APPENDIX G
Impact of ASD Operation on Basement Moisture Conditions

A Conceptual Model

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

Contractor Report to EPA

December 6, 2007

Impact of ASD Operation on Basement Moisture Conditions

A Conceptual Model

March 1, 2006

John F. Straube
Balanced Solutions
Waterloo, Ontario   Canada

Bradley H. Turk
Environmental Building Sciences, Inc.
Las Vegas, New Mexico USA

Introduction

The EPA has been aware of anecdotal information on the perception of moisture reduction as a result of ASD operation since the beginning of residential radon mitigation in the mid-1980s. Typical comments from occupants of houses with ASD installed pointed out that musty odors in basements were reduced, dehumidifiers operated less frequently, and wood in paneling, furniture and cabinets had shrunk.

Also, researchers conducting mitigation field studies during this period discovered that certain soils below concrete slabs were drying out from continuous operation of ASD systems. In many situations the drying of soil under slabs created void spaces which enhanced the pressure field extension of the ASD system, the differential pressures across the slab and the overall performance of the system.

A simple, conceptual model is needed to describe the flow of water vapor and the air which carries it through the soil near a building and around the basement structure induced by sub-slab depressurization. The general goal of the model in this study is to help understand and predict the impact of sub slab depressurization on the moisture regime within and immediately around a basement. The model will also be used to estimate boundary conditions so that experimental procedures can be developed and instrumentation specified for the field monitoring phase of the project. A fully-developed model is not in the scope of this project.

Moisture Storage and Transport

The flow of moisture through soil has been extensively studied by many researchers. The flow of gases (particularly unhealthy vapors from man-made organic compounds) has received great attention in the last few decades in response to industrial waste transport. These flows have been driven by natural forces of gravity, capillarity, and concentration gradient. Some research has been conducted on the flow of air and radon gas due to sub slab depressurization. All of this research has concluded that the soil and basement structure has very complex, almost random, variations in properties that result in flow potential variations in the range of two or three orders of magnitude on any given site and as much as 5 or 6 orders of magnitudes between different sites.

Table 1: Moisture Storage Mechanisms

Moisture Form	Storage Location
Free water vapor	In pore volume (porosity)
Adsorbed water vapor	On pore walls (specific surface area)
Capillary condensed water	Held in very small pores
Capillary bound liquid water	Held by surface tension in pores
Unbound liquid water	Held by containment

The moisture content of the soil around a home can vary dramatically with soil type, time of year, site conditions, and basement design. Significant quantities of moisture from all sources can be stored in the soil, and porous building materials such as concrete, wood, and gypsum, by a number of mechanisms. These are summarized in Table 1.

Moisture Storage in Soil and Porous Building Materials

To understand these mechanisms it is important to understand the nature of porous building materials and soil. The pores in these materials range in size from a few mm (between crushed stone) to a few nanometers (between gel sheets within hardened cement paste.). Figure 1 provides some definitions used in describing moisture within porous materials. In general, we apply macroscopic material properties to such porous materials by defining a representative elementary volume (REV) that has similar properties regardless of where the boundaries are drawn.

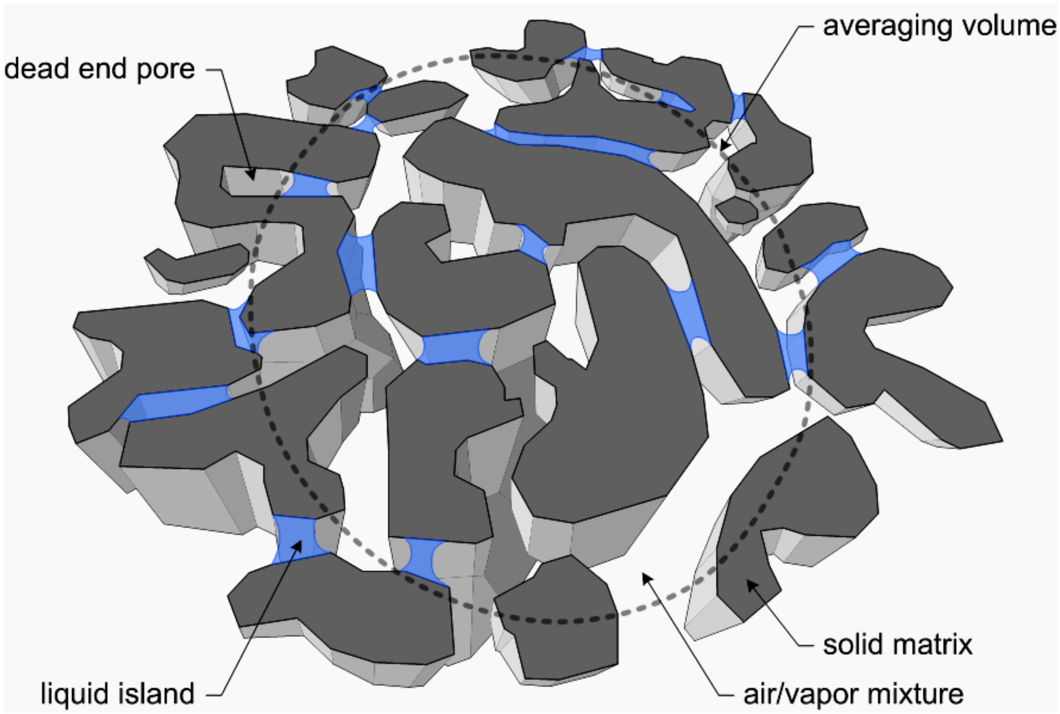


Figure 1: Micro-porous material containing some water

In almost all cases, the relative humidity is nearly 100% in the soil around a house, since the moisture from precipitation and ground water are distributed by either vapor or capillary flow.

The moisture storage function of a typical porous material is shown in Figure 2. Water vapor is stored in the pores (a small quantity) and adsorbed to the surface of the porous material. This is the primary storage mechanism up to a moisture content in equilibrium of relative humidity of about 95%. Above this, capillary condensation within pores becomes important and then near 100% capillary storage dominates. From the critical moisture content (W_{crit}) to capillary saturation (W_{cap}) the relative humidity is essentially 100%. Soil is within the range of partially saturated to capillary saturated most of the time in essentially all climates.

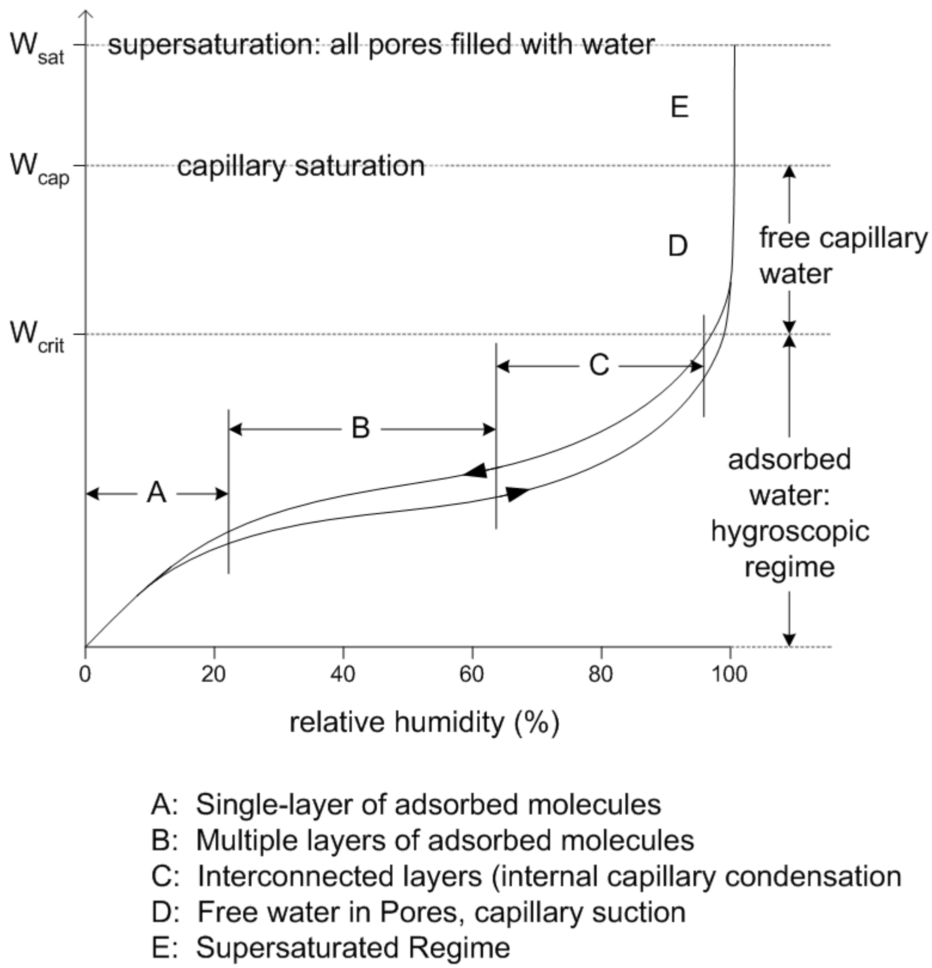


Figure 2: Moisture Storage Function for hygroscopic porous material

Moisture Transport through Soil and Building Materials Systems

Moisture is transported by four primary mechanisms:

1. Liquid flow driven by gravity. Flow is in the vertical direction, but significant deviations can occur when very different liquid flow permeabilities are encountered. Significant pressures are required to drive this flow (gravity head provides the pressure) and flow rate is significant in large pored materials. In most cases gravity flow drives surface and ground water to drains around a home. Gravity flow tends to be sporadic (during and shortly after rainfall and snowmelt events), and when it stops, a significant amount of water remains in the smaller pores of the soil.

2. Capillary flow driven by suction gradients. At lower moisture contents, flow occurs between pores driven by differences in suction pressure. This generally means that water will "wick" from areas of high moisture content to low moisture content, but it also means that materials with fine pores (clay soil, concrete foundations) will exert a strong suction and drive water into the small pores. The smaller the pores, the slower the flow. In the case of clay and concrete capillary flow is quite slow.

3. Vapor diffusion driven by vapor pressure gradients. Water and ice will evaporate into unfilled pores. The gas will diffuse through the open pore spaces along a concentration gradient (again, more to less). This process can dominate in large pored materials such as crushed stone since there is little or no capillary suction.
4. Vapor carried along with convective air flow driven by air pressure differences. The air permeability of soil can range over five orders of magnitude, but even small amounts of airflow can transport significant quantities of moisture in vapor form.

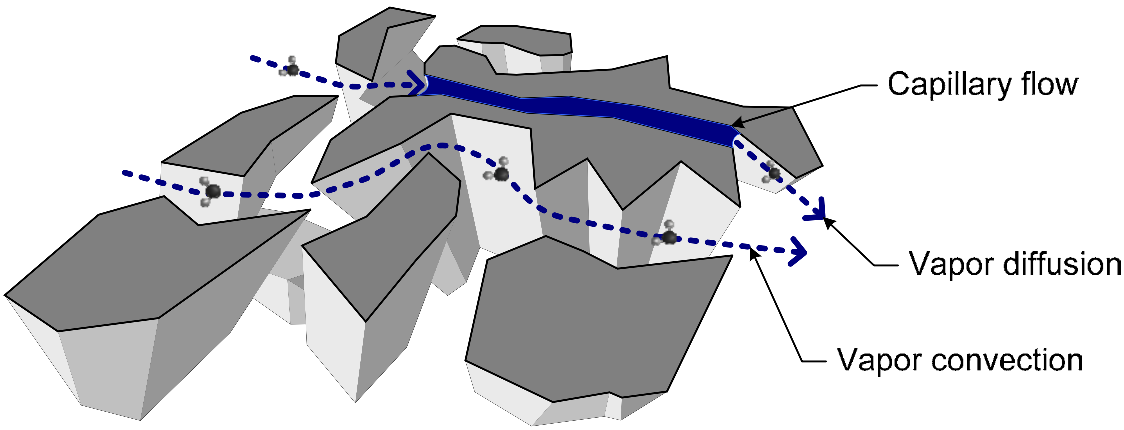


Figure 3: Capillary, diffusive, and convective moisture flows in a porous material

As air flows in close proximity to materials, moisture can diffuse as vapor from the surface of the material and from within small pores to the moving air, provided the water vapor pressure of the air is lower than that of the material's surface. The more surface area exposed to the air flow, the more moisture is transported. Hence, air that is drier than the materials (e.g., soil) through which it flows has the potential to provide excellent drying. If the air is drier than the materials, however, the same mechanism will ensure that the air gains moisture from the material.

Hypotheses

It is hypothesized that the drying observed during operation of ASD systems may be attributed to one, or a combination, of several mechanisms. The operation of an ASD may cause three classes of effects due to air flow:

Class 1. Increase the rate of airflow from outdoors to the basement via either the upper levels of the house (including through the rim joist), or through the soil.

Class 2. Increase the rate of airflow from the basement to the soil.

Class 3. Increase the rate of airflow from the outdoors to the vent stack without interacting with the basement air (i.e., air flows only through the soil directly to the ASD suction point).

Class 1

Within Class 1, two practical cases exist (Figure 4). ASD operation may alone, or in combination:

1-a) Reduce the basement air relative humidity (and vapor pressure) by increasing the ventilation rate of the basement with drier air that is indirectly pulled by the ASD from outdoors during dry weather, or from dehumidified interior spaces during hot-humid conditions. This mechanism acts by reducing the indoor basement water vapor concentration, and hence increasing the magnitude of the vapor diffusion rate from furnishings, interior finishes, and foundation materials (increased rate of drying). The ventilation also acts as a sink for the moisture removed. This mechanism could act quickly, in a matter of days to weeks, as it increases the drying capacity and reduces the indoor humidity within hours.

The additional ventilation air would also have the benefit of diluting the airborne concentrations of bio-contaminants and odor-causing metabolites from microbiological infestation, but has the disadvantage of increasing space conditioning energy.

If the source of ventilation air is the outdoors, it is quite possible to cause wetting of interior finishes and an increase in RH during hot humid weather. Although this possibly damaging scenario must be addressed, in many climates, drying will be predominately outward for many months.

The influence on the swing-season RH inside a basement is a function of outdoor air change rate, moisture production rate, and moisture ad/desorption to building materials within the basement.

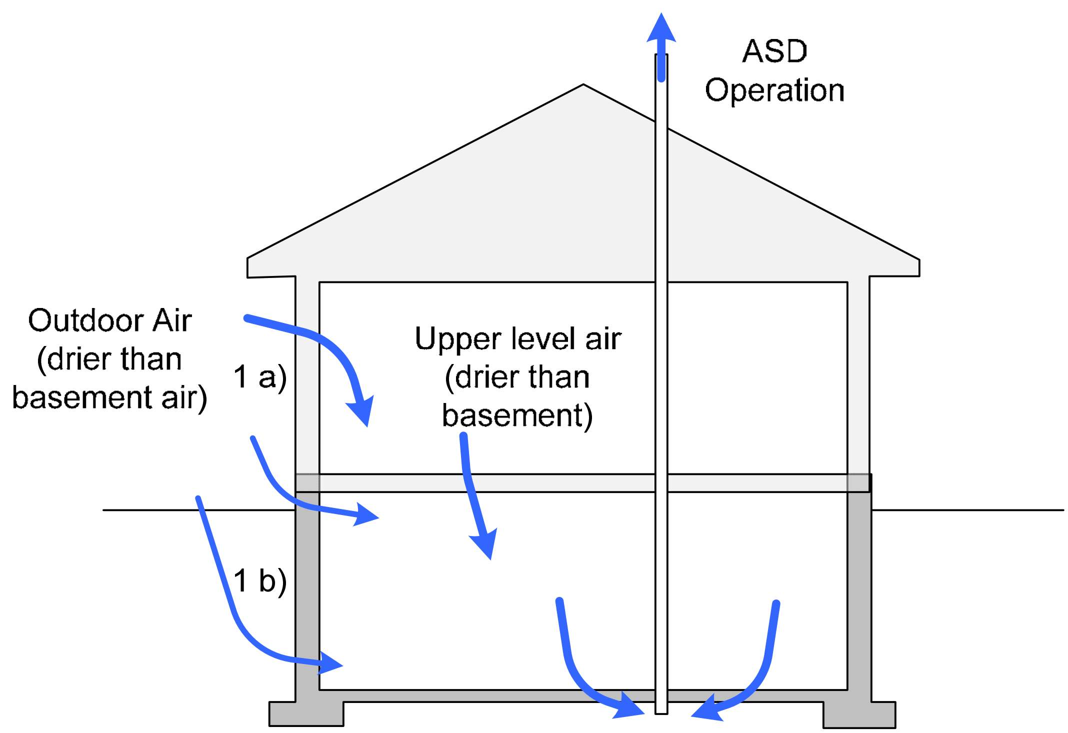


Figure 4: Class 1 Airflows – Air from outdoors enters the basement by several pathways and is then is exhausted by ASD

1-b) Dry the soil and materials near to foundation walls by increasing the flow rate of dry outdoor air through porous soils and through shrinkage/settling gaps commonly found adjacent to foundation walls. Diffusion and capillary movement of moisture into the foundation from soil surrounding the foundation near the surface would be reduced as the soil moisture content is reduced. Moisture content of interior materials would reduce much more slowly due to this mechanism, as it reduces the wetting potential indirectly (by reducing the moisture content of the source: the soil).

This mechanism may theoretically allow the moving air to collect radon gas or other contaminants (such as water vapor, bio-contaminants) and reduce the basement air quality. However, experience with ASD has not shown a reduction in IAQ, in fact, the opposite is observed. This improvement in IAQ could be due either to the fact that flow scenario 1 b) is not occurring, or that the flow is high enough to dilute and remove indoor air pollutants. Investigations of ASD performance show that, in some cases, radon concentrations in the soil near the building are reduced, presumably by dilution with additional outdoor air drawn through the soil (or by Class 3 flows, below) or with basement air pulled out of the building (2d, below).

Class 2

The natural pressure gradient across the basement walls and floors is from outdoors to indoors for much of the year in many climates. By reversing this natural air pressure gradient ASD operation encourages basement air to flow out through the foundation and into the surrounding materials/soil (Figure 5). This air flow reversal should:

2-a) retard entry of nearly saturated soil air that increases the vapor pressure of the basement air (and hence the RH near the surfaces of basement walls, slabs, and finishes). By reducing this moisture source, a source of wetting is removed, and the interior space RH would drop (as in 1-a) above).

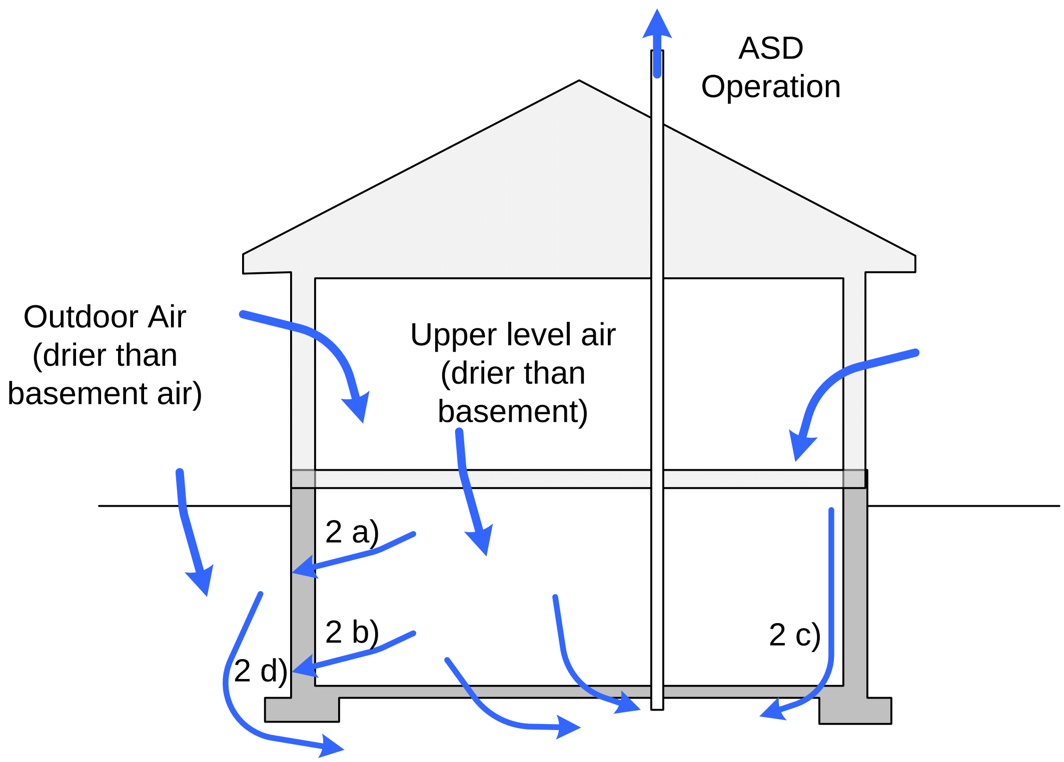


Figure 5: Class 2 Airflows – Basement air is pulled into the surrounding soil, then is exhausted by the ASD.

2-b) inhibit the transport into the basement of biocontaminants and odor-causing metabolites from microbes that are formed in the soils and materials surrounding the basement.

2c) dry basement materials, interior surfaces, construction assemblies (e.g., furred wall cavities), finish materials, furnishings, and other 'microclimates' close to exterior walls and floors as drier basement air passes through them and along side them.

2 d) dry the soil surrounding the exterior of the basement with drier interior air. Diffusion and capillary movement of moisture from these materials into the basement walls and floor would therefore be reduced.

Class 3

Finally, in Class 3 airflows (Figure 6), ASD operation would draw air from outdoors through the soil and to the vent stack without interacting with the basement air. This flow mechanism could dry the soil next to the basement wall and slab, and hence reduce basement wetting.

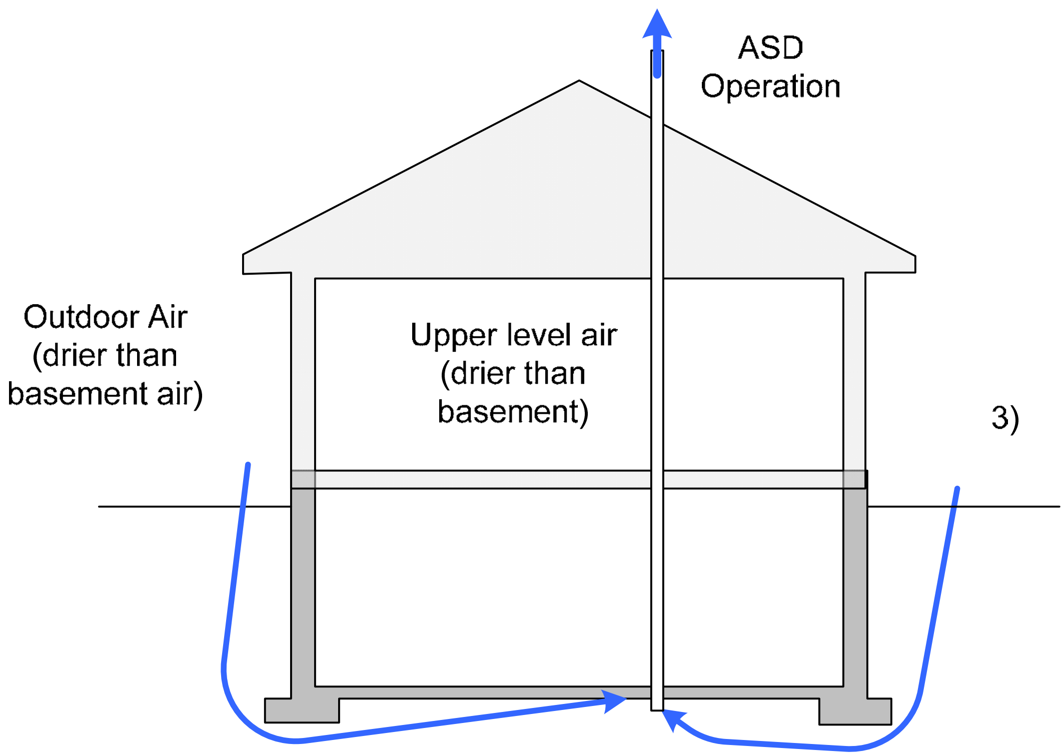
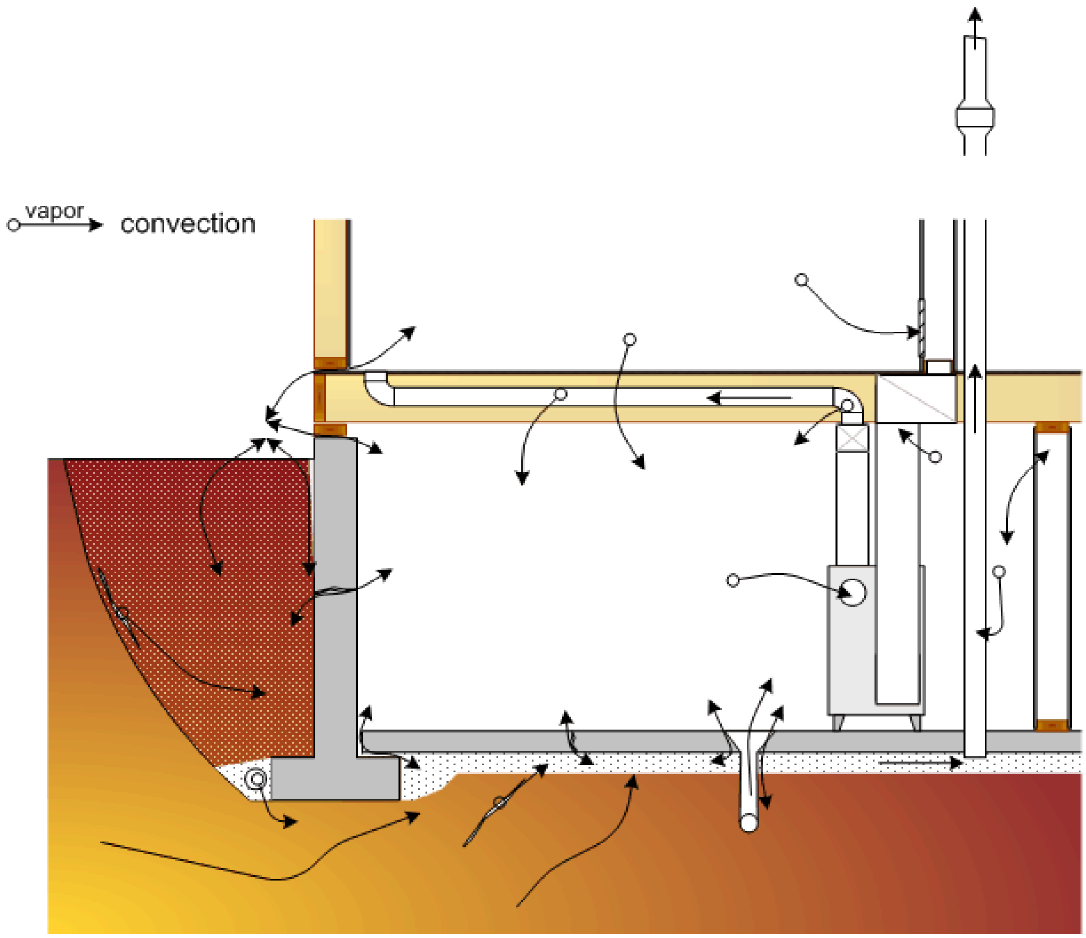


Figure 6: Class 3 Airflows – Outdoor air is pulled directly to the ASD suction point through the surrounding soil and is then exhausted by the ASD.

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

It is important to recognize that the ASD is only one mechanical air moving appliance involved in most house systems. The operation of forced air conditioning equipment (air handling units for furnaces and air conditioning) combined with leaky ducts and the operation of unsealed combustion appliances can, and often do, induce significant flows (measured in the 10 to 100 liters per second) and pressures (often 10 to 100 Pa). These flows and pressures are, by their very nature, intermittent and their frequency and duration is weather and system dependent.

Figure 7 shows a range of plausible potential flow paths and directions in and around a basement system. The number of flow paths that can exhibit airflow in either direction should be noted.



Airflow Paths

Figure 7: Potential airflow paths and likely direction (ASD on)

Figure 8 shows the mechanisms other than airflow usually at work moving moisture around a basement. It should be noted that moisture is transported from outside to inside below grade. This is the case since the soil almost always has a higher vapor content than indoor levels. Although this is not always true, the exceptions are rare, especially in mixed or warm climates. Moisture flow by diffusion is typically a very small proportion of the total moisture flow across the above-grade enclosure – airflow almost completely dominates the moisture transport.

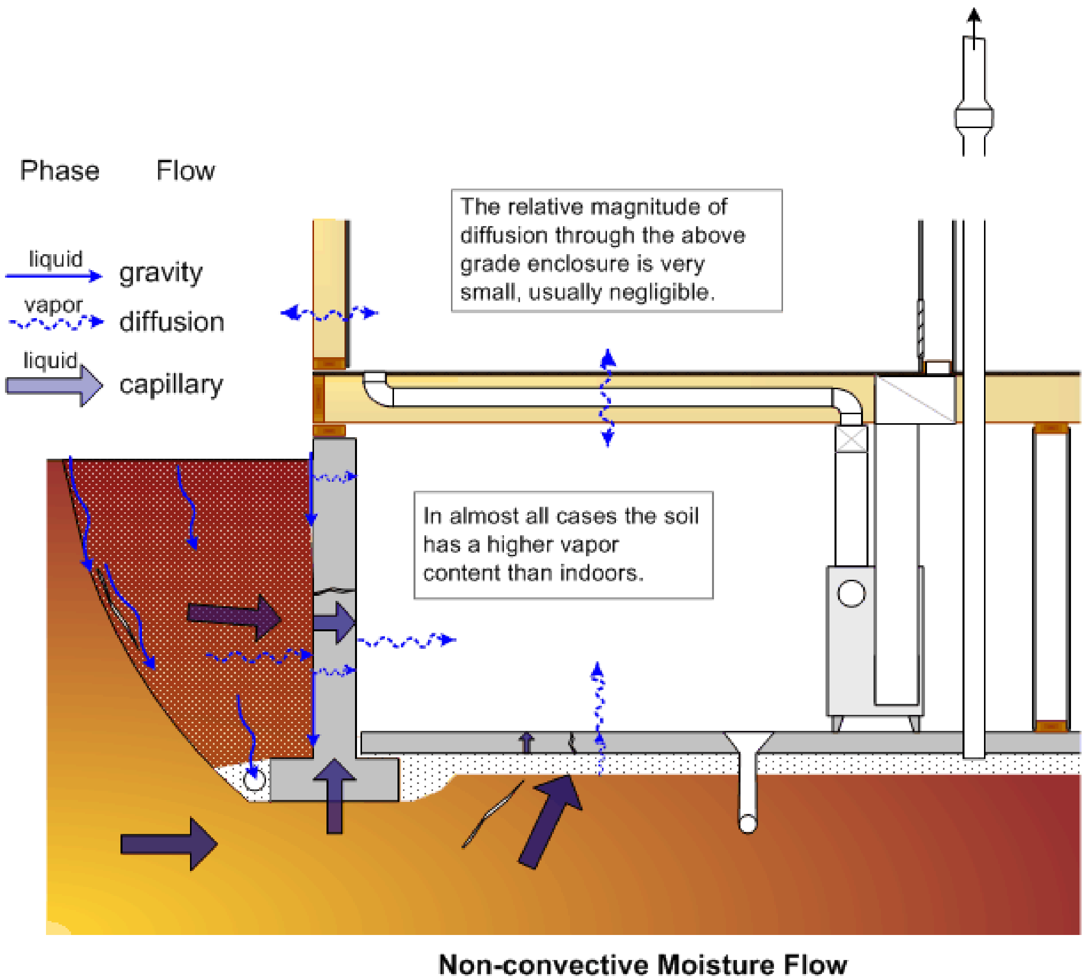


Figure 8: Moisture transport due to non-convective flows

A Simple Model

Given some knowledge of the outdoor conditions, transport mechanisms, flow paths, and magnitudes, a simplified model can be used to predict the interior basement water vapor content and RH.

The interior humidity level in a building is in constant flux with the interaction of indoor moisture production, the vapor stored and released from building materials and drying, and the incoming flow of air. The interior vapor pressure, and hence RH, of the basement air can be calculated from the following approximate equation:

$$P_{v,base} = \frac{P_{v,out} \cdot Q_{out} + P_{v,soil} \cdot Q_{soil} + P_{v,up} \cdot Q_{up} + \left(462 \times [t_i + 273] \times G_W\right)}{Q_T} \quad [1]$$

where:

$P_{v,base}$, $P_{v,out}$, $P_{v,soil}$, and $P_{v,up}$ are the basement, outdoor, soil, and upstairs air vapor pressures respectively [Pa],

G_w is the rate of moisture supply to the basement [kg/hr] due to occupancy and diffusion from the surfaces lining the basement,

t_i is the indoor basement temperature [Celsius], and

Q_T, Q_{out}, Q_{soil}, and Q_{up} are the volumetric flow rates of all incoming, outdoor, soil, and upstairs air (m^3/hr), respectively.

Moisture will desorb or adsorb to the surface materials in the basement in response to the vapor content of the interior air (not the RH).

For water vapor driven by vapor pressure gradients along one dimension, Fick's law can be written as:

$$\frac{dw_x}{d\theta} = -\overline{\mu} \cdot A \cdot \frac{dP_w}{dx} \qquad [2]$$

The quantity of water vapor w_X (ng) per unit time (dw_X) is water vapor flow in the x direction (m) through an area A (m^2) perpendicular to the flow, is equal to the product of the vapor pressure gradient dP_w (Pa/m) and the coefficient, μ (ng / m · Pa · s). This coefficient is defined as the average vapor permeability. The negative sign is a consequence of the fact that vapor flows from high vapor pressures to low vapor pressures. The same equation can be rewritten for the other two Cartesian directions, in three dimensional vector notation, or, if useful, in polar coordinates.

Fick's equation can be simplified to give the rate of vapor flow per unit area, the vapor flux, q_v (ng/m^2 · s) as:

$$q_d = h_m \cdot (P_1 - P_{v,base}) \qquad [3]$$

where:

h_m is the surface mass transfer coefficient (about 15,000 ng/Pa · s · m^2), and

P_1 and $P_{v,base}$ are the vapor pressure of a surface (one of many) and the basement vapor pressure (Pa).

Although the vapor permeance varies with temperature and RH, an average vapor permeability, μ, can be assumed for many practical building science situations, and Fick's law written as:

$$Q_v = A \cdot \frac{\mu}{l} \cdot (P_{w,1} - P_{w,2}) \qquad [4]$$

where Q_v is the time rate of vapor flow, l is the length of the flow path or thickness of the material, and P_1 and P_2 are the vapor pressures on either side of the material of interest.

It can be observed that the form of Fick's Law for diffusive vapor flow is exactly the same as Fourier's Law for conductive heat flow. In fact, on a general level, conductive heat flow is a diffusive flow process, just like vapor flow, and water and air flow in porous media. Therefore, all of the same forms of equations can be used with different variable names

The vapor pressure of the surface of a material can be found from its RH and temperature. The moisture content of each material is a specific function of relative humidity (see Figure 4??????) and the vapor pressure calculated from

$$P_1 = RH(w) \cdot P_{ws}(T) \qquad [5]$$

where:

RH(w) is the relative humidity as a function of moisture content (w),

$P_{ws}(T)$ is the saturation vapor pressure (Pa).

A useful approximate equation for saturation vapor pressure (Pa) over water at a temperature T (in Kelvin) is:

$$P_{ws}(T) = 1000 \cdot e\left(52.58 - \frac{6790.5}{T} - 5.028 \ln T\right) \quad [Pa] \qquad [6]$$

where T is the temperature (Kelvin).

The RH of the soil can often be assumed to be at an RH near 100%.

Because a rigorous and reliable theory has yet to be developed, unsaturated flow is often modeled using a phenomenological approach using a moisture content dependent moisture diffusivity, i.e.:

$$m_l = -D_l(w) \cdot \nabla w \quad + D_{T,l}(w) \cdot \nabla T \qquad [7]$$

where:

m_l is the liquid moisture mass flux density ($kg/m^2 \cdot s$),

$D_l(w)$ is the moisture content dependent liquid moisture diffusivity (m^2/s),

$D_{T,l}(w)$ is the moisture content dependent thermal liquid diffusivity ($m^2/(K \cdot s)$), and

w is the moisture content (kg/m^3).

As for pure Fickian diffusion, the second term (called thermal diffusion or Soret effect) is usually ignored because its effect is one to several orders of magnitude smaller than the isothermal liquid diffusivity. The thermal diffusivity should not be confused with the very significant effects of temperature on vapor and adsorbed moisture flow and the somewhat important impacts of temperature on viscosity and surface tension.

Flow by capillarity and vapor diffusion through solid materials to their surfaces is complex, and dynamic, but this can be simplified by lumped capacitance models for specific circumstances. Computer models such as WUFI have been field verified to have most of the proper physics and numerical capability to predict heat and moisture fields due to liquid transport and vapor diffusion.

Model Results: Example Outputs

Based on Class 1 air flows and the above relationships, basement moisture levels have been modeled for a hypothetical structure in Harrisburg, Pennsylvania (Appendix A). Meteorological data are from Typical Meteorological Year (TMY2) for Harrisburg, summer and fall indoor temperatures and RH are from preliminary monitoring in three Harrisburg study houses, while other data are best estimates (Table 2).

The model does not account for storage, and hence is not dynamic. However, Class 1 airflows are not sensitive to storage, and longer term (weeks) outdoor average conditions were used to "smear" short term variations. The airflow is driven by a number of forces, and has been left as a primary variable. The other important variable is the moisture from other sources, including evaporation from wet materials, human use or occupancy, and diffusion through the wall and floor.

The model assumes that diffusion into the basement is restricted by a one perm resistance. This resistance could be provided by a poor quality poured concrete wall or a block wall. This source of moisture is considered in separate calculations, and is generally not an important source of moisture.

Figure 9 shows the resulting equilibrium RH in the basement air during January for four indoor moisture production rates (including diffusion, occupancy, etc.), and assumes that all air entering the basement is from outdoors. In this representation, additional dry (low absolute humidity ratio) outdoor air during the winter creates a large reduction in basement RH. Adding warm, humid (high absolute humidity ratio) outdoor air in the summer months has less of an impact. In general, these same seasonal differences cause the equilibrium RH in the basement to be lower in the winter and higher in the summer.

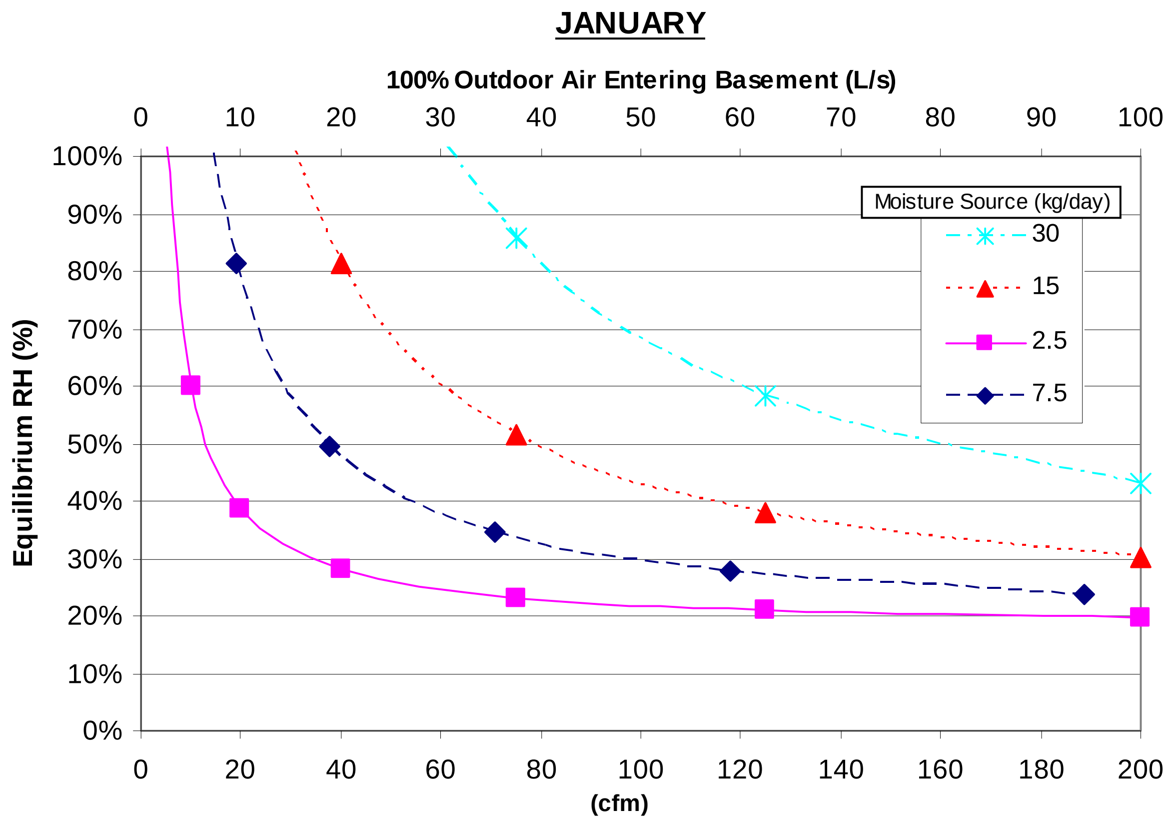


Figure 9. Basement equilbrium RH for four moisture production rates, while rates of outdoor air supply are varied during January (Harrisburg, PA). Air flow from other areas is not included.

If 100% of the air entering the basement were from outdoors, the soil, or upstairs (in the absence of other moisture sources), the resulting basement moisture levels can be estimated and are shown in Figure 10. These data indicate that all three air flow sources can produce elevated basement RH, especially for outdoor air during the summer months and air from the soil for all seasons. Conditioned air from upstairs causes slightly elevated basement RH principally due to the cooling of the air when it enters the basement. Air passing through the soil can pick up and deliver to the basement significant amounts of moisture over long periods in the Harrisburg climate – moisture supply rates may be many times greater than 1.0 kg/day (Appendix A).

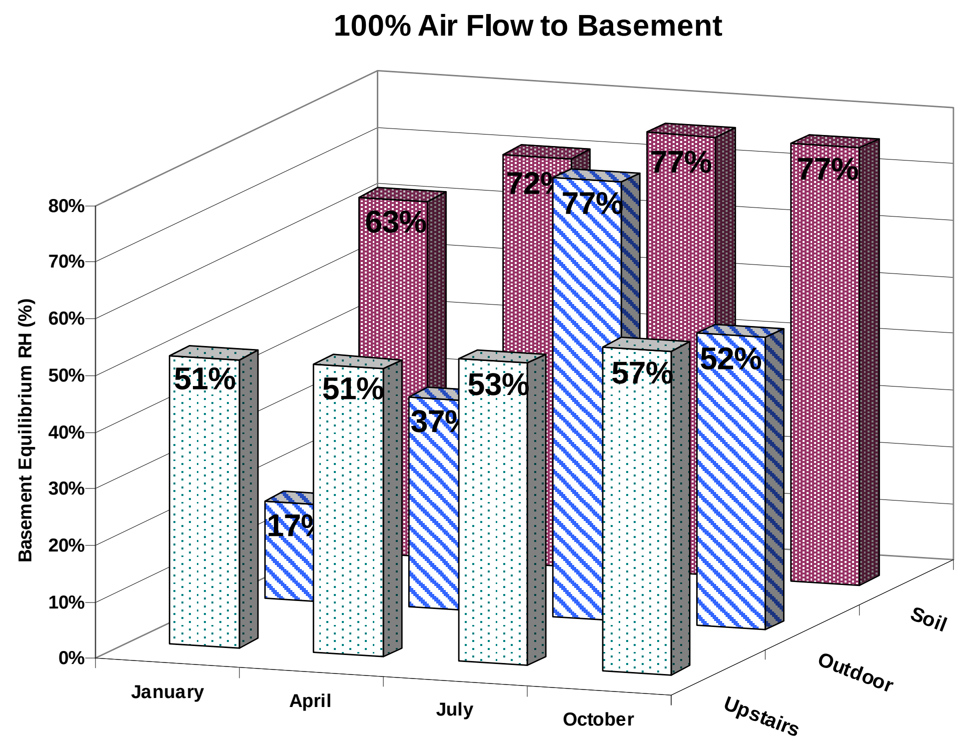


Figure 10. Basement RH if all entering air originated from one of three areas, for four different months in Harrisburg, PA.

Since the previous two analyses are limited to single sources of air flow, the more likely scenario of multiple air flow sources was explored (Equation1). In this exercise, diffusion through basement walls and floor was assumed to be 0.6 kg/day, with moisture from other sources incorporated into the air flows entering from the soil, upstairs, and outdoors. Three rates of total air flow (3 L/s – 0.06 ACH, 35 L/s – 0.70 ACH, and 100 L/s – 2.0 ach) were studied while the fraction of air entering from the soil (5%, 20%, 50%), outdoors (10 – 95%), and upstairs was varied. Results for January and July are shown in Figures 11a and 11b.

As in Figure 9, increasing the fraction of outdoor air will tend to dry the basement in the winter and add moisture during periods of warm, humid weather. In addition, an increasing fraction of soil air raises basement moisture, regardless of season. Boosting the total ventilation rate of the basement causes a slight drop in basement moisture as the moisture from diffusion is diluted.

Not only do these data illustrate the relative impacts of varying the incoming air flows, but they also hint at the effects of an operating ASD system. By depressurizing the surrounding soil and possibly further depressurizing the basement, ASD may reduce the fraction of air from the soil and increase the fraction of air from the upstairs and outdoors. ASD systems typically exhaust between 25 cfm (11.8 L/s) and 100 cfm (47.2 L/s) to the outdoor air. Anecdotal information from early radon studies suggests that 5-80% of this air originated in the basement, and was pulled out of the building through cracks and openings in the foundation, into the soil, collected by the ASD suction pipe. This gives a range of 1.25 cfm (0.59 L/s) to 80 cfm (37.8 L/s) of basement air that is exhausted. It is likely that this was made up by unknown fractions of air entering from the outdoors and upstairs (Class 1 flows).

To estimate a possible reduction in basement moisture levels due to operation of the ASD system, a pre-mitigation condition of 3 L/s total entering air flow, comprised of 20% soil air/50% outdoor air/30% upstairs air, was assumed. The ASD system was assumed to increase total ventilation to 35 L/s, eliminate entry of soil air, with the incoming air being equally split between the outdoors and upstairs. The humidity ratio dropped from 6.3 to 4.3 g/kg, while the RH declined from 52 to 35% for January. Calculated reductions were also significant in July: the humidity ratio went from 12.9 to 10.4 g/kg, and the RH from 83 to 67%. The data are also displayed in Figure 11 by the '+' and '×' symbols. These results show the potential for ASD to significantly reduce basement moisture levels under the right circumstances – other starting air flow conditions could diminish or enhance the reductions. While moisture reductions in the basement air during ASD operation have been calculated, drying of the materials in close proximity to the foundation may be even more dramatic and important to indoor environmental quality.

These simple modeling exercises do not account for many of the real-world complexities. e.g.:

- Diffusion rates, although typically small, vary as moisture levels in the indoor air change;
- Moisture levels in the basement and upstairs, and to some extent soil, air are interdependent;
- Outdoor air entering through the surrounding soil may not equilibrate at 100% RH after drying of the soil has begun to occur.

In addition, different structures and finishes on the interior of the basement will change both the airflow and vapor diffusion modes of moisture transport. Concrete block walls are suspected more open for air leakage and vapor diffusion. The addition of interior finishes will generally reduce the airflow and diffusive flow of moisture across the basement. The interior finishes will also tend to increase the moisture storage capacity and change the temperature of the soil around the basement. All of these factors are poorly characterized but likely to change the response of a basement to ASD operation.

(a)

(b)

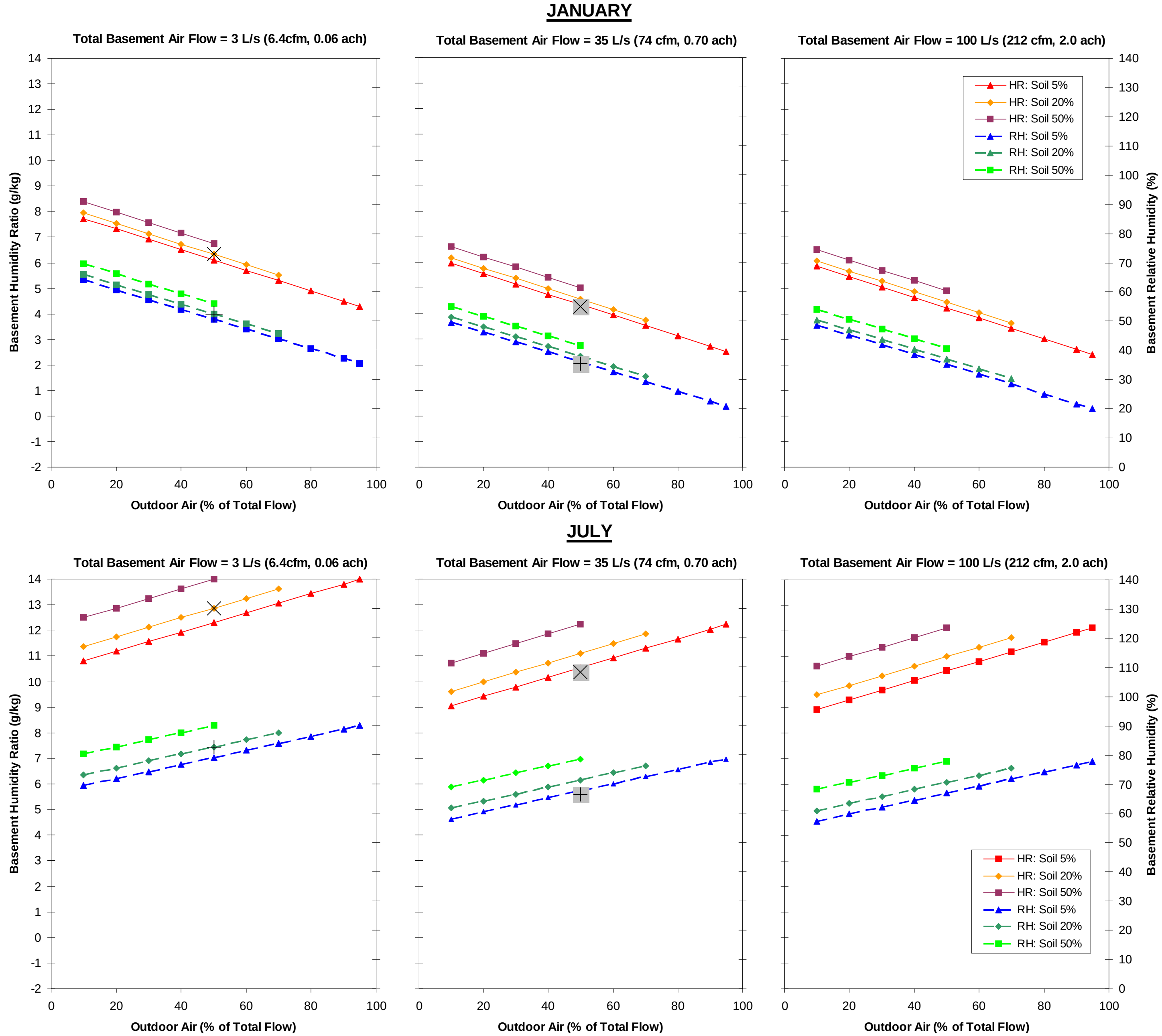


Figure 11(a and b). Basement humidity ratio and RH while fraction of entering air flow from soil, upstairs, and outdoors is varied for three different total air flow rates. '×'s and '+'s symbolize examples of pre- (3 L/s) and post- ASD (35 L/s) operation on basement HR

Implications for an Experimental Program

This modeling exercise has focused on modeling moisture entry, accumulation, and removal in basements where the moisture source is not due to bulk entry of liquid water that could be caused by high water tables, floods, or poorly-designed drainage from and around the building. Development of the model has outlined the possible mechanisms for ASD control of moisture problems in basements, and highlighted that the interactions of house, ASD, and the surrounding environment are complex. While the relative importance of the mechanisms involved in actual houses is not known, the model has established a framework for understanding and interpreting results as data are collected by field measurements.

Application of the model was not extended to examine the sensitivity of basement moisture levels to the many permutations of the interacting factors. Some of these factors include:

- Air Flow and Ventilation
  - Occupant activities and usage: door and window openings, operation of the HVAC and other equipment such as exhaust fans, clothes dryers, fireplaces, and radon control systems
  - Air leakage characteristics of the building envelope, substructure surfaces, and surrounding soils and materials
- Construction Characteristics:
  - Size and number of stories,
  - Construction materials,
  - Drainage,
  - Wall/floor/roof design and construction,
  - Floor separations,
  - Finishes
- Climate and Weather
  - Wind, precipitation, relative humidity, temperature, snow cover
- Other Moisture Sources/Sinks
  - Occupant activities and usage: cooking, showers, furnishings, number of occupants, humidifiers/dehumidifiers

While the ranges of parameter values, that are surrogates for the above factors, have been estimated based on the authors' experience (Table 2), field measurements in houses are lacking and necessary. Therefore, the experimental phase of this study is exploratory: there is little available quantitative data on the response of air flows and moisture in basements to ASD operation. As a result, experimental protocols must be developed and validated, key parameters must be identified and measured, and the impacts of ASD operation on air flows and basement moisture levels quantified.

The key parameters to be measured probably are moisture levels in air and materials, air flows and pressure differences, and indoor radon concentrations. The value of each of these variables will change in space and time, and will respond differently as the ASD is turned on and off. As indicated by the example outputs of this simple model, identification and quantification of interzonal air flows is of vital importance. These input and data were not emphasized during a planning session by experts, but will provide vital information regarding the supply and removal of moisture with the movement of air.

Response times for air pressure (and air movement) and radon levels are reasonably well-characterized. For example, changes in ASD operation typically causes air pressure changes within seconds to minutes, and changes in radon levels usually within 24 hours. Other effects, such as changes in barometric pressure and outdoor temperature, usually cause responses within minutes to days. Response times in moisture levels due to ASD operation have not been measured, but are expected to vary from hours to months, depending on the materials and the actual airflow paths and rates. The moisture content of the air and at the surface of unfinished wood exposed to the basement air should change quickly, whereas the wood in the center of a stud behind a panel finish may take weeks to react to a significant change in interior air moisture levels. Soil and concrete walls and floors have an even longer time constant, and moisture changes will usually require months or even years to be significant.

It is anticipated that monitoring and analyzing these moisture responses will provide important data on the response behaviors of the assembled building components, and offer insights into the dominant mechanisms for moisture control by ASD. For instance, a very rapid change in air moisture levels probably indicates that drier ventilation air has been introduced. Quick changes in the moisture level of soil or foundation materials will suggest that other air flow paths are participating in the drying.

Table 2: Key Model Parameters and Estimated Range of Values

Key Parameters			Related Parameters	Estimated Range of Values	Test Procedures/Device(s)
Air Flow In/Out of Basement:	Outdoor			0.03 – 2.0 L/s-m^2 * (0.01 -- 0.40 cfm/ft^2) (0.05 – 3.0 ach)	• Tracer Gas • Air Leakage Area - Blower Door • Diff. Pressures – Transducer
	Upstairs			0.03 – 2.0 L/s-m^2 * (0.01 -- 0.40 cfm/ft^2) (0.05 – 3.0 ach)	• Tracer Gas • Air Leakage Area - Blower Door • Diff. Pressures – Transducer
	Soil:			0.003 – 0.17 L/s-m^2 ** ($0.7x10^{-5}$ – 0.03 cfm/ft^2) 10^{-10} – 10^{-5} m^3/Pa-s‡	• Diff. Pressures - Transducer • Effective Resistances (floor, soil) • Soil Gas Entry Potential
			ASD Air Flow	0 – 50 L/s (0 – 100 cfm)	• Velocity Pressures - Transducer • Diff. Pressures - Transducer • Radon Concentrations - CRM • Tracer Gas
			Wind Speed	0 – 30 m/s (0 – 67 mph)	Cup Anemometer
			Wind Direction	0 – 360	Wind Vane
			Barometric Pressure	98 – 104 kPa (29 – 31 in Hg)	Pressure Transducer
			Soil Air Permeability	10^{-14} – 10^{-8} m^2	Soil Air Permeameter
Temperature & Water Vapor Content:	Outdoor Air:	T		-30 – 35°C (-22 – 95°F)	Thermistor
		RH		10 – 100%	Thin film capacitance
	Basement Air:	T		10 – 30°C (50 – 86°F)	Thermistor
		RH		10 – 90%	Thin film capacitance
	Microclimate Air:	T		10 – 30°C (50 -- 86°F)	Thermistor
		RH		10-100%	Thin film capacitance
	Upstairs Air:	T		10 – 35°C (50 – 95°F)	Thermistor
		RH		10 – 90%	Thin film capacitance
	Soil Air:	T		5 – 28°C (41 – 82°F)	Thermistor
		RH		30 – 100%	Thin film capacitance
	ASD Air:	T		10 – 20°C (50 -- 68°F)	Thermistor
		RH		20 – 90%	Thin film capacitance
Moisture Storage:	Walls			0.1 to 6% MC	Wood sensor / heated RH
	Floor			0.1 to 6% MC	Wood sensor / heated RH
	Soil:			0.1 to 10% MC	Gypsum block
			Precipitation	0.25 – 250 mm/day (0.01 – 10 in/day)	Tipping Bucket Rain Gage
	Finishes			5 to 25% MC wood	Moisture pin
	Furnishings			5 to 25% MC wood	Moisture pin
Diffusion:	Walls			10-90%/5 to 25C	RH/T – delta P_v only
	Floor			10-90%/5 to 25 C	RH/T – delta P_v only

* Based on 140 m^2 (1500 ft^2) basement with 2.44 m (8 ft) ceilings
** Assuming 1 to 50% of incoming ventilation air, at 0.05 to 0.5 ach, is from the soil
‡ Soil gas entry potential

Appendix A: Inputs to Simple Model

EPA Simple Model of a Ventilated Basement

Basement Data

Length	9	m		29.5 ft	
Width	8	m		26.2 ft	
Height	2.5	m		8.20 ft	
Permeance of interior	60	ng/Pa s m^2			1.05 US Perms Kraft paper is around 1 perm
	Jan	Apr	Jul	Oct	
Temperature, C	17	17	21	18	
Temperature, F	62.6	62.6	69.8	64.4	
calculated values					
Saturation, Pa	1928	1928	2474	2053	
Area	72	m^2		775 ft^2	
Volume:	180	m^3		6366 ft^3	
Wall:	85	m^2		915 ft^2	
Floor	72	m^2		775 ft^2	
Surface Area:	157	m^2		1689 ft^2	

Upstairs Air Conditions - Estimated

	$P_{v,out}$ (Pa)	Temp (C)	RH	$P_{v,out,sat}$ (Pa)	W (g/kg)	Temp (F)
January	990	21	40%	2474	6.1	69.8
April	990	21	40%	2474	6.1	69.8
July	1336	24	45%	2969	8.3	75.2
October	1184	22	45%	2631	7.4	71.6

Weather Conditions, Harrisburg, PA - Outdoor Air

	$P_{v,out}$ (Pa)	Temp (C)	RH	$P_{v,out,sat}$ (Pa)	W (g/kg)	Temp (F)
January	337	-1.0	59.6%	566	2.1	30.2
April	726	9.7	60.6%	1197	4.5	49.5
July	1928	24.4	63.6%	3033	12.1	75.8
October	1070	12.6	73.6%	1455	6.6	54.7

Soil Air Conditions - Estimated

	$P_{v,out}$ (Pa)	Temp (C)	RH	$P_{v,out,sat}$ (Pa)	W (g/kg)	Temp (F)
January	1221	10	100%	1221	7.6	50.0
April	1395	12	100%	1395	8.7	53.6
July	1928	17	100%	1928	12.1	62.6
October	1590	14	100%	1590	9.9	57.2

Soil Air Moisture Contribution

If air flows from outside to the basement through soil and picks up all possible moisture then

Total flow through soil				kg/day of moisture added to outdoor air by passage through soil and heating to soil temp			
cfm	L/s	L/s-m2	ACH	**January**	**April**	**July**	**October**
5	2.4	0.03	0.05	1.3	1.0	0.0	0.8
10	4.7	0.07	0.09	2.7	2.1	0.0	1.6
20	9.4	0.13	0.19	5.4	4.1	0.0	3.2
40	18.9	0.26	0.38	10.8	8.2	0.0	6.4
75	35.4	0.49	0.71	20.2	15.4	0.0	12.0
125	59.0	0.82	1.18	33.7	25.7	0.0	20.0
200	94.4	1.31	1.89	53.9	41.1	0.0	32.1

Hence, air flow through soil has the potential to add large amounts of moisture to basement in some situations -- high flow through soil (over 20 cfm) and cooler weather