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Cost Analysis of Soil Depressurization Techniques for Indoor Radon Reduction

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ABSTRACT

A parametric cost analysis was conducted to determine the importance of various system design and operating variables on the installation and operating costs of active soil depressurization (ASD) systems for indoor radon reduction in houses. The objective was to help guide the research and development (R&D) efforts of the U.S. Environmental Protection Agency (EPA) to reduce ASD costs. Annual lung cancer deaths due to radon cannot be reduced by more than about 14% to 22% unless houses having pre-mitigation levels of 148 Bq/m^3 and less receive radon reduction systems. Reductions in ASD costs might increase voluntary use of this technology by homeowners at those levels. The analysis showed that various modifications to ASD system designs offer potential for reducing installation costs by up to several hundred dollars[1], but would not reduce total installed costs much below $800-$1000. Reductions of this magnitude would probably not be sufficient to dramatically increase voluntary use of ASD technology. Thus, some innovative, inexpensive mitigation approach other than ASD would appear to be necessary. Decreased ASD fan capacity and increased sealing might reduce ASD operation costs (for fan electricity and house heating/cooling) by roughly $7.50 per month. It is unlikely that this amount would be a deciding factor for most homeowners.

Introduction

Active soil depressurization (ASD) techniques have been proven to be the most widely used indoor radon reduction techniques for houses, due to their effectiveness in reducing radon levels under a wide variety of conditions, their reliability, and their moderate installation cost (Henschel, 1988). These techniques use a suction fan to draw the radon-containing soil gas out from beneath the house, and exhaust it outdoors before it can enter the house. Variations of the ASD technique include: sub-slab depressurization (SSD), where suction is drawn on individual suction pipes that are inserted beneath the concrete slab in basement and slab-on-grade houses; drain-tile depressurization (DTD), commonly implemented by drawing suction on an existing sump connecting to drain tiles beneath the slab; and sub-membrane depressurization (SMD) in crawl-space houses, where suction is drawn beneath a membrane (usually plastic sheeting) placed over the earthen or gravel-covered crawl-space floor.

EPA estimates that thousands of lung cancer deaths occur in the U.S. each year as a result of exposure to indoor radon (Puskin and Nelson, 1989). EPA also estimates that only a small percentage of homeowners having elevated indoor radon concentrations have in-

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[1] All costs are expressed in U.S. dollars.

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stalled radon reduction systems. If there is to be a significant reduction in the number of radon-induced lung cancer deaths, it will be necessary for effective radon reduction systems to be installed in a large number of U.S. houses. Based upon the estimated distribution of indoor radon levels in this country (Nero et al., 1986; Puskin and Nelson, 1989), EPA has calculated that even houses having pre-mitigation concentrations below the initial guideline of 148 Bq/m^3 would have to receive radon reduction systems if the estimated death rate is to be reduced by more than about 14% to 22% (Puskin and Nelson, 1989).

While a number of factors contribute to the low response by homeowners in installing remediation systems, such as public perception of the risks involved, one of these factors is likely to be the cost of the systems. Typical SSD systems installed by a commercial radon mitigator cost in the range of $800 to $1500.

The objective of this cost analysis was to identify those ASD design and operating parameters which have the greatest impact on system installation and operating costs. Those parameters could then be considered as possible targets for EPA-sponsored research, development, and demonstration efforts, to enable improved guidance to the mitigation community concerning the most effective methods for reducing costs. Reduced costs might result in increased voluntary utilization of ASD technology by homeowners.

Approach

Installation Costs

The effects of 14 ASD design parameters on system installation costs were assessed by obtaining installation cost estimates from five commercial radon mitigation firms representing different major mitigation markets across the country. Initially, each mitigator developed cost estimates for baseline mitigation systems in each of eight different houses. Each mitigator then estimated the incremental impact on the baseline installation cost (and on the baseline labor and material cost requirements) as each one of the 14 design parameters was varied in turn, through a range of logical values.

The eight houses used in this analysis represented three house design/construction parameters (substructure type, number of stories, and degree of basement finish) (see Table 1). Two other house design/construction variables – the presence/absence of a soil drainage sump, and the nature of sub-slab communication – were also addressed, but were handled as mitigation system design variables (SSD vs. sump/DTD, and the number/location of SSD suction pipes).

The 14 ASD design variables that were considered are listed in Table 2, along with the baseline values that were assumed for each and the parametric variations that were evaluated. The baseline values were intended to represent typical values, although most of the five mitigators who participated in the study took exception to at least one of the baseline selections. The parametric variations were intended to cover the range of conditions commonly seen in practice, or which might be considered in some cases. Some of the variations (in particular, the grade-level exhaust variation for Variable 7, or the placement of the fan inside the basement in Variable 8) are inconsistent with current EPA recommendations; such variations were considered here to determine whether a cost incentive existed for investigating possible revisions to the recommendations.

The five commercial radon mitigators who provided installation cost estimates for this analysis represent service areas in and near Georgia, Iowa, Pennsylvania, Virginia, and Washington state.

In addition to the specified baseline values for the 14 system design parameters, each mitigator was also required to include, in the baseline cost estimates, certain key elements, to help ensure consistency. All of the mitigators included the following in the baseline:

(a) A pre-mitigation visual inspection. (No pre-mitigation sub-slab communication tests were included in the baseline.)
(b) Post-mitigation follow-up, including suction measurements in the system piping, and an indoor radon measurement.
(c) A warranty that the house would be reduced below 148 Bq/m^3 for 1 year or longer.
(d) Meeting all applicable building codes.
(e) Travel time for the work crews to and from the job site.

Despite the steps listed above to ensure the comparability of the estimates, the estimates still varied as a result of inherent differences between the five mitigators. These differences included:

(a) Direct labor plus fringe benefit rates (varying between $7 and $25 per hour), and combined overhead plus profit burden rates (varying between 40% and 400% of labor plus materials). Three of the firms applied overhead plus profit burden rates of 40% to 60%; with current demand, a radon remediation firm would not remain viable if the burden rate fell much below this level.
(b) Differences in certain system design details. These differences included, for example: whether the exhaust piping is boxed in where it extends inside and/or outside the house; whether interior stacks can be installed in existing utility chases; whether exterior stacks penetrate or jut around the roof overhang; the thickness of the membrane used for SMD systems in crawl spaces; and whether the membranes installed in crawl spaces must be attached to the perimeter wall using a wooden furring strip or simply adhered to the wall using a bead of caulk, when perimeter sealing is required.
(c) Differences in experiences between mitigators. For example, some mitigators provided significantly different estimates for the cost impact of installing an ASD stack inside the house, depending upon, e.g., the familiarity of their crews with such interior installations, the expectations of local homeowners, and perhaps whether the local house construction characteristics were amenable to interior stacks.

Table 1. Summary of the eight houses utilized in parametric analysis of ASD installation costs.

House No.	Substructure type[1]	Number of stories[2]	Degree of basement finish
1	Basement	1	Unfinished
2	Basement	2	Unfinished
3	Slab on grade	1	N/A[3]
4	Slab on grade	2	N/A
5	Crawl space	1	N/A
6	Crawl space	2	N/A
7	Basement	1	Finished[4]
8	Basement	2	Finished

1. Each substructure type is a "pure" substructure, not combined with adjoining living wings having a different substructure. For example, the basement houses do not have adjoining slab-on-grade or crawl-space living areas. Each house has an adjoining slab-on-grade garage.
2. "One-story" houses have one living level above the basement or crawl space; one-story slabs on grade have a living level only on the slab. The house "footprint" for all of the one-story houses is 180 m^2 (12 x 15 m). "Two-story" houses have two living levels above the basement or crawl space, or one living level above the living area on the slab on grade; the house "footprint" is 94 m^2 (8.5 x 11 m).
3. N/A = not applicable.
4. The basement finish includes carpeting, panelling or wallboard, and a suspended drop-down ceiling. A sheetrock ceiling would increase mitigation costs further.

Table 2. Summary of the baseline ASD mitigation systems utilized in parametric analysis of ASD installation costs.

ASD design variable	Baseline value	Variations
1. Variation of ASD techonology		
– basement houses	SSD	1. Sump/DTD
– slab-on-grade houses	SSD	None
– crawl-space houses	SMD	None
2. Number and		
3. Location of SSD/SMD pipes		
– basement houses	One pipe, 3 m (horizontally) from point where piping penetrates band joist to outdoors.	1. One pipe, 7.5 m from joist penetration. 2. Two pipes (one 3 m from joist penetration, one on opposite wall). 3. Two pipes (one 3 m from joist penetration, one in middle of bsmt). 4. Three pipes (one at 3 m, one on opposite wall, one central).
– slab-on-grade houses	One pipe, inside house, directly under point where piping will penetrate ceiling into attic and then through roof.	1. One pipe, inside house (as baseline), except 7.5-m horiz. piping run required in attic. 2. One pipe, penetrating horiz. through foundation wall from outdoors; fan at grade, exterior stack above eaves. 3. Two pipes, inside house; one pipe in each half of slab; each pipe penetrates ceiling directly above, manifolded to single fan in attic. 4. Two pipes, each penetrating horiz. through foundation from outdoors; each has own fan and exterior stack. 5. Three pipes, inside house, evenly distributed; each pipe rises through house, manifolded to one fan in attic.
– crawl-space houses	One pipe, penetrating SMD membrane in center.	1. Two pipes penetrating membrane, evenly distributed;manifolded together in crawl space, to single fan outdoors. 2. Three pipes penetrating membrane.
4. Pipe diameter (all houses)	10 cm	1. 7,5 cm
5. Type of pipe (all houses)	Thin-walled PVC	1. PVC Schedule 40
6. Nature of slab/membrane hole		
– basement, slab-on-grade houses	10- to 13-cm hole cored through slab; no excavation under slab at point where hole penetrates.	1. 10- to 13-cm hole through slab; excavate small pit by hand through cored hole 2. Jackhammer 0.6- by 0.6-m hole in slab; dig large pit to improve suction field when communication poor; restore slab.
– crawl-space houses	10- to 13-cm hole cut through membrance where pipe penetrates.	1. Dig pit under membrane where the suction pipe penetrates.
7. Exhaust piping configuration		
– basement houses	Vertical stack above eaves, rising outside house.	1. No stack; fan at grade outdoors, exhaust directed 90° away from house at grade, away from windows and doors. 2. Stack up through house interior; fan mounted in attic, exhaust through roof. 3. Basement piping penetrates band joist into adjoining garage; stack rises through garage, fan in garage attic, exhaust through garage roof.
– slab-on-grade houses	Suction pipe(s) through ceiling to fan in attic, exhaust through roof.	No additional variations here. Exterior stack(s) above eaves were added as a variation under "Number and Location of SSD/SMD Pipes" (Variables 2 and 3 above).
– crawl-space houses	Piping through a foundation vent to a vertical stack above eaves, rising outside house.	1. No stack (as for bsmt houses, above). 2. Stack up through house interior.

– slab-on-grade houses	Suction pipe(s) through ceiling to fan in attic, exhaust through roof.	3. Basement piping penetrates band joist into adjoining garage; stack rises through garage, fan in garage attic, exhaust through garage roof. No additional variations here. Exterior stack(s) above eaves were added as a variation under "Number and Location of SSD/SMD Pipes" (Variables 2 and 3 above).
– crawl-space houses	Piping through a foundation vent to a vertical stack above eaves, rising outside house.	1. No stack (as for bsmt houses, above). 2. Stack up through house interior. 3. Stack up through adjoining garage.
8. Location of fan		
– basement houses (exterior stacks only)	Immediately outside basement, at grade level (below stack).	1. Fan in basement (exterior stack only). 2. Fan on roof, on top of exterior stack.
– slab-on-grade houses	In attic.	None
– crawl-space houses (exterior stacks only)	Immediately outside crawl space, at grade level.	1. Fan in crawl space. 2. Fan on roof (on top of exterior stack).
9. Type of fan (all houses)	90-W in-line duct fan with 15-cm couplings, capable of moving 127 l/s at zero static pressure, and about 52 l/s at 250 Pa static pressure.	1. 50- to 70-W in-line fan with 10- to 13-cm couplings, capable of moving 57 to 96 l/s at zero static pressure. 2. 100-W in line fan with 15-cm couplings, capable of moving 169 l/s. 3. 100-W in-line fan with 20-cm couplings, capable of moving 193 l/s.
10. Degree of slab or membrane sealing		
– basement houses	No sealing, other than around pipe penetration through slab.	1. Wall/floor joint (*not* a perimeter channel drain) and other slab openings caulked where accessible. 2. Wall/floor joint (which *is* a perimeter channel drain) closed where accessible.
– slab-on-grade houses	As for basement houses.	1. Wall/floor joint, other slab openings, caulked where accessible.
– crawl-space houses	No sealing, other than around pipe penetration through membrane.	1. SMD membrane sealed at seams between sheets, but not around perimeter or around interior piers. 2. SMD membrane sealed everywhere (seams between sheets, around perimeter, around piers).
11. SMD membrane design		
– crawl-space houses	Membrane covers crawl-space floor everywhere. No sealing of membrane anywhere, suction system is one pipe through center of membrane.	1. Portions of crawl-space floor which are not reasonably accessible are not covered. 2. Membrane covers only perimeter of crawl space, sealed to perimeter walls. Suction drawn on loop of perforated piping laid around perimeter, under membrane. 3. Membrane covers entire floor, not sealed (as baseline); suction drawn on matrix of perforated piping under membrane.
12. Nature of gauge/alarm	Dwyer Magnehelic.	1. Curved inclined manometer. 2. U-tube manometer. 3. Floating-ball device.
13. Pre-mitigation diagnostics	Visual inspection only; no sub-slab communication testing.	1. Add pre-mitigation sub-slab communication testing using a diagnostic vacuum cleaner.
14. Post-mitigation diagnostics	Suction/flow measurements in piping after installation. Post-mitigation indoor radon measurement, using technique consistent with mitigator's normal practice.	None

No attempt was made to correct for variations created by such inherent differences. These inherent differences reflect the natural variations between different mitigators across the country, and provide a meaningful measure of the range of cost impacts that would be encountered if one were to apply one of these parametric variations on a nationwide basis.

Operating Costs

Four elements can contribute to the ongoing costs that homeowners will experience in operating ASD systems: (a) the cost of electricity to run the fan; (b) the heating and cooling penalty resulting from the exhaust by the system of some treated house air; (c) the cost of system maintenance, primarily fan repair/replacement plus some effort to re-caulk or re-cement broken seals; and (d) the cost of any periodic re-measurement of indoor radon levels to confirm continued system performance. This study focused primarily on fan electricity and the heating/cooling penalty.

For this analysis, the reductions in fan electricity and heating/cooling penalty were calculated assuming that the baseline 90-W, 127 l/s fan was replaced by a 50-W, 58 l/s fan (or that the 90-W fan was turned down to approximately that degree). This step would reduce both the cost of electricity for the fan, and the amount of treated house air exhausted. Calculations were also conducted for the case where the wall/floor joint and other slab openings were caulked closed, further reducing the amount of house air entrained into the system. Since there are almost no data quantifying how crack sealing will reduce the amount of house air entrained, it was assumed for these calculations that the caulking would reduce the percentage of house air in the exhaust from the average that has been typically observed (50%), to the lower end of the observed range (30%).

These general calculations require a number of assumptions, as listed in Table 3. While variations in these assumptions would impact the specific results of these calculations, and while the results are thus relatively rough, it is believed that the calculations provide a reasonable estimate of the magnitude of the maximum operating cost reductions that might be achieved through reduced fan capacity and increased sealing.

Table 3. Assumptions used in estimating the effects of smaller ASD fans and increased foundation sealing on ASD operating costs.

1. Fans are drawing the full amount of rated power (90 or 50 W) at all times. (This will not commonly be true. Actual power consumption will depend upon where the fan is operating on its performance curve. For example, in one field project, the 90W fans were found to be drawing 60 to 65 W.)
2. The fans are operating 24 hours/day, 365 days/year.
3. The 90-W fan is exhausting 35 l/s; and the 50-W fan (having roughly half the capacity of the larger fan) is exhausting proportionately less, 18 l/s.
4. About 50% of the exhaust flow is treated air drawn from inside the house, when foundation cracks have not been sealed. (Measurements in different houses show that this percentage is typically in the range 30-70%.) Sealing foundation cracks reduces this percentage to the lower end of the typical range (30%), and reduces the total exhaust flow accordingly.
5. The increase in the house ventilation rate caused by the ASD system is equal to the amount of house air in the ASD exhaust. (This will not necessarily be true. Some of the air exhausted by the ASD system might exfiltrate naturally if the ASD system were not operating, in which case the ASD system would be serving to modify the ventilation patterns but not increase the ventilation rate. However, available information does not permit any assumption other than the one being made here. It is doubted that any errors resulting from this assumption would significantly affect the results and conclusions.)
6. Cost of electricity: $0.08/kWh.
7. Climate (representative of Washington, D.C.)
   - Heating degree-days: 2340 C°-days
   - Cooling infiltration degree days: 1300 C°-days (from Sherman, 1986)
8. Heating system:
   - Forced-air furnace burning natural gas
   - Furnace is 70% efficient
   - Cost of gas: $0.0071/MJ
9. Cooling system:
   - Electric air conditioner
   - Coefficient of performance 2.0
   - Cost of electricity: $0.08/kWh

Most available data on the effect of fan capacity on ASD performance indicate that switching to the 50-W fan will commonly result in some increases in indoor radon levels (although these increased levels will sometimes still remain below 148 Bq/m^3). Thus, the reduction in the operating cost will commonly be offset by an increase in health risk.

Results and Discussion

Installation Costs

Baseline Installation Costs

The total installed costs for the baseline mitigation systems are presented for each of the eight houses in Table 4. The table presents the range of the estimates from the five mitigators, the arithmetic mean, and the estimated standard deviation of these five estimates. The magnitude of the range and of the standard deviation results from differences in design details and experiences, discussed previously.

Table 4 shows that the installation cost for the baseline SSD system is about the same for an unfinished basement or a slab-on-grade house, for a given number of stories. Finished basements add about $70 to the cost, beyond the cost for an unfinished basement; this cost would have been higher had the finished basements been specified as having a sheetrock rather than a drop-down ceiling. A second story adds about $90 to the basement houses (where the stack is outside the house) and about $120 to the slab-on-grade houses (where the stack rises through the house). Crawl-space houses are the most expensive to mitigate, due to the labor and materials required to install a membrane over the entire crawl-space floor. The system in the two-story crawl-space house is less expensive than in the one-story, because the two-story house has a much smaller "footprint"; the cost savings resulting from the need for a smaller membrane more than offset any cost penalty resulting from the need for a second story on the exterior stack.

Effects of System Design Parameters on Baseline Installation Costs

Tables 5a, 5b, and 5c present the incremental increases or decreases in the baseline installation costs resulting from variations to the 14 system design parameters. For each variation, the tables show the arithmetic mean of the estimates from the five mitigators, and the standard deviation of the estimates, unless noted otherwise.

Where the standard deviation is large, review of the individual estimates always revealed important differences in the design/installation approach or in the experiences of the mitigators which explained the variance. Large standard deviations reflect the inher-

Table 4. Total installation costs for baseline mitigation systems[1]

House No.	House description	Baseline installation costs[2] ($) Range	Mean	Estimated standard deviation
1	Basement (unfinished) – one story	790-1,383	1,080	268
2	Basement (unfinished) – two stories	833-1,576	1,168	326
3	Slab on grade – one story	760-1,343	1,048	275
4	Slab on grade – two stories	852-1,504	1,167	291
5	Crawl space – one story	966-1,852	1,418	320
6	Crawl space – two stories	977-1,716	1,317	308
7	Basement (finished) – one story	790-1,510	1,147	312
8	Basement (finished) – two stories	833-1,704	1,239	370

1. The baseline mitigation systems are defined in Table 2.
2. The installation cost range, mean, and estimated standard deviation are derived from the estimates of five mitigators. Costs are expressed in U.S. dollars.

ent differences between different mitigators across the country.

Of the parametric variations having a potential cost impact near $100 or greater (Table 5a), it is not surprising that three of them deal with houses having poor sub-slab communication (Items 1, 2, and 7 in the table). Adding each additional suction pipe beyond the first (Item 1), excavating a large sub-slab pit to aid in suction field distribution (Item 2), and conducting pre-mitigation sub-slab communication diagnostics (when a separate trip to the house is required), each adds between $135 and $274 to the total installation cost.

Possible R&D that could help avoid the need for additional pipes or large pits should be aimed at inexpensive methods for: (a) improving the communication (e.g., using high-pressure air or water jets beneath the slab); or (b) improving the performance of a simple, one-pipe SSD system in poor-communication houses without improving the communication (e.g., through better diagnostics or high-performance fans). To be cost-effective, any such methods that are developed through R&D would have to be commercially practical at a cost lower than the cost of adding suction pipes or excavating large pits (at $135 to $274 each).

It is doubtful that R&D can reduce the costs of conducting added pre-mitigation diagnostics. However, R&D might ultimately make the diagnostics more effective in identifying possibilities for reducing the number of suction pipes or eliminating the need for large sub-slab excavations. The cost savings resulting from these more effective designs might offset the cost of the improved diagnostics.

Also among the parametric variations having potential impacts near $100 or more are alternative SSD exhaust configurations (Item 3 in Table 5a). The one exhaust variation which could reduce costs – elimination of the stack altogether, and discharging at grade level – is contrary to current EPA recommendations that the exhaust be discharged above the house eaves in order to reduce reentrainment back into the house and to reduce exposure for persons outdoors. Elimination of the baseline exterior stack could reduce installation costs by $93-$169, depending upon the number of stories. In view of this fact, R&D could be of value to determine under what conditions grade-level exhaust might be acceptable (e.g., exhaust radon concentration, exhaust velocity, exhaust configuration, and house and weather characteristics).

As indicated in Table 5a, there is some disagreement as to whether a stack inside the house will cost more or less than the baseline exterior stack. Some of the mitigators who are most familiar with interior stacks feel that the interior stack will cost no more, and sometimes less, depending upon their specific approach. Mitigators most familiar with exterior stacks consistently estimate that the exterior stack will be less expensive. Except in one case involving special conditions, even the mitigators familiar with interior stacks did not estimate any significant cost savings for the interior versus the exterior stack. (That one special case is primarily responsible for the size of the mean savings for interior stacks, $38-$61, shown in Table 5a for mitigators familiar with interior stacks.)

The mitigators estimated that routing the stack through the adjoining garage would increase costs by about $100, relative to the baseline.

Thus, the decision to install an interior or a garage stack rather than the baseline exterior stack will be based upon practical and aesthetic considerations, and upon homeowner and mitigator preferences. In most cases, no significant cost savings would appear possible from interior or garage stack routing. Thus, no R&D to facilitate alternative routing would appear to be needed or to offer promise for reducing costs.

Increased sealing of the slab or membrane – to improve ASD performance and to re-

Table 5A. Parametric variations resulting in an installation cost impact of about $100 or more.

	Parametric variation	Cost impact ($)	Estimated standard deviation ($)
1.	Adding SSD suction pipes to basement and slab-on-grade houses, beyond the one pipe assumed for the baseline system (Variables 2 and 3):		
	– unfinished basements (increase per pipe added)	+135	44
	– finished basements (increase per pipe added)	+221	90
	– one-story slabs on grade (increase per pipe added)	+226	83
	– two-story slabs on grade (increase per pipe added)	+274	95
2.	Jackhammering one 0.6- by 0.6-m hole in the slab to enable excavation of a large sub-slab pit in basements and slabs on grade to improve suction field extension, rather than the baseline case of simply coring a hole through the slab (Variable 6):	+206	208
3.	Modifications to the SSD exhaust configuration in basements and crawl spaces, compared to the baseline exterior stack discharging above the eaves (Variable 7):		
	– elimination of stack (grade-level exhaust)		
	– one-story houses	-93	37
	– two-story houses	-169	84
	– locating stack inside the house rather than outdoors		
	– mitigators less familiar with interior stacks		
	– one-story houses	+91	10
	– two-story houses	+155	91
	– mitigators more familiar with interior stacks		
	– one-story houses	-38	35
	– two-story houses	-61	74
	– routing stack up through adjoining slab-on-grade garage	+96	59
4.	Locating fan on roof (above exterior stack) rather than at grade level outdoors, below the stack (Variable 8)	+235	35
5.	Increasing the degree of sealing of the slab or membrane, compared to the baseline case where no slab or membrane sealing is performed (Variable 10):		
	– sealing the accessible wall/floor joint in an unfinished basement, where that joint is *not* a perimeter channel drain		
	– one-story house (54-m perimeter)	+164	127
	– two-story house (39-m perimeter)	+108	91
	– sealing the accessible wall/floor joint in an unfinished basement, where that joint *is* a perimeter channel drain		
	– one-story house	+470	262
	– two-story house	+326	184
	– sealing the seams between membrane sheets in a crawl-space SMD system		
	– one-story house	+117	46
	– two-story house	+66	45
	– completely sealing the SMD membrane, including the perimeter as well as the seams between sheets		
	– membrane perimeter simply caulked to foundation wall		
	– one-story house	+248	113
	– two-story house	+102	70
	– membrane perimeter attached using furring strip nailed to wall		
	– one-story house	+620	160
	– two-story house	+456	71
6.	Modification of the baseline SMD design configuration (Variable 11):		
	– leave portion of crawl-space floor uncovered	-100 (approx.)[1]	
	– perforated piping loop around perimeter, membrane perimeter sealed using furring strip	+500 (approx.)[1]	
	– perforated piping under central membrane, no sealing	+100 (approx.)[1]	
7.	Increasing the baseline pre-mitigation diagnostics (visual inspection only) to include sub-slab communication measurements, in cases where the sub-slab diagnostics require an extra trip to the house (Variable 13):	+208	46

[1] Calculated independently of the estimates from the five mitigators. Thus, no standard deviation is shown.

duce the amount of treated house air drawn into the system, thus reducing the heating/cooling penalty – always has a significant impact on installation cost (Item 5 in Table 5a).

In basement houses, the slab sealing costs are especially pronounced when the perimeter joint is a 1- to 2-inch wide perimeter channel drain ($326-$470, compared to $108-$164 for caulking a typical, relatively tight wall/floor joint). The perimeter channel drain requires that a foam backer rod first be stuffed into the gap to serve as the support for a caulk layer on top. The one-story basement house has a much longer perimeter to be treated than does the two-story house, and hence is more expensive to seal. Further R&D might better define the improvements in SSD system performance and the reductions in heating/cooling penalty that can be achieved by such slab sealing, thus enabling better determination of when such a sealing expense is warranted. However, the results are likely to be house-specific, complicating the development of definitive guidance regarding when slab sealing is likely to be most cost-effective. At present, the best approach would be to close the perimeter joint and other openings in basement slabs, where accessible, whenever the joint is wider than a hairline crack.

In crawl-space houses, the cost of sealing the membrane is most pronounced when: (a) the entire membrane must be sealed (i.e., at the junction between the membrane and the

Table 5B. Parametric variations resulting in an installation cost impact of $50-$100.

	Parametric variation	Cost impact ($)	Estimated standard deviation ($)
1.	Increasing the horizontal piping run for the one-pipe SSD system by 4.5 m in a finished basement, increasing the 3-m horizontal run in the baseline system to 7.5 m (Variables 2 and 3):	+89	69
2.	Adding a 7.5-m horizontal run in the attic for the one-interior-pipe SSD system in slab-on-grade houses, relative to the baseline case where the interior SSD pipe extended straight up through the ceiling and through the roof (Variables 2 and 3):	+58	9
3.	Adding additional suction pipes through the membrane of the crawl-space SMD system, beyond the one pipe included in the baseline (Variables 2 and 3):		
	– increase per pipe added	+63	21
4.	Upgrading the type of pipe to 4-in. diameter Schedule 40, compared to the 4-in. thin-walled pipe used in the baseline systems (Variable 5):		
	– basement houses	+80	8
	– slab-on-grade houses	+54	29
	– crawl-space houses	+87	49
5.	Upgrading the fan to a 100-W unit having 15-cm or 20-cm couplings, compared to the baseline 90-W, 15-cm fan capable of moving 127 l/s (Variable 9):		
	– upgrade to 100-W unit with 15-cm couplings, capable of moving 169 l/s	+35 to +50[1]	
	– upgrade to 100-W unit with 20-cm couplings, capable of moving 193 l/s	+60 to +80[1]	

1. Calculated independently of the estimates from the five mitigators, based upon manufacturers' quotes and assuming a 50% mark-up by mitigators for overhead plus profit. Thus, no standard deviation is shown.

Table 5C. Parametric variations resulting in an installation cost impact of less than $50.

	Parametric variation	Cost impact ($)	Estimated standard deviation ($)
1.	Utilizing sump/DTD rather than the baseline one-pipe SSD system, in houses where a sump is present (Variable 1):	+33	15
2.	Increasing the horizontal piping run for the one-pipe SSD system by 4.5 m in an *un*finished basement, increasing the 3-m run in the baseline system to 7.5 m (Variables 2 and 3):	+33	16
3.	Utilizing a one-pipe *exterior* SSD system in a slab-on-grade house (with the suction pipe penetrating horizontally through the foundation wall from outdoors, with an exterior stack), rather than the baseline case of one suction pipe vertically through the slab indoors, with an interior stack (Variables 2 and 3):		
	– one-story slab on grade	+10	34
	– two-story slab on grade	-25	54
4.	Using 7.5-cm diameter piping rather than the baseline thin-walled 10-cm piping (Variable 4):		
	– if thin-walled 7.5-cm pipe and fittings available	-20[1]	
	– if only Schedule 40 7.5-cm pipe and fittings available	+35[1]	
5.	Excavating a small pit beneath the cored hole through the slab in basement and slab-on-grade houses, compared to the baseline case of no pit (Variable 6):	+18	18
6.	Locating the fan inside the basement or crawl space, compared to the baseline case where the fan is immediately outside the house, with an exterior stack (Variable 8):	0	0
7.	Using a smaller fan (50-70 W, 10- to 13-cm diameter couplings), compared to the baseline 90-W, 15-cm fan (Variable 9):	-15[1]	
8.	Installing a less expensive alarm, rather than a Magnehelic gauge (Variable 12):		
	– replace Magnehelic with curved inclined manometer	-30[1]	
	– replace with U-tube manometer or floating-ball device	-45[1]	
9.	Increasing the baseline pre-mitigation diagnostics (visual inspection only) to include sub-slab communication measurements, in cases where the sub-slab diagnostics can be conducted when the crew arrives to install the system (Variable 13):		
	– unfinished basement	+45	47
	– finished basement or slab on grade	+106[2]	[2]
10.	Increasing post-mitigation diagnostics, beyond the suction and indoor Rn measurements included in the baseline (Variable 14):	0[3]	

1. Calculated independently of the estimates from the five mitigators, based upon manufacturers' quotes and assuming a 50% mark-up by mitigators for overhead plus profit. Thus, no standard deviation is shown.
2. Includes estimate from only one mitigator.
3. Any post-mitigation diagnostics will likely result from failure of the initial installation to achieve 148 Bq/m^3 and less, and thus would be conducted under the warranty that most mitigators offer, resulting in no additional direct cost to the homeowner.

perimeter foundation wall, as well as at the seams between membrane sheets); and (b) the perimeter must be sealed by wrapping the edge of the membrane around a wooden furring strip which is nailed and caulked to the wall, to improve the durability of this seal. From Table 5a (Item 5), such complete membrane sealing adds $456-$620 to the installation cost, compared to the baseline case of no membrane sealing, depending upon the size of the crawl space. By comparison, if the membrane is simply attached to the perimeter wall with a bead of caulk – clearly a less durable approach – the cost increase drops to $102-$248 above the baseline. And if perimeter sealing can be eliminated altogether, and the sealing effort limited to caulking/cementing the seams between sheets of membrane, the cost increase drops further, to $66-$117.

The required degree of membrane sealing can have a substantial cost impact (adding as much as $620) on the cost of SMD, which is the most expensive ASD variation even when no sealing is needed. Some mitigators have observed adequate SMD radon removal performance without any liner sealing, except near the point where the suction pipe penetrates the liner (Findlay et al., 1990; Pyle and Williamson, 1990). The available data on SMD performance in crawl-space houses are very limited. Further R&D would appear warranted to better define the degree of membrane sealing that is required under different conditions (e.g., gravel vs. bare-earth floor in crawl space, crawl-space size, design details of the SMD system).

Three alternative design configurations were considered for SMD systems (see Variable 11 in Table 2). These alternatives differed from the baseline by reducing the amount of crawl-space floor covered by the membrane, and/or by using perforated piping underneath the membrane as a means for distributing suction. Each of these had an impact of about $100 or greater on the installation cost (Item 6 in Table 5a).

Only one of the three SMD alternatives resulted in reduced costs. Eliminating coverage by the membrane of difficult-to-access portions of the crawl-space floor could reduce costs by about $100 or perhaps more, depending upon how much of the floor is left uncovered and how inaccessible the areas in question are. The major uncertainty is to what degree such incomplete floor coverage might degrade the radon reduction performance of the system. Some testing suggests that complete floor coverage is not always necessary (Findlay et al., 1990), but the data are limited and not definitive. Further field testing, supported by applied R&D, could determine to what extent system performance is degraded when different amounts of the floor are left uncovered under various conditions, to enable better guidance regarding the cost-vs-performance tradeoffs in leaving portions of the floor uncovered.

The other two SMD design alternatives that were considered involved drawing suction on perforated piping beneath the membrane (rather than simply penetrating an individual suction pipe through the membrane), in an effort to improve the distribution of the submembrane suction field. See Variations 2 and 3 for Variable 11 in Table 2. Neither of these cases appeared to offer potential for reductions in the installation cost.

As a minimum, the costs for these two SMD design alternatives increased by an amount equal to the burdened materials cost for the perforated pipe, about $100. (In Variation 2, where the perforated pipe forms a loop around the crawl-space perimeter and where the central crawl-space floor remains uncovered, the cost of the perforated piping is offset by the savings from not having to cover the central floor.) With the perimeter loop in Variation 2, there is concern that placing the suction so close to the perimeter could require careful sealing of the membrane to the perimeter wall using a furring strip, to reduce short-circuiting of crawl-space air into the piping (Findlay et al., 1990). As discussed earlier, such careful perimeter sealing increases installation cost by an additional $400-$500. Further evaluation of the two perforated piping configurations would require R&D to determine whether the perforated piping improves radon reduction performance sufficiently to warrant its cost, and whether the two different configurations either increase or decrease the need for sealing the membrane to reduce air leakage (thus increasing or decreasing their respective cost impacts).

The other parametric variations listed in Tables 5a, 5b, and 5c, beyond those discussed above, offer less potential for significant installation cost savings that can be enhanced or encouraged by further R&D.

In many cases, the decisions regarding these other parameters are determined based on site-specific characteristics, or on homeowner and mitigator preferences, and are not likely to be influenced by R&D. For example, the decision to utilize sump/DTD rather than SSD (Item 1, Table 5c) will commonly be determined by whether a sump is present in the basement. As another example, the length of horizontal piping runs (Items 1 and 2, Table 5b, and Item 2, Table 5c) will usually be determined by the house floor plan, finish, and obstructions. (However, the R&D discussed above to reduce costs in poor-communication houses could potentially reduce the horizontal runs in such houses by increasing the flexibility in pipe placement.)

In some cases, the cost impact of these other parametric variations is small. For example, locating the fan inside the house shell rather than outdoors when there is an exterior stack (Item 6, Table 5c) has essentially no impact on installation cost. EPA discourages locating the fan inside the shell, because leaks that may subsequently develop on the pressure side of the fan would then result in high-radon fan exhaust being blown into the house. From the results in Table 5c, there does not appear to be a cost incentive to conduct R&D to define system designs and conditions under which locating the fan indoors might be acceptable.

Operating Costs

Effect of Switching to a Smaller Fan

For the purposes of this analysis, it was assumed that the baseline 90-W, 127 l/s fan was replaced by the 50-W, 58 l/s fan (the smallest fan considered in this analysis). This reduction in fan capacity was assumed to be generally representative of the maximum reduction that might be considered in practice, thus suggesting the maximum reductions in operating costs that might be anticipated. A similar calculation would apply if, instead of replacing the 90-W fan, that fan were turned down to consume less power.

With the switch to the 50-W fan, the annual cost for electricity to operate the fan would decrease from $63 to $35 per year, based on the assumptions indicated in Table 3. This represents a saving of $28 per year in the electricity bill, or about $2 per month.

In addition to consuming less electricity, the smaller fan would exhaust less treated house air, reducing the heating/cooling penalty. From the assumptions in Table 3, the amount of exhausted house air would decrease from 50% of 35 l/s (or 18 l/s) with the 90-W fan, to 50% of 18 l/s (or 9 l/s) with the 50-W fan, a 9 l/s reduction. If the house ventilation rate is also reduced by 9 l/s, the combined heating plus cooling penalty would be reduced by $40 per year (from $79 to $39 per year). This reduction corresponds to an average saving of about $3 per month in the gas plus electricity bills.

Considering the combined effects of reduced fan electrical consumption and reduced heating/cooling penalty achieved by switching to the smaller fan, annual operating costs would decrease from $63 + $79 = $142 per year with the 90-W fan, to $35 + $39 = $74 per year with the 50-W fan, a saving of $68 per year. This corresponds to a saving of about $5.50 per month, on average. It is unclear whether many homeowners could distinguish this reduction from the normal monthly variation in their gas and electricity bills. Most of the limited data available indicating the effects of fan capacity on radon reduction performance suggest that this decrease in fan capacity will often be accompanied by an increase in indoor radon levels. Thus, this relatively modest decrease in operating cost would generally be accompanied by some increase in health risk.

Effect of Slab Sealing

As indicated in Table 3, for the purposes of this analysis, it was assumed that sealing the slab would reduce the percentage of house air in the exhaust from 50% to 30%. The total exhaust flow rate was assumed to be reduced accordingly.

With the 90-W fan, slab sealing would thus decrease the total exhaust rate of the system from 35 to 25 l/s, and would decrease the amount of house air exhausted from 50% of 35 l/s (or 18 l/s) to 30% of 25 l/s (7.5 l/s). This would reduce the combined heating/cooling penalty from $79 to $33 per year, a saving of $46 per year, or about $4 per month.

If slab sealing is combined with switching to the 50-W fan, the total exhaust rate from the 50-W system falls from the 18 l/s indicated in Table 3 to 13 l/s, and the amount of house air exhausted decreases to 30% of 13 l/s (or 4 l/s). Comparing this to the amount of house air exhausted by the 90-W fan without slab sealing (50% of 35 l/s, or 18 l/s), the heating/cooling penalty relative to the baseline is reduced from $79 to $17 per year, a saving of $62 per year (about $5 per month).

When the $28 per year savings in the cost of electricity for the smaller fan are considered, the total operating cost savings resulting from switching from the 90-W fan/unsealed slab to the 50-W fan/sealed slab are $28 + $62 = $90 per year. The total operating cost falls from $63 + $79 = $142 per year, to $35 + $17 = $52 per year. This corresponds to a saving of $7.50 per month.

Conclusions

1. R&D aimed at the following variations of ASD system design parameters offers the greatest potential for achieving significant reductions in installation costs:
   (a) Reducing the number of SSD suction pipes required in houses having poor sub-slab communication. Each additional pipe beyond the first adds about $135 - $274 to the installation cost.
   (b) Eliminating the need for large sub-slab excavations under SSD pipes as an aid to suction field extension in poor-communication houses. Each large excavation adds about $200.
   (c) Improving the effectiveness of pre-mitigation diagnostic testing in reducing the number of SSD pipes required (and/or the number of large excavations required) in poor-communication houses. Achieving system designs needing fewer pipes (or fewer excavations) would reduce the installation cost, thus helping to offset the $50 - $200+ cost of conducting the diagnostics.
   (d) Eliminating the interior or exterior stack that is required to discharge ASD exhaust above the eaves. If conditions can be defined under which grade-level discharge is acceptable, the $50 - $325 cost of the stack would be eliminated.
   (e) Avoiding the need for complete sealing of the membrane in crawl-space SMD systems, and avoiding the need for complete coverage of the crawl-space floor by the membrane. Definition of the conditions under which complete membrane sealing and complete floor coverage are not necessary could reduce the installation costs of SMD systems by up to $600.
2. It is unclear how successful R&D might be in achieving the cost reductions indicated in Conclusion 1. Realistically, it would

appear possible to reduce the installation costs of selected ASD systems by several hundred dollars at best.

The baseline installation cost estimates assumed houses having good sub-slab communication, and SMD systems with no sealing of the membrane. Therefore, any savings that might result from items (a), (b), (c), and (e) in Conclusion 1 would not serve to reduce the baseline installation costs presented in Table 4. Rather, any savings would serve to prevent installation costs in poor-communication houses, or in houses where the SMD membrane might otherwise have to be sealed, from increasing so significantly above the Table 4 baseline figures.

3. While savings of several hundred dollars in the installation cost can be expected to create some increase in voluntary installation of ASD systems by homeowners, it is not likely that it will increase the demand dramatically among homeowners in houses having pre-mitigation levels near or below EPA's current guideline of 148 Bq/m3. Mitigation is required in a significant number of such marginally elevated houses if there is to be a substantial reduction in the estimated annual number of deaths due to radon. Since it is not likely that R&D will be able to reduce ASD installation costs sufficiently to achieve widespread voluntary mitigation of marginally elevated houses, an inexpensive innovative mitigation approach would appear to be needed.
4. The maximum operating cost savings that appear achievable through reductions in fan size and through slab sealing to reduce the house heating/cooling penalty are on the order of $7.50 per month. It is expected that many homeowners will not be able to distinguish these savings from the normal monthly variations in their utility bills. While these operating cost savings may influence some homeowners, and while the smaller fans and reduced heating/cooling penalty will reduce national energy consumption, the reduced operating cost is not likely to be a deciding factor for most homeowners as to whether or not to install an ASD system. It must also be recognized that reductions in fan size will often be accompanied by increases in indoor radon levels, even if levels remain below 148 Bq/m^3. Thus, the modest reduction in operating cost will be offset by an increase in health risk. Accordingly, R&D to determine conditions under which fan capacity can be reduced is considered to be of secondary priority.

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