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# RADON MITIGATION EFFECTIVENESS IN NEW HOME CONSTRUCTION: PASSIVE AND ACTIVE TECHNIQUES

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## ABSTRACT

A study was conducted to evaluate the effectiveness of the radon mitigation methods outlined in the EPA's Model Standards and Techniques for Control of Radon in New Residential Buildings. Forty seven homes were constructed and monitored. Forty two were located in counties designated as Zone 1 by the EPA's Map of Radon Zones. All homes contained passive vent pipes to vent soil gases from beneath the foundation, up through the roof, and to the outdoors. Two-week tests were conducted in each home with the pipe capped and uncapped. Nineteen homes yielded radon concentrations exceeding the EPA action level of 4 pCi/l when pipes were capped. Radon concentrations in thirteen of these homes fell below the EPA action level when pipes were uncapped. Radon levels in the remaining homes were reduced below the action level by activation of duct fans.

## INTRODUCTION

The U.S. Environmental Protection Agency (EPA) published its *Model Standards and Techniques for Control of Radon in New Residential Buildings*[1] in March, 1994. The objective of this study was to evaluate the radon mitigation construction techniques described in the standard. More specifically, the focus was on evaluating the effectiveness of both passive and active radon mitigation systems in a large group of homes.

Twelve builders were successfully recruited for the project and collectively built 47 homes. Forty two homes were located in Zone 1 counties as identified on the EPA Map of Radon Zones[2]. These counties were located in Idaho, Colorado, New Mexico, North Dakota, Iowa, Massachusetts and Maryland. The five remaining homes were built in a New Hampshire county designated as Zone 2. Table 1 lists the number of builders recruited by state, counties in which candidate homes were constructed, the number of candidate homes constructed, and the EPA radon zone in which candidate homes were located.

**Table 1.** Results of Builder Recruiting

| State | Builders | Counties | Homes Built | Radon Zone |
|---|---|---|---|---|
| Idaho | 2 | Kootenai | 8 | 1 |
| Colorado | 1 | Arapahoe, Douglas | 5 | 1 |
| New Mexico | 2 | Santa Fe, Bernalillo | 10 | 1 |
| North Dakota | 1 | Grand Forks | 3 | 1 |
| Iowa | 2 | Polk | 4 | 1 |
| Massachusetts | 1 | Middlesex | 4 | 1 |
| Maryland | 2 | Montgomery | 8 | 1 |
| New Hampshire | 1 | Rockingham | 5 | 2 |

## TEST METHOD

Radon Resistant Construction Methods

The candidate homes were built substantially in accordance with the construction techniques in the proposed EPA Model Standards and Techniques for Control of Radon in New Residential Buildings (The final version of this standard was published in March, 1994). All radon mitigation systems essentially consisted of a vent installed to remove soil gas from underneath the foundation.

Construction methods for basement and slab-on-grade homes typically included four-inches of clean aggregate under all slabs. Aggregate layers were covered with 6-mil thick polyethylene barriers lapped at joints and fitted closely around pipes. A three-inch PVC vent pipe was routed through each home from a tee fitting installed in the aggregate layer to above the roof. (Poly barriers were not installed under slabs in the Idaho, Massachusetts, New Hampshire and Colorado homes due to local climatic conditions that would cause problems with the concrete curing process. In addition, subslab aggregate layers were omitted from the Colorado homes. These homes were alternatively fitted with drain tile loops that were routed throughout subslab areas and connected to the vent pipes.)

After slabs were cast, pipe penetrations and slab/foundation wall joints were sealed with a polyurethane caulk. Sumps were fitted with a sealed or gasketed covers, and wiring was installed in attics for installation of duct fans if active subslab depressurization is required.

Construction methods for crawl space homes included continuous ground cover over crawl space floors. This consisted of a minimum 6-mil thick polyethylene barrier lapped a minimum of 12-inches at joints and sealed to interior piers, pipe penetrations and joints. Lengths of three or four inch diameter drain tile were inserted below the ground cover. The drain tile extended the width of each crawl space and was connected to a tee fitting. A 3-inch PVC vent pipe was routed through each home from the tee fitting up through the roof. All ductwork passing through crawl spaces was insulated and sealed with duct tape. Crawl space access doors, and all penetrations through floors above crawl spaces, were sealed with polyurethane caulk. Each crawl space was constructed with passive foundation vents that remained opened for the duration of the tests. Wiring was installed in attics for future installation of duct fans, if required.

*Indoor Radon Level Measurements*

Each candidate home was subjected to a series of indoor radon tests after construction was completed. The tests were conducted with passive electret radon monitors (E-PERMs) manufactured by Rad Elec, Inc.. Each series, or "phase", of indoor radon tests were scheduled for a duration of 14 days. E-PERM canisters were placed in the lowest indoor level of each home and, where relevant, the level above the lowest[3,4]. All radon measurements were reported in picocuries per liter of air (pCi/l). The program included up to three phases of testing for each home. The decision to proceed with the next phase of testing was based on lowest floor measurements. Specific test phases were as follows:

- Phase 1: This phase was designed to establish a baseline radon level. The radon vent pipe installed during construction was capped during this phase. It is important to note that the homes still had elements of passive radon resistant construction while stacks were capped. These elements included the caulking at floor/wall joints and at pipe penetrations.

- Phase 2: The radon vent stack was uncapped and a soil depressurization system was operated in the passive mode. In houses where Phase 2 test results were less than 2.0 pCi/l, no additional testing was conducted.

- Phase 3: An axial duct fan was installed at or near the top of the radon vent pipe, thus activating the soil depressurization system. Phase 3 was conducted only if the results of measurements during Phase 2 indicated radon levels of 2.0 pCi/l or higher.

Radon levels were determined by measuring voltage drops on E-PERM electrets (electrically charged teflon surfaces) with a SPER-1 voltmeter provided by Rad Elec. The accuracy of the voltmeter was periodically checked against two reference electrets with voltages certified by Rad Elec. The voltages obtained from these reference electrets were consistently within Rad Elec specifications during the duration of the study.

Quality assurance procedures also included the use of duplicate E-PERMs in eight of the candidate homes. These homes were instrumented with two E-PERMs installed side-by-side in the lowest occupied floors. Ideally, each pair of E-PERMs should yield identical measurements. Project protocol specified that corrective action must be taken if duplicate measurements differ by more than 10-percent. The maximum variation of duplicate measurements in the study was 8.1-percent, with an average variation of 4.6-percent.

## TEST RESULTS AND DISCUSSION

Radon levels were monitored on the two lowest occupied levels of homes. For homes with basement foundations, this consisted of the basement and first floor levels. First floor and second floor levels, if applicable, were measured in slab-on-grade and crawl space homes. Table 2 lists the indoor radon levels measured on the lowest occupied level of each candidate home. These measurements indicate the highest radon levels achieved in each home.

**Table 2.** Summary of Test Results from Lowest Levels of Homes

| State | Home | Foundation | Maximum Measured Indoor Radon (pCi/l) Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|---|---|
| Iowa | IA1 | Basement | 5.9 | 2.9 | N/C[b] |
| | IA2 | Basement | 3.3 | 2.5 | 0.9 |
| | IA3 | Basement | 2.5 | 2.4 | 2.4 |
| | IA4 | Basement | 4.1 | 3.2 | N/C[b] |
| Massachusetts | MA1 | Basement | 6.9 | 2.0 | N/A[c] |
| | MA2 | Basement | 5.3 | 2.2 | N/C[b] |
| | MA3 | Basement | 6.4 | 1.8 | N/A[c] |
| | MA4 | Basement | 5.8 | 5.4 | 3.6 |
| New Hampshire | NH1 | Basement | 3.1 | 3.6 | 3.5 |
| | NH2 | Basement | 22.6 | 12.4 | 1.6 |
| | NH3 | Basement | 2.4 | 1.3 | N/A[c] |
| | NH4 | Basement | 5.7 | 2.4 | 1.5 |
| | NH5 | Basement | 8.1 | 2.0 | 1.0 |
| Colorado | CO1 | Basement | 6.4 | 3.4 | N/C[b] |
| | CO2 | Basement | 1.6 | 1.0 | N/A[c] |
| | CO3 | Basement | 3.0 | 3.1 | 0.3 |
| | CO4 | Basement | 7.6 | N/C[d] | N/C[d] |
| | CO5 | Basement | 6.5 | 7.1 | 1.2 |

Table 2 (Con't). Summary of Test Results from Lowest Levels of Homes

| State | Home | Foundation | Maximum Measured Indoor Radon (pCi/l) Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|---|---|
| Maryland | MD1 | Basement | 10.4 | 5.7 | 0.3 |
| | MD2 | Basement | 3.8 | 1.2 | N/A[c] |
| | MD3 | Basement | 12.8 | 8.9 | N/C[b] |
| | MD4 | Basement | 16.3 | 0.7 | N/A[c] |
| | MD5 | Basement | 32.9 | 4.6 | N/C[d] |
| | MD6 | Basement | 34.9 | 1.5 | N/A[c] |
| | MD7 | Basement | 4.5 | 0.2 | N/A[c] |
| | MD8 | Basement | 3.1 | 0.2 | N/A[c] |
| North Dakota | ND1 | Basement | 2.8 | 1.0 | N/A[c] |
| | ND2 | Basement | 3.3 | 0.7 | N/A[c] |
| | ND3 | Basement | 2.6 | N/C[d] | N/C[d] |
| New Mexico | NM1 | Slab-on-grade | 2.4 | 1.8 | N/A[c] |
| | NM2 | Slab-on-grade | 1.6 | 2.5 | N/C[b] |
| | NM3 | Slab-on-grade | 1.3 | 1.7 | N/A[c] |
| | NM4 | Slab-on-grade | 0.4 | 1.5 | N/A[c] |
| | NM5 | Slab-on-grade | 1.2 | 1.5 | N/A[c] |
| | NM6 | Slab-on-grade | 5.6 | 0.8 | N/A[c] |
| | NM7 | Slab-on-grade | 0.9 | 3.2 | N/C[b] |
| | NM8 | Slab-on-grade | 1.2 | 0.2 | N/A[c] |
| | NM9 | Slab-on-grade | 0.8 | 0.4 | N/A[c] |
| | NM10 | Slab-on-grade | 1.0 | 0.2 | N/A[c] |
| Idaho | ID1 | Basement | 8.9 | 4.2 | 0.9 |
| | ID2 | Basement | 2.8 | 1.2 | N/A[c] |
| | ID3 | Basement | 4.5 | 3.3 | 3.0 |
| | ID4 | Crawl space | 3.5 | 2.4 | 0.9 |
| | ID5 | Crawl space | 0.8 | 2.2 | N/C[b] |
| | ID6 | Basement | 1.8 | 1.2 | N/A[c] |
| | ID7 | Crawl space | 1.2 | 0.9 | N/A[c] |
| | ID8 | Basement | 2.4 | 1.4 | N/A[c] |
| | | Average | 5.3 | 2.5 | 1.6 |

a: Value from adjacent site
b: Test not conducted at owners request.
c: Test not applicable (not needed)
d: Testing was not completed in time for inclusion in this report.

Note: Phase 1 tests conducted with radon vent pipes capped.
Phase 2 tests conducted with radon vent pipes uncapped (passive system).
Phase 3 tests conducted with duct fans installed and operating in vent pipes (active system).

Tests were not completed in CO4, MD5 and ND3 due to construction delays that forced indoor tests to be initiated late in the study. Therefore, the average Phase 1 and 2 test results are based on the remaining 44 homes in which tests were completed. The average Phase 3 test result is based on the 13 homes subjected to this test phase.

Radon Measurements from Lowest Levels of Homes

Phase 3 (active system) tests were only performed in homes exhibiting Phase 2 (passive system) radon levels greater than or equal to 2.0 pCi/l. Thus, only 13 homes were subjected to Phase 3 tests. Table 3 lists the results of the passive systems and active systems with respect to baseline conditions for lowest level measurements.

**Table 3.** Classification of Indoor Radon Measurements from Lowest Levels of Homes

| Maximum Indoor Radon Level | Number of Homes | | |
|---|---|---|---|
| | Phase 1 | Phase 2 | Phase 3 |
| Greater than the EPA action level (4.0 pCi/l) | 19 | 6 | 0 |
| Between 4.0 pCi/l and 2.0 pCi/l | 13 | 16 | 4 |
| Less than 2.0 pCi/l | 12 | 22 | 9 |
| Total | 44 | 44 | 13 |
| Average maximum indoor radon level | 5.3 pCi/l | 2.5 pCi/l | 1.6 pCi/l |

Phase 1 test results indicated that radon levels in 19 of the 44 homes exceeded the EPA action level of 4.0 pCi/l[5]. The passive radon vents operated during Phase 2 reduced radon levels in 13 of these homes below the action level. The active systems (with duct fans) reduced radon levels below the action level in the remaining homes. Since tests were not completed in CO4, MD5 and ND3, they are not included in Table 3.

The average Phase 1 radon level of 5.3 pCi/l for the 44 homes was greater than the EPA action level. The passive vent pipes in these homes reduced this average to 2.5 pCi/l. However, Phase 2 radon levels in eight homes experienced a slight increase over Phase 1 levels. In three of these homes, Phase 1 tests were conducted during the summer months and Phase 2 tests were conducted during the winter months. It is possible that seasonal variations in radon levels account for these increases. The five remaining homes were slab-on-grade adobe-style homes that exhibited Phase 2 levels consistently below the EPA action level, despite the slight increases.

The active radon mitigation systems effectively reduced radon levels in all homes below the EPA action level of 4.0 pCi/l. It should be noted that this conclusion is based exclusively on the results obtained from 13 homes exhibiting Phase 2 levels of 2.0 pCi/l or greater. Radon levels in nine of the 13 homes with active systems were reduced below 2.0 pCi/l. The average Phase 3 test result from the 13 homes was 1.6 pCi/l, with a maximum measurement of 3.6 pCi/l. The average Phase 1 result from these 13 homes was 6.8 pCi/l, and the average Phase 2 result was 4.3 pCi/l.

Radon Measurements from First Floors of Candidate Homes

Radon levels on the first floors in six of the candidate homes exceeded the EPA action level during Phase 1 tests. The average Phase 1 first floor radon level was 2.2 pCi/l, and the maximum level was 10.3 pCi/l. The passive radon vent pipes reduced the first floor radon levels below the action level in all of these homes. Radon levels in one of the Colorado homes increased from 3.8 pCi/l to 4.7 pCi/l after opening of the vent pipe. The average first floor radon concentration from the remaining homes during Phase 2 tests was 1.2 pCi/l, and the maximum level was 3.9 pCi/l. Table 4 compares the effectiveness of the passive systems and active systems with respect to baseline conditions for first floor measurements. Since tests were not completed in CO4, MD5 and ND3, they are not included in Table 4.

Table 4. Classification of Indoor Radon Measurements from First Floors of Homes

| Maximum Indoor Radon Level | Number of Homes Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| Greater than the EPA action level (4.0 pCi/l) | 6 | 1 | 0 |
| Between 4.0 pCi/l and 2.0 pCi/l | 8 | 5 | 0 |
| Less than 2.0 pCi/l | 30 | 38 | 13 |
| Total | 44 | 44 | 13 |
| Average maximum indoor radon level | 2.2 pCi/l | 1.2 pCi/l | 0.6 pCi/l |

Seasonal Effects on Radon Measurements

Local and seasonal climatic factors complicate indoor radon test results. Indoor radon levels in a home are usually highest during the winter months when the home is tightly sealed and the heating system is in operation.

Daily climatic data was obtained for all test homes. This data was obtained from a weather station located in the same geographic area as the test homes. Monthly average temperatures were calculated from this data and were used to determine the season in which indoor tests were conducted. The winter season was defined as months during which the average monthly temperature was less than or equal to 50°F, and the summer season consisted of months when the average temperature exceeded 50°F.

Results from the 36 homes tested during the same season indicate measurable reductions of indoor radon levels when radon vent pipes were opened. The average Phase 1 measurements for homes tested exclusively during summer and winter months exceeded the EPA action level of 4.0 pCi/l. Both of these averages fell below the action level after vent pipes were opened during Phase 2 tests.

Phase 1 and 2 tests on eight homes were conducted in different seasons. Phase 1 tests on five of these homes were conducted during summer months, while Phase 2 tests were conducted during the winter. Conversely, Phase 1 tests on three homes were conducted during the winter, while Phase 2 tests were conducted during the summer. Due to seasonal differences, it is difficult to draw conclusions from tests conducted during different seasons.

Table 5 lists the Phase 1 and Phase 2 test results from the lowest level of each home in accordance with the season in which testing occurred.

**Table 5.** Indoor Test Results According to Season

| Test Season | House | Radon from Lowest Level (pCi/l) Phase 1 | Phase 2 |
|---|---|---|---|
| Phase 1 and Phase 2 tests both conducted during winter months | IA1 | 5.9 | 2.9 |
| | IA2 | 3.3 | 2.5 |
| | IA3 | 2.5 | 2.4 |
| | NM1 | 2.4 | 1.8 |
| | NM2 | 1.6 | 2.5 ← |
| | NM3 | 1.3 | 1.7 |
| | NM5 | 1.2 | 1.5 |
| | MA1 | 6.9 | 2.0 |
| | MA2 | 5.3 | 2.2 |
| | MA3 | 6.4 | 1.8 |
| | MA4 | 5.8 | 5.4 |
| | ID1 | 8.9 | 4.2 |
| | ID4 | 3.5 | 2.4 |
| | ID5 | 0.8 | 2.2 ← |
| | ID6 | 1.8 | 1.2 |
| | ID7 | 1.2 | 0.9 |
| | ID8 | 2.4 | 1.4 |
| | CO1 | 6.4 | 3.4 |
| | CO5 | 6.5 | 7.1 ← |
| | MD1 | 10.4 | 5.7 |
| | MD3 | 12.8 | 8.9 |
| | MD4 | 16.3 | 0.7 |
| | MD6 | 34.9 | 1.5 |
| | MD7 | 4.5 | 0.2 |
| | MD8 | 3.1 | 0.2 |
| | ND1 | 2.7 | 1.0 |
| | ND2 | 3.4 | 0.7 |
| | Average | 6.0 | 2.5 |
| Phase 1 and Phase 2 tests both conducted during summer months | IA4 | 4.1 | 3.2 |
| | NM8 | 1.2 | 0.2 |
| | NM9 | 0.8 | 0.4 |
| | NM10 | 1.0 | 0.2 |
| | NH1 | 3.1 | 3.6 ← |
| | NH2 | 22.6 | 12.4 |
| | NH3 | 2.4 | 1.3 |
| | NH4 | 5.7 | 2.4 |
| | NH5 | 8.1 | 2.0 |
| | Average | 5.4 | 2.8 |
| Phase 1 tests conducted during summer months and Phase 2 tests conducted during winter months | NM4 | 0.4 | 1.5 ← |
| | NM6 | 5.6 | 0.8 |
| | NM7 | 0.9 | 3.2 ← |
| | CO2 | 1.6 | 1.0 |
| | CO3 | 3.0 | 3.1 ← |
| | Average | 2.2 | 1.9 |
| Phase 1 tests conducted during winter months and Phase 2 tests conducted during summer months | ID2 | 2.8 | 1.2 |
| | ID3 | 4.5 | 3.3 |
| | MD2 | 3.8 | 1.2 |
| | Average | 3.7 | 1.9 |

## CONCLUSIONS

Forty seven homes were constructed for this study. Monitoring was not completed in three homes in time for this paper. Ten homes were constructed on slab-on-grade foundations and three were constructed over passively

ventilated crawl spaces. The remaining homes were constructed with basement foundations. The following conclusions can be drawn from the study:

- Phase 1 test results indicated that 19 of the 44 homes that were monitored exhibited indoor radon levels exceeding the EPA action level of 4.0 pCi/l. These tests were conducted with the radon vent pipe closed. The average indoor radon concentration from the lowest levels of all homes during Phase 1 tests was 5.3 pCi/l. Operation of radon vent pipes during Phase 2 tests reduced indoor radon levels below the EPA action level of 4.0 pCi/l in 13 of the 19 homes. The average indoor radon concentration from the lowest level of all homes during Phase 2 tests was 2.5 pCi/l. Although a few Phase 2 results were marginally higher than corresponding Phase 1 results, they may be related to seasonal influences.

- First floor (typically the lowest lived-in level) radon levels in six homes exceeded the EPA action level of 4.0 pCi/l during Phase 1 tests. The average first floor radon level during Phase 1 was 2.2 pCi/l. Operation of the radon vent pipes reduced the first floor radon levels below the action level in all of the homes. The average first floor radon concentration during Phase 2 tests was 1.2 pCi/l.

- The passive radon pipe seemed to exhibit the most effective performance in the Maryland homes. Two of these homes yielded Phase 1 radon levels of 32.9 pCi/l and 34.9 pCi/l in the basements. Operation of the passive vent pipes in these homes lowered these levels to 4.6 and 1.5 pCi/l, respectively. Phase 1 levels of 16.3 pCi/l in another Maryland home were reduced to 0.7 pCi/l during Phase 2 tests. Measurable reductions were also experienced in Iowa, Massachusetts, New Hampshire and Idaho. Reductions from the New Mexico, Colorado and North Dakota homes were either low or results were inconclusive regarding passive vent performance.

- Active radon mitigation systems (with duct fans installed and operating in vent pipes) were successfully installed and tested in 13 homes with Phase 2 test results greater than or equal to 2.0 pCi/l. Test results from the lowest levels of these homes indicated an average indoor radon level of 1.6 pCi/l. The average Phase 2 result from these 13 homes was 4.3 pCi/l, and the average Phase 1 result was 6.8 pCi/l.

It should be noted that these results are based on less than 50 homes and that the sample of homes was not randomly selected. Additional testing is recommended to further confirm the ability of passive systems to reduce indoor radon levels. Particular attention should be focused on the year round performance of passive systems to better address climatic effects.

## REFERENCES


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