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Project Summary

Follow-up Durability Measurements and Mitigation Performance Improvement Tests in 38 Eastern Pennsylvania Houses Having Indoor Radon Reduction Systems

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Follow-up testing was conducted in 38 houses in eastern Pennsylvania where indoor radon reduction systems had been installed under an EPA-sponsored demonstration project 2 to 4 years ago. These study houses were mostly "difficult" basement houses, in that soil gas radon concentrations were extremely elevated, and sub-slab communication was often not good. This follow-up testing was to assess: the durability of these mitigation systems; why the systems had not consistently reduced residual radon concentrations below 4 pCi/L* in some of the houses; and methods for reducing the installation and operating costs of systems.

The durability testing indicated that indoor radon levels, and the flows and pressures in the mitigation systems, have not experienced any significant deterioration since installation, except in six houses where system fans have failed, and except where the system has been turned off by the homeowner. Where indoor radon levels over the years have varied by an amount greater than twice the standard deviation expected based upon measurement uncertainty and natural variations, this situation is not due to failure of the systems to adequately prevent soil gas entry through the slabs. Rather, the variations in indoor levels have likely resulted from changes in re-entrainment of the high-radon exhaust from active soil depressurization systems, and/or from radon released to the air from well water.

Testing to assess the causes of elevated residual radon levels in some of these houses indicates that—with one exception—failure to adequately depressurize beneath the slab is *not* the cause for elevated levels in houses having sub-slab depressurization (SSD) or drain-tile depressurization (DTD) systems. (Inadequate depressurization beneath the slab *might* be a contributing cause in houses having block-wall depressurization (BWD) systems.) The primary cause for elevated residual levels in houses with SSD and DTD systems are: 1) re-entrainment of the exhaust from the systems; and 2) airborne radon resulting from high radon concentrations in the well water. Essentially all of the houses could be reduced below 4 pCi/L, and probably below 2 pCi/L, if these two sources of radon could be eliminated. The significance of re-entrainment (due to high radon levels in system exhausts) and of well water as a source results from the high radon content in the soil gas, a characteristic of this region that makes these houses "difficult" to mitigate. Testing showed that the elevated residual indoor levels are not the result of unduly elevated radon concentrations

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* 1 pCi/L = 37 Bq/m³

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in the outdoor air, or to undue emanation of radon from the concrete slabs and foundation walls.

Testing to assess means for reducing installation and operating costs showed that pre-mitigation sub-slab suction field extension measurements using a vacuum cleaner would have given general guidance regarding whether the sub-slab communication was good or poor. However, where communication was poor, the diagnostics would not have given definitive guidance regarding the required number and location of SSD suction pipes, overpredicting the number required. Where communication was good or intermediate, as shown by the diagnostics, testing confirmed that the number of SSD pipes in some of these systems could be reduced significantly (from four or six, to two or perhaps less). Fan capacity could not be reduced significantly without increasing indoor radon levels, despite diagnostic results suggesting that such capacity reductions should be possible. SSD systems will not always provide adequate treatment of block walls, necessitating a BWD component to the system. Between 6 and 42% of the system exhaust consisted of air withdrawn from the basement.

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

During the period June 1985 through June 1987, developmental indoor radon reduction systems were installed and tested in 40 houses in communities on the Reading Prong in eastern Pennsylvania. All of the houses had basements, and several had an adjoining slab-on-grade or crawl-space wing. The primary mitigation method in all but eight of these houses was some form of active soil depressurization (ASD). Four of the eight houses received active block-wall pressurization, three received air-to-air heat exchangers, and one received only a radon-in-water removal unit. The initial evaluation of these systems was conducted primarily by means of short-term (several-day) radon measurements with the systems on and off, obtained using Pylon AB-5 continuous radon monitors. Various other diagnostic tests, such as measurements of suctions and flows in ASD system piping, were also conducted. This project, including the results from the short-term measurements, is reported in detail elsewhere.

To evaluate the performance of these radon reduction systems over a longer time period, follow-up alpha-track detector (ATD) radon concentration measurements were subsequently made in 38 of these 40 demonstration houses over several periods, after the systems had been in operation for a year or more. Only 38 of the original 40 houses were measured; one of the houses had been removed from the original site, and the owner of a second house had discontinued participation in the project.

The first, 3-month ATD measurement period was during the winter of 1987-88, at which time the systems had been in operation for 1 to 3 years. The second, 4-month measurement period was over the winter of 1988-89, after an additional year of system operation. The winter quarters were selected for these 3- to 4-month exposure periods in order to determine the performance of the systems during cold weather, which would normally be expected to provide the greatest challenge to the systems. For these winter-quarter measurements, detectors were deployed both in the basements of the houses, and in the living area on the story above the basement. Finally, during the 12-month period December 1988 through December 1989, an annual ATD measurement was made in the living area of the 38 houses, to estimate the impact of the mitigation systems on the actual annual average exposure of the occupants.

These previous follow-up projects were limited to ATD measurements, and to the collection of any system failure information that could be obtained by interviewing the homeowner. None of these follow-up campaigns included any other "diagnostic" testing (such as ASD system suction/flow measurements in system piping, or suction field extension measurements underneath basement slabs), to obtain a more complete assessment of system durability.

The systems in these 38 houses represent some of the earliest mitigation installations of this type in the U. S. Most of the relatively limited number of prior installations in this country had addressed indoor radon resulting from human-activity-related sources (in particular, where uranium mill tailings were used as fill during construction or as aggregate in the construction materials). With human-activity-related sources, mitigation approaches often focused on source removal, and the cost of mitigation was less of a concern, since this cost was usually not borne by the homeowner. But for naturally occurring radon in soil gas, as for the eastern Pennsylvania houses, source removal was not an option, and cost was crucial, since homeowners would ultimately be paying for such systems themselves. Adding to the difficulties was the fact that the indoor concentrations in many houses in this region were extremely high (commonly 200 to 1,500 pCi/L, much higher than generally experienced with human-activity-related sources), requiring the immediate attention of the homeowners.

In view of this environment, a primary objective of the early project was to demonstrate that: 1) effective systems (capable of reducing these highly-elevated houses to 4 pCi/L and less) could be designed; and 2) such systems could be installed at relatively low cost, with equipment and with a skill level comparable to that of the typical worker in the building trades. Accordingly, the intent was to demonstrate that systems could be successfully designed for a significant number of houses without elaborate diagnostic testing, and that most of the information needed could be obtained from visual inspection supplemented by information that could be provided by the homeowner. To compensate for the reduced pre-mitigation diagnostics, and in view of the much more limited understanding of mitigation systems existing at that early stage, it was less expensive to simply over-design the system, utilizing more ASD suction pipes or a larger fan. Because of the need to demonstrate success (≤ 4 pCi/L) on a fair number of houses (ultimately 40), extensive adjustments were not possible in an effort to optimize the systems or to further improve performance, once the goal of 4 pCi/L had apparently been met.

The results of this necessary approach were that:

1) some of the houses were not reduced below 4 pCi/L on a long-term basis (although, for all, the percentage radon reductions were substantial). For example, from the annual ATD measurements, 6 of the 28 houses where the mitigation system had been operating throughout the year had an average annual indoor radon concentration above 4 pCi/L in the living area.

2) some houses were reduced well below 4 pCi/L, and it was not known to what degree the system fan capacity might have been reduced, or the number of suction pipes reduced, and still have met the 4 pCi/L goal.

Since this original project was completed, interest has increased in being able to reduce radon concentration well below 4 pCi/L (e.g., to ≤ 2 pCi/L). Only 13 of the 28 houses with continuously-operating systems were reduced to an annual average of 2 pCi/L and less in the living area. The ability to achieve below 2 to 4 pCi/L in these eastern Pennsylvania houses is of particular interest because they represent "difficult" houses, due to the poor communication beneath some of the slabs, and to the very high radon source term under many of the slabs.

Project Objectives

In view of the above considerations, the project described in this report had two objectives: 1) to further evaluate system durability, and 2) to test improvements to some of the systems in an effort to achieve ≤ 2 pCi/L in these "difficult" basement houses and to reduce costs.

System Durability

A more complete assessment was made of the durability of the mitigation systems in these houses, beyond what had been possible in the previous follow-up ATD measurements. These ASD systems, among the oldest in the U. S., had been operating 2 to 4 years at the outset of this study. This duration is only a few percent of the required system lifetime, but it is still long enough to provide an insight into the early failure modes of ASD systems.

This more complete measure of durability included:

- Further evaluation of the previous follow-up ATD measurements in these houses.
- Measurement of the pressures, flows, and radon concentrations in system piping, for comparison against measurements made soon after installation.
- Thorough inspection of the system to more completely identify hardware and materials failures.
- Inspection of the houses and systems, and appropriate measurements, to evaluate the causes for any apparent degradation in system performance, and the causes for observed hardware and materials failures.
- Measurements with the mitigation systems turned off for one to four days, to assess the long-term impact of ASD systems on the radon source term under the slabs.

System Evaluation/Improvements

There were two elements to this objective: 1) to assess how the performance of selected installations (initially achieving > 4 pCi/L) might be improved to achieve ≤ 2 pCi/L in these "difficult" basement houses, and 2) to assess how costs might be reduced by scaling down selected systems which were initially achieving below 2 to 4 pCi/L, and thus seeming to be over-designed.

Testing addressing element 1, above, involved efforts to determine why certain houses were still above 2 or above 4 pCi/L, and what additional steps would be necessary to achieve levels below 2 pCi/L. These efforts included:

- Measurements of sub-slab pressures with the original system operating, to determine whether inadequate suction field extension might be responsible for the residual indoor radon levels.
- Measurement of the re-entrainment into the house of high-radon exhaust gas from the ASD system, using tracer gases, and tests of modifications to the ASD exhaust, to determine the contribution from re-entrainment.
- Installation of temporary charcoal water treatment units on incoming well water in selected houses, to permit measurement of the contribution of radon in the well water to the residual airborne radon in the house.

As part of this effort, sub-slab communication measurements were conducted using an industrial vacuum cleaner to induce the suction, to assess how effectively such pre-mitigation diagnostic testing might aid a mitigator in immediately achieving ≤ 2 pCi/L in difficult houses such as these.

Testing addressing element 2, above, to reduce system installation and/or operating costs, included:

- Modifications to selected ASD systems, including reducing the number of sub-slab depressurization (SSD) pipes or reducing the fan suction, to determine whether scaled-down systems would provide adequate reductions. (This effort also included evaluation of vacuum cleaner communication testing to assess the extent to which such pre-mitigation diagnostic testing might aid in preventing inadvertent system over-design).
- Assessment of when block-wall depressurization (BWD) is required, in addition to or instead of SSD, in order to adequately treat difficult basement houses. BWD systems would typically be expected to exhaust much more treated house air, increasing system operating costs. In selected houses where the original installation was entirely a BWD system, temporary SSD systems were installed TO provide suction beneath the entire slab. The independent BWD and SSD systems were each operated alone, to indicate whether the SSD system by itself could equal or surpass the performance of the original BWD system.
- Measurement of the amount of basement air in selected ASD system exhausts, using tracer gases, to permit enhanced estimates of the operating costs of ASD systems in these types of houses.

Results and Conclusions

Durability of the Mitigation Systems

The durability of the 2- to 4-year-old mitigation systems in the 38 accessible study houses was evaluated through further analysis of the previously collected winter-quarter and annual ATD radon measurements, through measurements of mitigation system flows and suctions, and through system inspections. All of these houses have a basement, in some cases with an adjoining slab-on-grade or paved crawlspace wing. All but two of these houses had pre-mitigation radon concentrations above 20 pCi/L, and several had pre-mitigation levels well above 200 pCi/L.

The following conclusions are based on this effort:

1. Based on analysis of the ATD measurements since 1986, the systems in these 38 houses have not experienced any significant degradation in their ability to treat the radon entry routes, except where the fan has failed or where the homeowner has turned the system off. Considering the standard deviation in the ATD measurements, resulting from quantified uncertainty in the measurement method and from natural variations in indoor levels, the winter-quarter ATD measurements over the years have generally remained constant within two times this standard deviation (i.e., within the 95% confidence interval). In the 11 houses where individual results varied by greater than twice the standard deviation, this variation can almost always be attributed to causes other than failure of the system to treat the soil gas entry routes. (Re-entrainment of exhaust gas from soil depressurization systems, or airborne radon resulting from radon in well water, have been shown to be the likely causes of these variations in most of these 11 houses.)
2. Based upon further analysis of the ATD data, and of other data obtained during this project, essentially all of

the still-elevated study houses having sub-slab depressurization (SSD) or drain tile depressurization (DTD) systems could be reduced below 4 pCi/L (and probably below 2 pCi/L) by redesigning the mitigation system exhaust and/or by treating the well water. That is, the elevated residual (post-mitigation) levels in these houses are not due to failure of the SSD and DTD systems to treat the soil gas entry routes. However, the elevated residual levels in houses having block-wall pressurization and block-wall depressurization (BWD) systems are probably indicating that wall treatment alone sometimes cannot consistently treat all entry routes adequately in these highly-elevated houses, at least not during cold weather. Elevated residual levels in houses having heat recovery ventilators (HRVs) are consistent with the moderate reductions expected with HRVs.

3. Based upon further analysis of the ATD data, the annual average radon levels in the living area are equal to the winter-quarter levels, within ± 1.0 pCi/L, in the large majority of the houses (21 out of 28 in which reliable annual results were successfully obtained). Of those houses where the difference was greater than 1.0 pCi/L, the annual average was *higher* than the winter-quarter value in more than half of them, the reverse of what would have been expected. Thus, winter measurements do not necessarily ensure worst-case results. Re-entrainment of mitigation system exhaust gases, and unreported occasions where the homeowners might have turned off the system during mild weather during the annual measurement, might be contributing to the annual measurements being relatively higher than expected.
4. Measurements of flows, suctions/pressures, and radon concentrations in mitigation system piping during this project indicate that, within the range of uncertainty in the measurement techniques, these parameters have remained very consistent over the years. There has been no apparent degradation in the performance of the 38 systems, in terms of these operating parameters.
5. Of the 34 active soil ventilation fans operating in this project, 6 have failed over the 2 to 4 years that these systems have been operating. Five of these six failures have been the result of failure of an electrolytic capacitor in the fan circuitry; an increased number of failures might be expected in the near future, as more fans surpass the 4.5-year operating lifetime thought to apply to the capacitors in many of the fans. Recent experience has shown that the fans commonly used on this project can continue to operate for a year or more, at dramatically reduced performance, after the capacitor fails; this observation underscores the need for flow- or pressure-actuated alarms or gauges on soil depressurization systems.
6. One of the three HRVs installed in the original project has had to be repaired since installation, due to seizure of the bearings in the motor.
7. The silicone caulk used to seal SSD pipes into slab holes is continuing to provide generally intact seals after 2 to 4 years, although the caulk often was no longer adhering to the concrete slab. In some cases, air movement induced by the operating system as the caulk originally set created small openings in the seal. The PVC cement used to connect segments of piping continued to provide good seals except where sections of polyethylene (PE) piping had inadvertently become mixed with the PVC piping generally used. The PVC cement could not bond to the PE piping; in this project, silicone adhesive was found to be an effective sealant for PE piping joints.
8. Of the two granular activated charcoal (GAC) units installed to remove radon from well water, the unit containing a charcoal specifically selected for radon removal has continued to provide removals greater than 95% since installation 3 years earlier. However, the unit containing a generally-available charcoal not specifically selected for radon removal has exhibited a continued deterioration in performance, from 95% removal immediately after installation in 1986, to 38% removal in December 1989.
9. Homeowner intervention in system operation, usually in the form of turning the system off, has been a common experience (reported in eight of the houses). Fans were usually turned off: during mild weather (when windows were commonly open); when the owners were away; or as the result of fan noise. In these high-radon houses, opening windows often did not compensate for the system being off, since the annual ATD measurements often showed radon levels increasing having increased over winter-quarter readings where the fan was known to have been turned off. In two houses, the owners modified the systems, relocating the fan or installing a fan power controller.
10. Turning off these systems after several years of operation resulted in a relatively rapid return to the original pre-mitigation indoor levels (over 1 to 3 days), confirming that the source term is "durable". This rapid recovery suggests that large amounts of radon are being generated in the soil relatively near to the houses, and/or that soil gas movement through the soil is relatively rapid, so that there is a ready supply of radon.

Testing to Improve System Performance

The residual radon concentrations in these study houses suggest a greater-than-average difficulty in achieving EPA's original 4 pCi/L guideline, and a possible problem in reliably achieving the goal of near-ambient indoor radon concentrations specified in the U.S. Indoor Radon Abatement Act of 1988. Half of the houses were above 4 pCi/L in the basement according to the average of the winter-quarter ATD results; about one-quarter were above 4 pCi/L on an annual average in the living area, and about half were above 2 pCi/L. Accordingly, in this project, testing was undertaken to assess to what extent the residual radon levels are due to: inadequate treatment of soil gas entry routes; re-entrainment of exhaust from ASD systems; well water usage; ambient radon infiltrating from outdoors; and emanation from building materials.

The following conclusions are based upon this effort:

1. Sub-slab depressurizations being maintained by the ASD systems were measured. Of the houses with SSD systems (and the one with an interior DTD system), only in House 39 does it clearly appear that the elevated residual radon levels are due to uneven and inadequate distribution of the suction field under the basement slab. Exterior DTD systems generally produce lower sub-slab depressurizations than do SSD systems, as expected; however, in those exterior DTD houses having elevated residual radon, other testing conducted in this project indicates that the residual radon is largely due to re-entrainment and/or radon in well water, not to

inadequate slab treatment. Houses with BWD systems generally have only marginal sub-slab depressurizations, and this might be partly responsible for the elevated residual radon levels in many of these houses.

2. The exhaust configuration was modified in nine houses having a SSD or DTD system where exhaust re-entrainment was suspected of being a problem, to assess the possible effect of re-entrainment on indoor levels. No significant reductions in indoor levels were achieved by converting from horizontal exhausts at grade (directed 90° away from the house) to vertical discharges above the eaves. Thus, re-entrainment from these two configurations appears generally comparable; horizontal exhaust at grade might be acceptable, especially when the radon concentrations in the exhaust are not high, as long as the exhaust is directed 90° away from the house. However, where the exhaust at grade was vertical immediately beside the house—or where it is horizontal and is directed parallel to the house—converting to vertical above-eave discharge, or to discharge at grade directed away from the house, resulted in significant reductions in indoor levels. Thus, the vertical-at-grade and horizontal/parallel at grade configurations were clearly causing significant re-entrainment in these houses, and should be avoided. Attempts to quantify the actual re-entrainment using PFT tracer gases in some of these nine houses did not give meaningful results. Exhaust re-entrainment is thought to be the predominant contributor to residual radon levels in a number of the houses.
3. Temporary GAC well water treatment units were installed in four houses where well water was suspected of being a major contributor to residual airborne levels, and the effects on the indoor airborne concentrations were measured. The data were also reviewed from the two houses which had received permanent GAC units 3 years before. In four of these six houses, removal of radon from the water caused a reduction in airborne levels consistent with the 10,000:1 rule-of-thumb (i.e., 10,000 pCi/L in the water contributes an average of approximately 1 pCi/L to the airborne concentrations). In the fifth house, the airborne reduction was about half that which would have been predicted from the rule-of-thumb. The results from the sixth house are not meaningful. These results confirm that well water is an important, though generally not the sole, contributor to the residual airborne levels in a number of the study houses.
4. Outdoor radon concentrations in the study area were not unduly contributing to indoor concentrations. Of ambient measurements in seven locations, six gave readings below the estimated national average of 0.5 pCi/L. The seventh location yielded 0.8 pCi/L.
5. Radon flux measurements from uncracked concrete in one house suggested that the slab and poured concrete foundation walls in this house were contributing less than 0.2 pCi/L to the indoor concentrations. Thus, as expected, building materials do not appear to be a significant residual source in these houses.

In summary, based upon the measurements made in this project, it is believed that the reasons are now understood why all of the study houses still above 2 pCi/L are above that level. Commonly, more than one of the first three contributors discussed above are contributing to the residual levels.

Testing to Reduce System Installation and Operating Costs

Tests were conducted in a number of the houses to obtain a better understanding of mitigation installation and operating costs, and to explore ways in which these costs might be reduced. These tests included: investigation of whether the number of SSD suction pipes might be reduced in some cases where the SSD system appears to be over-designed, including an assessment of whether appropriate pre-mitigation diagnostic testing might have been cost-effective in identifying the desirable number and location of suction pipes; investigation of the effects of reducing fan capacity, where the system seems over-designed based upon diagnostic testing; assessment of when BWD is required, in addition to or instead of, SSD (since BWD might be expected to have a greater operating cost, in view of the significant amount of house air expected to be exhausted); and measurement of the amount of house air in ASD exhaust.

The following conclusions are based on this testing:

1. Pre-mitigation suction field extension measurements using a vacuum cleaner can give general guidance regarding how bad or how uneven sub-slab communication is, when communication is not good. But such testing cannot give quantitative direction regarding the number and location of suction pipes for optimum design in such poor-communication houses, since the diagnostics tend to over-predict the number of SSD pipes required. For example, in one study house, seven SSD pipes proved more than adequate to treat the slab, whereas the vacuum cleaner diagnostics would have predicted that 17 pipes would have been needed. And where there is a good layer of aggregate and communication is thus very good, the vacuum cleaner diagnostics will provide no information beyond that which would be obtained by visual inspection of the aggregate.
2. The SSD systems in five houses, each initially having four to six suction pipes through the slabs, were reduced to two pipes each. In the two houses having excellent sub-slab suction field extension, where the original system appeared to be over-designed, the reduction in the number of pipes had no significant effect on indoor radon levels, as would have been predicted by the diagnostics. In another two houses having intermediate suction field extension, reduction in the number of pipes again had no significant impact on indoor levels. However, in the fifth house—where the diagnostics had suggested that the original six-pipe SSD system should have been marginal in treating the entire slab—reduction of the number of pipes did indeed result in a significant increase in indoor concentrations, from 0.7 to 6.3 pCi/L. These results confirm that the diagnostics can give general guidance regarding the number of pipes required.
3. In three houses having intermediate to excellent sub-slab suction field extension and system flows well below the capacity of the SSD fan, the fan capacity was reduced by reducing power to the fan. The power reductions reduced system suction to 25 to 40% of full suction. In all three houses—despite the suggestion by the diagnostics that the tested reductions in fan power still should have provided adequate slab treatment—the reduction of fan suction resulted in a significant increase in indoor levels, by 44 to 250%. While insufficient testing was carried out to deter-

mine why the reduced fan capacity resulted in the increased indoor levels, it is clear that good sub-slab depressurizations and low system flows do not automatically mean that significant reductions in fan capacity are going to be possible. Perhaps a lesser reduction in fan power would have been possible without increasing indoor levels.

4. To assess whether the BWD systems in some of these study houses might be effectively replaced with state-of-the-art SSD systems, temporary SSD systems were installed in three houses where: 1) the original system was entirely or predominantly BWD; and 2) sub-slab communication is very good. Despite effective depressurization of the sub-slab by the temporary SSD systems, the BWD systems were far more effective in reducing radon concentrations in the basements and living areas of all three houses (giving residual radon levels half or less of the residual levels with SSD). This result confirms that block walls can sometimes be important sources that are not adequately treated despite effective depressurization of the sub-slab. Additional SSD pipes, near to the walls, might have improved the performance of the SSD systems.
5. Through measurements of tracer gases in the ASD exhausts in seven houses, it was determined that between 6 and 42% of the exhaust gas consisted of basement air. This is at the low end of the range reported by other investigators for houses having SSD systems (21 to 90%). The two houses in this testing having exterior DTD systems showed the least basement air in the exhaust (6 and 15%), as would be expected. The one house having a BWD system, where the percentage of basement air in the exhaust would be expected to be the highest, had 34% basement air in the exhaust; this is not the highest percentage among the houses tested here, and is at the low end of the range reported by other investigators for houses having SSD systems. Of the four houses tested here having SSD systems, the two with block foundation walls had generally higher percentages (26 and 42%) than did the two with poured concrete foundation walls (15 and 32%). These relatively low percentages might be suggesting that the slabs in these houses are relatively tight, consistent with the excellent suction field extensions observed in some houses.

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The complete report, entitled "Follow-up Durability Measurements and Mitigation Performance Improvement Tests in 38 Eastern Pennsylvania Houses Having Indoor Radon Reduction Systems," (Order No. PB91-171389/AS; Cost: $45.00, subject to change) will be available only from:

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