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Project Summary

Parametric Analysis of the Installation and Operating Costs of Active Soil Depressurization Systems for Residential Radon Mitigation

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Recent analysis has shown that cost-effective indoor radon reduction technology is required for houses having initial radon concentrations below 148 Bq/m³, because 78-86% of the national lung cancer risk due to indoor radon is associated with those houses. Active soil depressurization (ASD) is a very effective, widely applicable, and well demonstrated radon reduction technology. However, many homeowners having pre-mitigation levels above 148 Bq/m³ have not installed an ASD system; application of ASD by homeowners *below* 148 Bq/m³ is insignificant. In part, this limited voluntary use of ASD systems is likely due to their installation costs (typically $800-$1,500) and operating costs. Thus, a comprehensive cost analysis was conducted to determine if EPA might be able to reduce ASD installation and operating costs enough to significantly increase voluntary use of this effective technology, especially among homeowners having low initial radon concentrations.

The analysis showed that various modifications to ASD system designs offer potential for reducing installation costs by up to several hundred dollars, but would not reduce total installed costs much below $800-$1,500. Because the price/demand curve is thought to be relatively inelastic, cost reductions of this magnitude would probably not be sufficient to dramatically increase voluntary use of ASD technology, especially not among homeowners having only marginally elevated pre-mitigation levels. Thus, to reduce the 78-86% of the national risk associated with houses below 148 Bq/m³, some innovative, inexpensive mitigation approach(es) would appear to be necessary, in addition to ASD. Even if such innovative alternative approaches provided lower radon reductions than did ASD in a given house, they could provide a much greater reduction in the national health risk, if their low costs resulted in very wide utilization. EPA's radon mitigation R&D program is currently focused on the development of such innovative, low-cost approaches.

Decreased ASD fan capacity and increased sealing might reduce ASD operating costs (for fan electricity and house heating/cooling) by roughly $7.50 per month. This amount would not likely be a deciding factor for most home—owners.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering Information at back).

Introduction

Active soil depressurization (ASD) techniques have been proven to be the most widely used indoor radon reduction technique for houses, due to their effectiveness in reducing radon levels under a wide variety of conditions, their reliability, and their moderate installation cost. 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 result in the U.S. each year as a result of exposure to indoor radon. EPA also estimates that only a few houses with elevated indoor radon concentrations have installed 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 the U.S., 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 33%.

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 ASD systems installed by a commercial radon mitigator cost in the range of $800 to $1,500.

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 (R,D & D) efforts, to improve 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. Since the price/ demand curve for mitigation systems is thought to be relatively inelastic, the cost reduction would probably have to be substantial in order to significantly increase demand.

The question underlying this study was, What will be the relative role of highly efficient, well-demonstrated ASD technology in reducing the national health risk due to radon, compared to the role(s) of as-yet undeveloped, innovative, low-cost, moderate-reduction technique(s)? Through appropriate R,D&D, can ASD costs be reduced sufficiently to achieve more widespread voluntary utilization, thus helping ASD play a greater role in reducing national risk?

Approach

Installation Costs

The effect of 14 ASD design parameters on system installation costs was assessed by obtaining installation cost estimates from five mitigation firms representing different major mitigation markets across the country. Initially, each mitigator developed cost estimates for baseline mitigation systems in eight different houses. The eight houses represented three house design/construction parameters (substructure type, number of stories, and degree of basement finish). Two other house design/construction variables — presence/ absence of a sump, and nature of sub-slab communication — were also addressed, but were handled as mitigation design variables (sub-slab vs. drain-tile depressurization, number/location of suction pipes).

The baseline mitigation system for the eight houses consisted of selected values for the 14 system design parameters. The baseline values for the 14 parameters are listed in Table 1.

The parametric analysis was then conducted by asking each mitigator to estimate the incremental impact on the baseline installation cost (and on labor hour and material cost requirements) as each of the 14 design parameters was varied in turn, through a range of logical values.

In addition to the 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. (There were some differences in how the post-mitigation measurements were made.)

c) a warranty that the house would be reduced below 148 Bq/m^3 for a year or longer. The exact nature of the warranty varied from mitigator to mitigator.

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. Among these inherent differences were:

a) direct labor, fringe benefit, and overhead/profit rates.

b) differences in system design details, such as whether exhaust stacks are boxed in inside or outside the house, whether interior stacks can be installed in existing utility chases, whether exterior stacks penetrate or jut around the roof overhang, or whether membranes installed in crawl spaces must be attached to the perimeter wall using a wooden furring strip or fastened to the wall using a bead of caulk.

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 the amenability of the local house construction characteristics to interior stacks.

No attempt was made to correct for variations created by such inherent differences. These inherent differences reflect the natural variations between mitigators across the county, 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 on-going costs that homeowners experience in operating ASD systems: 1) the cost of electricity to run the fan; 2) the heating and cooling penalty resulting from the exhaust by the system of some treated house air; 3) the cost of system maintenance, primarily fan repair/replacement,

Table 1. Summary of the Baseline ASD Mitigation Systems Utilized in Parametric Analysis of ASD Installation Costs

ASD Design Variable	Baseline Value
1. Variation of ASD technology	
- basement houses	Sub-slab depressurization (SSD).
- slab-on-grade houses	Sub-slab depressurization (SSD).
- crawl-space houses	Sub-membrane depressurization (SMD).
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.
- slab-on-grade houses	One pipe, inside house, directly under point where piping penetrates ceiling into attic and then through roof.
- crawl-space houses	One pipe, penetrating SMD membrane in center.
4. Pipe diameter (all houses)	10 cm.
5. Type of pipe (all houses)	Thin-walled polyvinyl chloride (PVC).
6. Nature of slab/membrane hole	10- to 13-cm hole cored through slab (or cut through SMD membrane); no excavation under slab or membrane at point where hole penetrates.
7. Exhaust piping configuration	
- basement houses	Vertical stack above eaves, rising outside house.
- slab-on-grade houses	Through ceiling to fan in attic, exhaust through roof.
- crawl-space houses	Through a foundation vent to a vertical stack above eaves, rising outside house.
8. Location of fan	
- basement houses	Immediately outside basement, at grade level.
- slab-on-grade houses	In attic.
- crawl-space houses	Immediately outside crawl space, at grade level.
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.
10. Degree of slab and membrane sealing (all houses)	No sealing, other than around pipe penetration through slab or membrane.
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, as indicated previously.
12. Nature of gauge/alarm	Dwyer Magnehelic
13. Pre-mitigation diagnostics	Visual inspection only: no sub-slab communication testing. Estimates should include cost penalty based upon experience, reflecting subsequent system modifications and call backs resulting from decision to bypass pre-mitigation sub-slab measurements.
14. Post-mitigation diagnostics	Suction/flow measurements in piping after installation. Post-mitigation indoor radon measurement, using technique consistent with mitigator's normal practice.

plus some effort to re-cement/re-caulk broken piping joint seals or slab caulking; and 4) the cost of any periodic re-measurements of indoor radon levels. This report focusses primarily on fan electricity and the heating/cooling penalty, since these elements can be addressed most quantitatively, and impacted most readily by additional R & D.

The obvious method for reducing both the electricity cost and the heating/cooling penalty is to use a smaller (lower-wattage, lower-flow) fan, or to operate a larger fan at reduced capacity using a controller. But in addition to reducing operating costs, use of reduced fan capacity will often result in some degradation in the radon reduction performance of the system, even if indoor levels remain below 148 Bq/m^3.

Since the data base is so limited in defining the effect of reduced fan capacity on indoor radon levels, the calculations here do not attempt to quantify the tradeoff between reduced operating costs and resulting increased health risk from higher radon levels. Rather, the calculations address only the operating cost reductions that can be achieved with alternative reductions in fan capacity. If the cost reductions appear to be high, they could warrant further R&D to determine the conditions under which such reductions in capacity might be acceptable, including consideration of the tradeoffs with increased health risk.

Another method for potentially reducing the heating/cooling penalty would be to seal slab cracks and openings, to reduce the amount of treated house air exhausted by the system. Again, there are very little data defining to what degree the flow of house air into the system can be reduced by such slab sealing efforts. Tracer gas studies by various investigators have indicated that between 10 and 90% of the air in ASD exhausts can be drawn from inside the house. For the calculations here, to obtain a rough estimate of the operating cost penalty, it was assumed that an average of 50% of the exhaust was house air prior to any slab sealing, and that slab sealing reduced this to 30% (the lower end of the range most commonly observed). It was also assumed that the increase in house ventilation rate caused by the ASD system is exactly equal to the amount of house air in the ASD exhaust; this assumption is not necessarily accurate.

The calculations make various assumptions regarding fan power consumption, electricity and fuel costs, the nature of the furnace and air conditioning system, and the climate. These assumptions are all specified in the complete report.

Results and Discussion

Installation Costs

Table 2 presents the average of the total installation costs for baseline systems in the eight houses. The figures in the table are the arithmetic mean of the estimates from the five mitigators. Tables 3, 4, and 5 indicate the average incremental increases or decreases in those baseline costs caused by the variations to the 14 system design variables. Table 3 presents those parametric variations having a cost impact near to, or greater than, $100 (relative to the baseline system); these are the parameters for which additional R&D would be expected to offer the greatest potential for installation cost reductions. Parametric variations having an impact between $50 and $100 are listed in Table 4, and parametric variations having cost impacts less than $50 are listed in Table 5. While the parameters in Table 5, taken together, can have a noticeable combined effect on the total cost, the cost impact of any one of them alone is probably lost within the uncertainty level of the cost estimates that mitigators provide to prospective clients.

Parametric variations having a cost impact of about $100 or greater (Table 3). Three of the parametric variations having significant cost impact deal with houses having poor sub-slab communication, which is not surprising. Adding additional suction pipes in basements and slabs on grade (Item 1 in Table 3), jackhammering a 0.6- by 0.6-m hole in the slab to enable excavation of a large pit beneath the suction pipe (Item 2), and conducting pre-mitigation sub- slab communication testing (Item 7), are all steps for addressing poor-communication houses. Each additional suction pipe adds about $135 to $274 to the total installation cost, depending upon house characteristics; each jackhammered hole adds roughly $200, with a broad standard deviation; and the pre-mitigation sub-slab communication testing adds about $200, where these diagnostics require a separate trip to the house. Whether sub-slab diagnostics are conducted during a separate trip, or on the morning that the crew arrives to install the system, depends upon the particular situation and the practices of an individual mitigator. As shown in Table 5, the cost of these diagnostics decreases significantly when the communication testing and the installation can be conducted during the same visit.

To reduce the need for additional suction pipes (Item 1) or for large sub-slab pits (Item 2), R&D would have to identify inexpensive methods for: a) improving the communication; and/or b) improving the performance of a one-pipe SSD system without improving the communication. An example of means for improving communication is the use of high- pressure air or water jets under the slab to create channels between the bottom of the slab and the underlying soil. Examples of approaches for improving performance without improving communication might include improved pre-mitigation diagnostics and higher- performance fans. At the present time, EPA's R&D program is addressing only one of the above possibilities, in a relatively limited manner; this possibility is improved pre-mitigation diagnostics, which should result from improved fundamental understanding resulting from the on-going fundamental/innovative research effort. Other investigators are conducting some

***Table 2.** 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 1.

[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.

studies on the use of sub-slab air and water jets, and on improving fan performance. Any re-direction of the EPA R&D program would have to be preceded by an appropriate planning effort.

In evaluating possible R&D to reduce system costs in poor-communication houses, consideration must be given to the fact that — to be cost-effective — the methods developed for improving communication, or for improving the performance of a one-pipe SSD system without improving communication, must be commercially applicable at a cost significantly lower than the cost of the alternatives. That is, they must add less to the total installation cost than the roughly $200 required to add another suction pipe or to excavate a large pit.

It is doubtful that R&D can reduce the cost of conducting added pre-mitigation diagnostics in poor-communication houses, where a separate trip to the house is required (Item 7 in Table 3). Improved diagnostics would not reduce the travel time, nor the time to actually perform the diagnostics. (The time to conduct the improved diagnostics might even increase, compared to the current sub-slab communication test methods.) However, if R&D ultimately results in diagnostics which permit more effective SSD system designs, the cost of the sub-slab diagnostics might be at least partially offset by cost reductions resulting from the need for fewer suction pipes, or from avoiding the need for sub-slab excavations.

Note that the baseline installation costs (averaging $1,000 to $1,200 for SSD systems, as shown in Table 2) assume houses having relatively good communication, requiring only one suction pipe, no sub-slab excavation, and no communication testing. Thus, if the R&D discussed above were successful in reducing the number of pipes or excavations in poor-communication houses, or in making the diagnostics more efficient, this R&D would not reduce average installation costs below $1,000-$1,200. Rather, it would only prevent installation costs in poor-communication houses from increasing so significantly above these baseline costs.

In addition to means for addressing poor-communication houses, another variable shown as having a potentially significant cost impact is the configuration of the exhaust (Item 3 in Table 3). Exhausting at grade level (eliminating the exterior stack) reduces costs by $93 to $169, depending primarily on the number of stories. Locating the stack in the adjoining garage rather than outside the house increases costs by $96. Locating the stack inside the house, rather than outdoors, can result in either a significant cost increase ($91-$155) or some cost reduction ($38-$61), depending upon the estimator; whether the interior stack is more or less expensive appears to depend at least in part upon the degree of experience that the particular mitigator has with interior stacks.

It is doubtful that any R&D that EPA could perform would significantly impact the cost of interior vs. exterior stacks, or of stacks in the garage vs. outdoors. To the extent that lack of experience is in fact responsible for the higher estimates from some mitigators for interior stacks, reducing the cost of interior stacks by those mitigators would appear to reflect a potential need for improved training, improved technology transfer, and increased market demand for interior stacks, rather than a need for R&D.

However, the mitigators are in general agreement that eliminating a stack releasing the exhaust immediately beside the house, could result in a potentially significant reduction in cost. EPA's current recommendation is that the exhaust should be released above the eave; i.e., that a stack is desirable. In view of the potential cost reductions from eliminating the stack, R&D would appear justified 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). Such R&D could include tracer gas studies to assess re-entrainment of the exhaust back into the house, and to identify "plume effects" in the yards of the homeowners and their neighbors. In addition to reducing costs, elimination of the stack might also increase homeowner acceptance of SSD systems by eliminating the aesthetic impact of stacks.

Sealing the slab also has a significant impact on installation costs in basement houses (Item 5 in Table 3). This cost is especially pronounced when a perimeter channel drain (French drain) is present ($326-$470). The range of the costs shown in the table for sealing the wall/floor joint or for closing the French drain results because the one-story house has a much larger footprint than the two-story, thus a longer perimeter joint to seal. Some R&D (involving demonstration testing in houses having SSD systems) might be warranted to assess the impact of crack and French drain sealing on the radon reduction performance of the systems and on the heating/cooling penalty, to enable a better judgement of the cost-effectiveness of slab sealing. However, the effects of slab sealing are likely to be so site-specific, that it is not clear that a reasonably-sized demonstration effort would answer these questions definitively.

Sealing the membrane for crawl-space SMD systems (Item 5 in Table 3), can have a significant impact in crawl-space houses. This cost impact is especially large ($456-$620) if a complete sealing job is necessary, including careful perimeter sealing, which would require wrapping the edge of the membrane around a 2.5- by 10-cm furring strip and nailing/caulking the strip to the foundation wall. By comparison, if the membrane can simply be attached to the foundation wall with a bead of caulk — clearly a less rigorous approach — the cost of the complete sealing would fall to $102-$248. If perimeter sealing can be eliminated altogether, since the suction pipe is at a central location some distance from the perimeter, and if only the seams between sheets are caulked, the cost increase would drop to $66-$117. (Again, these ranges result because of the differences in crawl-space floor area between one- and two-story houses.)

The completeness of the membrane sealing effort required depends upon how significantly the leakage of crawl-space air into the SMD system degrades radon reduction performance, and how significantly it increases the heating/cooling penalty in the house. Some field testing results suggest that little membrane sealing is required in some cases, except in the immediate vicinity where the suction pipe penetrates the membrane. However, testing in crawl-space houses has been quite limited, relative to that in basements and slabs on grade. As a result, EPA cannot give rigorous guidance regarding what degree of membrane sealing is cost-effective. In view of the significant additional cost that careful sealing requires, further R&D in crawl-space houses appears desirable in order to define the conditions under which alternative degrees of membrane sealing are required, and the performance and operating cost penalties that will result under the various conditions if the sealing is not performed (or if it degrades over time, as may occur if the membrane is simply caulked to the foundation wall). Both field demonstration testing and more fundamental studies would appear to be warranted.

Modifications to the design configuration of crawl-space SMD systems (Item 6 in Table 3) can also have a significant impact on cost. The one alternative configuration which offers potential for reducing costs is the approach of leaving "diffi-

Table 3. Parametric Variations Resulting in an Installation Cost Impact of About $100 or More

	Mean Cost Impact[1] ($)	**Estimated Standard Deviation[1] ($)**
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
5. Increased degree of sealing, Variable 10 (continued)		
- 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 and 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

Table 3, Continued

Table 3. Continued

	Mean Cost Impact[1] ($)	Estimated Standard Deviation[1] ($)
6. Modification of the baseline SMD design configuration (Variable 11):		
- leaving a portion of crawl-space floor uncovered	-100 (approx.)[2]	
- perforated piping loop around perimeter, membrane perimeter sealed using furring strip	+500 (approx.)[2]	
- perforated piping under central membrane, no sealing	+100 (approx.)[2]	
7. Increasing the baseline pre-mitigation diagnostics (visual inspection only) to include sub-slab communication measurements, where the sub-slab diagnostics require an extra trip to the house (Variable 13):	+208	46

[1] The arithmetic mean increases (+) or decreases (-) in installation costs, relative to the baselines, are calculated from the estimates from the five mitigators contributing to this study. The estimated standard deviations reflect the range covered by the five estimates.

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

Table 4. Parametric Variations Resulting in an Installation Cost Impact of $50-$100

	Mean Cost Impact[1] ($)	Estimated Standard Deviation[1] ($)
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 10-cm diameter Schedule 40, compared to the 10-cm 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- 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	+50 to +75[2]	
- upgrade to 100-W unit with 20-cm couplings, capable of moving 193 L/s	+90 to +120[2]	

[1] The arithmetic mean increases (+) or decreases (-) in installation costs, relative to the baselines, are calculated from the estimates from the five mitigators contributing to this study. The estimated standard deviations reflect the range covered by the five estimates.

[2] Calculated independently of the estimates from the five mitigators, based upon manufacturers' quotes and assuming a 50% markup by mitigators for overhead plus profit. Thus, no standard deviation is shown.

cult" or inaccessible portions of the floor area uncovered by membrane (rather than ensuring coverage of the entire floor, as in the baseline case). Depending upon how much of the floor area is left uncovered, and upon how inaccessible that area is (i.e., how much it would have cost to ensure complete coverage), leaving portions of the floor uncovered could result in installation cost reductions of $100 or more. The uncertainty, of course, is how such incomplete coverage might impact the radon reduction performance of the system.

The other SMD modifications considered involved the use of perforated piping underneath the membrane in an effort to improve the distribution of the suction field under the membrane. These other modifications either increased costs, or left them unchanged. The question is whether the increased costs resulting from drawing suction on a matrix of perforated piping, rather than simply inserting a suction pipe through the plastic, would result in sufficiently improved performance to warrant the increased cost. If the simple pipe penetration through the complete but unsealed membrane (the baseline case) is replaced by suction on a matrix of perforated piping under a complete but unsealed membrane, the installation cost increases by about $100.

If the baseline system is instead replaced by a loop of perforated piping around the crawl- space perimeter, and if the membrane covers only the perimeter (from the foundation wall out to a distance equal to the width of the polyethylene sheeting), then the effect on costs will depend upon the amount of membrane sealing necessary. If this perimeter membrane can be left largely unsealed, then the cost increase resulting from the materials cost for the perforated piping is essentially offset by the cost reduction resulting from being able to leave the central portion of the crawl-space floor uncovered, and this configuration has a cost comparable to the baseline. If, on the other hand, location of the suction around the perimeter (with this perforated piping loop) requires careful sealing of the membrane to the perimeter foundation wall using a furring strip, whereas suction on a central pipe penetration (as in the baseline) does not require such careful sealing, then the perimeter-loop configuration will be $500 more expensive than the baseline, due to the expense of careful perimeter sealing, discussed previously. If careful perimeter sealing is *not* necessary with the perimeter-loop configuration, and if that configuration gave good radon reductions (as

Table 5. Parametric Variations Resulting in an Installation Cost Impact of Less Than $50

		Mean Cost Impact[1] ($)	**Estimated Standard Deviation[1] ($)**
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	-21[2]	
	- if only Schedule 40 7.5-cm pipe and fittings available	+36[2]	
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[2]	
8.	Installing a less expensive alarm, rather than a Magnehelic gauge (Variable 12):		
	- replace Magnehelic with curved inclined manometer	-30[2]	
	- replace with U-tube manometer or floating-ball device	-45[2]	
9.	Increasing the baseline pre-mitigation diagnostics (visual inspection only) to include sub-slab communication measurements, 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[3]	[3]
10.	Increasing post-mitigation diagnostics, beyond the suction and indoor Rn measurements included in the baseline (Variable 14):	0[4]	

[1] The arithmetic mean increases (+) or decreases (-) in installation costs, relative to the baselines, are calculated from the estimates from the five mitigators contributing to this study. The estimated standard deviations reflect the range covered by the five estimates.

[2] Calculated independently of the estimates from the five mitigators, based upon manufacturers' quotes and assuming a 50% markup by mitigators for overhead plus profit. Thus, no standard deviation is shown.

[3] Includes estimate from only one mitigator.

[4] 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.

it has in two study houses), this could make the SMD approach feasible in houses where the central area of the crawl-space floor was inaccessible. Again, an unanswered question is the relative effectiveness of the two configurations in reducing radon levels.

Because of the limited data base on crawl-space houses, EPA is not able to give guidance regarding the ability to reduce SMD costs by leaving a portion of the floor uncovered, or regarding the cost-effectiveness of using perforated piping to improve system performance and to extend SMD applicability to houses where portions of the crawl-space floor are inaccessible. As discussed previously, in connection with the need to seal the membrane, further R&D would be valuable in crawl-space houses, in order to better define the tradeoffs between the cost savings (or cost increases) obtainable through these SMD design modification, and the reductions (or improvements) in radon reduction performance that might result.

The one other parametric variation listed in Table 3 as having a significant cost impact — locating the fan on the roof, above the exterior stack (Item 4 in the table) — increases the installation cost by about $235, due primarily to the increased cost of the roof-mountable fan itself. No R&D is warranted to address this parameter. Roof mounting clearly offers no potential for cost savings. There could be some advantages in roof mounting (e.g., ice built up inside the piping in cold weather could not fall into the fan blades, as could happen when the fan is mounted at grade level, at the bottom of the stack). However, there are also disadvantages, including increased difficulty in performing maintenance. Mitigators generally do not mount fans on the roof at this time, and there does not appear to be any technical or cost justification to warrant encouragement of that practice.

Parametric variations having a cost impact between $50 and $100 (Table 4). Among the parametric variations creating an intermediate cost impact are increased lengths of horizontal piping runs in finished basements (+ $89) and in the attics of slab-on-grade houses (+ $58) (Items 1 and 2 in Table 4). The need for such horizontal runs is usually determined by site-specific considerations, involving the degree of finish or other obstructions in the house, and logical exit routes for the exhaust piping. No R&D specifically addressing this parameter would appear warranted.

Another parametric variation in this category is the addition of suction pipes penetrating the membrane in crawl-space SMD systems (increasing costs by about $63 per additional pipe). Multiple SMD pipes have been found to be helpful in a few R&D study houses having large crawl spaces and poor soil permeability, although it does not appear that many mitigators have used such multi-pipe systems commercially. In the R&D recommended previously for crawl-space houses, it could be of value to investigate whether multiple pipes, or a sub-membrane matrix of perforated piping, or perhaps a layer of fiber matting beneath the membrane, or perhaps more careful sealing of the membrane, would be the preferred approach when a single central suction pipe through a complete, unsealed membrane (the baseline system) appears insufficient.

Upgrading the type of pipe used, from 10-cm diameter thin-walled PVC piping to heavier, 10-cm Schedule 40 piping (Item 4), would increase installation cost by $54-$87, depending upon the length of piping and the number of fittings required in the system. Most mitigators consistently use the thin-walled pipe, on the basis that it provides sufficient strength for this application, so that the increased material and labor cost involved with the heavier pipe is not warranted. The primary concern with the thin-walled pipe is inadequate resistance to ultraviolet (UV) radiation where used outdoors. Some mitigators paint thin-walled pipe installed outdoors, for UV protection (as well as aesthetics). There does not appear to be any significant potential for reducing installation costs through R&D addressing this variable.

Upgrading the system fan to a 100-W unit (with either 15- or 20-cm couplings) increases the total installation cost by about $50-$120 relative to the baseline 90-W, 15-cm fan, assuming a 50% overhead/profit burden rate (Item 5 in Table 4). The larger fans would also increase the operating cosl. Most residential installations do not require such a large fan, and the 100-W fans are usually considered only in cases involving unusually high flows. Such large fans appear to be needed so infrequently in residential applications, that R&D to define more precisely when they are cost-effective would appear to be of only secondary priority.

Parametric variations having a cost impact of less than $50 (Table 5). Most of the parametric variations in this category, offering less potential for significant installation cost reductions, probably could not be influenced by additional R&D. The use of sump/ DTD rather than SSD (Item 1 in Table 5) will usually be determined by whether a sump is present in the basement, and will be the preferred approach in that case regardless of the marginal, $33 average cost increase that results. Increased horizontal piping runs in unfinished basements (Item 2), or use of an exterior rather than interior SSD system in slab- on-grade houses (Item 3), will generally be determined by practical, site-specific considerations; it is unlikely that additional R&D addressing these parameters would reduce system costs.

Most mitigators use of 7.5-cm instead of 10-cm diameter piping (Item 4) only in low-flow cases where there is some physical constraint (such as the need to fit inside a stud wall) requiring the smaller pipe. Since most mitigators stock only 10-cm pipe, use of 7.5-cm pipe would often result in increased complexity and increased cost (beyond the -$21 to +$36 indicated in Table 5) due to the additional planning required to obtain the needed 7.5-cm piping. Excavation of a small pit beneath cored slab holes (Item 5) is a step that many mitigators always take, because it is either easy (where aggregate is present) or is known (without further research) to be required (where no aggregate is present). Location of the fan inside the basement or crawl space generally has no cost impact relative to mounting immediately outside the house shell; since interior mounting of the fan is against EPA's recommendations , research on this issue is not necessary.

Further R&D might be warranted for smaller fans (Item 7 in Table 5), to better define the conditions under which the use of the smaller fan would offer benefits (reduced material cost, reduced operating cost) that would offset any reductions in radon mitigation performance. However, the potential reductions in the cost of the fan itself are minor (about $10). As discussed under Operating Costs, below, the reductions in operating cost will be relatively small as well, except when considered in terms of energy consumption nationwide by tens of thousands of installations. In addition, results to date suggest that such reductions in fan capacity will usually result in some increase in indoor radon level, even if levels remain below 148 Bq/m^3; hence, there will usually be some increase in health risk resulting from installing a smaller fan on a given system. Thus, R&D on this parameter would appear to be of secondary priority.

The use of alternative alarms (Item 8) is not an area where further EPA-sponsored R&D would appear to be warranted.

Regarding increased pre-mitigation diagnostics (sub-slab communication testing) where these diagnostics are conducted when the crew arrives to install the system (Item 9), the situation is the same as that discussed previously for the more expensive case where a separate visit is required to perform the added diagnostics. Improved fundamental under- standing may lead to improved diagnostic methods and/or improved ways of interpreting the diagnostic results. It is unlikely that this fundamental R&D would reduce the costs of conducting the diagnostics; in fact, it might even result in diagnostics having an increased cost. However, if the improved diagnostic methods permit more effective and/or less expensive SSD system designs, the cost of these added diagnostics might be at least partially offset by decreases in installation cost (and/ or in reduced health risk through improved system performance).

Similarly, fundamental and applied R&D might improve the additional post-mitigation diagnostics that are necessary to determine why a system is not performing as desired (Item 10). Although the costs of any such troubleshooting diagnostics would commonly be borne by the mitigator under the warranties that many mitigators offer, and would thus not directly increase the installation cost for that specific job, installation costs do in fact include such call-back costs, usually in the form of the overhead/profit burden that is applied to all jobs. Again, the improved post-mitigation diagnostics that might result from the R&D might not be less expensive than current methods, but hopefully might help the mitigator solve the particular problem more efficiently, hence reducing overall costs.

Summary of discussion of installation costs. Several radon mitigation system design parameters have been identified for which additional R&D might contribute to reductions in the installation costs for systems. Among the R&D areas appearing to offer the greatest potential for cost reductions are:

a) investigation of methods for improving sub-slab communication in poor-communication houses, or for improving system performance without improvements in communication, to reduce the number of suction pipes necessary and/or to reduce the need to excavate a pit beneath the slab. Maximum potential savings: about \$135 to \$274 per suction pipe eliminated, roughly \$200 per 0.6- by 0.6-m excavation avoided. If successful, such R&D would prevent SSD installation costs in poor-communication houses from increasing so significantly above the \$1,000-\$1,200 cost for one-pipe SSD systems in houses having good communication.

b) fundamental and applied R&D efforts to improve pre-mitigation (and post-mitigation) diagnostics, and to improve the interpretation of these diagnostics, with the objective of achieving net reductions in the total system installation cost (even if the costs of performing the diagnostics themselves do not decrease). Maximum potential savings: difficult to define; the \$45 to \$240 cost of pre-mitigation diagnostics would be offset if the diagnostics eliminated one SSD suction pipe from the installation, saving \$200.

c) testing to define the conditions under which grade-level exhausts might be acceptable for ASD systems, so that the cost of an interior or exterior stack could be eliminated. Maximum savings (where grade-level exhaust is found to be acceptable): about \$93-\$169 if an exterior stack is eliminated; about \$189-\$265 if a stack through an adjoining garage is eliminated; and about \$55-\$324 if an interior stack is eliminated.

d) fundamental and demonstration testing to enable better guidance regarding the design of SMD systems for crawl-space houses, including identification of the cost-effectiveness of alternative degrees of membrane sealing, alternative degrees of floor coverage by the membrane, and alternative methods for using perforated piping to aid in suction field extension under the membrane, under different conditions. Maximum savings: as great as about \$600, if it is found that careful membrane sealing is not required. Major benefit of R&D could be improved system performance in reducing indoor radon levels.

It is difficult to predict how successful R&D addressing those parameters might be in reducing installation costs. From a practical standpoint, it is reasonable to assume that R&D efforts would likely achieve only a fraction of the maximum cost savings listed above for the parameters offering the greatest potential for cost reductions. (For example, the method used to enable the number of suction pipes to be reduced might cost, say, half as much as the additional pipes would have cost, so that the net savings from reducing the number of pipes would be only half of the roughly \$200/pipe indicated above.) Thus, realistically, the greatest cost reductions that might be expected resulting from the R&D effort on all of these parameters would be on the order of several hundred dollars (on systems having baseline installation costs ranging from \$1,000 to \$1,400). As discussed in connection with a) above, some of these savings would likely be achieved only for "difficult" houses (e.g., houses with poor sub-slab communication), where the installation costs would have otherwise been much greater than the baseline costs (which were derived for good-communication houses). Thus, some of these savings would not reduce the baseline installation costs below \$1,000-\$1,400, but rather, would simply prevent costs for difficult houses from escalating so significantly above this baseline.

In addition to the possible reductions in installation costs, R&D aimed at reducing the number of SSD suction pipes or eliminating the exhaust stack would also improve the aesthetics of these systems, possibly resulting in some incremental increase in voluntary utilization of this technology by homeowners.

The price/demand curve for ASD systems, though unknown, is anticipated to be relatively inelastic, based upon practical experience. Thus, it is not likely that cost reductions of several hundred dollars would be sufficient to create a dramatic increase in ASD utilization by homeowners, especially not for houses having only marginally elevated pre-mitigation radon levels.

Therefore, to reduce the 78-86% of the national lung cancer risk associated with houses below 148 Bq/m^3, *some innovative, simple, low-cost mitigation approach(es) — that will be widely utilized by homeowners having only marginally-elevated levels — will be required, in addition to ASD.* If such alternative mitigation approaches are widely used, they may provide a greater reduction in national health risk than will ASD, even if these alternatives provide less of a radon reduction in a given house than does ASD.

As one additional consideration, the prices actually being charged to homeowners for comparable ASD installations by the five mitigators participating in this study vary by more than \$500, reflecting a clear regional variation in the going market rate for mitigation systems. Based upon this observation, it would appear that market forces will have an impact on installation costs that is at least as great as the possible cost savings resulting from R&D.

Operating Costs

Cost of electricity to operate the fan. The baseline fan is a 90-W in-line duct fan having 15-cm diameter couplings. Assuming that this fan draws the full 90-W (which it likely will not do) for 365 days per year, and that electricity costs $0.08/kWh, the cost of electricity to operate this fan would be $63 per year, or about $5 per month.

Replacing this fan with the smallest fan considered here (50 W), or assuming that the 90-W fan was turned down to the point where it drew only 50 W, would result in an annual cost of electricity of $35. The annual savings in the cost of electricity, relative to the 90-W fan, would be $28, or about $2 per month.

On the other hand, replacement of the 90-W fan with one of the larger, 100-W fans would increase the cost of electricity by $7 per year, or about $0.50 per month.

Heating/cooling penalty. To estimate the heating/cooling penalty of the ASD systems, it was assumed that the ASD system with the baseline 90-W fan exhausts 75 cfm,* 50% of which is house air (discussed above under Approach). The house is assumed to be in a climate representative of Washington, D. C., with a gas-fired forced-air furnace and an electric air conditioner.

With these assumptions, for the baseline 90-W fan, the house heating cost increases by $49 per year, and the cooling cost increases by $30 per year, for a combined heating/ cooling penalty of $79 per year, or about $7 per month on average. Thus, for the 90-W fan, the total operating cost (the combined cost of electricity and heating/cooling penalty) is $63 + $79 = $142 per year, or about $12 per month.

The heating/cooling penalty could be reduced in two ways. One approach would be to reduce the capacity of the fan, so that less air would be exhausted. The second approach would be to seal cracks/openings in the slab, to reduce the fraction of the exhaust which is treated house air.

If the 90-W fan (75 cfm total exhaust) were replaced with a 50-W fan (assumed to have a total exhaust rate of about 38 cfm), and if the slab remains unsealed (as in the baseline), the amount of house air exhausted would decrease from 50% of 75 cfm (or 38 cfm) to 50% of 38 cfm (or 19 cfm). The corresponding heating/cooling penalty would fall from $79 to $39 per year. The total operating cost (electricity plus heating/cooling penalty) would thus decline from $142 per year with the 90-W fan, to $35 + $39 = $74 per year with the 50-W fan, a total savings of $68 per year, or about $5.50 per month, resulting from the switch to the smaller fan.

To assess the effect of slab sealing, it is assumed that caulking the wall/floor joint and other slab sealing steps reduce the percentage of house air in the exhaust to 30%, rather than 50%. The total exhaust flow from the ASD system is assumed to be reduced accordingly, due to the lower flow from inside the house. With the 90-W fan, with these assumptions, caulking the slab would reduce the total system exhaust from 75 to 54 cfm, and would reduce the amount of house air exhausted from 50% of 75 cfm (38 cfm) to 30% of 54 cfm (16 cfm). Thus, slab sealing would decrease the heating/cooling penalty with the 90-W fan from $79 to $33 per year, a savings of $46 per year or about $4 per month. Slab sealing would reduce the total operating costs for the 90-W fan from $142 per year to $63 + $33 = $96 per year.

Combined effect of reduced fan size and slab sealing. If the reduced heating/cooling penalty associated with slab sealing is combined with the operating cost savings associated with switching to a 50-W fan, the result should roughly represent the greatest reduction in operating costs that might reasonably be anticipated.

With the slab sealed, the total ASD exhaust rate with the 50-W fan would drop from 38 to 27 cfm. The amount of house air exhausted by the system would drop to 30% of 27 cfm (or 8 cfm). At this low house air exhaust rate, the heating/cooling penalty would fall to $17 per year. The total operating cost (electricity plus heating/cooling penalty) for this case (50-W fan, slab sealed) would thus be $35 + $17 = $52 per year. Comparing this cost to the $142 per year estimated for the baseline case (90-W fan, slab unsealed), the cost savings is $90 per year, or $7.50 per month.

Summary of discussion of operating costs. By switching to a small fan and by sealing the slab, the maximum potential operating cost savings that can result from the combined effects of reduced fan electrical consumption and reduced heating/cooling penalty are $7.50 per month. These savings might or might not be distinguishable among the normal variations that homeowners would see in their monthly gas and electric bills. The total savings of $90 per year might be important to some homeowners. On a national scale, the reduction in energy consumption by tens of thousands of installations could be significant. However, it is doubtful that the incremental operating cost savings resulting from the use of less electricity and less gas would often play a determining role in the decision by an individual homeowner whether or not to install an ASD system.

It is re-emphasized that the reduction in fan capacity will commonly cause some degradation in the radon reduction performance of the ASD system, even if indoor levels remain below 148 Bq/m^3. Thus, the modest reduction in operating cost would be achieved at the expense of some increase in health risk. A better understanding of the impacts of reduced fan capacity on ASD performance — and of any incremental increase in demand for ASD systems that might result from the reduced operating costs — would be required in order to perform a cost-benefit analysis which could integrate these considerations (i.e., which could estimate the effect of the reduced fan capacity on the cost-per-life-saved).

Additional R&D would be needed to support such a cost-benefit analysis. This R&D would include field testing, supported by fundamental R&D, to more rigorously define: a) how reductions in fan capacity influence indoor radon levels under various conditions; b) how reductions in fan capacity influence the amount of house air exhausted under various conditions; c) how alternative degrees of slab sealing influence the amount of house air in the ASD exhaust; and, if possible d) the actual impacts of ASD systems on house ventilation rates (as distinguished from the amount of house air in the exhausts).

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* 1 cfm = 0.00047 m^{3}s.

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The complete report, entitled "Parametric Analysis of the Installation and Operating Costs of Active Soil Depressurization Systems for Residential Radon Mitigation," (Order No. PB92-116 037/AS; Cost: $26.00, subject to change) will be available only from:

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