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Indoor Radon Reduction in Crawl-space Houses: a Review of Alternative Approaches

D. Bruce Henschel[1]
U.S. Environmental Protection Agency

Abstract

An analysis has been completed of the performance, mechanisms, and costs of alternative technologies for preventing radon entry into the living areas of houses having crawl-space foundations. Sub-membrane depressurization (SMD) is consistently the most effective technique, often providing radon reductions of 80-98% in the living area. It has a relatively high installation cost, but a moderate annual operating cost. Forced crawl-space depressurization is the second most effective, giving reductions of 70-96%. Crawl-space depressurization is less well demonstrated than is SMD, and performance will vary with crawl-space tightness and weather, but it will be a primary option when large radon reductions are needed in buildings with crawl spaces which are inaccessible for installation of SMD. Crawl-space depressurization has a lower installation cost than SMD, but its operating cost may be three times higher.

Natural crawl-space ventilation and forced crawl-space pressurization each typically provides roughly 50% reduction or less in the living area. The lack of a clear benefit of crawl-space pressurization in most installations probably indicates that the crawl space is in fact not being pressurized. Crawl-space sealing and barriers (as stand-alone methods) usually give little or no reduction.

KEY WORDS:
Radon, Mitigation, Crawl-space houses, Sub-membrane depressurization, Crawl-space pressure adjustment, Natural ventilation

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[1] Air and Energy Engineering Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711, USA

Introduction

The objective of this paper is to review the available experience with the various alternative techniques for preventing radon entry into the living area of crawl-space houses. Based upon an analysis of the available data, perspective is offered regarding: the mechanisms which appear to be playing a role in determining the performance of the technique; the radon reduction performances that have been observed with each technique under different conditions; the conditions under which each technique might be most applicable; and expected installation and operating costs. Finally, conclusions are drawn regarding the additional data that would be most valuable in improving our current ability to effectively select and design radon reduction techniques for crawl-space houses.

This paper addresses radon reduction techniques which function by reducing or preventing radon entry into the living area: soil depressurization, ventilation or pressure adjustments in the crawl space, and sealing of the living-area or crawl-space floors. The paper does not discuss radon reduction techniques intended to remove radon after entry into the living area, including ventilation of the living area and air cleaners; these techniques are largely independent of substructure type.

Crawl spaces can be subdivided into two categories:

- Those which are nominally isolated from the livable area. Such isolated crawl spaces are commonly, but not always, ventilated to the outdoors by screened vents in the perimeter foundation wall.
- Those which are open to the livable area. This commonly occurs when the crawl space adjoins a basement, and there is no frame wall separating the basement from the exposed soil in the crawl space. Such open crawl spaces are often not ventilated to the outdoors.

Crawl spaces can also be subdivided according to whether they are accessible (i.e., with sufficient headroom and with an access door) or inaccessible. In the extreme case, a house may be built over a "crawl space" which has head room no greater than about 0.3 m, and has no access.

The discussion here assumes that the crawl space has a floor consisting of bare earth, or of gravel or a plastic vapor barrier on top of bare earth. Crawl spaces having a concrete slab (or an unfinished concrete "wash" floor) would commonly be treated using sub-slab depressurization (SSD), similar to a basement or slab on grade, and are not considered directly in this paper.

Dynamics of Crawl-space Houses

Crawl spaces which are nominally isolated from the living area and are ventilated to the outdoors are not in fact decoupled from the living area. Some fraction of the radon that enters the crawl space by either convection or diffusion from the exposed soil, will always enter the living area by convective flow.

The degree of coupling between the crawl space and the living area will depend upon: a) the leakage area in the foundation wall, between the crawl space and outdoors; b) the leakage area between the crawl space and the livable space; and c) the presence of any forced-air ducting in the crawl space.

When the temperature in the living area is greater than the temperature outdoors, warm house air will exfiltrate from the living area above the neutral pressure plane. This air must be replaced by outdoor air infiltrating directly into the living area through the superstructure walls below the neutral plane, and by air infiltrating via the crawl space. The relative amounts of infiltrating air coming from these two sources will depend upon the relative leakiness of the living area vs. the crawl space.

The effective leakage area of crawl spaces will vary depending upon crawl-space size, foundation wall material (commonly hollow block vs. poured concrete), and method of construction. Blower door testing in nine crawl-space houses in Tennessee having an average floor area of 164 m^2 and having hollow block foundation walls, showed that the average effective leakage area of the crawl spaces (1,690 cm^2) was greater than that of the living areas (1,064 cm^2), even with the crawl-space foundation vents sealed (Brennan et al., 1990). The crawl-space leakage area included an average of 355 cm^2 in the floor between the crawl space and the living area, suggesting that the remaining 1,335 cm^2 was associated with the foundation wall. When a crawl space is as leaky as this, it is reasonable to assume that a significant fraction of the air infiltrating into the living area will be crawl-space air. The foundation walls will provide openings for infiltrating air to enter the crawl space from outdoors, even with the vents sealed, and the floor openings will provide access for that air (and the crawl-space radon) to then flow into the living area.

Tracer gas testing in two crawl-space houses in Alabama, without an adjoining basement wing, confirmed that at least 65 to 92% of the air exfiltrating from the living area had infiltrated into the structure via the crawl space (Matthews et al., 1989).

In terms of pressures, during the heating season, the living area (below the neutral plane) will tend to be depressurized relative to both the outdoors and the crawl space, causing infiltration from both locations. The crawl space will normally be slightly depressurized overall relative to outdoors. Natural crawl-space depressurizations of <0.2 to 4 Pa relative to outdoors have been reported, depending upon the leakiness of the foundation walls, with the living area being further depressurized by 0 to 2 Pa relative to the crawl space (Pyle and Leovic, 1991; Turk, 1991).

Radon will enter the crawl space from the soil floor by convective flow and by diffusion. The convective flow will be increased when the crawl space is depressurized relative to the soil, by the thermal effects created by the living area and by wind effects. Diffusion will always be a contributor, and will make its greatest contribution when soil or rock with elevated radium content is near the soil surface.

Some of the radon released into the crawl space will be carried outdoors by the outdoor air which will be infiltrating into, and exfiltrating out of, the crawl space through the foundation vents and other openings (i.e., as the result of natural ventilation of the crawl space). On the other hand, some of the radon will be carried up into the living area, in response to the thermally induced effects discussed previously. The amount of the radon that enters the living area rather than exfiltrating outdoors will vary significantly, depending on the foundation wall and floor leakage areas, and on temperature and wind effects. In one crawl-space house having 14 foundation vents, where sulfur hexafluoride (SF_6) tracer gas was released into the crawl space as a surrogate for radon, testing with and without the vents sealed showed that 30 to 65% of the SF_6 released into the crawl space entered the house (Nazaroff and Doyle, 1985).

The crawl-space dynamics would be altered if the leakage area were changed through the perimeter foundation wall, or through the floor between the crawl space and the living area. These effects are discussed later in this paper, in connection with natural ventilation of the crawl space and with sealing of the floor, respectively.

If present in the crawl space, ducting for a forced-air furnace can have several effects. Because this ducting is typically very leaky at its seams, and because it penetrates the floor decking, it would be expected to increase the leakage area in the floor between the crawl space and the living area. In the blower door study referenced earlier (Brennan et al., 1990), the floors in the four houses having forced-air ducting in the crawl space had an average effective leakage area of 484 cm^2; the floors in the five without ducting had an average leakage area half that size, 245 cm^2, appearing to confirm expectations. But much of this decrease in floor leakage area in these particular houses appears to be due to the fact that the houses without ducts were the smaller houses, which would be expected to have the lower total floor leakage areas anyway. The average *specific* leakage area of the floors for the five houses without ducts – 2.1 cm^2 of floor leakage area per m^2 of floor area – is only slightly lower than that for the four houses with ducts (2.4 cm^2 per m^2).

In addition to the expected increase in floor leakage area, any low-pressure return ducting in the crawl space will draw crawl-space air into the system and distribute it throughout the house. This will substantially increase interzonal mixing. On the other hand, any high-pressure supply ducting in the crawl space will be blowing circulating air into the crawl space through the unsealed seams in the duct, in effect pressurizing the crawl space using air from the living area. This will also increase interzonal mixing.

The preceding discussion has focused on the dynamics for a crawl space that is nominally isolated from the livable area. If instead the crawl space is open to an adjoining basement, the crawl space will be closely coupled with the basement, and the dynamics would be the same as those of the basement.

Alternative Radon Reduction Methods for Crawl-space Houses

In general, any radon which enters the living area as a result of the crawl space must first pass through the crawl space. The techniques for preventing soil gas entry into the living area can thus be subdivided into two categories: a) those which prevent the radon from entering the crawl space to begin with; and b) those which prevent the radon in the crawl space from entering the living area.

The radon reduction techniques considered here are summarized in Table 1. Each technique is discussed in further detail in the sections which follow. SMD, crawl-space pressurization, and barriers over the crawl-space floor are techniques aimed primarily at preventing radon entry into the crawl space. Crawl-space depressurization and sealing of the floor between the crawl space and the living area are techniques which function primarily by preventing crawl-space air from entering the living area. Natural ventilation of the crawl space reflects elements of both categories.

Estimated installation and operating costs are presented for each approach. The assumptions used in deriving the operating costs are presented in Table 2. To facilitate comparison of the techniques, operating costs are calculated for a "baseline" set of conditions (defined in Table 2) which are felt to represent a fairly typical set of circumstances. Operating costs are also calculated for a broad range of values for each of the parameters which impact operating costs, to illustrate the range of operating costs that may be encountered in practice.

Sub-membrane Depressurization (SMD)

Active SMD involves installation of a membrane (usually polyethylene sheeting) over the crawl-space floor, and drawing suction beneath this membrane using a fan. This is analogous to installing a plastic "slab" over the floor, and drawing suction beneath this slab using either individual suction pipes (analogous to SSD) or a segment of perforated piping beneath the membrane (analogous to drain-tile depressurization, or DTD). Installation of the membrane permits the treatment to concentrate on the soil (or on the narrow gap which may be visualized between the membrane and the soil), rather than addressing the entire crawl-space volume. SMD is thus the variation of the active soil depressurization technology which is applicable to crawl-space houses.

One specific configuration of a SMD system, utilizing sub-membrane perforated piping, is illustrated in Figure 1.

Like other active soil depressurization techniques, SMD probably works primarily by two mechanisms. Perhaps the primary mechanism is depressurization of the sub-membrane region relative to

Table 1 Summary of techniques to prevent radon entry into crawl-space houses

Technique	Radon reduction efficiency[1]	Installation cost[2,3]	Annual operating cost Baseline[2,4]	Annual operating cost Range[2,4]	Advantages/disadvantages
Active soil depressurization techniques					
Sub-membrane depressurization (SMD)	80-98%	$1,000-$2,500	$62	$30-$225	High radon reductions achieved consistently. Relatively well demonstrated. High installation cost. Crawl space must be accessible. Membrane durability not fully demonstrated.
Crawl-space ventilation/pressure adjustment techniques					
Crawl-space depressurization	70-96%	$400-$1,000[5]	$192	$50-$350	Second only to SMD in radon reduction performance. Potential low installation cost. Can treat inaccessible crawl spaces. Not well demonstrated. Ability to consistently achieve and maintain adequate depressurization unclear. Heating/cooling penalty high. Risk of combustion appliance back-drafting.
Crawl-space pressurization	35-80%	$400-$1,000[5,6]	$192	$50-$350	Can treat inaccessible crawl spaces. Avoids risk of back-drafting. Appears no more effective than natural ventilation. Not well demonstrated. Ability to achieve and maintain pressurization uncertain. Possible risk of water pipe freezing. May force crawl-space contaminants into living area. Will not address radon entering crawl space by diffusion.
Natural crawl-space ventilation	20-80% (often no more than ~50%)	0-$600[5,6]	>0	Variable	Potential low installation cost. Can be simple to implement. Completely passive. Only moderate radon reductions; performance may be variable. Possible risk of water pipe freezing.
Sealing and barrier techniques					
Sealing of floor between crawl space and living area	About 0	Variable	0	0	Completely passive. Ineffective for reducing radon levels in living area. May be more applicable in new construction.
Barrier over soil in crawl-space	0-30%	$300-$1,000	0	0	Completely passive. Limited effectiveness for reducing radon. Durability of barrier a major concern.

1 Range of radon reductions measured in the living area during testing of each technique.
2 All costs are expressed in U.S. dollars.
3 Installation costs based on assumption that system is installed by a commercial mitigator.
4 The assumptions used in deriving the annual operating costs are presented in Table 2. Operating costs include fan electricity and heating/cooling penalty only, not maintenance costs.
5 The maximum sealing effort included in these installation costs is caulking of accessible openings in foundation walls and/or overhead floor, and sealing of seams in forced-air ducts in the crawl space. The costs do not include a major effort to, e.g., isolate an open crawl space from an adjoining basement.
6 Includes insulation of water pipes; does not include insulation under floor between crawl space and living area.

Table 2. Assumptions used in estimating annual operating costs

Variable	Baseline value	Range	Comments
Fan power consumption			
– SMD	65 W	50-90 W	Fan rated at 90 W maximum. Baseline is average actual consumption observed for SSD systems in basements and slabs on grade using 90 W fans (Bohac et al., 1991; Turk, 1991), assuming SMD systems operating at about same point on fan performance curve. Range incorporates maximum as well as reasonable low consumption.
– crawl-space depressurization, pressurization	90 W	50-90 W	Due to high flows, baseline assumes 90 W fan operating near rated maximum. Range includes reduced consumption for lower flows observed in tight (inaccessible) crawl spaces (Turk, 1991; Kladder, 1992).
Fan operation	24 hr/day, 365 day/yr	--	No range considered.
Fan exhaust rate			
– SMD	20 l/sec	10-60 l/sec	Baseline is representative of flows observed with SMD systems with no gravel on the floor and the membrane well sealed (Findlay et al., 1990; Messing, 1990; Bohac et al., 1991;Howell and Jones, 1992; Kladder, 1992). Range includes lowest flows observed for that configuration; and high flows seen in systems with gravel, incomplete sealing, or high leakage through block foundation walls (Findlay et al., 1990; Messing, 1990; Shearer, 1992).
– crawl-space, depressurization, pressurization	60 l/sec	25-60 l/sec	Baseline represents 90 W fan operating at maximum flow that it can usually achieve when connected to length of 10-cm diameter piping typical of crawl-space depressurization and pressurization systems in leaky crawl spaces. Low end of range reflects low flows that have sometimes been sufficient in tight (inaccessible) crawl spaces (Turk, 1991; Kladder, 1992).
Fraction of fan exhaust which is treated air from the living area			
– SMD	25%	0-50%	Range is based on: limited data from four houses indicating that anywhere between 0% (Fitzgerald 1992) and 100% (Matthews et al. 1989; Bohac et al. 1991) of the SMD exhaust air can be drawn from the crawl space, even when the membrane is nominally well sealed; and the arbitrary estimate that between 25 and 50% of this crawl-space air may be treated air drawn into the crawl space from the living area (depending upon relative leakiness of foundation walls vs. floor). Baseline is mid-point of range.
– crawl-space depressurization, pressurization	60%	30-100%	Range assumes that: 100% of exhaust air is drawn from crawl space (or that 100% of pressurization supply air is blown into crawl space); and that up to 100% of this crawl-space air is drawn from (or blown into) living area in inaccessible crawl spaces with tight foundation walls (Turk 1991). The percentage of air drawn from the living area is higher than that estimated for SMD, assuming that the depressurization or pressurization system has more effectively changed the pressure differential across the floor. Baseline is approximate mid-point of range.

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Table 2. Continued ...

Variable	Baseline Value	Range	Comments
Increase in ventilation rate in living area			
– SMD, crawl-space depressurization, pressurization	See comments	--	Living area ventilation rate is assumed to increase by an amount equal to the amount of living-area air in the fan exhaust (or the amount of air blown into living area by pressurization system). (In fact, the actual change in ventilation rate may be less; some portion of the system exhaust may simply be modifying the ventilation patterns of the house rather than increasing the ventilation rate.)
– natural ventilation	0	0 to >0	Baseline reflects fact that the limited tracer gas results show that opening foundation vents increases ventilation rate of the living area by no more than 0 to 10% (Nazaroff and Doyle 1985; Findlay et al. 1989). Except in tight houses, the increase infiltration via the crawl space by opening vents may often be offset by a decrease in infiltration via the superstructure walls.
Climate	Washington, D.C.	Los Angeles to Minneapolis	Baseline climate (Washington) is 2,340 heating C°-days and 1,300 cooling infiltration C°-days (Sherman 1986). Mild climate (Los Angeles) is 940 heating C°-days and 310 cooling C°-days; extreme climate (Minneapolis) is 4,460 heating C°-days and 820 cooling C°-days.
Heating system	Forced-air furnace	--	Furnace burns natural gas and is 70% efficient.
Cooling system	Electric air conditioner	--	Air conditioner coefficient of performance is 2.0.
Cost of electricity	$0.077/kWh	$0.060-$0.096/kWh	Baseline is average cost of electricity in the U. S. in 1989 (U. S. Bureau of the Census, 1991). Range covers cost of electricity around the U. S. in 1987 (U. S. Department of Energy, 1987).
Cost of natural gas	$0.0052/MJ	$0.0043-$0.0064/MJ	Baseline, range obtained from same sources as the cost of electricity, above.
Maintenance costs	--	--	Maintenance costs are not included in these estimates.

the crawl space, preventing soil gas flow up into the crawl space from beneath the membrane. If there are any unsealed openings in the membrane, the flows will consist of crawl-space air flowing down into the sub-membrane region, rather than soil gas flowing up into the crawl space. Since all of the radon which enters the living area of a crawl-space house usually flows first through the crawl space, preventing radon entry into the crawl space will prevent entry into the living area.

If the sub-membrane region can be effectively depressurized everywhere, the depressurization will create a continual flow of air beneath the membrane toward the system fan. This air can be crawl-space air leaking through unsealed membrane openings, air leaking from the block foundation walls, or soil gas (including outdoor air drawn through the soil). This air flow will sweep away any radon leaving the soil by either convection or molecular diffusion. In theory, only a few liters per second of flow in the SMD piping should be sufficient to maintain adequate sub-membrane flows (i.e., adequate sub-membrane depressurization) when the crawl space is depressurized relative to the soil by a fraction of a pascal, assuming a reasonable leakage area in the membrane. In practice, with the 50 to 90 W fans commonly used in SMD systems, flows are much greater, commonly 10 to 30 l/sec and higher. Although these fans may be oversized in some installations, they can be necessary to ensure that adequate sub-membrane flows are in fact maintained everywhere.

Limited measurements of depressurization be-

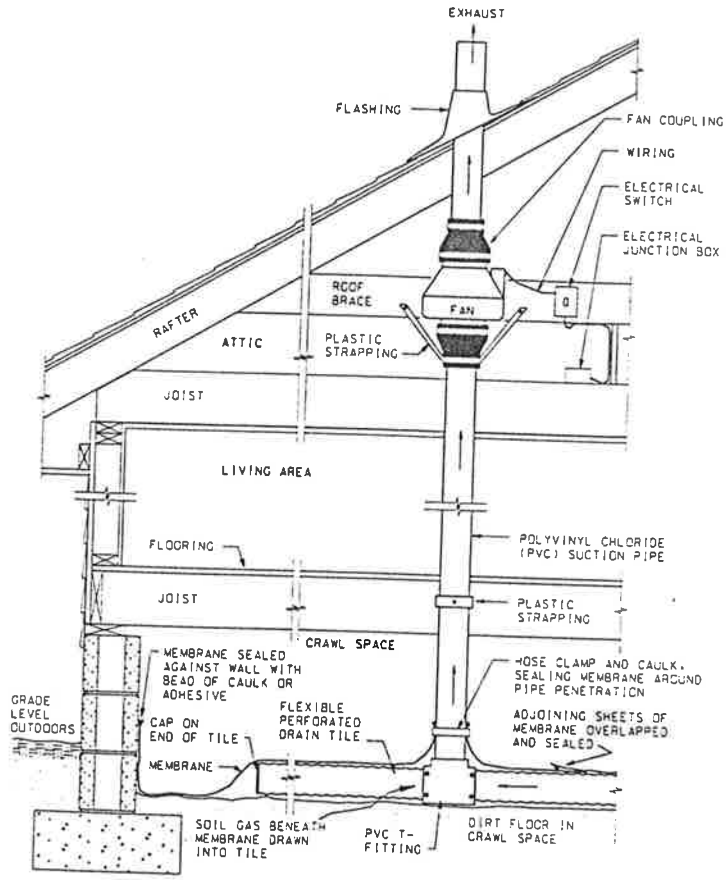

Fig. 1. One typical design for a sub-membrane depressurization (SMD) system.

neath SMD membranes in a number of Tennessee houses have shown that measurable suctions (down to 0.2 to 0.4 Pa) may extend perhaps only 3 to 5 m from a suction pipe when the membrane is resting on low-permeability soil (Pyle and Williamson, 1990). However, smoke tracer testing at openings in the membrane at more distant locations in these houses confirms that flows are often still downward, from the crawl space into the sub-membrane region, despite the lack of measurable depressurization (Brennan, 1992).

A second SMD mechanism, common to soil depressurization systems, is ventilation/dilution of the sub-membrane radon levels by air flow from the crawl space and outdoors. With reduced radon concentrations beneath the membrane, the amount of radon entering the crawl space by convective flow will be less, if the sub-membrane depressurization is overwhelmed at any location where there is an opening through the membrane. Also, less radon would diffuse through the membrane.

A third mechanism that can also come into play is ventilation or depressurization of the crawl space by the SMD fan. This could occur because up to 100% of the air exhausted by the SMD fan can be drawn from the crawl space, even when the membrane is nominally sealed.

As shown in Table 1, SMD has consistently been found to be the most effective approach for reducing radon in crawl-space buildings. It commonly provides radon reductions of 80 to 98% in the living area when the crawl space is the sole source of the indoor radon (Osborne et al., 1989; Findlay et al., 1990; Pyle and Williamson, 1990; Pyle and Leovic, 1991). Commercial radon mitigators working in regions having a significant number of crawl-space houses have reported similar success with SMD (Anderson, 1992; Howell and Jones, 1992; Kladder, 1992; Shearer, 1992). The fact that SMD sometimes achieves only 80% reduction indicates that the suction field sometimes does not extend beneath the entire membrane, or perhaps that block foundation walls are not being adequately treated by the system.

SMD would be the primary mitigation method considered in any house where: a) radon reductions greater than about 50% are needed, thus ruling out natural ventilation of the crawl space as an option; b) the crawl space is a major (or the sole) radon source;

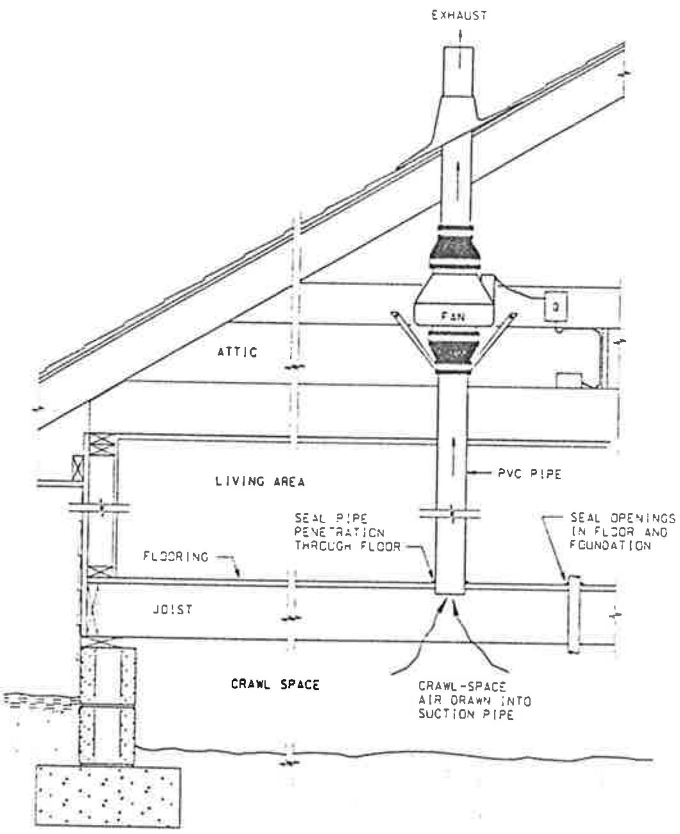

Fig. 2. One possible design for a crawl-space depressurization system.

and c) the crawl space is accessible, permitting installation of the SMD system. Because of its high efficiency, SMD may still be the technique of choice even where reductions below 50% would be sufficient.

Where the crawl space is adjoined by a basement wing, which is common, the basement will often be the major radon entry route. In this case, the SMD system will usually need to be supplemented (or replaced) by a SSD or DTD system in the basement (Gilroy and Kaschak, 1990; Messing, 1990; Pyle and Williamson, 1990; Dudney et al., 1991; Anderson, 1992; Howell and Jones, 1992; Kladder, 1992; Shearer, 1992).

A national survey of mitigators indicated that SMD is the technique most commonly utilized in crawl-space buildings by about one-third of the mitigators surveyed (Hoornbeek and Lago, 1991). The two-thirds preferring other techniques are most likely dealing with: a) houses having adjoining basements, where SSD or DTD in the basement is often sufficient (perhaps in combination with crawl-space isolation or ventilation, if the crawl space is treated at all); or b) low indoor radon levels, where crawl-space ventilation can prove sufficient.

As shown in Table 1, the installation cost for SMD is typically in the range of $1,000-$2,500 if installed by a commercial mitigator (Henschel, 1991). (All costs in this paper are expressed in U.S. dollars.) Among the factors contributing to the breadth of this range are the characteristics of the house (such as the crawl-space size) and the specific design of the SMD system.

SMD has the highest installation cost of any of the crawl-space treatment options, with the possible exception of an intensive crawl-space sealing effort. However, relative to the next most effective approach – crawl-space depressurization, where the entire crawl space is depressurized – SMD has a much lower annual operating cost (including fan electricity and the heating/cooling penalty in the house, but excluding system maintenance). The estimated annual operating cost for SMD is $62 at baseline conditions, as defined in Table 2, about one-third that for crawl-space depressurization. The membrane reduces the amount of air drawn out of the crawl space, and hence the amount of conditioned air drawn out of the living area overhead.

Crawl-space Depressurization

With active crawl-space depressurization, an exhaust fan is mounted to blow crawl-space air outdoors. Installation of the fan may have to be accompanied by some sealing of the crawl space, to reduce the crawl-space leakage area and to thus aid in depressurizing the crawl space. As a minimum, any foundation vents should be closed. The objective is to depressurize the entire crawl space relative to the living area, rather than depressurizing just the region beneath a membrane over the floor.

One configuration for a crawl-space depressurization system is illustrated in Figure 2. Another configuration that has been tested involves mounting the fan in the crawl space or outdoors near grade beside the house, and discharging the fan exhaust near grade.

Crawl-space depressurization works primarily by reversing the natural flow patterns between the crawl space and the living area. If depressurization relative to the living area is successful, the normal flow of radon-containing crawl-space air up into the living area, discussed in the earlier section on house dynamics, would be stopped. The flow between the two regions would instead consist of radon-free living-area air flowing down into the crawl space.

Crawl-space depressurization might also be expected to function in part by increasing the ventilation rate of the crawl space, diluting the crawl-space radon with an increased flow of air from outdoors and from the living area. In that case, any crawl-space air which did flow into the living area would carry less radon. However, crawl-space depressurization would also be expected to increase the convective flow of soil gas into the crawl space, at least partly offsetting any reductions in crawl-space radon due to increased ventilation.

Thus, the role of the ventilation/dilution mechanism in a given house will depend upon the relative increases in radon flow from the soil vs. the air flow from outdoors and the living area into the crawl space. In several cases, radon concentrations in the crawl space have been found to remain about the same, or to increase, when the crawl space is depressurized (Findlay et al., 1989; Pyle and Williamson, 1990; Pyle and Leovic, 1991). In these cases, increased radon flow was largely or entirely offsetting the increased ventilation, and the dilution mechanism was providing little or no net benefit. But in two other houses, crawl-space radon levels fell 40 to 50% when the exhaust fan was turned on, indicating that the dilution mechanism was having a net effect (Findlay et al., 1989).

As shown in Table 1, crawl-space depressurization has consistently proven second only to SMD in effectiveness in reducing living-area radon levels. Living-area reductions ranging from 70 to 96% have been reported from tests in nine crawl-space buildings where crawl-space exhaust flows ranged between 25 and 60 l/sec (Findlay et al., 1990; Pyle and Williamson, 1990; Pyle and Leovic, 1991; Turk, 1991).

As a stand-alone system, this technique has been used only infrequently by commercial mitigators in the U.S., in houses where the crawl spaces were inaccessible and SMD was thus not an option (Kladder, 1992). Usage has been limited due to concerns regarding reliability of performance, the high heating/cooling penalty, and possible combustion appliance back-drafting. Where a basement adjoins the crawl space, some mitigators have reported connecting a crawl-space depressurization leg into a basement SSD system (Howell and Jones, 1992; Shearer, 1992). However, it is unclear to what extent these crawl-space legs effectively depressurize the crawl space, and to what extent they contribute to the performance of the basement SSD system.

Performance will depend on the degree of crawl-space depressurization that can be achieved relative to the living area. This will in turn depend on the tightness of the crawl space and the size of the exhaust fan.

Crawl-space depressurizations have been reported in only a few houses. In one house with an inaccessible crawl space, having very tight foundation walls and an unusually tight floor between the crawl space and the living area, a fan exhaust flow of 25 to 50 l/sec depressurized the crawl space by about 5 Pa relative to the living area, providing living-area radon reductions of over 90% (Turk, 1991). In a second house with an inaccessible crawl space (90 m^2) and a tight foundation wall, but with a much leakier floor, an exhaust of 60 l/sec provided a depressurization of only 0 to 1 Pa relative to the living area, and a radon reduction of about 70% (Turk, 1991). In a 430 m^2 school building that had a poured concrete floor overhead (much tighter than a conventional wooden floor), an exhaust of 130 l/sec provided a crawl-space depressurization of 0 to 1 Pa and a radon reduction greater than 90% (Pyle and Leovic, 1991). With the foundation vents sealed, this school crawl space had a very low specific leakage area of only 1 cm^2 per m^2 of floor area.

Typical crawl spaces, with relatively leaky floors and foundation walls, were reported to have specific leakage areas of 8 to 13 cm^2/m^2 in one house with the vents closed (Turk et al., 1987) and in nine houses with the vents sealed (Brennan et al., 1990). Unless that leakage area can be substantially reduced as part of the installation, it would be expected that crawl-space depressurizations relative to the living area will commonly be a fraction of a pascal, at best, with the maximum exhaust flows that can be generated by a standard 90 W mitigation fan when it is connected into any piping (60 to 80 l/sec).

Some of the leakage area in a crawl space may be difficult to access and seal, but significant reductions in area can be achieved with sufficient effort. In one crawl space with poured concrete foundation walls, the crawl-space leakage area was reduced from 513 to 153 cm^2 (from 10 to 3 cm^2/m^2) by careful sealing of the forced-air ductwork, floor penetrations, and the frame wall between the crawl space and an adjoining basement (Turk et al., 1987).

Sealing standard 20 by 41 cm foundation vents will reduce the measured effective leakage area by about 130 cm^2 for each vent, relative to the leakage when the vent is wide open (Brennan et al., 1990; Pyle and Leovic, 1991). This is significantly less than the gross area which would be calculated from the dimensions of the vent (820 cm^2). The obstruction created by the vent grille and insect screen probably reduced the net free area of these particular vents to roughly 200 to 400 cm^2 each (Brennan, 1992; Pyle, 1992). The remaining difference is probably explained by an inability of the blower door technique to measure the true physical area of the openings of this configuration.

In the one house for which these data are available (Brennan et al., 1990), the effective leakage area of the block crawl-space foundation wall when the 10 vents were open was about 2,720 cm^2. Less than half (1,290 cm^2) was associated with the open vents. Thus, simply sealing vents may not always be sufficient to ensure good depressurization.

Because crawl-space depressurization will produce such small depressurizations relative to the living area in typical crawl spaces, there is a risk that the system will sometimes be overwhelmed by weather- or appliance-induced depressurizations within the living area. This could be of particular concern where the system has caused radon levels in the crawl space to increase.

Because these systems are designed to depressurize the crawl space, there is concern that they may cause back-drafting of combustion appliances in the crawl space. During cold weather, when the draft in the flue is strong, the onset of back-drafting typically occurs when the space is depressurized by 5 to 7 Pa relative to outdoors. Since crawl-space depressurization systems usually do not achieve that degree of depressurization, back-drafting should not occur often in well designed flues during cold weather. However, during warm weather – or if the draft is weak because the stack is short, partly blocked, cold, or poorly connected to the appliance – back-drafting can begin at space depressurizations of 3 Pa or even less (Fitzgerald, 1992). Back-drafting can be so dangerous if it occurs that anyone installing a crawl-space depressurization system should be alert to this threat.

The one documented case where back-drafting was measured was in a 57 m^2 house with an inaccessible crawl space, and with an adobe block foundation wall that extended all the way up to a flat roof (Turk et al., 1992). Because the foundation wall and superstructure walls were so tight, and the floor between the crawl space and the living area was leaky, the crawl-space depressurization system depressurized the living area sufficiently to cause back-drafting of combustion appliances in the living area. It is estimated that the depressurization system was exhausting more than 40 l/sec, and had depressurized the crawl space by more than 5 to 7 Pa (relative to the living area) in some locations. The living area may have been depressurized by less than 1 Pa relative to outdoors.

The installation cost of a crawl-space depressurization system will generally be much lower than that of a SMD system. Extrapolation of the installation costs for SMD (Henschel, 1991), together with the limited available commercial experience with crawl-space depressurization systems (Kladder, 1992), indicates that a crawl-space depressurization system would cost $400-$1,000 if installed by a commercial mitigator. Costs will be at the lower end of the range if the fan simply exhausts at grade outside the house, and at the upper end if there is a stack up through the house as in Figure 2. The installation cost would increase if additional effort is required to seal the crawl space, beyond sealing of major accessible openings and forced-air ducting.

As shown in Table 1, the estimated operating cost for a crawl-space depressurization system at baseline conditions is $192. This is about three times the baseline annual cost of a SMD system, primarily as a result of the increased heating/cooling penalty.

In summary, crawl-space depressurization will be most applicable in existing houses where: a) the crawl space is inaccessible, ruling out SMD as an option; b) the crawl space is relatively tight and well isolated from the living area to begin with, reducing the need to seal and isolate the crawl space; c) radon reductions of greater than 50% are required in the living area, ruling out natural ventilation as an option; and d) there is no combustion appliance in the crawl space that might back-draft. But even where conditions b) through d) above are favorable for crawl-space depressurization, SMD should still be considered, due to its potential for greater and more consistent radon reductions at reduced operating cost.

Crawl-space depressurization might find increased application in new construction (Brennan 1992). New houses could be built with tight crawl spaces and, in particular, a very tight foundation wall. Under these conditions, a reduced exhaust flow would be sufficient to maintain adequate depressurization. And, due to the tight foundation walls, most of the air exhausted by the system would be drawn into the crawl space from the living area, as part of a deliberate design to provide proper ventilation of the living area.

Crawl-space Pressurization

In crawl-space pressurization systems, a fan is mounted to blow outdoor air (or air from the living area) into the crawl space. Some sealing or isolation of the crawl space may be needed in order to achieve effective pressurization.

One configuration of a crawl-space pressurization system would look very similar to the crawl-space depressurization system in Figure 2, except with the direction of the fan reversed. More commonly, the fan would be mounted at grade level.

Crawl-space pressurization works by causing the pressure of the crawl space to be higher than the pressure in the soil. If effective, this would prevent the convective flow of radon-containing soil gas into the crawl space. It would not reduce the amount of radon entering the crawl space by diffusion.

A second mechanism – ventilation of the crawl space and dilution of the crawl-space radon – may play a more important role for crawl-space pressurization systems than was expected in the previous discussion for crawl-space depressurization systems. Unlike depressurization systems, pressurization systems will not increase the convective flow of soil gas into the crawl space; thus, the increased flow of outdoor air into the crawl space will not potentially be offset by increased radon flow. If the crawl space cannot be effectively pressurized, the ventilation mechanism may become more important than the pressurization mechanism in crawl-space pressurization systems.

Crawl-space pressurization systems would be expected to impact the crawl-space dynamics discussed earlier, by increasing the amount of crawl-space air flowing into the living area. Thus, it is crucial that the pressurization system reduce radon levels in the crawl-space air, whether it be by reduced convective entry or by dilution.

In limited testing of crawl-space pressurization in six structures (Findlay et al., 1990; Pyle and Leovic, 1991; Stoop and de Meijer, 1991; Turk, 1991; Turk et al., 1992), where outdoor air was blown into the crawl space, crawl-space pressurization was found to give living-area radon reductions usually in the range of 35 to 80%. These reductions are generally comparable to those obtained using natural crawl-space ventilation (i.e., simply opening the foundation vents, with no fan).

This result could suggest that the pressurization system may not always effectively pressurize the crawl space relative to the soil (i.e., to the outdoors), and that ventilation/dilution may be the primary mechanism coming into play. Indeed, in one of the cases where pressure measurements were reported (Pyle and Leovic , 1991), the crawl space was still under 1.5 Pa negative pressure relative to outdoors with the pressurization system operating. This lack of pressurization resulted despite a relatively high flow (110 l/sec) being blown into a school crawl space having an effective leakage area (535 cm^2) much smaller than the crawl-space leakage area in many houses. The resulting radon reductions in the overhead occupied space were only about 40%.

The best results with crawl-space pressurization systems were observed with two tight inaccessible crawl spaces. In one house (Turk, 1991), where the overhead floor decking as well as the foundation wall were very tight, a flow of about 40 l/sec pressurized the crawl space by over 5 Pa relative to outdoors. In the second house (Turk et al., 1992), where the walls were tight but the floor was leaky, 40 l/sec pressurized the 57 m^2 crawl space by 1 to 8 Pa. (The pressurization varied with location apparently because the floor joists contacted the soil and interfered with the distribution of the pressure field.) In each house, indoor radon reductions were over 80%, the highest that have been observed with this approach.

One reason why radon reductions were no greater than 80% in the above two houses, despite the excellent crawl-space pressurization, may have been the continued diffusion of radon into the crawl space from the soil.

If the pressurization system fails to pressurize the crawl space relative to outdoors, convective flow of radon into the crawl space from the soil can continue, if at a reduced rate. Since the pressurization system will increase the flow of crawl-space air into the living area, this increased flow may partly offset the benefits resulting from reduced convective entry and from dilution of the radon in the crawl space.

Pressurization avoids the risk of combustion appliance back-drafting that can be present with crawl-space depressurization systems. But with outdoor air being blown into the crawl space, pressurization creates a risk of freezing in water pipes in the crawl space.

The installation cost of a crawl-space pressurization system would be about the same as that for crawl-space depressurization ($400-$1,000), unless special effort is required to seal or isolate the crawl space, or to install insulation under the overhead floor. This installation cost includes insulation of water pipes.

The operating cost for pressurization should be about the same as that for crawl-space depressurization, with a baseline of $192 per year. The ventilation rate of the living area should be impacted to about the same extent with both pressurization and depressurization. With pressurization, the increased flow of outdoor air will enter via the crawl space rather than infiltrate through the superstructure.

In summary, crawl-space pressurization would appear to be most applicable where: a) the crawl space is inaccessible, ruling out SMD; b) the crawl space is particularly tight to begin with; c) concerns about back-drafting discourage the use of crawl-space depressurization; and d) only moderate radon reductions are needed. If the crawl space is not tight, pressurization probably should not be considered unless the needed reductions are no more than about 50%.

As discussed later, natural crawl-space ventilation gives about the same living-area radon reductions as does crawl-space pressurization. Also, natural ventilation is simpler to implement and operate, if foundation vents already exist. Therefore, active crawl-space pressurization might be selected over natural ventilation only in crawl spaces where there is not a sufficient number of properly distributed foundation vents to permit natural ventilation to be easily implemented. Even where sufficient vents do not exist, the installation of additional vents and the implementation of natural ventilation can still be considered as an alternative to pressurization.

Where foundation vents are opened, the question arises regarding whether it is worthwhile to operate a fan anyway, to supplement the natural ventilation with a forced ventilation component. There are not sufficient data to enable a definitive answer regarding when a forced ventilation component may be cost-effective. In one reported house, natural ventilation was supplemented by 71 l/sec of forced ventilation, which was balanced so that the crawl-space pressure would not be altered. In this house, the forced ventilation provided no additional indoor radon reduction compared to natural ventilation alone (Turk et al., 1987).

Even when conditions are favorable for natural ventilation or crawl-space pressurization, SMD or crawl-space depressurization will often give greater and potentially more reliable radon reductions. Thus, SMD and depressurization should still be considered as options, unless the house is not amenable to these techniques.

Natural Crawl-space Ventilation

In general, natural crawl-space ventilation consists of opening existing vents in the crawl-space foundation wall, and/or installing new vents, to increase the natural infiltration of outdoor air.

Natural ventilation works through two mechanisms. First, it tends to neutralize the pressure between the crawl space and outdoors. By thus reducing crawl-space depressurization during cold weather, this technique reduces the convective flow of radon-containing soil gas into the crawl space. Second, by providing an increased infiltration rate for fresh outdoor air into the crawl space, the technique dilutes any radon that enters the crawl space.

But the reduced radon concentrations in the crawl space, resulting from the two above-mentioned mechanisms, can be partly offset by increased flow of crawl-space air into the living area. As discussed previously in connection with crawl-space dynamics, increased leakage areas in crawl-space foundation walls will reduce the resistance to outdoor air flow into the crawl space. This will tend to increase the amount of air infiltrating into the living area from the crawl space rather than directly from outdoors. As a result, opening crawl-space vents can increase the flow of crawl-space air into the living area.

Crawl-space foundation walls can sometimes be fairly leaky even without vents. In the one house from which data are available (Brennan et al., 1990), unsealing ten 20 by 41 cm vents approximately doubled the effective leakage area of the foundation wall, increasing it from 1,430 to 2,720 cm^2 (129 cm^2 per vent).

In one study (Nazaroff and Doyle, 1985), opening 6 to 14 foundation vents in three crawl-space houses was calculated to have increased the average ventilation rate of the crawl space by a factor of 3, from an average of 0.6 to 1.9 air changes per hour (ACH). (The calculated ventilation rate of the living area of these three houses was unchanged at an average of 0.5 ACH.) In another study using tracer gases (Matthews et al., 1989), opening 6 to 13 foundation vents in four houses increased the average crawl-space ventilation rate by a factor of over 5, from 0.5 to 2.7 ACH.

The performance of natural crawl-space ventilation will depend upon factors which influence the increase in ventilation rate: the number and location of vents; the tightness of the crawl space; weather conditions, especially wind and temperature; and the presence of vent obstructions (such as shrubbery). It will also depend upon activities by the homeowner, such as the operation of depressurizing appliances in the house or crawl space. Because of the role of weather and of homeowner activities, performance will vary with time.

In limited testing as part of EPA's R&D program, natural ventilation was found to provide radon reductions ranging from 46 to 83% in the living area of five buildings in which five to eight existing foundation vents were opened (Findlay et al., 1990; Pyle and Leovic, 1991). These reductions are based upon relatively short-term testing, usually for 2- to 4-day periods both before and after the crawl-space vents were opened. This short measurement period probably contributed to the scatter in the results, since performance is expected to vary with time.

In a somewhat longer-term study, testing over 5 to 7 weeks in two houses having 6 to 10 vents, provided indoor radon reductions of 40 to 45% (Nazaroff and Doyle, 1985). In another house having 14 vents, where SF_6 was released into the crawl space as a surrogate for radon, natural ventilation reduced SF_6 concentrations in the living area by 21 to 35%, based upon 2- to 3-day measurements with and without the vents open (Nazaroff and Doyle, 1985). The higher reduction was achieved after the leakage area was reduced in the floor between the crawl space and the living area.

Investigators testing three houses in which only two vents were opened (one in each of two opposing walls), and in which steps were taken to seal the overhead floor, observed living-area reductions of 18 and 27% in two of the houses, and 75% in the third, based upon 2- to 4-day measurements (Pyle and Williamson, 1990). Natural ventilation combined with crawl-space sealing/barriers provided indoor reductions of 50 to 60% in three Spokane houses, each of which had an adjoining basement which was not treated for these measurements (Turk et al., 1987). In a mitigation effort where multiple vents were retrofitted into a number of existing crawl-space houses (to provide 1 m^2 of vent area per 150 m^2 of floor area), living-area reductions consistently ranged between 0 and 50% (Fisher, 1992).

These limited current data suggest that average indoor reductions will probably be no greater than about 50% in most cases.

Researchers have found that natural crawl-space ventilation consistently reduces radon concentrations in the crawl-space air to a greater extent than it reduces radon concentrations in the living area (Nazaroff and Doyle, 1985; Turk et al., 1987; Findlay et al., 1989; Pyle and Williamson, 1990; Pyle and Leovic, 1991). In the 10 houses for which simultaneous crawl-space and living-area data are available, crawl-space radon levels were reduced by an average of 72%, while living-area concentrations were reduced by an average of only 58%. This result supports the expectation discussed previously, that reduced radon concentrations in the crawl space will be partly offset by an increased flow of crawl-space air into the living area.

If natural crawl-space ventilation can be implemented simply by opening existing foundation vents, the installation cost will be near zero. Where the crawl space has no vents (or too few vents), vents will need to be retrofitted. Extrapolation of the installation costs for soil depressurization systems (Henschel, 1991), together with commercial experience (Fisher, 1992), indicates that the installation cost for retrofitting multiple vents into an existing house will be about \$100 to \$125 per vent. This includes some effort to caulk openings in the floor decking and to insulate water pipes. It does not include any major effort to isolate the crawl space from the living area, or to install insulation beneath the overhead floor for occupant comfort or to reduce the heating penalty.

The baseline case for operating cost calculations assumes that, on average, the ventilation rate of the living area will not be increased by opening foundation vents (see Table 2). Thus, there will be no heating/cooling penalty associated with increased living-area ventilation. However, there will still be a heating/cooling penalty due to increased heat loss through the floor, resulting from the fact that the crawl space will now be colder in the winter (and hotter in the summer). This heating/cooling penalty cannot be rigorously quantified. The baseline operating cost in Table 1 is thus listed simply as being greater than zero.

In summary, natural crawl-space ventilation will most likely be useful primarily where: a) only a limited indoor radon reduction is needed; or b) the crawl space is not a major radon source, and crawl-space ventilation is simply supplementing SSD or DTD in an adjoining basement.

Sealing Openings between Crawl Space and Living Area

If the leakage area between the crawl space and the living area could be reduced, the resistance to the flow of crawl-space air into the living area should be increased. The flow of radon-containing crawl-space air into the living area would nominally be reduced. More of the air infiltrating into the living area would be outdoor air entering the living area directly.

Such effort typically includes sealing relatively small but widely distributed openings through the floor which separates the living area from the crawl space, and through any wall separating the crawl space from an adjoining basement wing. Such openings include, for example, gaps in the decking around utility penetrations, and seams in the subflooring. The effort would also include sealing the seams in any forced-air ducting present in the crawl space, especially on the low-pressure return side of the furnace or air conditioner. In extreme cases, the effort could include closure of major openings; e.g., constructing a frame wall to isolate a crawl space which is initially open to an adjoining basement.

The limited data available suggest that sealing openings between the crawl space and the living area, by itself, may provide little or no reduction in the radon concentrations in the living area. In one study house, an extensive effort to isolate the crawl space from the living area – reducing the effective leakage area of the crawl space by 70%, from 513 to 153 cm^2 – reduced living-area concentrations only by about 15% (Turk et al., 1987). In two other studies on a total of three houses (Nazaroff and Doyle, 1985; Pyle and Williamson, 1990), attempts to isolate the crawl space resulted in changes in indoor concentrations ranging from a 10% decrease to a 15% increase. All of these houses had forced-air ducts in the crawl space, complicating the isolation of the crawl space.

These observed changes in radon levels due to sealing are within the normal variability of indoor concentrations in a given house.

There may be two explanations why floor sealing does not provide greater indoor radon reductions.

One explanation may be that the floor leakage area is not reduced sufficiently to significantly reduce the flow of crawl-space air into the living area. While some openings between the crawl space and the living area (such as those around utility penetrations) may be reasonably accessible for sealing, others (such as the seams in the decking) can be widely distributed and sometimes inaccessible. It is unclear to what extent these openings – which provided an average effective leakage area in the overhead flooring of 355 cm^2 in nine Tennessee houses (Brennan et al., 1990) – can be sealed with a practical level of effort. As an added concern, the durability of the seals is sometimes uncertain.

A second explanation why indoor radon reductions are not greater may be that – since so much of the living-area infiltration comes from the crawl space – the sealing of the floor leakage area decreases the ventilation rate of the living area. The reduction in radon flow into the living area thus may be offset by a reduction in the infiltration of outdoor air which, prior to sealing, had been entering the living area via the crawl space.

These effects of floor sealing are illustrated in one house where floor sealing reduced the living-area effective leakage area from 1,220 to 890 cm^2 (Nazaroff and Doyle, 1985). Based upon measurements of SF_6 released in the crawl space, this sealing appeared to decrease the fraction of the SF_6 entering the living area by 12% (with the foundation vents sealed) to 35% (with the vents open). However, it also decreased the calculated ventilation rate of the living area by 24% (vents sealed) to 30% (vents open). These two effects largely offset one another, resulting in an increase of 8% in the measured indoor radon levels with the vents sealed, and a 10% decrease with the vents open.

According to the survey of mitigators (Hoornbeek and Lago 1991), 12% of the mitigators preferred some type of sealing approach in treating crawl-space houses. Discussions with mitigators suggest that, in fact, sealing in the crawl space is most commonly utilized as a supplement to SSD or DTD in an adjoining basement when the crawl space is not a major source. In these cases, it is unclear what contribution, if any, the crawl-space sealing effort makes to the observed radon reductions.

Because the nature and extent of a stand-alone sealing effort can vary, it is not possible to estimate a meaningful installation cost for stand-alone sealing in Table 1. The annual operating cost for sealing is assumed to be zero, but this excludes any maintenance costs that may be incurred in subsequent repairing of seals that break over time.

In summary, sealing should never be relied upon as a stand-alone mitigation method where the crawl space is an important radon source. A homeowner may wish to try sealing as a stand-alone method on a do-it-yourself basis, to see how well this approach might perform in that particular case. However, its potential on a stand-alone basis is so small that a commercial mitigator would most likely never propose sealing except perhaps in combination with SSD in an adjoining basement, or as a necessary component of crawl-space pressurization or depressurization. Floor sealing may be more promising in new construction, where the floor can be made particularly tight, and provisions made for infiltration of outdoor air directly into the living area.

Barrier over Soil in Crawl-Space

Installation of a sealed barrier such as polyethylene sheeting over the crawl-space floor, and over the interior face of block foundation walls, should reduce the entry of radon into the crawl space, except by diffusion through the barrier. A barrier potentially could overcome the problems identified above for floor sealing, in that: a) if fully sealed, the leakage area of a barrier should be far smaller than could be achieved by sealing the overhead floor; and b) it will not interfere with ventilation of the living area by crawl-space air.

Reliable testing of the effect of a completely sealed barrier of plastic sheeting over the crawl-space floor and foundation walls has been completed in only one house, where a basement wing adjoined the crawl space (Turk et al., 1987). This barrier by itself, without any other sealing to isolate the crawl space, resulted in indoor reductions of 31%, based upon 2 to 3 weeks of testing both before and after installation of the membrane. Tests by other investigators, without the membrane being completely sealed, suggest that essentially no indoor reductions are achieved when the barrier is not fully sealed (Findlay et al., 1990).

Based upon extrapolation of the installation costs for SMD systems (Henschel, 1991), the installation cost for a floor barrier is estimated to be $300-$1,000, depending primarily upon the size of the crawl space. The operating cost would be zero, excluding maintenance costs to repair punctures in the membrane.

Because of the limited effectiveness of crawl-space floor barriers, and concerns about the durability of the membrane, this technique should not be relied upon as a stand-alone method.

Major Issues Requiring Further Study

- The method for ensuring that adequate suctions and flows are established everywhere beneath the membrane of SMD systems. Some mitigators routinely use sub-membrane perforated piping to help distribute the suction; many mitigators routinely seal the membrane everywhere. These two steps are recommended, but may not always be necessary (Henschel, 1992).
- The durability of the membrane in SMD systems. Deterioration of the membrane over time could seriously degrade SMD performance, essentially converting it to a crawl-space depressurization system.
- The performance of crawl-space depressurization systems as a function of crawl-space leakage area and the amount of air exhausted. Performance includes: radon reductions in the living area over time, as weather conditions and appliance usage vary; depressurizations achieved in the crawl space; combustion appliance back-drafting; and actual system operating costs.

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