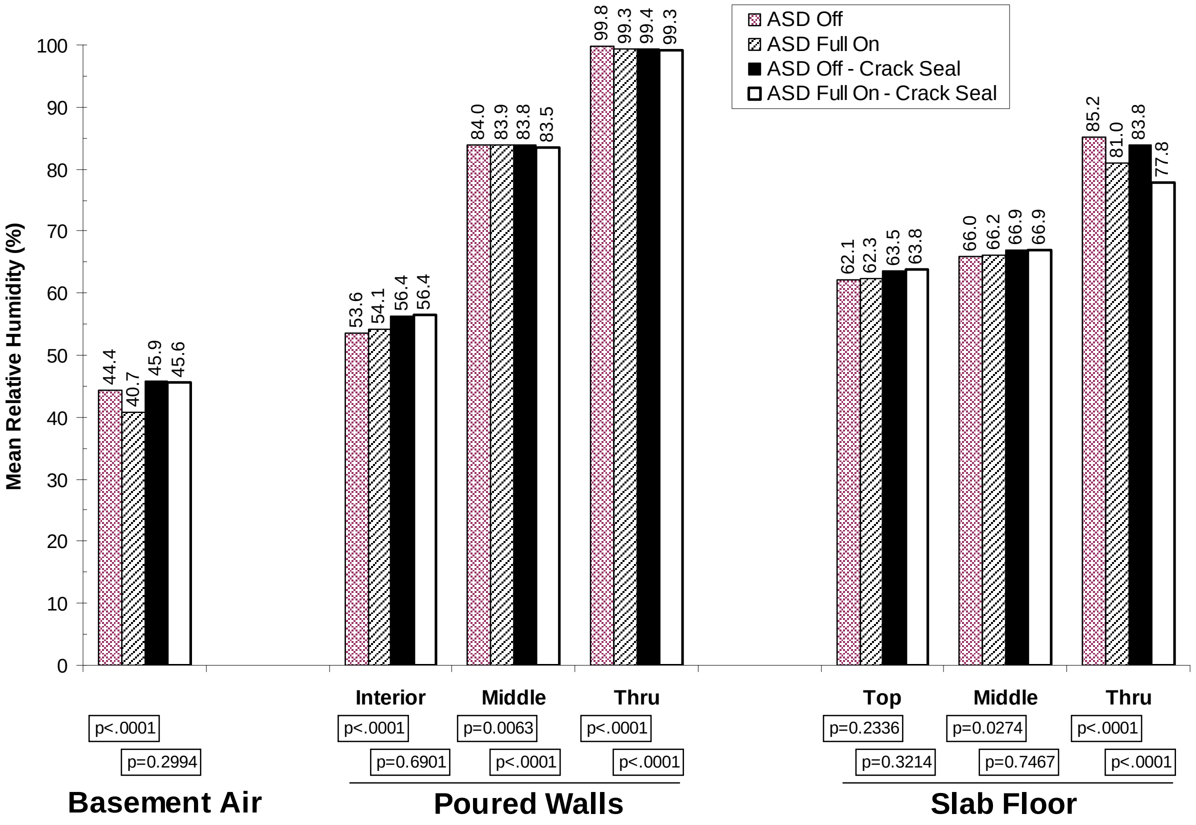

Figure 19. *Summary of arithmetic mean RH for second 7 days of 14-day, or longer, cycling periods at PA01. In addition to RH in basement air, all wall and slab floor cluster locations (Interior, Top, Middle, Thru) with legitimate sensor values were aggregated. The wall/floor joint was sealed in March 2006, and is separately presented in the data as 'Crack Seal'. The statistical significance of the difference (p, two-tail) between various 'off' and 'on' segments is indicated in the boxes below. These non-summer data are from September 2005 through May 2006.*

Sufficient data were available at PA02 to present results from single-pipe ASD operation (ASD Reduced), and for the summer months (Figure 20). Insufficient data are available from the Thru wall and Thru slab locations due to sensor failures. The mean RH in the basement air, block surfaces within 2 cm of the basement interior, and the block cores experienced large and significant reductions during non-summer operation of both the full and single-pipe ASD system. Mean humidity reductions in basement air during non-summer operation were more than 7% RH. Moisture reductions in block Interior and Core during full operation averaged over 18% and 23% RH, respectively. For the single-pipe configuration, reductions in the wall were smaller – over 15% and 13%. There are similar, but attenuated, responses at the slab floor locations. Moisture in the basement air for the reduced, single-pipe configuration was reduced from 56% RH to 49% RH. A moisture level favorable to dust mites and some molds is commonly assumed to be 50% RH, or greater, in the air. The single-pipe configuration (PA02 and PA03) was operated for 5½ months, from August 2006 into January 2007, so that data on the four-season performance of this configuration is not available.

Changes in the mean RH during the summer period were smaller and more equivocal, but most apparent at the two depths of the walls. The basement air RH of 62%, with the ASD system on, would be suitable for the growth of some microbiological organisms.

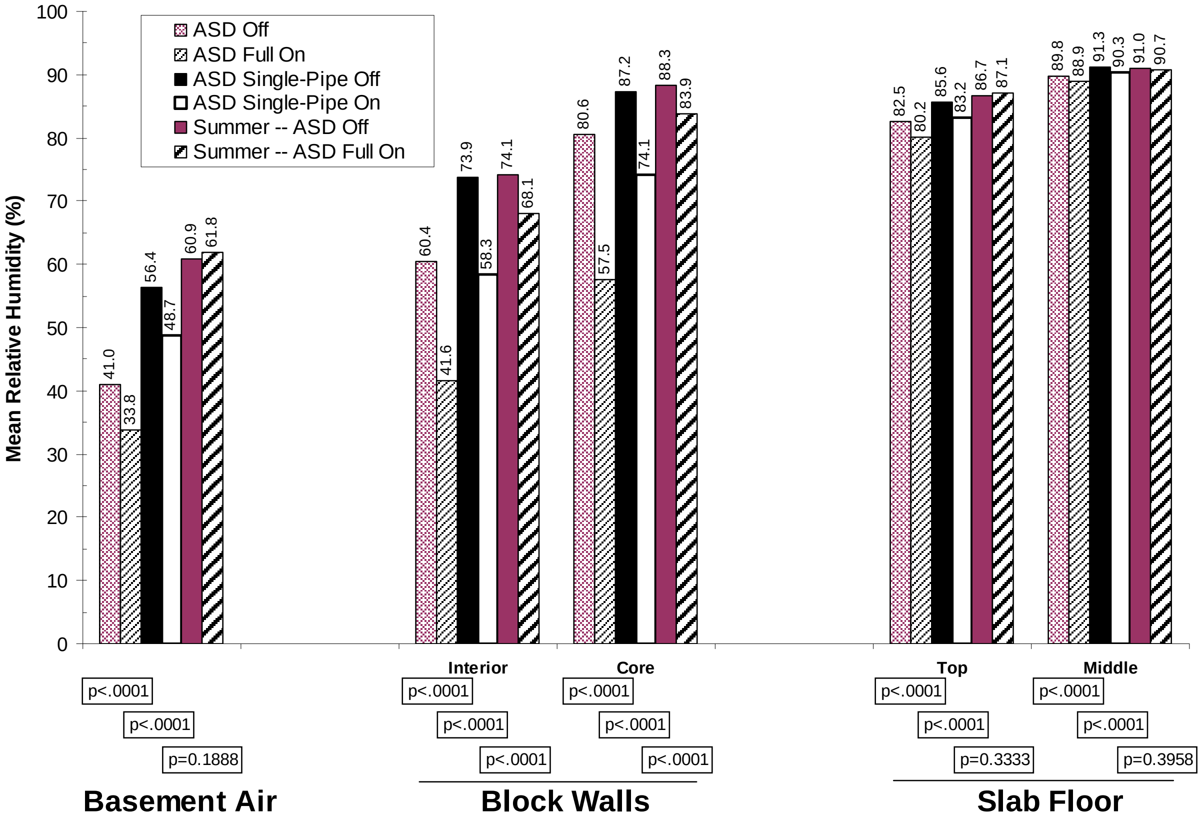

Figure 20. *Arithmetic mean RH for second 7 days of 14-day, or longer, cycling periods at PA02. These data are for December 2005 through January 2007, and include summer periods, and periods when the ASD operation was reduced to a single pipe.*

At PA03, mean RH changes mimic those for PA02, but with an even larger change in the cores of the block walls during full system, non-summer, operation (30% RH). This enhanced response in the block cores is due to the additional ventilation applied by the ASD pipes installed directly into the wall blocks. The average drop in basement air RH was 10%, and 18% for block

Interior during full system operation. While the single, sub-slab pipe was being used, the reductions were smaller: 8% RH in the basement air, 3% RH for the block Interior, and 6% in the block Core locations. Moisture reductions at the slab floor and through-block locations were generally less than 2%. The decrease in moisture levels during the summer was much less: 1% RH in basement air RH, 8% in block Interior, and 14% in the block Cores.

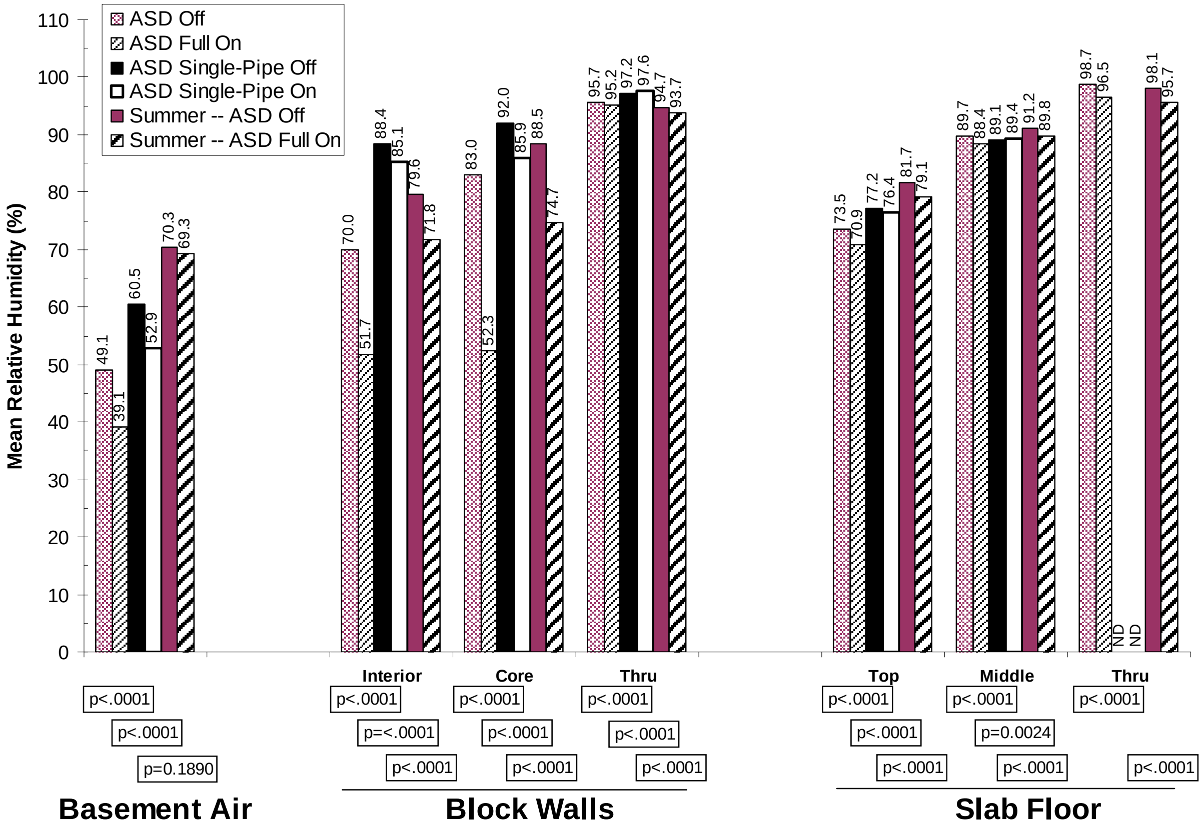

Figure 21. *Arithmetic mean RH for second 7 days of 14-day, or longer, cycling periods at PA03. These data are for December 2005 through January 2007, and include summer periods, and periods when the ASD operation was reduced to a single sub-slab pipe. When data were not available, it is indicated by ND.*

A more revealing analysis of the change caused by the ASD operation is to examine the rate of change in moisture (RH). Performing autoregression analysis (with lag of 2) for the first seven days of seven day and longer cycle periods yields results similar to those shown in Figure 22 for basement air RH at PA02. The first seven days were chosen as being expected to demonstrate the largest and measurable change in moisture – if any had occurred. The regression lines clearly show the trends as the ASD operating condition is changed. The slope of the regression lines for each phase of the ASD cycle were then aggregated and used as a surrogate for the rate of change in moisture in the air and within the foundation materials. Since the moisture rate of change slowly diminishes over time, a linear regression is not a true representation of long-term moisture changes. Therefore, the slopes should not be used to extrapolate beyond the seven-day period of analysis.

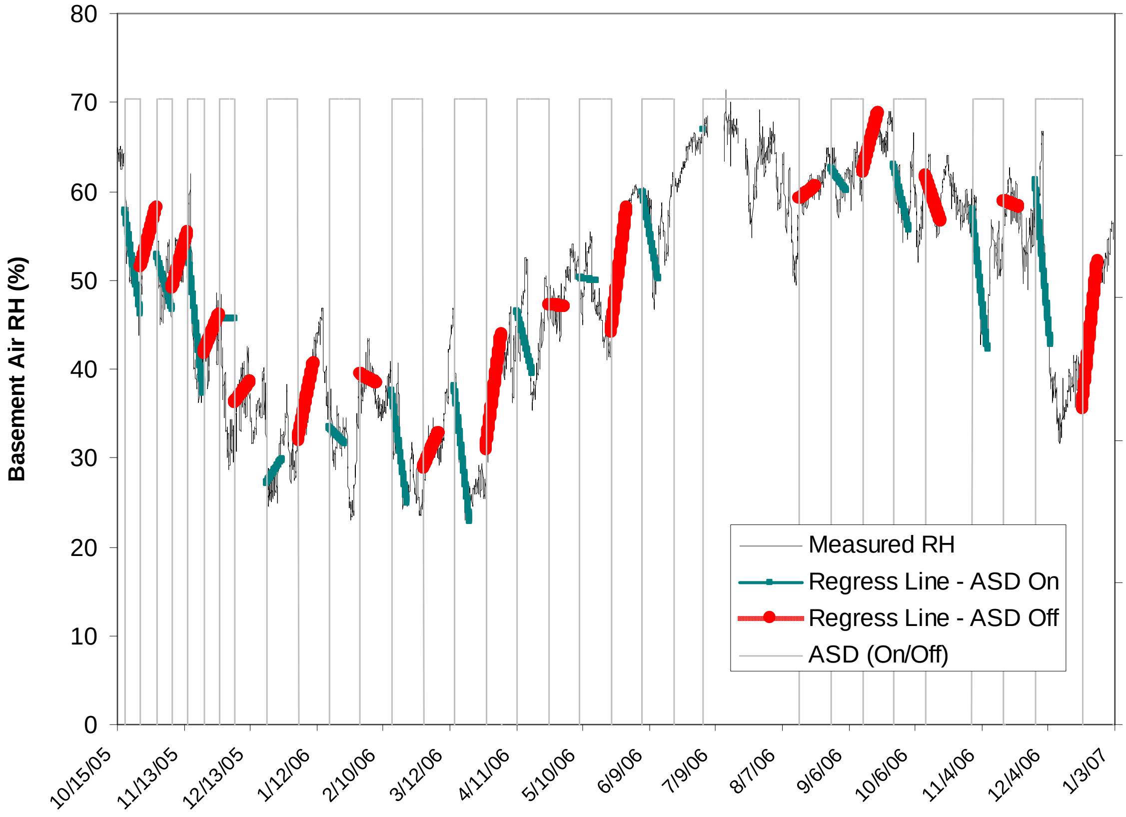

Figure 22. *Example of analysis using autoregression on 1st seven days of each cycle as ASD is cycled on and off at PA02 for basement air RH. The slope of the regression line is used as a measure of the rate of change in moisture.*

Summaries of the regression analyses performed on basement air, walls, and floors at each house are shown in Figures 23 – 25. The mean daily change in RH is computed from the slope of regression for all periods greater than or equal to seven days in length. The statistical significance of the difference in mean daily change in RH is displayed (p-value), along with the number of periods where the rate of change (out of the total) is above or below zero. Sufficient data were available to include the results for the modified/reduced, single-pipe ASD operation at PA02 and PA03.

Most locations experienced significant ($p<0.05$) reductions in moisture for the non-summer periods during ASD operation. The exceptions include slab floors at PA02 and PA03, and the basement air at PA03 during reduced single-pipe cycling. Non-parametric analysis of some of these data do show the differences to be statistically significant (note the number of periods with daily changes less than or greater than zero), although perhaps not practically significant. The sub-slab material at PA03 was observed to be wet with liquid water during installation of the sensors. This condition probably results from poor drainage conditions around the outside of the building. It's not expected that the ASD systems will be able to control this type of moisture problem – and was the reason that houses with bulk water problems were to have been excluded from the study. The occupants of PA02 noted that the basement felt less damp when the ASD was running. Block walls tended to have the greatest reductions, possibly because the relatively open and porous nature of the blocks permitted greater air flow in and around the walls. The poured walls at PA01 exhibit a response like that of the slab floors in all houses, probably because of their similar dense construction and slower response to changing moisture conditions. Longer ASD on periods may result in more pronounced changes in these materials, as is suggested by preliminary data from PA01 where the ASD system was operated almost continuously after May 2006.

As seen in Figures 9 – 12, basement moisture levels tend to increase during the summer – however, ASD operation still may have a modest impact on the mean daily change in RH at PA01 and PA02. Although some of these reductions are not considered significant according to classical statistical tests (assuming normal distribution), non-parametric analyses indicate the differences may be significant. If additional basement ventilation with upstairs and outdoor air accounts for the drying observed during the non-summer, it may also cause a countervailing effect during the summer. Humid air drawn into the basement from outdoors in the summer could add significant moisture to the basement, as Figure 25 may show for PA03.

In contrast with the data for mean RH (Figures 20 and 21), the mean daily change in RH during non-summer operation of the ASD systems with reduced, single-pipe configurations for PA02 and PA03 is similar to that for full system operation. During the summer, these 'typical' ASD configurations appear to be more vulnerable to the high moisture loads in the outdoor air – with their moisture-reducing performance becoming more marginal.

A similar trend analysis of moisture levels was performed on the first 14 days of each cycle period for the three houses. The data, included in Appendix H, tend to exhibit smaller changes during both ASD Off and ASD On periods. This dampened response for the longer analysis times is likely due to the gradually decreasing change in moisture as the house and its materials slowly approach a new moisture equilibrium. However, the pattern of moisture reductions during ASD operation is still apparent. The data from the 14-day analysis at PA01 supports the observation that sealing of the perimeter wall/floor joint in the basement tended to diminish the moisture reductions during ASD operation.

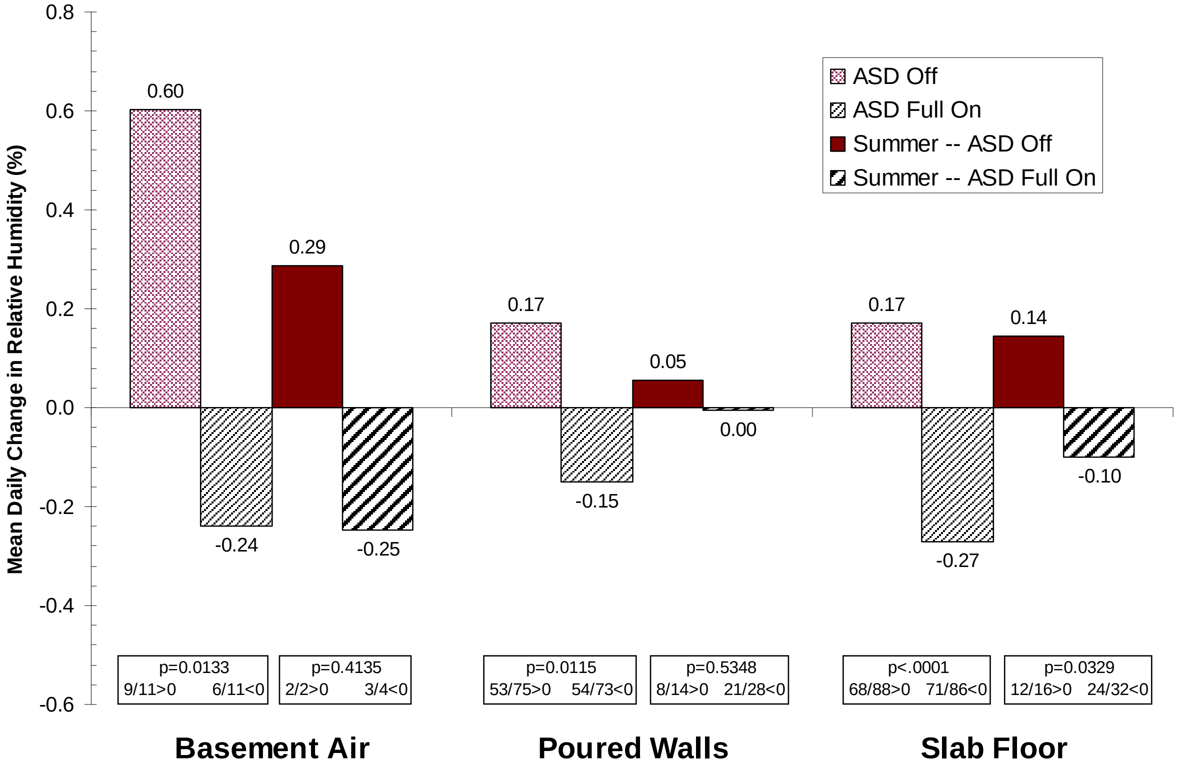

Figure 23. *Summary of arithmetic mean daily change for first 7 days of period in basement moisture levels in the air, walls, and slab floor at house PA01 during ASD cycling. Periods with full ASD + crack sealing are grouped with ASD Full On. The statistical significance of the difference (p, two-tail) between 'off' and 'on' is indicated in the box below, along with the number of 'off' and 'on' cycles (out of total) with a rate of change greater than and less than 0, respectively. For walls and floors, data from a number of different locations are aggregated, as reflected in the total number of cycles. Data include summer and non-summer periods from September 2005 through October 2006.*

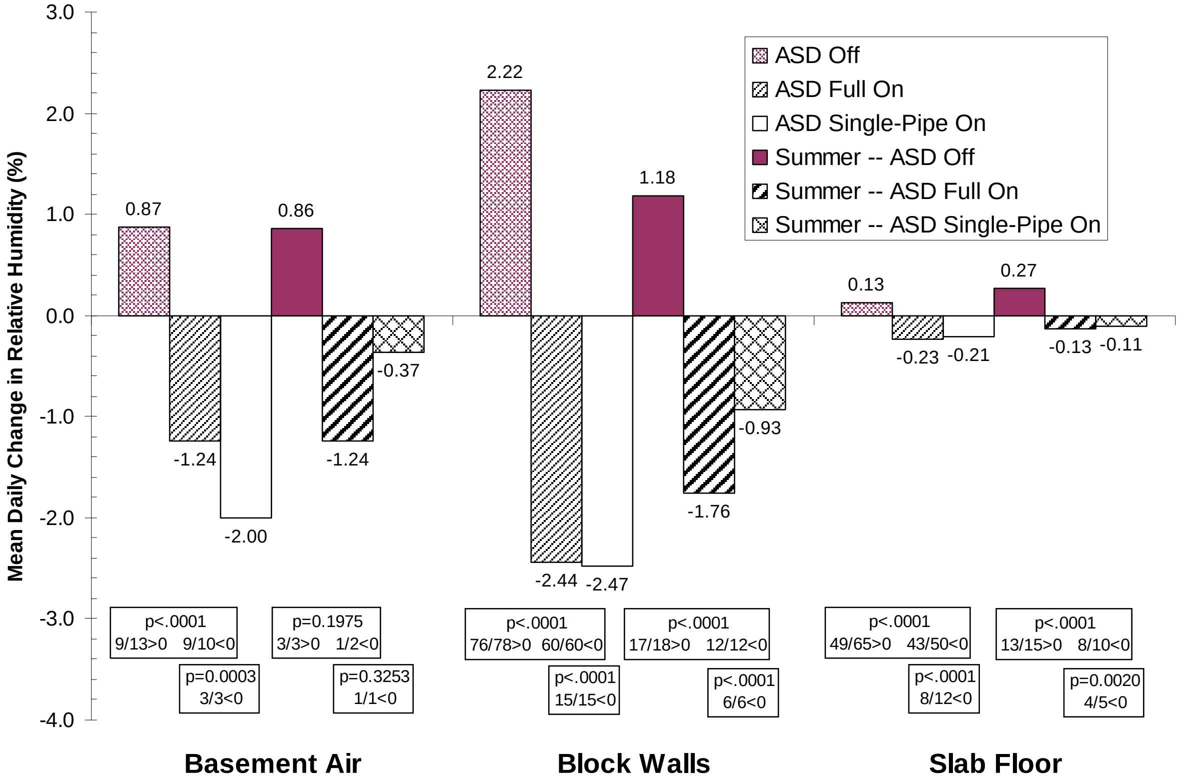

Figure 24. *Mean daily changes for first 7 days of period in basement moisture at house PA02 for air, block walls, and slab floors. These data are for October 2005 through January 2007, and include periods when the ASD operation was reduced to a single pipe. The bottom row of boxes with p-values and cycle counts of rates of change greater and less than 0, test the difference between the 'reduced' ASD operation cycles and ASD 'off' cycles. Note the change in scale for the y-axis as compared with house PA01.*

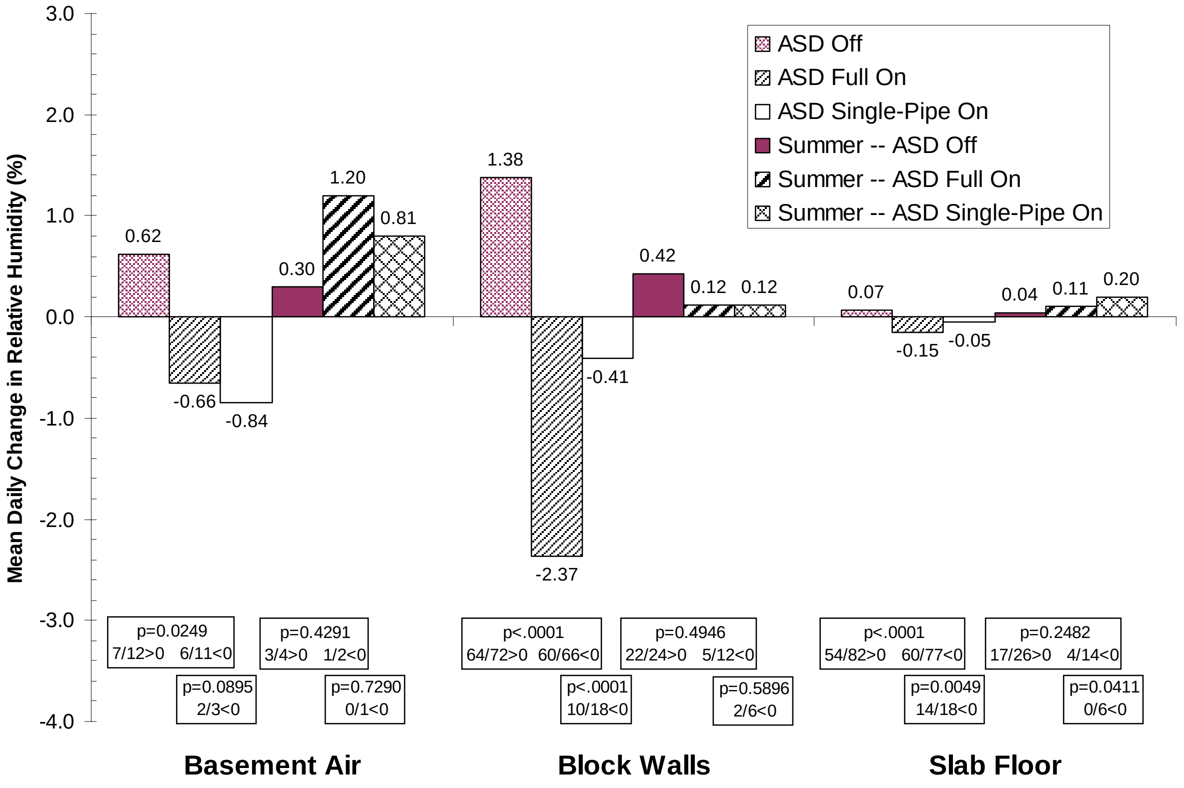

Figure 25. *Mean daily changes for first 7 days of period in basement moisture at PA03 for September 2005 through January 2007, where single-pipe, reduced ASD operation is included. Note the change in scale for the y-axis as compared with house PA01.*

3.8 Hand-held Measurements of Surface Moisture

Measurements of the moisture content in the joists of the basement ceiling and at the surface of the walls and floors tend to track the moisture in the basement air and within the basement-facing foundation surfaces. Figure 26 demonstrates this trend for data from house PA02, and is representative of the other houses. Data from all of the handheld measurements for a particular surface/material were averaged for each test period.

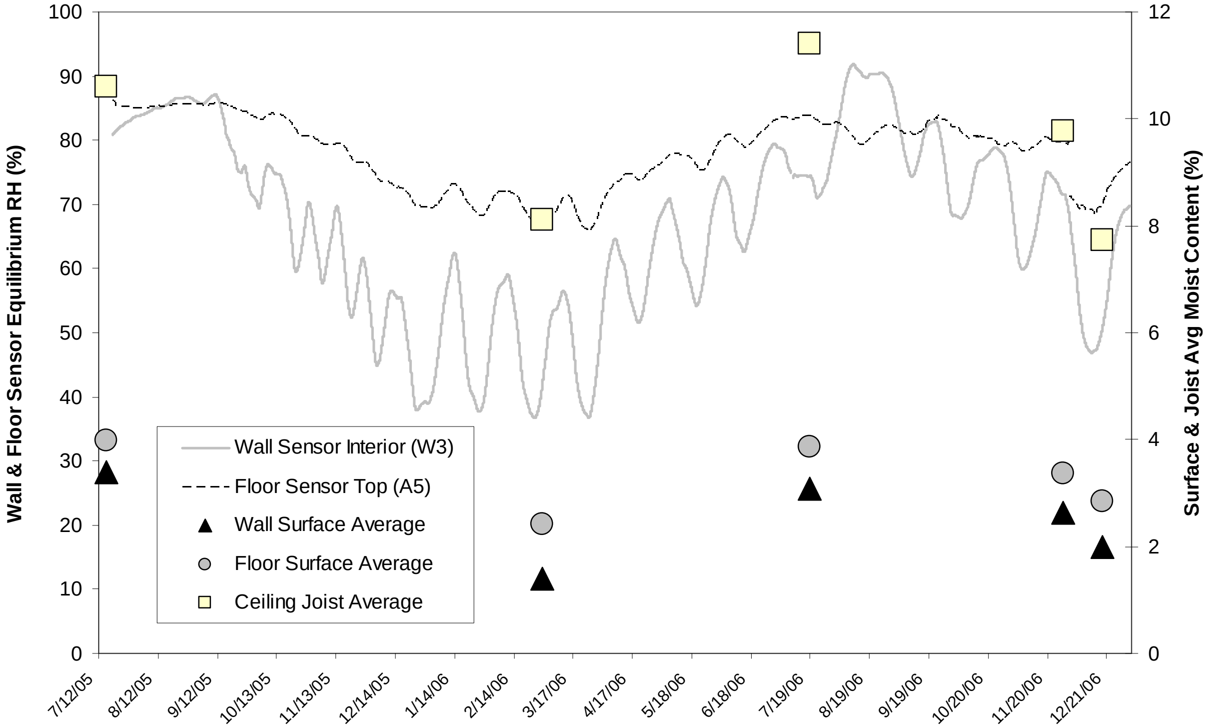

Figure 26. *Average of all moisture measurements made in the wood joists of the basement ceiling and at the surface of the walls and floor at PA02 during ASD cycling. Seven-day running averages of the equilibrium RH from an embedded wall and floor sensor are also shown for comparison. The wall "Interior" and slab floor "Top" sensor locations are within 2 cm of the basement-facing surface.*

The surface measurements also indicate that the moisture content of the slab floors tends to be higher than that for the walls, with the slab floor at PA01 having the highest overall moisture levels (Table 8). This is surprising given that conditions in the basement of PA01 tended to be the driest of all houses throughout the study. By contrast, the block walls of PA02 and PA03 were measured to have higher moisture content than the poured wall of PA01. Surface measurements also suggest that moisture in the walls increases along with depth below the surrounding grade. Additional summaries of the moisture data collected using the handheld measurement devices can be found in Appendix I.

Table 8. Wall and Floor Surface Measurements

House ID / Surface	**Test Dates and Average of Measurements (% Moisture)**				
PA01	*5/9/05*	*4/4/06*	*7/21/06*	*10/2/06*	
Floor	4.56	3.72	4.34	4.5	
Wall	2.67	2.17	2.64	2.61	
PA02	*7/14/05*	*3/28/06*	*7/19/06*	*11/28/06*	*12/19/06*
Floor	3.98	2.43	3.86	3.36	2.85
Wall	3.34	1.37	3.04	2.64	1.92
PA03	*7/18/05*	*4/11/06*	*7/20/06*	*12/12/06*	*1/2/07*
Floor	4.47	3.54	4.31	3.66	3.73
Wall	3.74	2.80	3.77	3.29	3.48

3.9 Dehumidifier

All of the occupants of the study houses report that they used dehumidifiers in the basements to control dampness during the summers prior to the study. A short-term, 3-cycle comparison of a standard off-the-shelf dehumidifier with ASD operation was conducted in PA03. The unit was operated on demand by a built-in humidistat set to 50% RH. This set point was chosen so that the dehumidifier would continue to operate into the drier weather conditions of the fall operating cycle (October). It was not chosen as a target to control microbial growth or as the target RH for the ASD systems. Figure 27 displays radon and moisture levels, and ASD operation starting four months prior to dehumidifier use. The dehumidifier shows dependable and stable moisture reductions in the basement air for all three cycles, although it did not bring levels down to the 50% set point during the first cycle (note that the ASD system caused a smaller reduction in basement air RH than the dehumidifier during a contiguous time period). This may be because the humidistat control mounted on the cabinet of the dehumidifier may be influenced more by the dry air discharge of the unit than the basement air sensors that were deployed at greater distance throughout the zone. The dehumidifier appears to have no impact on the moisture in the block wall core at location W9, nor, of course, does it affect indoor radon levels. Conversely, the full ASD configuration with wall extraction pipes had a larger impact on air within the block than the air in basement. The configuration of the ASD system was changed to reduced, single-pipe operation at about the same time that dehumidifier use began, but was still able to successfully control basement radon levels.

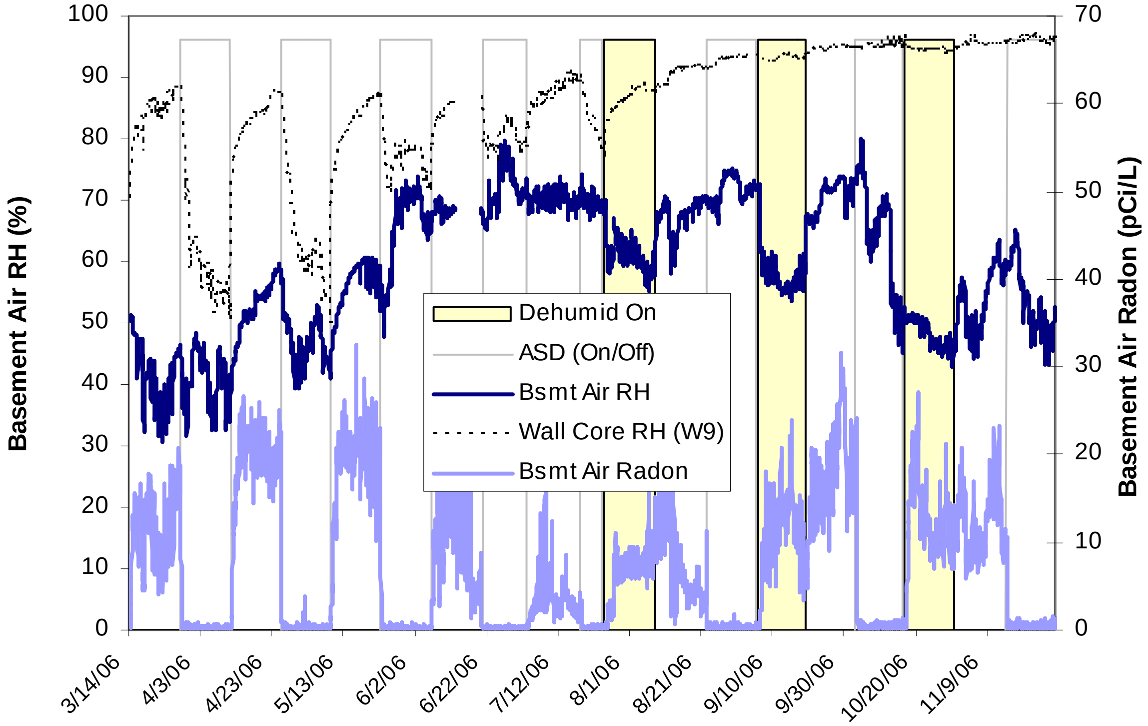

Figure 27. *Time series data from house PA03 showing dehumidifier effect on basement moisture and radon, as compared with ASD operation. The dotted line is data from the core of the block wall at location W9. Reduced ASD operation began 8/22.*

Data aggregated and averaged from Day 7 – Day 14 for the basement air, walls, and floors during the dehumidifier operation are presented in Figure 28. Two summer cycles of dehumidifier/all systems off are included with one non-summer cycle. Monitoring of dehumidifier use indicate that it operated approximately 70% of the time during the first cycle, declining to 47% of the time during the last cycle. For the single-pipe ASD, one summer and two non-summer cycles are averaged. The dehumidifier caused an almost 12% RH drop in the basement air, almost achieving the 50% RH set point on the device's humidistat. This moisture reduction in basement air is larger than that of the full and reduced ASD system (Figure 25), and, except for the block wall cores, is similar to the single-pipe ASD system in the foundation materials.

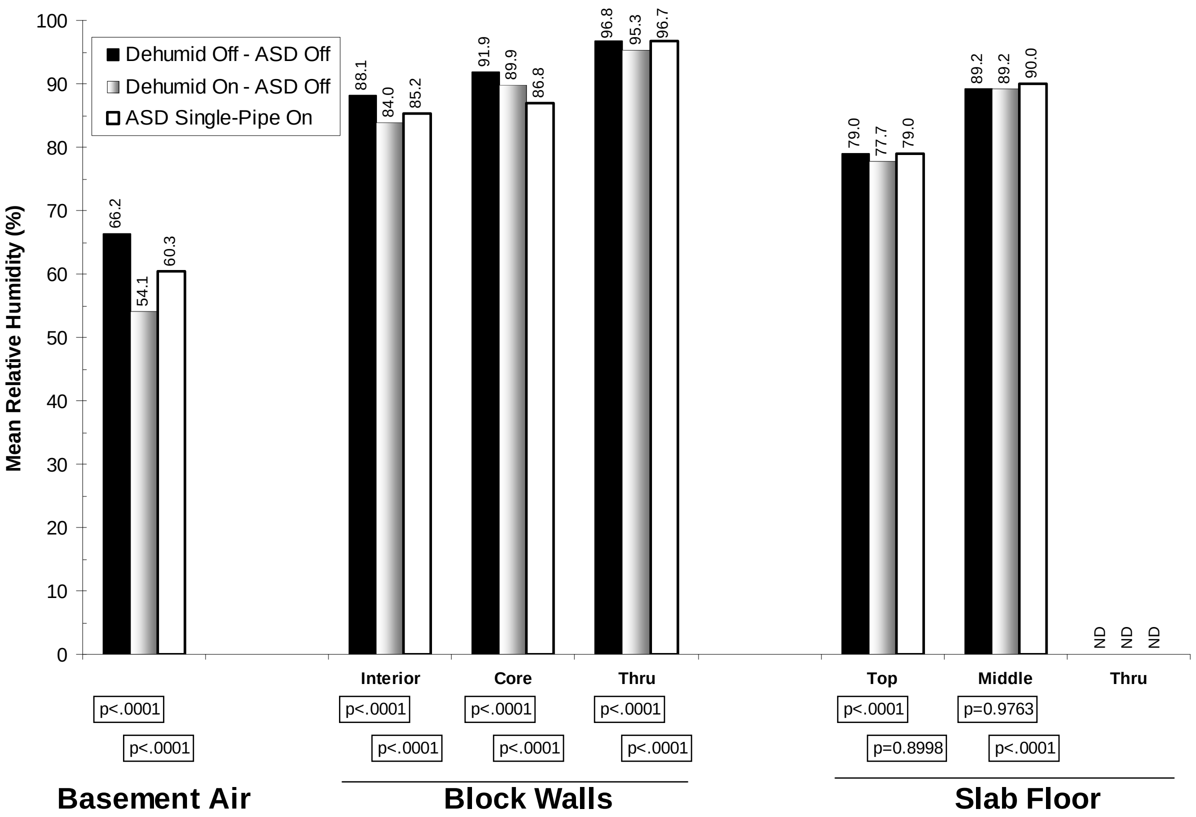

Figure 28. *Summary of arithmetic mean RH for second 7 days of 14-day, or longer, cycling periods at PA03. Values are for basement air, block walls, and slab floor during dehumidifier cycling. The set point on the humidistat of the dehumidifier was at 50% RH. The period of testing and analysis combines summer and non-summer data from July through November 2006 (dehumidifier on and off periods: 2 summer cycles / 1 non-summer, ASD 1-pipe: 1 summer cycle / 2 non-summer).*

The mean daily change in RH for all locations during dehumidifier use has been aggregated and compared with data from single-pipe ASD operation and is presented in Figure 29. These data demonstrate that while the dehumidifier produced reductions in the basement air RH, it had no impact on the block moisture levels, and minor effects on slab floor moisture. Again, note that both full and reduced, single-pipe ASD use caused a significant reduction in block wall moisture during non-summer periods (Figure 25). This has implications for achieving moisture control in basement walls that are finished with materials vulnerable to microbial growth.

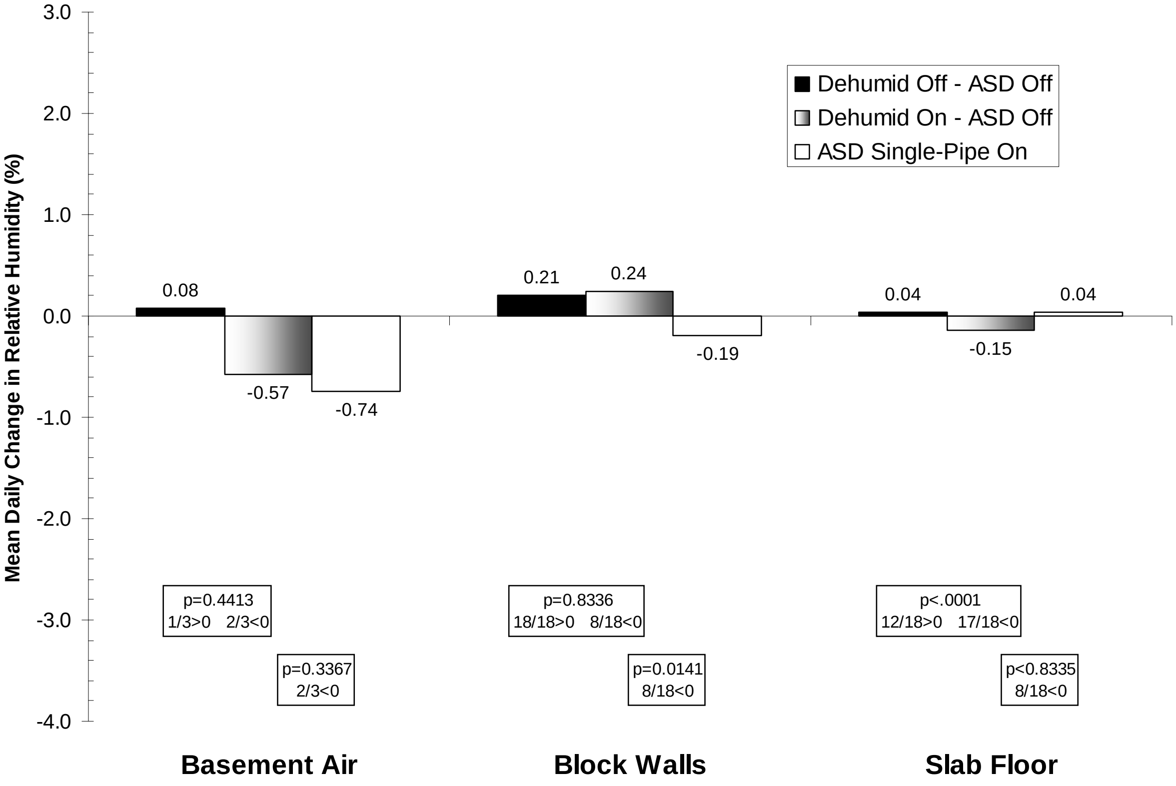

Figure 29. *The averages of three on/off cycles of dehumidifier operation at PA03 are compared with three adjacent ASD cycles. The dehumidifier was used from July through October 2006, while the single-pipe ASD was cycled from August through November.*

The quantity of water extracted from the air by the dehumidifier steadily declined from 3.5 gal/day (13.4 L/day) during the first cycle to 0.9 gal/day (3.6 L/day) during the last cycle. Using the flow rate and moisture concentration in the ASD pipes for the adjacent ASD On periods, calculations determined that the water extracted by the ASD system declined from 13.8 gal/day (52.2 L/day) to 12.7 gal/day (48.1 L/day). These results indicate that the ASD systems are probably mining moisture from sources other than the basement air alone. The most likely source is the wet/damp soil surrounding the foundation that is constantly being replenished due to poor drainage conditions.

3.10 Moisture Extraction by ASD

The moisture extracted by the ASD systems under different operating configurations is summarized in Table 9, and indicates that significant quantities of moisture are being removed from within and around all three houses by the ASD systems. These data are averages for particular configurations over one or more seasons, partially explaining the large variations that are observed. A preliminary inspection of the data indicates that moisture removal during the summer is higher than for winter, for the same configuration. This seasonal effect is probably due to changes in moisture in the outdoor air and/or precipitation. A more detailed assessment of moisture extraction is planned.

Table 9. Summary of Moisture Extracted by ASD Systems

House ID	**Initial (Full) Configuration** (gal/day \ std.dev.) *(kg/day \ std.dev.)*	**Wall/Floor Joint Seal** (gal/day \ std.dev.) *(kg/day \ std.dev.)*	**Single-Pipe Configuration** (gal/day \ std.dev.) *(kg/day \ std.dev.)*
PA01	13 \ 4.21 *49 \ 15.9*	12 \ 1.45* 44 \ 5.50*	10 \ 2.4* 37 \ 9.80*
PA02	15 \ 7.84 *58 \ 29.6*	--	13 \ 3.67 *49 \ 13.9*
PA03	19 \ 5.93 *71 \ 22.4*	--	11 \ 3.15 *42 \ 11.9*

* Because of sensor failure, data for these two periods are based on moisture entering the two ASD suction pipes. Actual rates of moisture discharge may be lower because of condensation and drain-back in the pipe. All other data were determined from measurements made at the discharge end of the ASD pipes.

3.11 Estimated Energy Use

The energy to condition the incoming outdoor air and to operate the radon fan was estimated for each of the three houses (Table 10). Since the basements of the houses were not intentionally conditioned, the amount of additional outdoor air entering the upstairs during ASD operation was used in the calculation. Additional heating loads are based on heating degree days totaling 5186 (base 65°F) for September – May. Cooling loads are derived from sensible cooling for 943 cooling degree days (CDD – base 65°F) for May – September, and latent cooling for days when CDD is greater than zero, using average first floor humidity ratios for the same period. For comparison, energy use for a representative dehumidifier operated for five months (May – September) at 70% duty cycle is also shown.

Table 10. Estimate of Additional Annual Energy Use for ASD Operation

House ID / Season	**Out-1st Flr Median Flow Change[1] (cfm \ *m^3/s*)**	**Heating (Annual)**			**Cooling (Annual)**		**Radon Fan (Annual)**	**Total Add. Energy Cost (Annual) ($)**
		Add. Heat (BTU)	**Add. Gas Cost[2] ($)**	**Add. Heat Cost[3] ($)**	**Add. Sens + Latent (kWhr/yr)**	**Add. Cool Cost[4] ($)**	**Total Elect Cost[5] ($)**	
PA01								
Fall-Win-Spr	+3.9 *0.0018*	$53x10^4$	6	7	--	--	70	79
Summer	+3.3 *0.0016*	--	--	--	20	2		
PA02								
Fall-Win-Spr	+22 *0.010*	$304x10^4$	37	39	--	--	70	134
Summer	+41 *0.020*	--	--	--	243	24		
PA03								
Fall-Win-Spr	+30 *0.014*	$408x10^4$	49	53	--	--	70	164
Summer	+63 *0.030*	--	--	--	411	41		
Dehumidifier								
Summer	0	--	--	--	1799	--	--	180[6]

[1] Difference in median of flows for periods with ASD off versus ASD on
[2] AFUE of 80%, 1000 BTU/cu ft, and $15/cu ft
[3] Includes additional operation of 700 W blower, assuming 100,000 BTU/hr burner, at $0.10/kWhr

[4] Includes latent and sensible loads of cooling when cooling degree days are >0 for May – Sept, with equipment SEER of 15 (BTU/Watt-hr), at $0.10/kWhr.

[5] Assume 80 Watt fan operated continuously, at $0.10/kWhr.

[6] Assumes 700 Watt dehumidifier used 70% of time for 153 days

Obviously, energy use increases along with the amount of outdoor air drawn into the upstairs, with PA01 having the least additional annual energy cost (approximately $79) and PA03 the largest (approximately $164). Radon fan energy costs were assumed to be the same for all houses, and were by far the largest fraction of additional costs for PA01 (89%), and much less for PA03 (43%). While ASD at these houses appears to create greater moisture reductions when operated in the full configuration with higher exhaust flow rates, the limited ventilation data in this study do not show large or significant flow differences between the full and single-pipe configurations. Therefore, the ASD systems will still cause the estimated additional energy usage in order to control indoor radon levels even in the single-pipe configuration. The extra benefit of moisture reduction piggybacks on the energy necessary for radon control. While the ASD systems in these houses probably do not eliminate the need for dehumidification during warm and humid periods of summer, they may reduce the moisture load in the basement and usage of the dehumidifier. The effect of additional sealing of openings between the basement and soil and outdoors on radon reduction, air flows, moisture reduction, and energy use has not been investigated or quantified.

4. SUMMARY AND CONCLUSIONS

As the first systematic and intensive study of moisture changes in buildings caused by operation of ASD systems, normally used for indoor radon control, this project broke new ground by developing novel design and monitoring protocols and applying them over 12 – 18 months in a group of three homes. The project has also created a large data set on how ASD systems function and their impact on moisture and air movement in homes.

The primary finding of this project has been that ASD systems caused statistically significant and beneficial reductions in moisture levels and dampness in the basements of three Pennsylvania houses in the non-summer months. During the warm and humid summer months, when dehumidifiers are typically needed in these homes, overall changes in building moisture with the ASD operating were much smaller or negligible, and of less practical importance. ASD-caused moisture responses in the basement air were observed to be secondary to and superimposed on the larger trend of the basement air moisture to track outdoor air moisture levels. Block wall surfaces facing the basement, and especially block cores, showed the largest moisture reductions during ASD operation – possibly because the porous blocks permit greater air flow that dries the materials. Moisture changes in slab floors and poured walls were smaller and occurred more slowly than in porous block walls, and may require longer cycle periods to show a significant change. Since the foundation walls and floors of these homes were generally not finished, moisture changes in the micro-environments of furred wall cavities and beneath carpet were not examined. However, it is possible that ASD operation could have a relatively larger impact on moisture levels and microbial growth in these moisture sensitive materials, by increasing the flow of drying air, and reducing moisture ingress from diffusion and convective air movement. Robust system configurations, with more suction points and higher air flows and pressures than typical installations, produced larger moisture reductions. When configured for more typical flows and pressures, the systems caused smaller, but encouraging, moisture reductions. The effects were apparent in the basement air and walls of all three houses, and in the slab floor of two houses.

A number of innovative measurement protocols and techniques were evaluated and employed to monitor moisture and ventilation flows in houses. These included a novel adaptation of the constant injection, multi-PFT ventilation measurement technique, and long-term continuous monitoring of many environmental parameters, including moisture in the basement walls and floors and ASD exhaust. To evaluate the value of simpler and less-costly measurements techniques, handheld instrument measurements of moisture were conducted periodically over an extensive grid of locations in the basements, These handheld measurements within the interior surfaces of foundation materials track continuous measurements with sensors embedded within approximately the first two centimeters of the surface, and with measurements of moisture in the basement air. This approach may be an effective replacement in future studies for the intensive monitoring protocols used in these three houses. Additional work is required to study the relationship between these surface measurements and moisture stored at depth within the foundation materials.

Consistent with the guidance of the conceptual model, interzonal flow testing and results suggest that quantity of air drawn into the basement from upstairs and outdoors increases during ASD operation. In the non-summer months, this comparatively low moisture air can cause drying of the basement air and foundation materials. Under these conditions, it may be possible to reach a minimum moisture level, below which little additional drying will take place. Conversely, in the summer, the systems have the potential to add moisture to the basement by drawing in warm humid air from outdoors – while at the same time pulling in dry conditioned air from upstairs (in buildings with air conditioning). The ratio of the air leakage from outdoors to air leakage from the upstairs may be an important factor in determining the success of ASD moisture reduction in humid climates during the summer. The amount of air leakage from the soil through openings in the foundation surfaces is probably another important factor that influences the moisture-reducing performance of ASD systems.

With the ASD systems operating, outdoor air ventilation rates were boosted both in the basement and upstairs. When the systems were off, basement ventilation rates at all houses often fell below the requirements of ASHRAE Standard 62.2 (2007), while the upstairs ventilation rates often did not meet the minimum at PA01 and PA02. Therefore, the ASD systems tend to act as whole house exhaust ventilation in these three houses and could provide additional indoor air quality benefits, albeit at the cost of conditioning the incoming, outdoor air. Care must be taken with exhaust ventilation systems not to depressurize the building, causing combustion appliances to backdraft or other contaminants to be drawn into the occupied spaces. All of the houses participating in this study had sealed-combustion furnaces and hot water heaters with power-vented draft inducers, and wouldn't be vulnerable to backdrafting. As mentioned above, exhaust ventilation systems can also draw in humid outdoor, that may add unwanted moisture to the building air and materials.

In houses with bulk water entry (as in the case of PA03), ASD systems are probably not well-suited to control the resulting dampness and moisture accumulation. However, few remedial techniques can successfully address this issue. The best solution is to correct the source of water.

Portable dehumidifiers are currently one of the most common methods for seasonal control of moisture in basements and crawlspaces. A dehumidifier used for three months in one study house produced stable reductions in basement air RH, but had little impact on moisture in the block walls and slab floor. This may be an important consideration for finished walls, since, by contrast, the ASD system tended to reduce moisture in block walls. The dehumidifier extracted approximately 8% to 25% of the moisture removed by the ASD system. Presumably, the dehumidifier removed moisture primarily from basement air, while the ASD system pulled moisture from the air as well as from the foundation and materials surrounding the foundation.

Estimates of additional energy usage during ASD operation show increases from $79 to $164 per year for these houses. These costs may be representative of many ASD systems installed to control indoor radon. However, the data suggest that ASD operation may also reduce dehumidifier usage during the warm, humid summer months and may reduce the overall energy bill in houses with a radon problem and where a dehumidifier is being used at least 5 months out of the year.

Concerns over drying, and subsequent shrinkage and settling, of materials around the foundation were not addressed in this study.

4.1 Recommendations

It is not known whether the moisture and ventilation findings for these three houses apply to other houses in other regions. There appear to be many factors that could affect the effectiveness of ASD in reducing substructure moisture, and additional investigation is necessary to address these issues. This study was a good investment for future research. Some recommendations for this further work include:

- Conduct national survey of moisture in houses to identify vulnerable house construction and climates
- Examine the relationship between outdoor conditions (RH and precipitation) and ASD system effectiveness.
- Using information from this study, enhance and refine the conceptual model to forecast ASD moisture performance in other climates, house construction and soil types, incorporating air leakage areas and locations, house construction features and HAC systems, and climate characteristics
- Design and conduct investigation of ASD impact on building moisture in other climates, soil types, house foundation types, and mechanical cooling.
- Further explore less-intensive testing and measurement protocols so that evaluations of moisture control by ASD can be more easily and economically conducted in other houses.
- Monitor moisture levels during longer periods of ASD operation.
- Conduct extended, four season evaluation of additional configurations of ASD systems, with a wider range of operating flows and pressures and suction point placement.
- Consider what, if any, design and installation changes would improve moisture control capabilities of ASD systems.
- Examine the ASD-caused moisture changes in moisture sensitive materials and assemblies that are commonly installed to finish basement floors and walls: wood framing, gypsum board, paneling, carpet, etc.

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