Another HVAC Design Parameter to Consider

Stack Pressure-Created Airflows in Insulation Envelopes, Part 1: Buildings

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Building design codes with one exception* generally do not recognize the impact stack pressures play in finished basement energy use and the moisture and air quality concerns and problems they are responsible for creating. Neither do they provide measures to resolve these concerns and problems, and this is the focus of this paper. The authors' stack pressure and basement batt insulation envelope flow measurement experience and related calculations to quantify and solve these problems indicate that when countermeasures are not taken, a substantial portion of thermally conditioned air circulates behind the basement insulation in winter due to these stack pressures; in summer lower stack pressures create stagnant air pockets behind the insulation air barrier, which trap ground-sourced humidity and moisture.

Stack pressures arise across insulated boundaries such as insulated perimeter basement walls due to the air density differences on either side, which in turn arise from their temperature differences. The higher the wall, the greater the temperature difference; and the denser the air, the higher the equal and opposite stack pressures at the top and bottom of the wall. In winter the air behind the insulation is coldest at the top basement wall at the aboveground portion of the envelope. This cold air, being denser than the

*The Ontario Building Code (BMEC approval 97-05-214) allows the interior finished basement insulated envelope ventilation system described in this paper as an alternative to foundation exterior water sealing and drainage measures. It also solves basement soil gas and odor air quality concerns.

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air below, sinks to the floor, pulling warm living space air into the envelope behind the insulation after it, via leaks. The falling cold air behind the insulation goes to the floor and then recirculates through leaks back into the living space. In summer, this circulation around the insulation does not occur to the same extent, as now the coldest air behind the insulation is at the base of the wall, not the top.

This paper provides the science behind these stack pressures and their effects and analyzes the current situation for batt-insulated basements and their energy implications. It also provides details for creating tightly sealed and insulated perimeter walls and low-E floors that can be depressurized throughout with small exhaust airflows (10 cfm to 30 cfm [4.7 L/s to 14 L/s]) to the outdoors; this efficiently eliminates typical basement dampness and mold odors, soil and envelope moisture, humidity, and air contaminants without relying on less energy-efficient whole-house ventilation and dehumidification systems. This insulation envelope sealing and depressurization system has been successfully used in several hundred residential basements in Canada and the U.S., in some cases for over three decades.

Foamed-in-place insulation over interior foundation walls as an alternative solution to depressurized batt or shimmed board insulation envelopes is not practical for a number of reasons, including cost. Further, it does not solve water leakage problems.

This paper describes an integrated method for the construction and mechanical ventilation of basements to improve air quality. It eliminates or reduces mold and similar airborne contaminants, excess humidity, radon gas and energy loss.

The suggested method, while requiring some extra time to make the seal tight enough, is in principle simple to implement, using existing construction methods and materials. Careful attention is given to sealed air barriers and continuity of the insulated wall (and sometimes floor) cavity with low-level ventilation of this cavity to the exterior.

The suggested method is supported by a demonstration of the results of stack effect within typical existing basement wall assemblies, which contribute to heat loss, mold growth and poor air quality. The addition of very low-level continuous ventilation greatly improves the passive performance of the physical construction.

This is the first of a two-part series of papers on the subject of batt and blanket-insulated envelope stack pressures. Part 2 addresses aircraft.

Most of us are aware of the water leakage, weeping tile failure, sewer backup, sump failures, mold growth, moisture problems with cracked foundation walls and interior wood stud walls and subfloors, and radon entry problems that finished basements can suffer. However, the winter energy loss due to envelope air circulation is not on the list of concerns, but should be. This loss is caused by stack pressures across the insulation vapor barrier and drywall finish that draw basement air behind the insulation via leakage pathways at the insulation envelope air barrier at the top of the wall and push it out into the room after it is cooled at the bottom of the wall.

The leakage pathways at the top of the wall are unintentional and the result of poor sealing of air barriers to the underside of the floor above. Leakage pathways at the bottom are sometimes intentional—intended to ensure water condensation does not occur on the cold foundation by allowing house air to travel behind the insulation. The amount of this insulation bypass is at least 100 cfm (47 L/s) in a typical 1,000 ft^2 (93 m^2) finished basement even when the insulation is kept 1 ft (0.3 m) or more above the floor, and the vapor barrier is not intentionally poorly sealed. The insulation bypass could be several times that when the vapor barrier is intentionally left open at the bottom to prevent winter condensation collecting behind the insulation on the aboveground portion of the foundation, a potential major moisture problem in humidified houses and in new houses.

Stack Pressures

Stack or buoyancy pressure differentials across perimeter walls and foundations are created by indoor and outdoor temperature differences. In winter, these pressures increase with increased height of the cold air column in the insulation envelope and increased temperature difference. If the bottom of the wall is open to the room, the stack pressure is based on the full height of the wall. However, the floor can act as a flow blocker if the attachment to the wall is sealed. If this is done, the stack pressure is reduced by half. Air will continue to enter and exit the envelope through other cracks and seams throughout the wall.

Stack pressures are predicted by[1,2]

$$\Delta P_r = (\rho_2 - \rho_1) \times g \times h \quad (1)$$

Substituting

$$\rho = P/RT \quad (2)$$

Gives

$$\Delta P = P_1(1/T_1 - 1/T_2) \times g \times h/R \quad (3)$$

where

ΔP_r = Pressure differential at the reference altitude

ρ_1 = Air density in the living space (slug/ft^3; one slug is 32.1740 lb)

ρ_2 = Air density behind the insulation (slug/ft^3)

h = Height above the neutral plane (ft)

P_1 = Living space air pressure (lb/ft^2)

T_1 = Temperature in room (°R)

T_2 = Temperature behind the insulation (°R)

R = Individual gas constant for dry air = 1,716 ft^2/(s^2·°R)

g = Acceleration due to gravity (32.2 ft/s^2)

ΔP = Stack pressure (lb/ft^2) or customarily in units of Pa (47.88 Pa/lb·ft^2)

Using *Equation 3*, the stack pressure at the top of a basement wall with the air barrier sealed at the floor is shown in *Figure 1a* for a range of temperatures behind the insulation and wall heights. Leaving the insulation envelope air barrier open at the floor doubles the stack pressures, which are shown in *Figure 1b*.

The soil in cold climates is colder than the living space year-round (e.g., 46°F to 50°F [7.8°C to 10°C] at foundation depth and 26°F to 32°F [–33°C to 0°C] at the ground surface in winter and near average air temperatures at the ground surface in summer). Hence, temperatures between the insulation and the foundation wall inside the building are always colder than in the living space.

FIGURE 1 (a) Stack pressure at the top of insulated basement stud wall sealed at floor, (b) basement stud wall open at floor. Room air temperature = 70°F; air pressure = 14.694 psia.

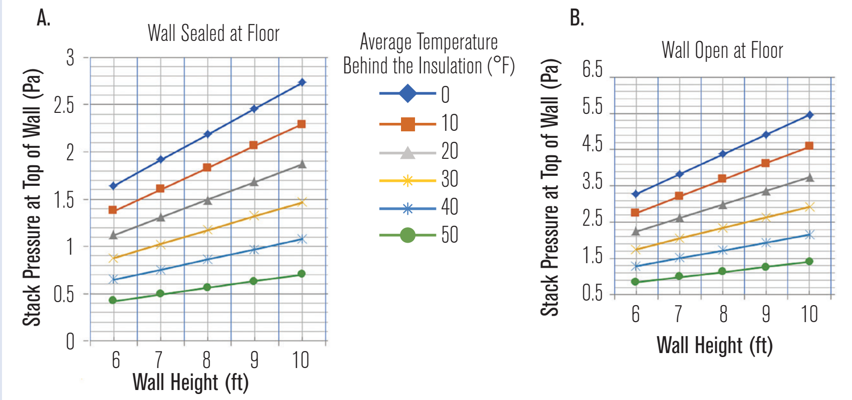
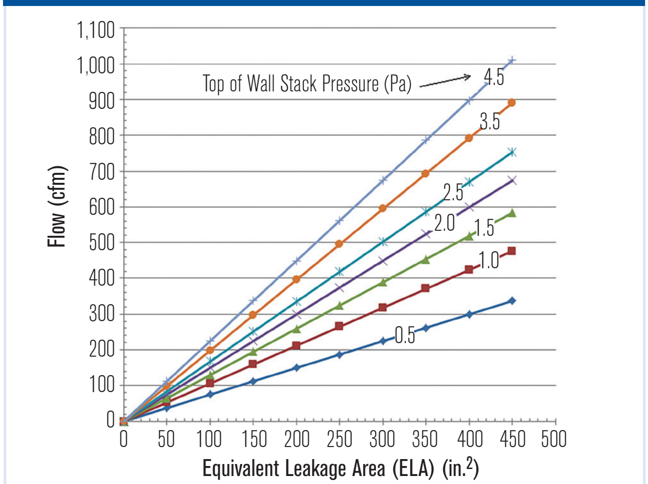


FIGURE 2 Conditioned airflow behind basement insulation versus ELA, stack pressure, ΔP. Air pressure = 14.694 psia. Envelope leakage C_d = 0.6.



Airflows Behind the Insulation

The airflow rate through the insulation envelope, Q, is governed by the following equation

$$Q = (ELA)C_d\sqrt{(2\Delta P_r)}/\rho \quad (4)$$

where

Q = Predicted flow rate, ft^3/s (= cfm/60)

C_d = Discharge coefficient (varies between 0.6 for small sharp-edged openings and 1 for large openings)

ELA = Equivalent or effective leakage area, ft^2 (= in.^{2}/144)

ρ = Mass air density, 0.002379 slug/ft^3 (=0.07659 lb/ft^3/g) at sea level and 59°F

ΔP_r = Reference pressure difference (lb/ft^2) or customarily in units of Pa (= 47.88 × lb/ft^2)

Figure 2 shows a range of conditioned air circulation behind the insulation for a range of peak stack pressures (see *Figure 1b*) under winter conditions and a range of air barrier total (in + out) leakage areas.

In home basement stud wall insulation envelopes that are sealed at the wall top and bottom, we have measured flows through the envelope of much greater than 100 cfm (47 L/s) under winter stack pressures. Air barrier seals at discontinuities such as at pipes, wall plugs, electrical breaker or around furnaces in subfloors also may be leaky. In some basement wall insulation, the air barrier has been left open at the bottom to avoid winter condensation and summer mold growth problems. In these houses the stack pressure doubles with the envelope equivalent or effective leakage areas (ELA) limited by the tightness of the top edge seal. In fact, it is practically impossible to depressurize most standard basement walls envelopes. From *Figure 2*, this suggests typically insulated basement envelope ELAs of much greater than 50 in.^{2} (0.03 m^2) and likely more than 500 in.^{2} (0.3226 m^2). These homes may have had baseboard heating or forced air heating and cooling systems in the 1,000 cfm to 1,500 cfm (472 L/s to 708 L/s) range. This suggests winter basement insulation air barrier leakage rates approaching 50% or more of the house conditioned air circulation rate.

This circulation can cause cold surface condensation turning into ice buildup, especially in humidified homes, behind the insulation on the aboveground portion of the foundation. When spring comes, this condensation will melt and drain to the bottom of the wall where it creates mold growth. In the summer, stack pressure flow decreases. The moisture wicking via foundation walls will dampen floor-level cellulose materials with an associated microbial growth particularly in corners where temperatures behind the insulation are lowest and humidity highest.

Heat Loss

Estimating Foundation Temperatures

A transient conduction model was made using heating degree days (HDD) weather data for Seattle with the following conditions:

Density of soil = 120 lb/ft^3

Thermal conductivity of soil = 0.8 Btu·ft/h·ft^2·°F

Specific heat of soil = 0.345 Btu/lb°F

Density of concrete = 65.5 lb/ft^3

Concrete thickness = 8 in.

Thermal conductivity of concrete = 0.439 Btu·ft/h·ft^2·°F

Fiberglass insulation = 3.5 in. k (thermal conductivity/in.) = 0.27 Btu·in./h·ft^2·°F

0.5 in. plywood = C (conductance) = 2.12 Btu/h·ft^2

Inside air film = h (heat transfer coefficient) = 1.5 Btu/h·ft^2·°F

f = 1/(1/1.5 + 3/0.27 + 1/2.12) = 0.0816 Btu/h·ft^2·°F to inside of concrete

Outside effective heat transfer coefficient = 6.0 Btu/h/ft^2·°F based on forced convection (15 mph wind max) and sky radiation

Far field (groundwater) temperature = 52°F

Daily temperature time = $\theta = (n_{day}/365)(2\pi)-0.75\pi$ (Jan. 1 is $n_{day} = 1$) radians

Daily temperature variation = $T_{\text{mean}} = 52 + 12.45\sin(\theta)$

Hourly variation = $T_{\text{outside}} = T_{\text{mean}} +$ 12(time of day/24)-2π

Solution time step = 0.01 hours

Effect of Daily Variation in Temperature

The first simulation was run to determine the short-term temperature variation on cold days (20°F [–6.7°C] mean temperature). The inner concrete wall temperatures seemed to reach a (slowly ramping down) equilibrium after 72 hours. The sinusoidal variation in concrete temperature with time reduces with depth. At about 0.5 ft (152 mm) depth (line B in *Figure 3*), the sinusoidal variation is nearly gone, and the long-term seasonal variation is more significant. This thermal behavior justifies the use of overall daily averages in the calculation of energy loss.

An equation was fit to the average temperature from the heating degree days (HDD) for the Seattle area and is compared in *Table 1*.

The second simulation was run for 13 months, starting January 1, to have correct initial conditions for the following January. The seasonal mean temperature for Seattle was applied as the air temperature boundary condition.

The warmest month was August, with an average upper soil surface temperature near 64°F (18°C), while the coldest month had an average upper soil temperature near 40°F (4.4°C) (*Figure 4*).

The average inner surface temperature contours for the insulated wall show that the upper sections are warmer than the lower sections during summer and the reverse during winter (*Figure 5*). This raises the possibility for internal condensation on cooler wet surfaces due to evaporation from warmer wet surfaces within the envelope during any time of year, especially when the envelope is tightly sealed.

When these surface temperatures are converted to heating degree days, a clear distinction exists between the heating requirements of the house compared to the basement (*Figure 6*).

To estimate the energy penalty of leakage through the envelope, some simple assumptions are made: that the stack pressure drives the flow, the stack pressure is derived from the averaged wall temperatures, and the energy lost is related to leakage flow using the temperature entering and exiting the envelope.

$$E = \rho g Q c_p \left(T_a - T_{env\ exit}\right) \quad (5)$$

$$T_{env\ exit} = T_{concrete} + 0.292\left(T_{wall} - T_{concrete}\right) \quad (6)$$

$$Q = C\left(ELA\right)\sqrt{2\Delta p / \rho} \quad (7)$$

E = Energy lost due to envelope leakage, Btu/s

T_a = Temperature of air in basement = 65°F

T_{wall} = Average monthly temperature for inner surface of the concrete

$T_{env\ exit}$ = Air temperature exiting the envelope,† °F

ρ = Density of air in basement, slug/ft^3

Q = Leakage flow, ft^3/s

c_p = Specific heat of air, 0.24 Btu/lb-°F

ΔP = Stack pressure from equation, lb/ft^2 (= Pa/47.88)

g = Gravity acceleration, 32.2 ft/s^2

C = Flow coefficient, 0.3 for glass wool loosely filled envelopes

A = Physical leakage area, ft^2

ELA = Equivalent insulation leakage area = 0.353 × A (includes flow in and out, in series), ft^2

FIGURE 3 Effect of daily temperature variation on inside basement wall temperatures on a cold (20°F) day.

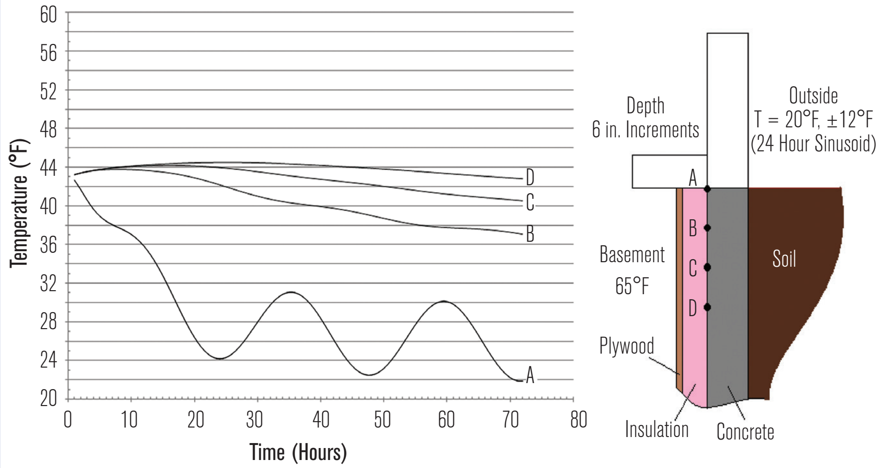


TABLE 1 Comparison of the equation for daily ambient temperature variation to that from HDD.

MONTH	Θ RADIANS	MEAN TEMPERATURE FROM EQUATION	HEATING DEGREE DAYS	NUMBER OF DAYS (M)	n_{day}	AVERAGE FROM HEATING DEGREE DAYS =65-HDD/M
Jan.	–1	39.5483871	828	31	1	38.29032258
Feb.	–0.866	41.21690323	678	28	31.33333	40.78571429
Mar.	–0.5	45.77419355	657	31	61.66666	43.80645161
Apr.	0	52	474	30	91.99999	49.2
May	0.5	58.22580645	295	31	122.3333	55.48387097
Jun.	0.866	62.78309677	159	30	152.6667	59.7
Jul.	1	64.4516129	56	31	183	63.19354839
Aug.	0.866	62.78309677	62	31	213.3333	63
Sep.	0.5	58.22580645	162	30	243.6666	59.6
Oct.	0	52	391	31	274	52.38709677
Nov.	–0.5	45.77419355	633	30	304.3333	43.9
Dec.	–0.866	41.21690323	750	31	334.6666	40.80645161

After some unit conversions, the monthly variation in energy loss for physical leakage area is shown for the Seattle area (*Figure 7*):

An Envelope Sealing and Ventilation Solution

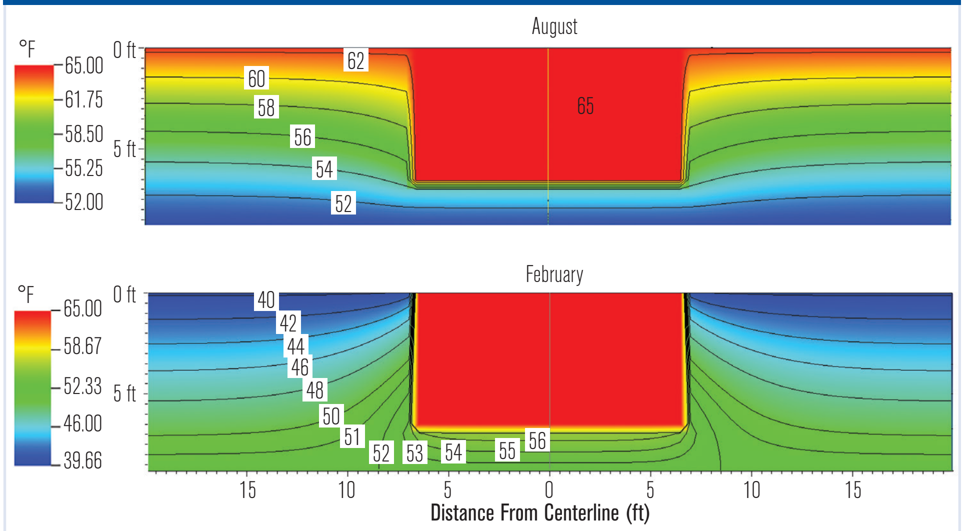
The objective is to create a tightly sealed perimeter wall subfloor insulation envelope and to depressurize this envelope to the outdoors with a continuous duty blower.

Figure 8 illustrates typical basement foundation walls and slabs, and a tightly sealed stud wall, and also a stud wall and subfloor insulation envelope system constructed over top. The basement foundation walls can be poured concrete, concrete block and rubble mound. Typically, there is a concrete slab floor. Sometimes the basement floor is just the ground soil, bedrock, or a gravel layer and poly over the soil.

The top wall edge seal is above the ground level and below the joists supporting the floor above. This creates a flow blocker near the bottom of the coldest section of insulated wall and the top of the underground wall. This "L"-shaped seal near the top of the wall creates a tight air seal and minimizes airflow from outdoors into the envelope system. It also reduces stack pressures affecting air leakage into the insulated space above. The insulation can be batt, foam board or a combination of both. Foam board insulation with its higher thermal resistance is used where thinner walls that meet code

†CFD models of 7 ft tall wall, 3.5 in. insulation, K=0.27 Btu·in/h·ft^2·°F, permeability 3 × 10^6 Darcy's, at given temperatures, show factor or 0.292 (i.e., simple average factor is 0.5)

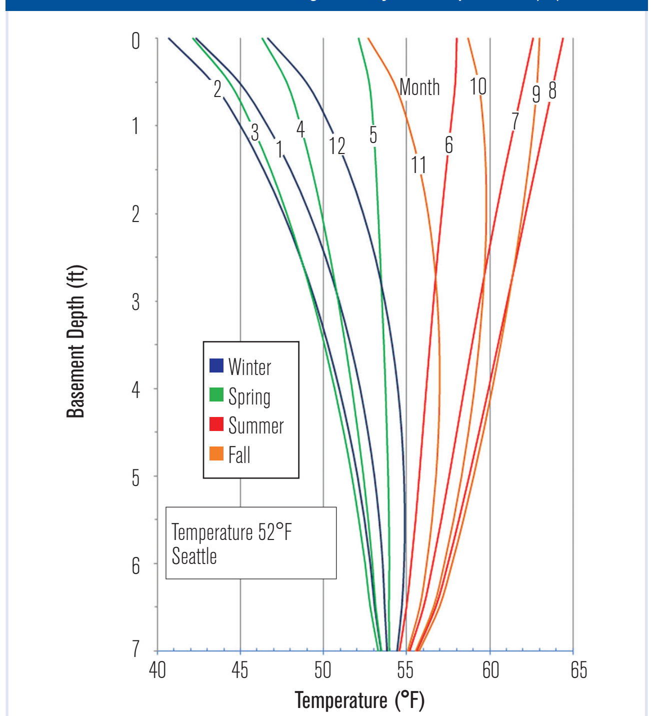
FIGURE 4 Temperature contours for warmest and coolest months.



insulation requirements are desired. Foam board insulation is slightly shimmed off the foundation to accommodate any foundation water leakage and to enable moisture removal behind the insulation.

The plywood or fiberboard floor (*Figure 8b*) continues the sealed wall "cavity" envelope with 4 ft × 8 ft (1.2 m × 2.4 m) sheets that are sealed at joints. 1 in. × 4 in. (25 mm × 102 mm) wood sleepers support the subfloor. The sleepers themselves are supported on spaced sill plate gasket shims to prevent the wood from touching the concrete slab and to allow air and water movement (if there is flooding) beneath the sleepers. The subfloor has aluminum foil paper (shiny side down giving an R-4 insulation value) over the sleepers, which themselves are supported on spaced and folded sill plate gasket "shims" on the slab to allow air and water to pass underneath if there is foundation leakage. The sleepers can be replaced by dimpled plastic sheets, dimples down, in which case the R-4 insulation value is lost and there is no need for the aluminum foil. Further, if dimpled plastic is used, the ability is lost to safely accommodate basement flooding from a foundation leak or a sewer backup.

FIGURE 5 Inner concrete surface average monthly wall temperatures (°F).



There is a standard water drain within the floor system and one on top of the subfloor system. Any water entering the envelope will be removed by evaporation and, if a lot of water exists, also by drainage. Note that all drain P-traps should be periodically topped up with clean water. To do this in the subfloor, run a tube to the drain under the subfloor from a tap off the hot water tank supply pipe, for example.

A continuous duty blower exhausts the envelope air to the outdoors. The blower exhaust rate is controlled by a three-speed fan control set according to the reading of a differential pressure gauge measuring the pressure differential between the basement and the sealed envelope in units as small as 2 Pa (0.04 lb/ft^2).

The sealed envelope is precommissioned prior to the drywall going up, and if the depressurization versus exhaust rate is too low (less than 10 Pa at 85 cfm), leaks are searched for using a smoke pencil and sealed.

Once deemed acceptable, the drywall and baseboards are installed and the floor finished as desired with hardwood, carpet, tile, etc. The system then undergoes final commissioning, and the minimum ventilation rate is set for summer and winter. Emissions from basement sump pits normally connected to perimeter weeping tile flexible drainage irrigation pipe around the outside of

FIGURE 6 Heating degree days (HDD) environment for the aboveground part of the house versus the insulated basement (Seattle).

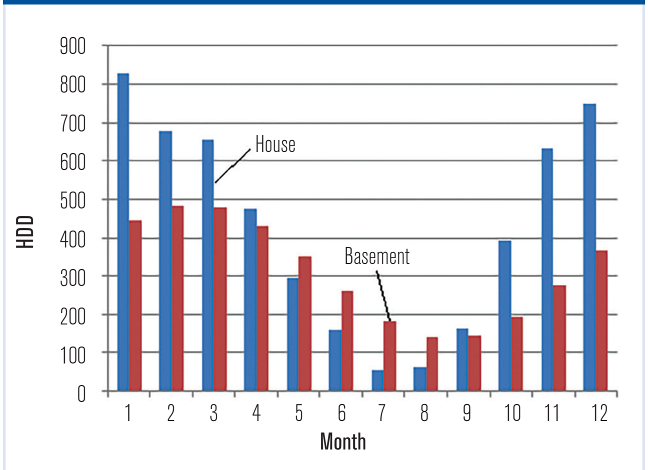


FIGURE 7 Heat loss due to envelope leakage for a basement in the Seattle area, C=0.3 (insulation coefficient).

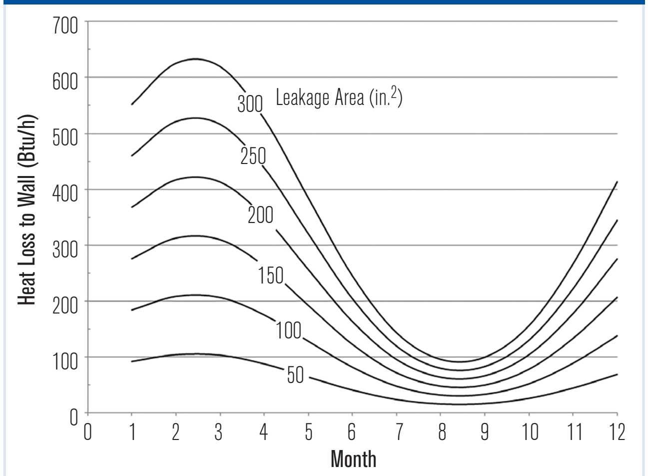
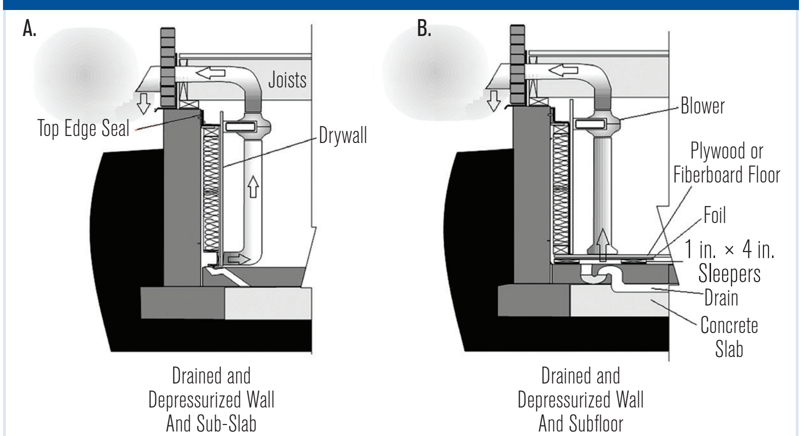


FIGURE 8 Main elements of depressurization system (a) wall only and (b) wall and floor.



the foundation at the footing are also separately exhausted by this system.

The sealed envelope system is continuously depressurized by at least 2 Pa (0.04 lb/ft^2) year-round, typically by a flow in the 10 cfm to 30 cfm (4.7 L/s to 14 L/s) range, with air taken from the living space and exhausted outdoors. In setting a minimum year-round exhaust rate, take into account that winter stack pressures to be offset typically are about 2 Pa (0.04 lb/ft^2) higher than those in summer. Exhausting this air provides continuous energy-efficient low-level house ventilation and envelope air contaminant and moisture exhaust. It is energy efficient with the exhaust air drying the envelope insulation, warming the envelope, while house radiant heat loss warms the replacement air entering via aboveground walls leaks. At the same time, the exhaust air with its soil gases, such as radon, microbial, concrete and envelope sealant material off-gases, cannot enter the living space; otherwise, these can only be addressed by considerably less efficient whole-house ventilation dilution and filtration.

The occupants will know if the system is working properly by observing the depressurization instrumentation shown in *Figure 9* and, if necessary, they can adjust the blower exhaust rate to ensure system depressurization relative to the living space at all times. Some wall and floor areas of the basement are not covered by this system (e.g., the electrical circuit board and the furnace and hot water tank).

The system is robust, surviving even sewer backups that raise water levels above the floor. Some of these systems are three decades old and have maintained their same tightness. The system helps prevent living space interior condensation and high humidities by preventing the humid air in the envelope from entering the basement living space by removing the soil moisture wicking through the concrete footings and slabs. This moisture can be as much as 2 gallons (7.6 L) per day in summer—moisture that would otherwise be trapped by standard basement finishing and summer stack pressures. Note that house living space air humidity above 65% can cause microbial growth inside the living space. So, while this system helps reduce house humidity, it does not replace air conditioners or dehumidifiers. These devices are required to maintain living space humidity below 65% (target 50% in an open area in the basement) in summer high humidity conditions.

This design is approved by the Ontario Building Code as an acceptable foundation water leakage protection system. Foundation water leakage is either evaporated or drained from the envelope without causing any damage to the system or the finishing materials. It has been used as a backup to exterior foundation leakage protection systems that can or have failed. Such failures can happen when the perimeter footing weeping tile clogs up and/or there are edge sealing or other imperfections in exterior foundation surface coatings and membranes.

Isn't Basement Ventilation Equally Effective?

An important note to make: the infiltration energy loss from the basement is similar to the infiltration from the house aboveground, *without the benefit of fresh air quality*. This air contains odors and gases emitted from wet soils and concrete or other things that might incubate in the envelope.

For example, the worst scenario would be a house and basement that doesn't use forced air heating. Instead, it uses point sources like electric heaters or heat pump split units. Since the only connection between levels is the stairway, the stairway is the only path for dilution of "basement gases." If the recommended envelope flow of 10 cfm to 30 cfm (to 14 L/s) is simply circulated to the basement instead of through the envelope to the outdoors, the basement contaminant gas levels remain high.

A simple compartment model shows that basement contaminant gases for a contaminant free airflow of 30 cfm (14 L/s) reduces the basement air concentration by only 12% versus 100% for the depressurized envelope (*Figure 10a*). It would be even less effective for 10 cfm (4.7 L/s) (*Figure 10b*).[3]

With the depressurization system properly working, these basement gas levels essentially drop 100% to a level of 0% in the basement breathing air.

Conclusions

At least 10% and perhaps 50% or more of building

FIGURE 9 Depressurized insulated wall with fan control.

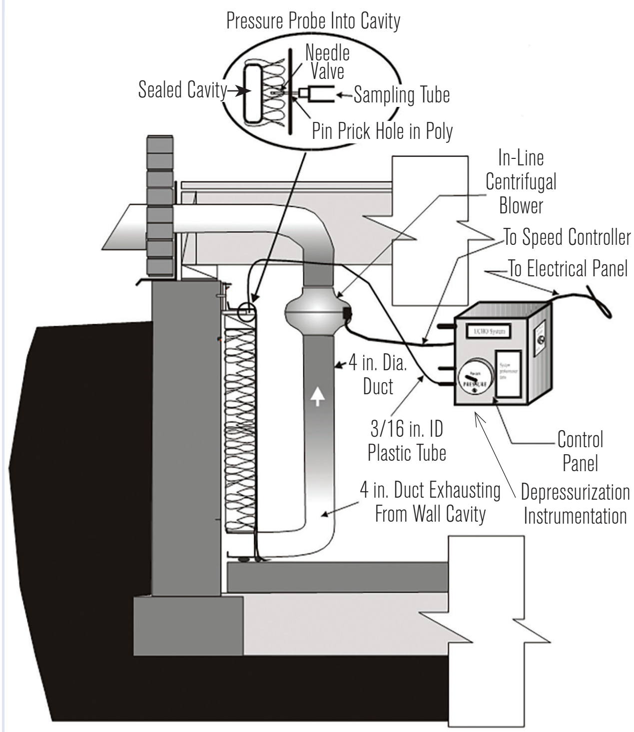
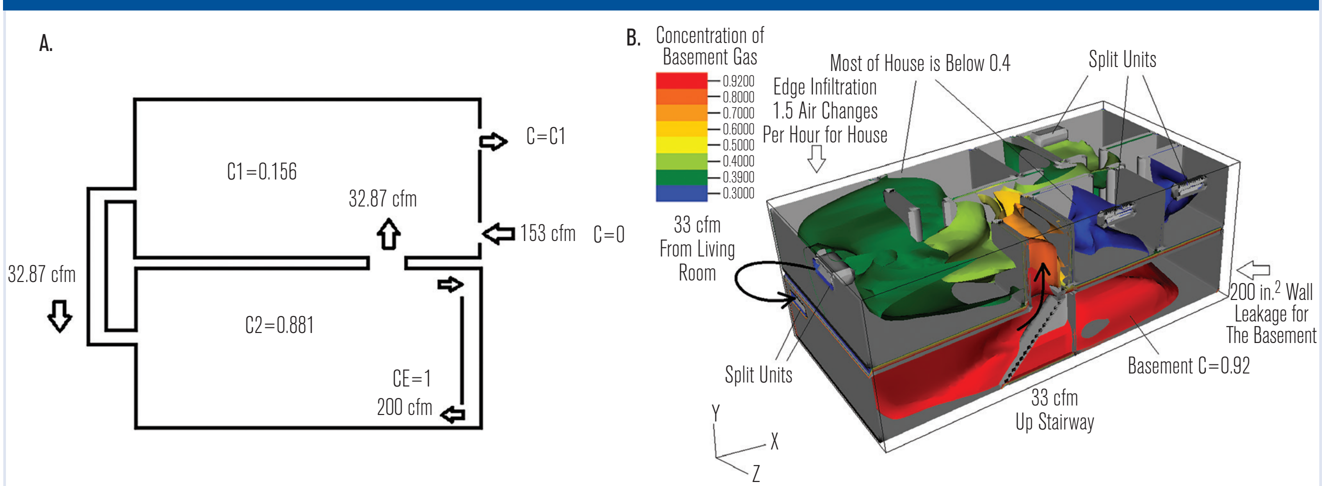


FIGURE 10 (a) Compartment flow and (b) CFD estimates of "basement gas" dilution. C = concentration of the containment gas.



conditioned air circulates behind the insulation in batt-insulated finished basements under winter stack pressures in Canadian and northern U.S. houses and buildings, increasing heating costs more or less commensurately.

Typical batt and foam board-insulated finished basements may not only be wasting winter heating energy, their insulation systems may also be hiding winter condensation and bringing damp envelope concrete and cellulose microbial off-gassing and allergenic aerosols and soil air contaminants into the living space where they can only be addressed by costlier and less-efficient whole-house ventilation and filtration systems.

This heat loss and potential air contamination warrants the attention of building code-setting bodies and agencies promoting building energy conservation and the benefits of healthy and efficient finished basements in homes.

The solution described for the stack-induced airflow problem and for foundation leakage damage mitigation has worked for the many installations built over the last three decades. The solution has kept basements odor-free and comfortable and the envelope materials dry. And, it has conserved winter heating energy, provided an air barrier to soil gas entry, and solved foundation leakage and sewer backup problems. The solution described is approved as a foundation drainage system and, if used in a retrofit, solves foundation leakage problems without costly exterior excavation.

The cost to operate the blower continuously is about $10 to $20 annually, and blowers are typically lasting 20 years or more under continuous operation. This ventilation removes typical basement envelope and soil gas air pollutants with a small amount of ventilation air, something a standard heat recovery ventilator cannot do as completely with a much larger flow rate. It is energy-efficient ventilation as the air exhausted from the basement gives up a portion of its heat as it passes through the insulation envelope, and the basement air that replaces it comes from aboveground infiltration air that has absorbed some of the house radiant heat loss. Home builders should consider developing the tools and skills necessary to seal and depressurize the envelope adequately. This solution has been used in other applications including creating common wall air barriers around smoking rooms and between contaminated and occupied aboveground spaces.

Sprayed on foamed-in-place insulation over interior foundation walls will prevent conditioned air from traveling behind foundation insulation. However, it is expensive, requires fire-rated drywall over it, and makes retrofitting electrical outlets and bathroom vent pipe outlets difficult. Further, unlike the solution proposed in this article, it does not solve a foundation leakage problem without the need to dig outside the foundation to seal cracks. Neither can it mitigate sewer backups. Finally, if there is a fire, post-fire odor cleanup is more difficult. Hence, its use is mainly limited to sealing and insulating foundation walls above the sill plate, and insulating envelopes where flooding has occurred.

References

1. *2005 ASHRAE Handbook—Fundamentals*, 27.12.
2. *2009 ASHRAE Handbook—Fundamentals*, 16.14.
3. California State University. 2014. Center for Energy and Environmental Research and Services split unit prototype code. ■

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