Ventilation for Energy Efficiency and Optimum Indoor Air Quality
13th AIVC Conference, Nice, France
15-18 September 1992

Poster 14

Impact of Subslab Ventilation Technique on Residential Ventilation Rate and Energy Costs.

Y.C. Bonnefous*, A.J. Gadgil**, W.J. Fisk**

* Laboratoire des Sciences de l'Habitat, Ecole Nationale des Travaux Publics de l'Etat, Vaulx-en-Velin, France

** Indoor Environment Program, Lawrence Berkeley Laboratory, Berkeley, California, USA

Summary

Radon is the largest source of risk to human health caused by an indoor pollutant, at least in the industrial countries. Subslab Ventilation (SSV) is one of the most effective and common methods of reducing indoor Rn concentrations in houses with a basement.

In this paper, we first quantify the impact of this technique on the air exchange rate, through numerical modeling of a prototype house with basement for a range of permeabilities of soil and subslab aggregate and various sizes of the cracks in the basement floor. We show that a SSV system can increase the air exchange rate by as much as a factor of 4.5

We then compare the energy and capital costs of a Subslab Depressurisation (SSD) system to those of direct ventilation of the basement as required to lower the indoor radon concentration to an acceptable level, for a Chicago climate. We show that 1) an exhaust ventilation cannot reduce efficiently the indoor radon concentration and may even increase it; 2) a balanced ventilation with heat recovery is only efficient for low premitigation radon concentrations. However, both SSV and balanced ventilation systems are too expensive to be used in low premitigation level houses. A SSD system is the most cost effective technique for reduction of high radon concentrations.

Introduction

Within the United States, exposure to the radioactive decay products of radon (^{222}Rn) in buildings is the most important source of human exposure to environmental radiation and also one of the largest sources of risk to human health caused by an indoor pollutant [1]. In houses with elevated indoor Rn concentrations, the primary source of Rn is usually the surrounding soil where Rn is generated by the radioactive decay of trace amounts of radium. The predominant process of Rn entry into houses with a concrete basement is pressure driven flow of high-Rn soil gas into the basement through small cracks, joints, and holes in its concrete envelope [2].

Subslab ventilation (SSV) is one of the most effective and common methods of reducing indoor Rn concentrations in houses with basements. There are two basic methods of SSV. In subslab depressurisation (SSD), a fan exhausts soil gas from beneath the slab floor to the outside. The fan usually draws air through one or more plastic pipes that penetrate the slab floor. This process decreases the pressure beneath the floor and, therefore, reverses the pressure difference that normally causes soil gas and Rn to flow into the structure. In subslab pressurisation (SSP), outdoor air is forced beneath the slab using a fan (i.e., the direction of air flow is reversed compared to that in a SSD system). SSP ventilates the soil beneath the slab floor, thus reducing radon concentrations within the soil near the slab. Soil gas entry into the structure continues but the concentration of Rn in the entering soil gas is decreased.

Approach

We used a previously tested numerical model [3] to assess the impact of SSV systems on building air exchange rate. The numerical code called Non-Darcy STAR (Non-Darcy Steady State Transport of Air and Radon) is a fully three-dimensional finite difference model, using the Semi Implicit Method for Pressure Linked Equations (SIMPLE) and the Alternate Direction Implicit (ADI) method to solve the Darcy-Forchheimer law (equation 1) together with the continuity equation (2) assuming incompressible gas:

$$\vec{\nabla} p = -\frac{\mu}{k}(1 + c|\vec{V}|)\vec{V} \tag{1}$$

$$\vec{\nabla}.\vec{V} = 0 \tag{2}$$

where p is the disturbance pressure (i.e., pressure change due to the depressurized basement and/or operation of a SSV system), V the soil-gas bulk velocity, k the permeability of the porous media, μ the dynamic viscosity of the fluid, and c the Forchheimer term.

Once pressure and velocity fields are computed we use the model "Ra-Trans" (Radon-Transport) to solve the radon mass balance equation :

$$\vec{\nabla}.(D\vec{\nabla}C_{RN}) - \vec{\nabla}.(\vec{V}C_{RN}) + \varepsilon(S - \lambda_{RN}) = 0 \tag{3}$$

where D is the bulk diffusivity of radon in bulk soil, C_{RN} is the radon concentration in the soil-gas, S is the production rate of radon into the soil-gas per cubic meter of bulk soil, λ_{RN} is the radon decay constant, and ε is the porosity of the media.

Lastly, we compute the radon entry rate and the indoor radon concentration. We assume a typical house geometry consisting of a one story building with a basement and a garage on its side (see figure 1).The pressure, velocity and concentration fields are computed in a soil block of about 27 m x 27 m in an area centered on the basement of the house, and 12.5 m deep below the soil surface. Thanks to a plane of symmetry, only half of this domain is to be modeled. The models assume that 1) each material (i.e. ; soil, backfill and aggregate) is homogeneous and isotropic; 2) the concrete is perfectly impermeable except for cracks; 3) the effect of buoyancy in the soil-gas flow field is negligible; and 4) diffusive transport of radon through concrete and inside the cracks is negligible. The garage is modeled as an impermeable surface. A L-shaped crack is uniformly distributed at all wall/footer/slab joints. The basement is assumed to be depressurized by 10 Pa.

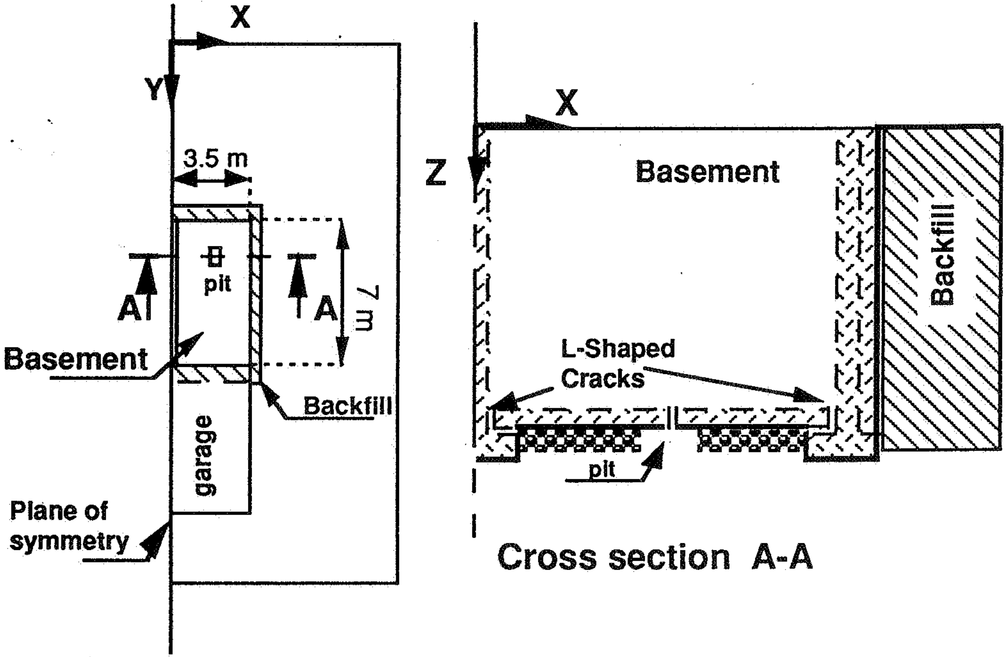

Figure 1: Schematic representation of the typical house as modeled by Non-Darcy STAR .

Impact of SSV systems on building air exchange rate.

We conducted a parametric study on SSV systems. Parameters are soil and gravel permeabilities, mode (SSD or SSP), crack width, and applied pressure. We describe here the effect of SSV systems on the air exchange rate of the building when operating with different parameter values.

The mode of operation, SSD or SSP, has a minor effect on the added air exchange rate. Air is extracted from the basement through the cracks in the slab by a SSD system instead of being blown into the basement through the cracks in the slab by a SSP system. Differences in the flow extracted from and blown into the basement are mainly due to the differences in the pressure gradient between the pit and the basement, e.g.: -60 Pa to -10 Pa for a SSD system versus +60 Pa to -10 Pa for a SSP system. As a consequence, the impact on the building air exchange rate of a SSP system is higher than the one of a SSD system for the same absolute value of applied pressure at the SSV system pit. However, for high values of applied pressure (±250 Pa) and tight soils (configuration leading to high impacts of the SSV system on the building air exchange rate) flows blown into the basement by a SSP system and flows extracted from the basement by a SSD system differed by less than 10 %. We will only present here results for a SSD system, which is the most common.

Gravel permeabilities and Forchheimer terms used in the numerical simulations were previously measured in a laboratory test [3] and are given in Table 1. Soil permeabilities were chosen in the very top of their reported range. With low permeabilities, the soil acts like a perfectly impermeable media. In addition, models using similar hypothesis than non-Darcy STAR tend to under predict flows in the soil by as much as a factor of eight [4], probably because the effective permeability of soils around houses is greater than the average of several point measurements.

Table 1: Gravel permeabilities and Forchheimer terms.

	Gravel N° 1	Gravel N° 2	Gravel N° 3
Permeability [m^2]	2 10^{-8}	1 10^{-7}	3 10^{-7}
Forchheimer term [s/m]	6	13	20

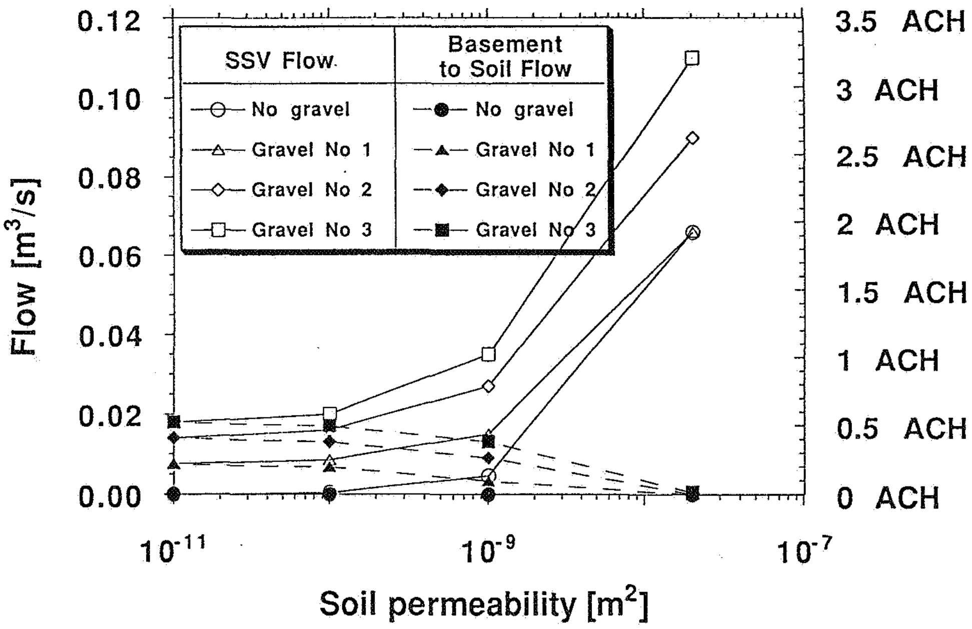

Figure 2: Predicted flows of air in the SSD system and flows of air extracted from the basement through the cracks in the slab. Basement depressurisation is -10 Pa. Applied pressure at the system pit is -60 Pa. A 1 mm L-Shaped crack is uniformly distributed at all wall/footer/slab joints.

We show (Figure 2) that for high soil permeability most of the flow originates from the top soil surface, while for low permeability soils, most of the flow extracted by the SSD system originates from the basement. The flow through the SSD system for a given depressurisation at the pit increases with increasing soil permeabilities and increasing gravel permeabilities. The flow extracted from the basement by the SSD system increases with decreasing soil permeabilities and increasing gravel permeabilities.

Increasing the depressurisation from -60 Pa to -250 Pa at the system pit doesn't affect much the partition of the flows (originating from the top soil surface or from the basement), only their magnitude is increased. The flow extracted from the basement by a SSD system operating at -250 Pa in a 10^{-11} m^2 permeability soil and a 3 x 10^{-7} m^2 permeability gravel, is 0.06 m^3/s (1.8 ACH). The air exchange rate is [5]:

$$R_{tot} = \sqrt{R_{typ.}^2 + R_{add}^2} \qquad (4)$$

where R_{tot} is the total building air exchange rate, $R_{typ.}$ is the typical air exchange rate (0.4 ACH [6]) and R_{add} is the additional air exchange rate due to SSV operation (i.e. , the flow from the basement to the gravel).

The air exchange rate of the building can be increased by as much as a factor of 4.5. Figure 3 shows that the ratio of air extracted from the basement to total SSV flow increases rapidly with decreasing soil permeabilities : from 0 % to 100 % in 2 orders of magnitude of soil permeability. Sealing the cracks can only modify this ratio for high soil permeabilities. However, by increasing the resistance to flow of the cracks, sealing will lower the SSD system flow.

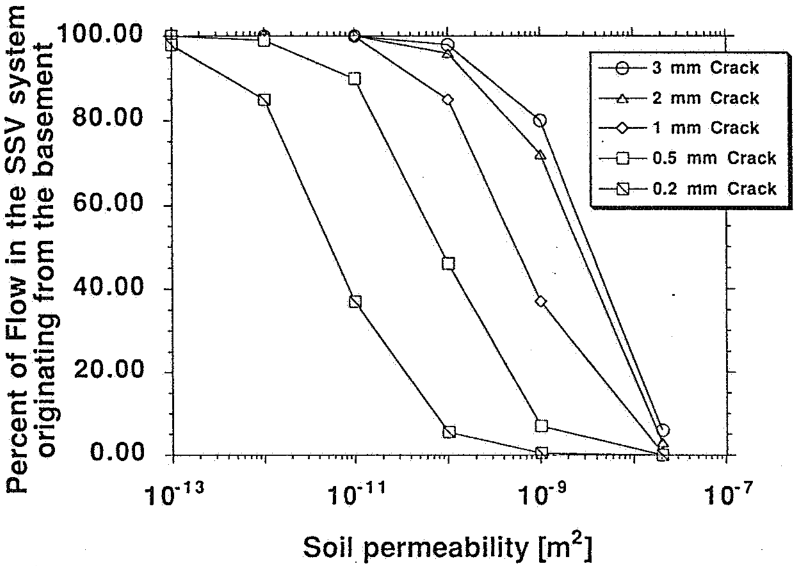

Figure 3: Percent of flow in the SSD system exhaust pipe originating from the basement for various soil permeabilities and crack widths. The gravel permeability is 3.10^{-7} m^2, and the basement depressurisation is -10 Pa.

Cost effectiveness of a SSD system compared to an exhaust ventilation and to a balanced ventilation with heat recovery as a radon mitigation technique.

We used the previously described geometry with a 1 mm L-Shaped crack, soil permeabilities of 10^{-10} m^2 and 10^{-11} m^2 and gravel n° 2. We computed the indoor radon concentration assuming a single zone well mixed building resulting from combinations of three deep soil radon concentrations (30,000 Bq/m^3, 90,000 Bq/m^3 and 180,000 Bq/m^3) and three different winter conditions: A) T_{out} = -10 ºC; B) T_{out} = 0 ºC; C) T_{out} = +10 ºC, with a constant wind speed of 3 m/s.

We made this comparison study on the part of the building modeled. Two SSD systems would be used in our typical building, and we assumed that similarly, up to two exhaust fans or two balanced ventilation systems (or twice as expensive) would be installed as each part of the building would be treated separately. The part of the building considered, has an ELA (Effective Leakage Area) of 0.015 m^2 uniformly distributed on its sides. Its volume is 122.5 m^3.

Case 1: No Mitigation System.

Assuming natural ventilation and no mitigation system, the depressurisation at the basement floor level of the building is given by [7]:

$$\Delta p_f = \Delta p_s + \Delta p_w \qquad (5)$$

where the depressurisation due to the stack effect is:

$$\Delta p_s = \rho g \Delta T (z_f - z_n) / T_{\text{int}} \qquad (6)$$

and z_f-z_n , the difference of elevation between the pressure neutral point and the basement floor level is 3.75 m., Δp_w= 0.6 Pa for a wind speed of 3 m/s.[7], ρ is the density of air, g the acceleration of gravity, ΔT the indoor - outdoor temperature difference and T_{int} the indoor temperature.

The resulting indoor radon concentrations are calculated by:

$$C_{RN,indoor} = \frac{Entry * C_\infty + Q_{Tot} * C_{RN,outdoor}}{Q_{Tot}} \qquad (7)$$

where $C_{RN,indoor}$ is the indoor radon concentration, $C_{RN,outdoor}$ is the outdoor radon concentration equal to 9 Bq/m^3, Entry is the radon entry rate normalised by the deep soil radon concentration, C_∞, and Q_{Tot} is the total flow of air between the building and its surrounding (including the soil).

Table 2 gives the results from this first set of simulations which constitute the base case for the comparison.

Table 2: Radon Entry rate and indoor radon concentration without any mitigation system.

Out. Temp. [°C]	Soil Perm. [m²]	Air change Rate [ACH]	Basem. Depres. [Pa]	Entry Rate [cm³/s]	$C_{RN,int}$ C_∞=30000 [Bq/m³]	$C_{RN,int}$ C_∞=90000 [Bq/m³]	$C_{RN,int}$ C_∞=180000 [Bq/m³]
-10	10^{-10}	0.46	-5.1	195	370	1100	2200
0	10^{-10}	0.40	-3.6	150	320	950	1900
+10	10^{-10}	0.33	-2.1	89	250	740	1500
-10	10^{-11}	0.46	-5.1	24	55	150	290
0	10^{-11}	0.40	-3.6	17	46	120	230
+10	10^{-11}	0.33	-2.1	10	36	92	170

Case 2: With a SSD system

A SSD system is installed and operated with a -150 Pa depressurisation at the system pit. The new depressurisation in the basement is determined by iterating the following process: 1) computation with non-Darcy STAR of the flow exhausted from the basement by the SSD system for a given basement depressurisation, 2) calculation of the depressurisation in the basement integrating the depressurisation associated to the flow extracted from the basement by the SSD system (equations 8 & 9). If the depressurisation is different than the one used in Non-Darcy STAR return to step one with the newly calculated depressurisation.

$$Q_{Tot}=\sqrt{Q_{stack}^2+Q_{wind}^2+Q_{ext.}^2} \tag{8}$$

$$\Delta p_{ext.}=\frac{\rho}{2}\left(\frac{Q_{ext.}}{ELA}\right)^2 \tag{9}$$

where: Q_{stack}, Q_{wind} are the flows due to the stack effect and the wind effect, Q_{ext} is the flow extracted by the system from the basement, and Δp_{ext} is the depressurisation induced by the Q_{ext}.

Table 3: Basement depressurisations and building air exchange rates when a SSD system is operated with a-150 Pa. depressurisation at the pit.

Out. Temp. [°C]	Soil Perm. [m²]	Induced Depres. [Pa]	Total basem. Depres. [Pa]	SSD Flow [m³/s]	Flow from basem. [m³/s]	Flow entering basem. [m³/s]	Indoor Radon Conc. [Bq/m³]	Air change rate [ACH]
-10	10^{-10}	-2.6	-7.7	0.036	0.031	0	9	1.0
0	10^{-10}	-2.6	-6.2	0.037	0.031	0	9	1.0
+10	10^{-10}	-2.7	-4.8	0.037	0.032	0	9	0.99
-10	10^{-11}	-2.8	-7.9	0.034	0.033	0	9	1.1
0	10^{-11}	-2.9	-6.5	0.034	0.033	0	9	1.0
+10	10^{-11}	-2.9	-5.0	0.034	0.033	0	9	1.0

In each case, the SSD is fully successful : no soil gas is entering the basement as the depressurisation in the gravel is lower than the depressurisation in the basement. As a result the indoor radon concentration is equal to the outdoor radon concentration (Table 3, col. 8). However, we see (Table 3, col. 3) that depressurisation induced in the basement by SSD system operation is substantial. This could cause backdrafting of the exhaust fumes of the furnace or other appliances into the house. The ventilation rate of the house is also increased greatly.

Case 3 : Exhaust ventilation as radon mitigation technique

We computed the required air exchange rate to reduce the indoor radon concentration given in Table 2 to either the EPA action limit guideline of 150 Bq/m^3 or either 37 Bq/m^3. From equation 7,

$$R_{tot} = \left[\frac{3600}{Vol}\right]\frac{Entry \bullet C_\infty}{C_{RN,indoor} - C_{RN,outdoor}} \qquad (10)$$

Where: Vol is the volume of the building considered.

Then, we computed the depressurisation induced by the exhaust ventilation at the basement floor level (equation 9) and we used non-Darcy STAR with the new basement depressurisation to compute the actual indoor radon concentration when the exhaust ventilation is operated.

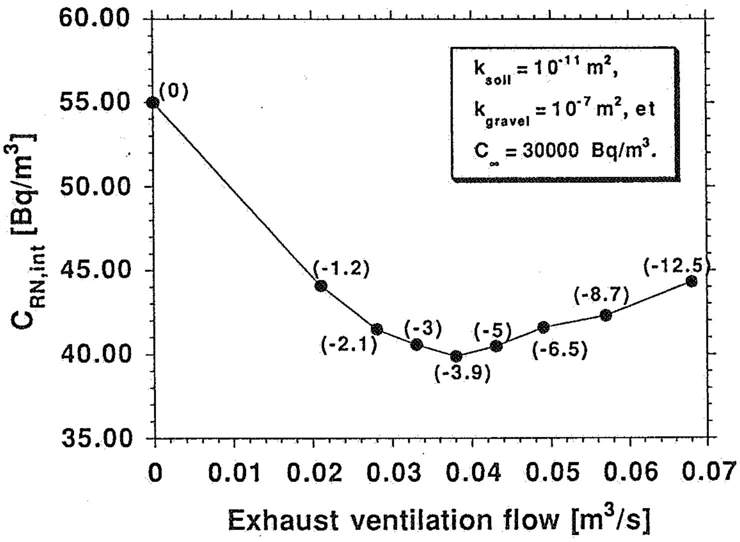

Figure 4: Indoor radon concentration when an exhaust ventilation is operated. The depressurisation in the basement induced by the exhaust ventilation is given in between parenthesis.

For elevated premitigation radon concentration levels, flows required in the exhaust ventilation are unrealistic (up to 6 ACH) When a small reduction of the indoor radon concentration is required, the depressurisation induced by the exhaust ventilation increases the radon entry rate, and the desired indoor radon concentration level is not obtained. We iterated the process : calculation of the required air exchange rate with the latest radon entry rate, calculation of the induced depressurisation and computation of the obtained indoor radon concentration. Figure 4 shows that after a first small decrease in the indoor radon concentration for low exhaust ventilation flows, higher flows may increase the indoor radon concentration. An Exhaust Ventilation shouldn't be used for radon mitigation purposes.

Case 4 : A balanced ventilation system with heat recovery is installed.

A balanced ventilation system doesn't affect the building pressure profile. The building air change rate and then the flow in the balanced ventilation are calculated so that the indoor radon concentration does not exceed 1) 10 Bq/m^3 ($\approx$ outdoor radon concentration), 2) 37 Bq/m^3, and 3) 150 Bq/m^3. (EPA guideline). Air exchange rates are given by equation 11, flows in the balanced ventilation are given by :

$$Q_{bal} = Q_{Tot} - \sqrt{Q_{stack}^2 + Q_{wind}^2} \qquad (11)$$

where Q_{bal} is the flow in the balanced ventilation system.

The maximum flow handled by a practical balanced ventilation is around 0.1 m^3/s. As a consequence, only premitigation levels lower than 16 Bq/m^3 could be reduce to 10 Bq/m^3.

Similarly only premitigation levels lower than 210 Bq/m^3 and 1030 Bq/m^3 could be reduced to 37 Bq/m^3 and 150 Bq/m^3, respectively.

Attaining an acceptable indoor radon concentration, (but not to the outdoor radon concentration) with a balanced ventilation is only possible if the premitigation concentration is low or moderate. Our simulations show a perfectly working SSD system, however we remind the reader that the geometry of the typical house is design for best performances of a SSD system. Nonetheless, SSD system have shown very good performances in field studies and is the most efficient technique to mitigate houses with high radon concentration premitigation levels.

<u>Cost comparison.</u>

For this cost comparison, we considered the "moderate" climate of Chicago. To compute the heating penalty associated with an additional air change rate, we used the bin method as described in Fisk et al. [9]. We use the weather data from the US-Air Force manual [10]. The indoor temperature is 20°C, the building balanced point is 15.6 °C, and the heating season for Chicago is from October to April. The heating load imposed by ventilation is given by:

$$E = \rho.C_p.Vol.R\sum_j \left(T_{in} - T_j\right)\theta_j \qquad (12)$$

Where E is the heating load, C_p is the specific heat at constant pressure of air, T_j is the outdoor temperature at the midpoint of the bin j, θ_j is the number of hours the outdoor temperature falls within the temperature bin j.

The electricity cost in 1992 is \$0.0786 KW/h and the projected real escalation rate for the next 10 years is + 0.12 %[*] . We assumed a 3% real discount rate for money. The net present cost of a system over the next 10 years is then given by:

$$NPC = CC + OPC\sum_{i=1}^{10}\left[\frac{1+f}{1+d}\right]^i \qquad (13)$$

where NPC is the net present cost, CC is the capital cost, OPC is the operating cost, f is the real price escalation rate, and d is the real discount rate.

The installation cost of a SSD system is ≈ \$1100. [11]. The SSD operating cost comprises the fan energy consumption : (50 W) \$35 for 1992, and the heating load. The fan energy is lost as the fan is placed in the stream. Maintenance is done by the homeowner at no cost. The building air change rate when the SSD system is operating, is about 1 ACH (Table 3) compared to about 0.4 ACH in absence of the SSD (Table 2). The heating load of a 0.6 ACH added air change rate is 7.9 GJ (from equation 12) which leads to an additional \$172.5 operating cost in 1992. The net present net cost over 10 years of the SSD system is \$2880 .

The installation cost of a balanced ventilation is: \$1700[**] . Maintenance is done by the homeowner at no cost. The flow in the balanced ventilation is supposed to be fixed over the year at either the value computed for a -10°C outdoor temperature which means that the indoor radon concentration will be lower than the goal concentration 94 % of the time, or either for a 0°C outdoor temperature which means that the indoor radon concentration will be lower than the goal concentration 65 % of the time, but higher 35% of the time.

The effective sensible recovery efficiency of the system is 65 %[**]. This figure accounts for fan energy consumption and the part of this energy recovered by the building. During the heating season, the operating cost of the balanced ventilation is then equal to the energy cost of the heating load of 35% of the air change rate induced by the balanced ventilation. For the rest of the year, the operating cost of the system is equal to the cost of the fan energy consumption.

---

[*] Electricity price and projected real escalation rate from Energy Information Agency, Annual Energy Outlook 1992, p. 66

[**] Source: Conservation Energy Systems Inc, vänEE, Mineapolis, USA

Table 5 give the net present cost of the balanced ventilation for the different combinations. We see that for small reductions of the indoor radon concentration (≤250 Bq/m^3), a balanced ventilation system could be cheaper than a SSD system. However the cost of both systems is probably too high for most homeowners to be used for such a purpose. New techniques (passive techniques ?) that do not substantially increase energy use are needed to deal with low premitigation level houses.

Table 5: Net Present Cost of a balanced ventilation with heat recovery over 10 years.

Out. Temp. [°C]	Soil Perm. [m^2]	Indoor Radon Concentration [Bq/m^3]	PNC C_∞ 30000 over 10 years	PNC C_∞ 90000 over 10 years	PNC C_∞ 180000 over 10 years
-10	10^{-11}	37	2250	**3600**	NR
0	10^{-11}	37	2100	**3000**	**4460**
-10	10^{-10}	150	2600	NR	NR
-10	10^{-11}	150	NA	NA	2370

Conclusion

Our numerical model shows that with low permeability soils a SSD system can have a great impact on the building air exchange rate, as for tight soil all of the flow in the SSD system comes from the basement. Sealing the cracks in the basement floor will reduce the flow in the SSV system and the amount of increased ventilation in the house.

An exhaust ventilation cannot reduce the indoor radon concentration efficiently and may even increase it. A balanced ventilation with heat recovery could be a cheaper alternative to a SSD system for small required radon concentration reductions (≤ 250 Bq/m^3). However, both system are too probably expensive to be recommended at such low premitigation levels.

For elevated premitigation radon levels, a SSD system is the most efficient and cost effective technique.

Acknowledgements

This work was supported at Indoor Program of Lawrence Berkeley Laboratory by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy under Contract DE-AC03-76SF00098

References

1. Nero A.V. Sci. Am. 1988, 258 (5), 42-48.

2. Nazaroff, W.W.; Nero A.V. Radon and its decay products in indoor air; John Wiley & Sons: New York, 1988.

3. Bonnefous, Y.C., Gadgil, A.J, Fisk, W.J., Prill, R.J. and Nematollahi "A. Field Study and Numerical Simulation of Subslab Ventilation Systems". Lawrence Berkeley Laboratory Report LBL-31942, Berkeley, CA, 1992, submitted to E. S. & T.

4. Garbesi, K., Sextro, R.G., Fisk, W.J., Modera M.P., and Revzan, K.L. "Soil-Gas Entry into an experimental Basement: Model-Measurement Comparisons and Seasonal Effects", Lawrence Berkeley Laboratory Report, LBL-31873, University of California, Berkeley, CA, submitted to E. S. & T

5. Sherman, M. H. (1990) "Superposition in infiltration modelling", Lawrence Berkeley Laboratory Report, LBL - 29116, University of California, Berkeley, CA, submitted to J. Indoor Air.

6. Palmiter, L. and Brown, I. (1989) "Northwest residential infiltration survey: analysis and results". Ecotope, 2812 East Madison, Seattle, WA.

7. Fisk, W. J. and Mowris, R.J. (1987) "The Impacts of Balanced and Exhaust Mechanical Ventilation on Indoor Radon", Proceedings of the 4th International Conference on Indoor Air Quality and Climate: Indoor Air '87, Berlin, West Germany, 17-21 Août 1987, vol 2 pp 316-320.

8. Mowris, R.J. and Fisk, W. J. (1987) "Modeling the effects of exhaust ventilation on radon entry rates and indoor radon concentrations, Lawrence Berkeley Laboratory Report, LBL-22939, University of California, Berkeley, CA.

9. Fisk, W. J. and Turriel (1983) "Residential Air-to-Air Heat Exchangers: Performance, Energy Savings, and Economics", Energy and Buildings, (1983) 197-211.

10. Facility Design and Planning, Engineering Weather Data, US Air Force Manual 88-29, 1978.

11. Henschel, D.B., "Cost Analysis of Soil Depressurisation Techniques for Indoor Radon Reduction" Indoor Air, Vol 1, N° 3, 1992