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Paper

# BLIND TESTING OF COMMERCIALLY AVAILABLE SHORT-TERM RADON DETECTORS

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*Abstract*—**A sample of commercially available, charcoal adsorption type, short-term radon detectors was blind tested under controlled laboratory conditions in order to obtain a "snapshot" of the accuracy and precision of the detectors. The results of the controlled exposures were then compared to a previous field study of the same type of commercially available radon detectors. Radon detectors, purchased from seven different commercial vendors, were exposed to a reference $^{222}$Rn gas concentration at the U.S. Environmental Protection Agency's (EPA) Radon Chamber located at the Radiation and Indoor Environments National Laboratory in Las Vegas, Nevada. EPA Test 1 was performed under a controlled simulated field exposure paralleling, to the extent possible, the previous actual field exposure conditions. A second controlled exposure, EPA Test 2, was performed under a relatively steady state of $^{222}$Rn gas concentration, at the same temperature, but a more moderate relative humidity. In the previous field setting evaluation of detectors, five out of six companies tested did not pass the accuracy guideline (all individual relative errors ≤25%) established during the EPA's former Radon Measurement Proficiency Program (EPA-RMPP). As compared to the field test, the detectors in this study generally exhibited better accuracy and precision. Not surprisingly, it appeared temporal fluctuations in radon concentrations and increased humidity had a negative influence on the accuracy and precision of detectors for some companies. The inability of three out of seven companies to meet former EPA-RMPP guidelines for accuracy, even under ideal exposure conditions (constant temperature, humidity, and radon concentration), highlights the importance of blind testing commercially available radon detectors. Furthermore, the consistent over-reporting or under-reporting trends in the overall results for all three tests suggest a potentially widespread systematic bias for the individual companies that merits further investigation. It is unknown if this one-time "snapshot" represents the overall reliability of commercially available charcoal-based radon detectors. Nonetheless, the findings suggest the need for improved vigilance to assure that the public can rely on commercially available radon detectors to make an informed decision whether or not to perform additional testing or to mitigate.**

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**Key words: radon; $^{222}$Rn; detector, radiation; quality assurance**

## INTRODUCTION

RECENTLY, TWO large-scale epidemiologic studies, a North American study (Krewski et al. 2005, 2006) and a European study (Darby et al. 2005, 2006), pooled data from 20 previously performed epidemiologic studies that directly assessed the risk of prolonged residential radon exposure. Both the North American as well as the European pooled studies support the risk projections extrapolated from occupational studies of radon-exposed underground miners (NRC 1998), and provide direct evidence that prolonged residential radon exposure represents a major cause of lung cancer. These findings have stimulated a renewed effort to promote radon testing internationally. For example, the World Health Organization (WHO) in 2005 initiated the International Radon Project stating, "the latest pooled analyses of case-control studies from Europe and North America as well as China provide a strong argument for an international initiative to reduce indoor radon risks" (WHO 2007). Two focuses of the WHO project are to promote testing and provide testing guidance for WHO member countries. In addition, Health Canada, after considering the "new evidence" from the pooled radon studies, has enacted a new radon guideline of 200 Bq $m^{-3}$, which is four times more stringent than its previous guideline of 800 Bq $m^{-3}$. In the U.S., following the results of the pooled analyses, the U.S. Surgeon General, Richard Carmona, issued a Health Advisory warning Americans about the health risk from exposure to radon in indoor air. Dr. Carmona urged Americans to test their homes to determine the concentration of radon they might be breathing and also stressed the need to remedy the

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problem as soon as possible when the radon concentration is 150 Bq $m^{-3}$ or greater. Dr. Carmona noted that more than 20,000 Americans die of radon-related lung cancer each year (U.S. EPA 2007).

The EPA's publication, "A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family From Radon," (U.S. EPA 2004) recommends performing a short-term radon test in the lowest lived-in level of the home. The Citizen's Guide goes on to state that if the initial reported radon result is 150 Bq $m^{-3}$ (4 pCi $L^{-1}$) or higher and quick results are needed, homeowners should take a second short-term test. The Citizen's Guide recommends homeowners take appropriate steps to reduce the radon concentrations in their home if the average of the first and second tests is 150 Bq $m^{-3}$ (4 pCi $L^{-1}$) or higher. In fact, the U.S. EPA noted in their 1995 Radon Proficiency Handbook (U.S. EPA 1995), "because homeowners often decide whether action is required to reduce their home's radon concentrations based solely on these two measurements, it is crucial that the initial and follow-up screening radon measurements produce accurate and precise results."

According to the criteria applied by the EPA's former Radon Measurement Proficiency Program (EPA-RMPP) to evaluate radon measurement providers, the individual relative errors (IREs) of the measurements of all detectors exposed to known radon concentrations should be less than or equal to 25% (U.S. EPA 1995). Prior to 1992, the EPA calculated detector accuracy by exposing several detectors to known radon concentrations and requiring that the mean of the absolute relative error (MARE) be less than or equal to 25% (Field and Kross 1990). The EPA also provided precision guidelines for incorporation into a radon measurement company's quality assurance procedures. Precision was to be monitored frequently using duplicate (collocated) detectors over a range of radon concentrations as "consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated" (U.S. EPA 1992). EPA provided a benchmark for monitoring precision as a coefficient of variation of 10% or less at 150 Bq $m^{-3}$ or greater (U.S. EPA 1992). It is important to note that precision was not used by the EPA as a criterion for proficiency testing and subsequent listing of a company.

Obviously, differences exist between the environmental conditions encountered in homes and the environmental conditions maintained in the EPA's environmental radon chamber. Even under "closed-house conditions," ambient conditions (temperature, relative humidity, condensation nuclei) tend to be dynamic resulting in differences between homes and even within the measurement period for an individual home. For example, in a survey of over 200 homes in Iowa, performed as part of the Keokuk County Rural Health Study and funded by the Centers for Disease Control and Prevention/National Institute for Occupational Safety and Health, the investigators noted that the average relative humidity for the first floor (not basement) of homes varied slightly by season (Fall: 56% ± 10%; Spring: 56% ± 11%; Summer: 64% ± 10%; Winter: 47% ± 10%). However, the investigators noted that the range of relative percent humidity varied substantially between homes even within the same season (Fall: 20% to 80%; Spring: 27% to 92%; Summer: 37% to 98%; Winter: 23% to 77%).** In addition, unlike the radon chamber that can be either cycled dynamically or maintained at a steady state, homes are subject to both significant spatial (Fisher et al. 1998) and temporal variation (Zhang et al. 2007). In addition, the EPA's laboratories in Las Vegas and Montgomery did not yet have the capability to cycle their chambers during the former EPA-RMPP test windows, so exposures were performed under steady state conditions, which generally favor the ability of charcoal detectors to provide more precise and accurate results.

Little information is available to assess whether detectors that passed the EPA's accuracy criteria (all IREs ≤25%) during the former EPA-RMPP performance testing windows also yielded acceptable accuracy and precision under non-ideal, but more realistic residential measurement conditions. However, because individuals often rely on short-term radon measurements to decide if mitigation is necessary, it is important to know whether commercially available short-term radon detectors exhibit adequate accuracy and precision over the range of environmental conditions encountered in the home or other buildings.

This study follows up on a similar detector comparison (Sun et al. 2006) that determined the accuracy and precision of a limited sample of commercially available detectors under actual field conditions. Published studies examining the accuracy and precision of commercially available short-term radon detectors under both actual residential conditions and controlled conditions are almost nonexistent (Field and Kross 1990). The primary objectives of this study are to assess the accuracy and precision of a limited sample of commercially available short-term radon detectors under simulated field conditions as well as steady state conditions and then to compare these results to a previous study (Sun et al. 2006) where the same type of detectors were exposed under actual field conditions.

** Personal communication with K. Kelly, College of Public Health, Department of Occupational and Environmental Health, University of Iowa; 5 February 2007.

## MATERIALS AND METHODS

### Radon detectors

Designations A–H represent short-term radon detectors from different companies (Table 1). The electret ion chambers, which are generally used by professional radon testers, were supplied by Rad Elec, Inc. (Rad Elec, Inc., 5716A Industry Lane, Frederick, MD 21704; represented by company A). An electret ion chamber consists of an electrically charged Teflon disc, called an electret, located inside an electrically ~~non~~conducting plastic chamber of a known air volume. Electret ion chambers are passive devices that provide an integrated radon gas measurement by sensing the radon-related ionization occurring within the detector chamber. The electret ion chambers were included in the chamber exposures to maintain consistency with the previous field study (Sun et al. 2006). All electret ion chamber measurements were adjusted for background gamma radiation. The actual measurements of these detectors were performed by the authors using standard procedures recommended by the manufacturer (Rad Elec, Inc.).

Designations B-H represent seven different companies marketing radon detectors to the public. The charcoal detectors B and C are from the same supplier, but marketed under different names. The short-term activated charcoal-based radon detectors (B-H) were selected for the study based primarily on their widespread use (B-H) in the upper Midwest and the certification of the measurement laboratory (B-G) by the Iowa Department of Public Health. While other methodologies for measuring radon are available [e.g., alpha track detectors (ATs) and continuous radon monitors (CRMs)], short-term activated charcoal adsorption detectors (ACs: i.e., charcoal filled canisters, charcoal filled pouch type detectors, charcoal filled plastic trays) and charcoal adsorption liquid scintillation detectors (LSs) were selected for the study since ACs and LSs are the primary devices used by U.S. homeowners to test their homes for radon.

**Table 1.** Radon detectors used in the intercomparison.

| Company | Measurement method |
|---|---|
| A | Electret ion chambers[a] |
| B | Diffusion barrier charcoal adsorption[b] |
| C | Diffusion barrier charcoal adsorption[b] |
| D | Diffusion barrier charcoal adsorption[b] |
| E | Diffusion barrier charcoal adsorption[b] |
| F | Diffusion barrier charcoal adsorption liquid scintillation |
| G | Diffusion barrier charcoal adsorption[b] |
| H | Diffusion barrier charcoal adsorption[b] |

[a] Electret ion chambers obtained from Rad Elec, Inc.
[b] For the diffusion barrier charcoal adsorption detectors, the charcoal was contained either in a canister, envelope (bag), or plastic tray depending on the commercial vendors' preferred design.

The detectors were obtained from various sources in a manner much as if a homeowner would purchase detectors. The detectors were either purchased at local hardware stores (company F), directly from the company that manufactures the detectors (companies E, G, and H), online from a secondary vendor (company C), or donated (companies B and D) by a local health department that had previously purchased them with the intent to distribute to local homeowners. The detectors were purchased and mailed back to the commercial laboratories in a manner that precluded the companies from knowing that their detectors were undergoing independent evaluation.

**Previous field test (10/24/04–10/28/04).** Methodological details regarding how the field intercomparison of radon detectors was performed are presented elsewhere (Sun et al. 2006). In summary, the basement of a 100-y-old farmhouse in rural southeast Iowa was chosen as the exposure site. All detectors were placed on tables in the center of the basement in accordance with EPA protocols for screening measurements (U.S. EPA 1992, 1993). A femto-TECH, Inc. CRM (femto-TECH, Inc., 25 Eagle Court, Carlisle, OH 45005) that was recently calibrated by the manufacturer was used as the reference value for the radon gas concentration. Electret ion chambers were used both to assess spatial radon variability and as a secondary comparison for the radon reference value. The basement's temperature and relative humidity were monitored and recorded hourly during the entire exposure period.

### U.S. EPA chamber tests

Two sets of radon detectors were exposed under controlled environmental conditions at the U.S. EPA's radon chamber at the Radiation and Indoor Environments National Laboratory (R&IENL) in Las Vegas, Nevada. The first exposure (EPA Test 1) was performed under a simulated field exposure paralleling, to the extent possible, the previous actual field exposure conditions (Sun et al. 2006); and a second exposure (EPA Test 2) was performed under a relatively steady state of radon gas concentration and a more moderate relative humidity.

Details regarding the steady state operation of the EPA radon chamber and the methods used to generate reference values have been previously described (Budd et al. 1998). The cycling of radon gas concentration in the EPA radon chamber to simulate actual field conditions is achieved as follows: Normal chamber operation is shown in Fig. 1. Ball valves in the inlet (ambient air) and stack (radon exhaust) lines are closed. The ball valve in the bypass line is open. Air is continuously circulated, mixing in the chamber. In this mode, the system is a closed loop. The radon concentration is controlled by

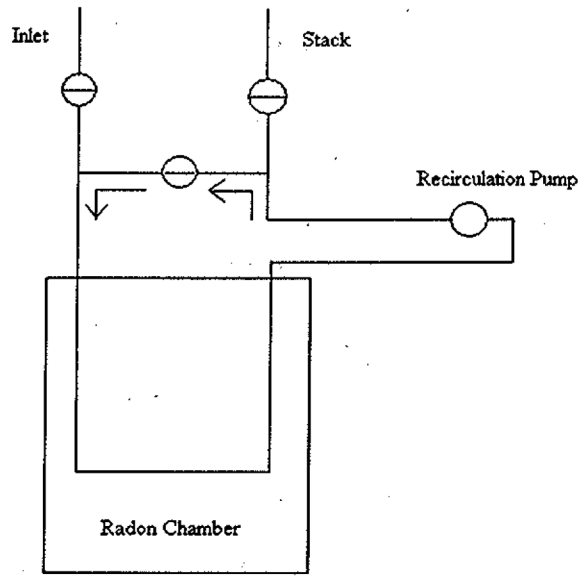


**Fig. 1.** The cycling of radon gas concentration in the EPA radon chamber: normal chamber operation.

limiting the amount of radon introduced to the system. In this mode, it is simple to raise the radon concentration by increasing the percentage of radon being introduced into the system using a mass flow controller. Lowering the radon concentration in this mode only occurs through decay and leakage from the chamber, which is minimal.

Venting the chamber is shown in Fig. 2. The inlet and stack valves are open. The bypass valve is closed. In this mode, ambient air is drawn into the chamber while radon is continuously vented. The system is an open loop. This mode allows the chamber concentration to be lowered in a controlled manner. Typically, the chamber will be vented repeatedly for one in five to one in twenty minutes until the desired concentration is reached. When cycling the chamber, radon is introduced to the chamber at a steady rate, usually at the full capacity of the source(s). The chamber is operated in normal closed loop mode to raise the radon concentration until the desired radon concentration is reached. Then the chamber is vented in open loop mode as described above to reduce the radon concentration, after which it returns to closed loop mode. The amount of time and frequency of venting the chamber is controlled automatically by software. Operating in this mode the chamber can continuously model diurnal variations or other varying radon conditions.

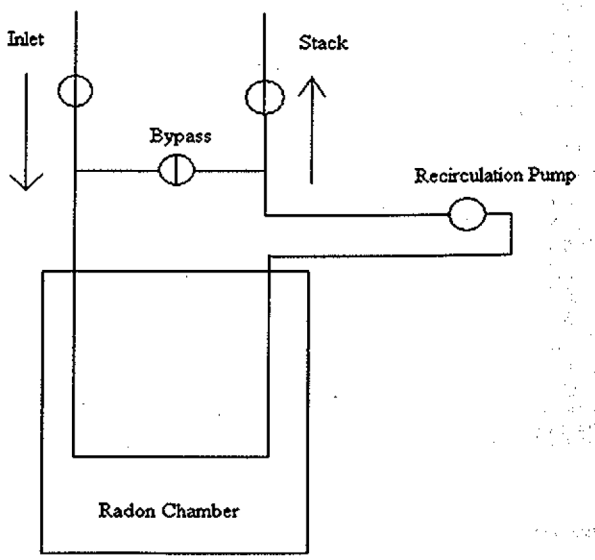


**Fig. 2.** The cycling of radon gas concentration in the EPA radon chamber: chamber venting.

During the two laboratory tests (see EPA Test 1 and EPA Test 2 below), the radon gas concentration in the EPA chamber was controlled automatically by software developed at the R&IENL. The temperature and relative humidity in the chamber were monitored and controlled during the course of the exposure periods. The hourly radon concentration, temperature, and relative humidity results recorded at the chamber were used as the reference values for analyses. Additional condensation nuclei were not introduced or measured during the two EPA tests as there was no comparison value available from the previous field test (Sun et al. 2006). In each of the two laboratory tests, fifteen trays containing the detectors were distributed at different locations within the radon chamber. On each tray, one detector from each company including one electret ion chamber were evenly distributed.

**EPA Test 1 (6/06/05~6/10/05).** The radon gas concentrations were cycled in the chamber to match, as closely as possible, the conditions measured during the previous Field Test (Sun et al. 2006). The percent relative humidity closely mirrored the relative humidity measured in the Field Test, but due to limitations of the chamber control system the exposure temperature was higher than in the Field Test and the temporal radon fluctuations were less pronounced than in the Field Test (Fig. 3).

**EPA Test 2 (6/13/05~6/17/05).** The radon gas concentration in the chamber was set at a steady state close to the mean average obtained during the simulated field test (EPA Test 1). The temperature was set to match EPA Test 1 while the relative humidity was lowered to a more moderate value of 50%.

The exposure periods and numbers of detectors exposed from each company for all three settings (Field Test, EPA Test 1, EPA Test 2) are presented on Table 2.

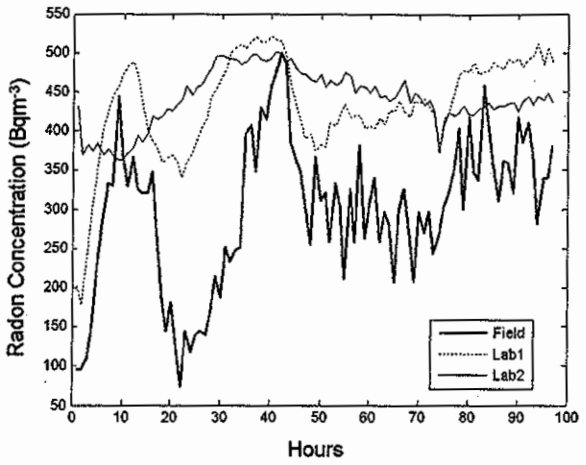


**Fig. 3.** Hourly plot of the CRM measurements for the 4-d sampling period for three different study settings.

With the exception of the electret ion chambers, the measurement periods were based on the recommended exposure duration, as indicated in the instructions that accompanied each type of detector. In all three tests, detectors B and C were exposed for three days and D-H were exposed for four days. The electret ion chambers labeled A accompanied the measurements in both 3-d and 4-d exposure periods. In each setting, all measurements were initiated at the same time, with two different measurement termination dates depending on the total duration of exposure required. One detector from each company in the field setting and five detectors from each company in each of the lab settings were used as field control detectors (blanks) that remained sealed and stored in a low radon environment during the course of measurements. The control detectors were labeled with identical dates of exposure and other information as their analogous exposed detectors to ensure identical processing. Both the exposed and control detectors were placed in their individual mailers supplied by the companies, with U.S. First Class Postage applied, and then placed directly in the mail at a local U.S. Post Office within 24 hours of the completion of the exposures.

The measurement results for each type of detector were compared to the reference values established for the various exposure periods by the CRM results. The IRE

**Table 2.** Precision and accuracy of commercially available radon detectors.

| Company | Test | Number of detectors | Exposure (d) | Radon conc. mean ± S.D. (Bq m$^{-3}$) | COV (%) | Number of detectors[a] with IRE >25% | MARE[b] (%) | Reference radon conc. mean (Bq m$^{-3}$) |
|---|---|---|---|---|---|---|---|---|
| A | Field | 4 | 3 | 292 ± 22 | 7.3 | 0 | 4.9 | 281 |
| | EPA1 | 5 | 3 | 414 ± 7 | 2.2 | 0 | 2.4 | 426 |
| | EPA2 | 5 | 3 | 437 ± 4 | 1.1 | 0 | 2.6 | 448 |
| B | Field | 15 | 3 | 274 ± 30 | 10.7 | 0 | 9.1 | 281 |
| | EPA1 | 11 | 3 | 363 ± 37 | 10.2 | 3 | 15.0 | 426 |
| | EPA2 | 11 | 3 | 463 ± 33 | 7.4 | 0 | 7.1 | 448 |
| C | EPA1 | 12 | 3 | 259 ± 56 | 21.5 | 10 | 38.9 | 426 |
| | EPA2 | 15 | 3 | 381 ± 37 | 10.2 | 2 | 15.2 | 448 |
| A | Field | 15 | 4 | 311 ± 15 | 4.3 | 0 | 4.1 | 300 |
| | EPA1 | 10 | 4 | 429 ± 7 | 1.7 | 0 | 2.3 | 437 |
| | EPA2 | 10 | 4 | 433 ± 11 | 2.4 | 0 | 2.0 | 440 |
| D | Field | 15 | 4 | 218 ± 30 | 13.4 | 8 | 27.8 | 300 |
| | EPA1 | 15 | 4 | 363 ± 22 | 6.6 | 0 | 16.9 | 437 |
| | EPA2 | 15 | 4 | 344 ± 19 | 5.1 | 4 | 21.7 | 440 |
| E | Field | 15 | 4 | 355 ± 52 | 14.6 | 3 | 19.1 | 300 |
| | EPA1 | 15 | 4 | 440 ± 41 | 8.8 | 1 | 5.6 | 437 |
| | EPA2 | 15 | 4 | 433 ± 15 | 3.1 | 0 | 2.7 | 440 |
| F | Field | 15 | 4 | 237 ± 41 | 16.8 | 5 | 21.0 | 300 |
| | EPA1 | 15 | 4 | 385 ± 22 | 5.9 | 1 | 11.5 | 437 |
| | EPA2 | 15 | 4 | 400 ± 22 | 5.3 | 0 | 9.3 | 440 |
| G | Field | 15 | 4 | 344 ± 22 | 6.5 | 1 | 14.8 | 300 |
| | EPA1 | 15 | 4 | 514 ± 26 | 5.4 | 1 | 17.5 | 437 |
| | EPA2 | 15 | 4 | 474 ± 22 | 4.9 | 0 | 7.5 | 440 |
| H | Field | 15 | 4 | 211 ± 15 | 6.6 | 13 | 29.8 | 300 |
| | EPA2 | 15 | 4 | 392 ± 89 | 22.3 | 4 | 17.5 | 440 |

[a] The results of all the individual relative errors (IREs) must be ≤25% to pass proficiency tests. Its calculation is shown below:

$$IRE = \frac{|M_i - T_i|}{T_i} \times 100\%,$$

where

IRE = individual relative error for device *i*, in percent, for each measurement;

$M_i$ = measured value for device *i*; and

$T_i$ = target value for device *i*.

[b] The mean of the absolute values of the relative errors.

was used as the measure of accuracy and the coefficient of variation (COV) was used to measure the precision of the measurements (Table 2).

## RESULTS

In the previous Field Test (Sun et al. 2006), the mean temperature was 15.6 ± 0.6°C with a mean relative humidity of 78.2 ± 2.2%. In the EPA Test 1 setting, the mean temperature was 21.4 ± 0.3°C with a mean relative humidity of 74.0 ± 0.8%. In EPA Test 2, the mean temperature was 21.3 ± 0.5°C with a mean relative humidity of 50.1 ± 0.6%. EPA Test 1 chamber conditions successfully mirrored the field humidity fairly closely, but the mean temperature was 5.8°C higher than the mean recorded field temperature for reasons described previously. EPA Test 2 chamber conditions maintained an almost constant relative humidity and temperature of 50% and 21.3°C, respectively. A plot of the hourly radon gas measurement results for all three settings is shown in Fig. 3. The radon concentration in the Field Test showed considerable variation, especially during the first 2 d of the study. The controlled radon gas concentrations in EPA Test 1 reflected the temporal radon trends noted in the Field Test fairly well. However, the overall average radon gas concentration was higher and exhibited less pronounced fluctuations in EPA Test 1 as compared to the Field Test. Although the radon concentration in EPA Test 2 was not as constant as desired, it still provided a much more steady state exposure with considerably less fluctuation than the Field Test.

Table 2 presents the average integrated radon gas concentrations for the different measurement periods. Detectors C were added for the study performed at the EPA radon chamber (EPA Test 1 and EPA Test 2), but were not included in the previous Field Test (Sun et al. 2006). Detectors from company H were tested as part of the EPA Test 1, but the company reported that they were not received in time for valid analyses. Therefore, there were no results for company H in EPA Test 1. Table 2 also provides the mean reported radon concentrations, standard deviation, COV, and the number of detectors with an IRE in excess of the EPA's previous EPA-RMPP testing requirements of ≤25%. The relatively small COVs within the two groups of electret ion chambers, exposed for each time period, provide evidence for a fairly homogeneous radon concentration in the measurement area for all three tests.

In the previous Field Test, other than the electret ion chambers that were used to assess homogeneity of the exposure, only the 3-d exposure detectors from company B reported radon concentrations all within IREs of ≤25%, and only the detectors from two companies (G and H) had a precision as measured by the COV of <10%. As compared to the Field Test (Sun et al. 2006), the detectors from most of the companies generally exhibited better precision and accuracy in EPA Test 1, except for detectors from company B that displayed similar precision but less accuracy in EPA Test 1 (3 detectors having an IRE >25% vs. none in the Field Test). The majority of companies exhibited both the highest precision and accuracy in EPA Test 2 with the exception of detectors from company D. Detectors from company D exhibited less accuracy than in EPA Test 1, but better accuracy than in the Field Test (Sun et al. 2006). In addition, detectors from company H exhibited very poor precision in EPA Test 2 but did not report results for comparison in EPA Test 1. The electret ion chambers displayed a high degree of precision and accuracy in all the exposure periods and throughout the three different testing situations.

Fig. 4 displays the distribution of the individual test results from each company for the 3-d and 4-d exposure periods, respectively, as compared to the radon reference value for all three settings. The reported radon concentrations for the control detectors were all <19 Bq $m^{-3}$ (0.5 pCi $L^{-1}$) with the exception of the detectors from company H. Company H reported values ranging from <19 Bq $m^{-3}$ (<0.5 pCi $L^{-1}$) to 70 Bq $m^{-3}$ (1.9 pCi $L^{-1}$) with 4 of the 5 reported values at 19 Bq $m^{-3}$ or greater.

## DISCUSSION

The EPA's former National Radon Proficiency Program (EPA-NRPP) was designed to test the competence of an individual measurement *system*, e.g., in general a measurement services provider using active or passive devices, either of which might be supported by an "analytical laboratory" capability. Although the EPA's proficiency program tested devices, the documentation for the program included the following disclaimer, *The radon measurement devices included on this checklist are not endorsed or approved by EPA and should not be interpreted as such.* Nonetheless, the devices listed in the EPA-NRPP (in *Application Device Checklists*) were presumed by the EPA, at a minimum, to be appropriate for making measurements in homes and schools. The EPA's premise in the design of the EPA-NRPP was that devices were generally being used to perform screening (<90 d) and to a lesser extent longer-term measurements (>90 d), the results of which were used to guide mitigation decision making. Given the EPA's recommended action level of 150 Bq $m^{-3}$ (4 pCi $L^{-1}$), it was most important that devices be proficient in making measurements in the vicinity of 150 Bq $m^{-3}$ (4 pCi $L^{-1}$) under environmental conditions typically

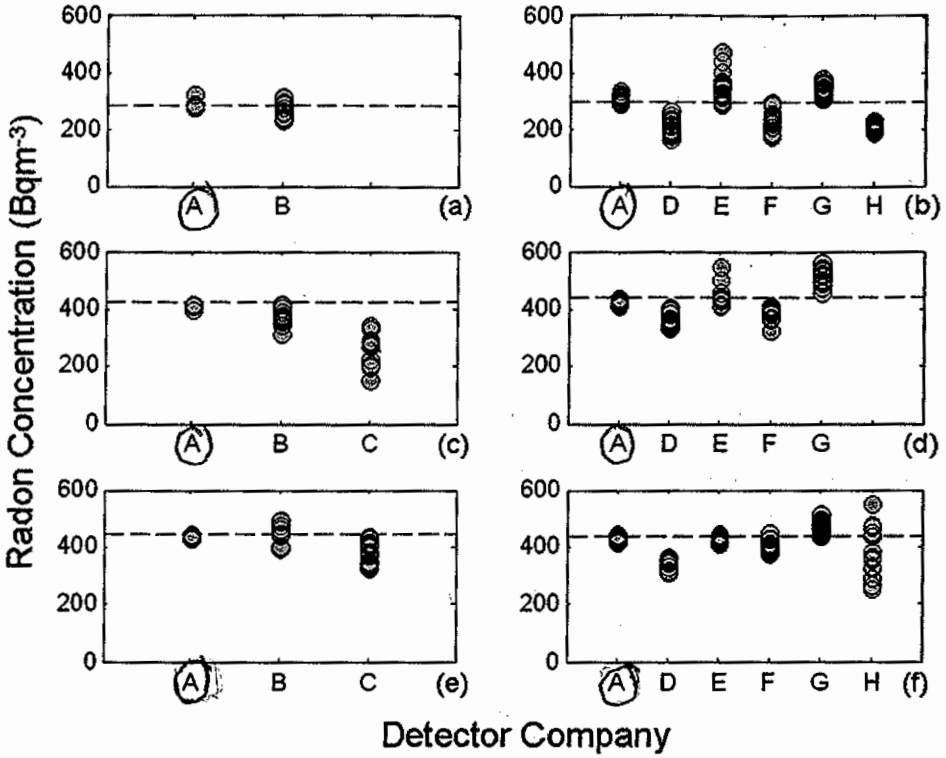


**Fig. 4.** Comparison of the detectors from different companies and electret ion chambers (company A) as compared to the radon reference concentration (dashed line) obtained from the CRM measurements for different measurement periods and different study settings: (a) 3-d; (b) 4-d measurements in the field setting; (c) 3-d; (d) 4-d measurements for EPA Test 1; (e) 3-d; and (f) 4-d measurements for EPA Test 2.

found in homes. In addition to announced performance testing, the EPA-NRPP also experimented with both blind testing of measurement services providers and with dynamic chamber exposures that attempted to mimic actual residential conditions.

After the EPA-NRPP was terminated in 1998, the EPA's official recognition (1998–2002) of the private proficiency programs was perceived as affirming that the quality of services that consumers were likely to receive from participants was similar to that of the old EPA-NRPP. This perception was strengthened by the fact that the private proficiency programs' design and operational structure closely mimicked the previous EPA-NRPP.

EPA's R&IENL in Las Vegas (NV) is the sole remaining technical radon asset from EPA's defunct NRPP. For all practical purposes, R&IENL serves as the national primary reference laboratory for radon measurements in air. R&IENL also provides technical verifications of new devices as a service to the two currently operating private proficiency programs; the National Radon Safety Board (NRSB), and the National Radon Proficiency Program (NRPP) under the aegis of the National Environmental Health Association (NEHA). The NRSB and the NEHA-NRPP "credential" both analytical labs providing general measurement services and calibration reference laboratories (e.g., Bowser-Morner as a secondary reference laboratory).

Neither the NEHA-NRPP nor the NRSB programs currently include blind performance testing at this time. Ideally, determinations of measurement proficiency would include announced and blind performance testing, especially for providers with an analytical capability or service offering. The feasibility of blind testing is primarily dependent on resources, whether passive and active measurement systems are tested, and the test conditions, e.g., in a laboratory or field setting. The advisability of blind testing involves weighing issues such as: how the results are to be used (publicly vs. privately); liability (equity); having a standardized test design; applying the test design systematically and consistently (all systems/devices); execution degree of difficulty (it is more difficult and expensive to test providers with active devices); and the benefit-cost of alternative detector evaluation methods (e.g., substituting more frequent announced testing for blind testing).

Radon exposures to test the proficiency of measurement services providers can be conducted either under static conditions or under dynamic conditions, or in some combination. Static exposure test conditions are unique

to a laboratory setting, e.g., the R&IENL facility. Dynamic, or field, conditions are those found in homes or schools. However, to some degree dynamic conditions or a dynamic environment can be mimicked or replicated in a laboratory setting. Theoretically, static testing in a laboratory setting "levels the playing field" for the systems/devices being tested. However, by virtue of their design, not all devices are equally capable of measuring radon accurately under all exposure parameters. Dynamic testing tends to reveal that not all systems/devices are equally capable of producing an integrated radon measurement.

The setting of the exposure parameters is a key determinant of measurement device performance. The parameters U.S. EPA typically included in its NRPP exposures included radon concentration, air velocity, concentration of condensation nuclei, humidity, and temperature. EPA set the values for these parameters in ranges believed typical of U.S. homes, e.g., 16–29°C (60–85°F) temperature range. Both temperature and relative humidity are well known environmental factors that may influence the testing results of charcoal-based short-term radon test devices (George 1984; Prichard and Marien 1985; Ronca-Battista and Gray 1988; Pojer et al. 1990; Luetzelschwab et al. 1994).

All of the companies tested in this study recommended to consumers that the test kits not be placed in areas where high humidity might be present or where extreme heat or cold might occur. However, only three of the six companies requested temperature information be recorded on the data cards, which are mailed back to the laboratories together with the detectors for post-exposure analysis. Information on the relative humidity in the test area was not requested by any of the companies. This is not unexpected as most non-professional consumers probably have no way of accurately measuring relative humidity. However, even if this information were made available, it is unknown how many companies that manufacture radon detectors for commercial sales perform a calibration of their charcoal detectors under different relative humidity conditions.

In the Field Test (Sun et al. 2006), the home averaged 78% relative humidity during the 4-d testing period. The 74% relative humidity in the EPA Test 1 mirrored the relative humidity in the Field Test fairly well, but EPA Test 1 had a higher temperature and in turn a higher absolute humidity. Nevertheless, the detectors exhibited better precision and accuracy in EPA Test 1 as compared to the Field Test, which may be attributed to the decreased magnitude of the temporal radon fluctuations and the higher average radon gas concentration in the EPA Test 1 setting (437 Bq $m^{-3}$ vs. 300 Bq $m^{-3}$ for the full 4-d exposure period). The average radon gas concentration in EPA Test 2 was almost identical to EPA Test 1 (440 Bq $m^{-3}$ vs. 437 Bq $m^{-3}$, respectively, for the full 4-d exposure period); however, the testing results in EPA Test 2 with a fairly constant reference radon gas concentration and lower relative humidity (50%) produced overall better accuracy and precision than in EPA Test 1 and the Field Test. This was not unexpected and may possibly be attributed to the influence of both the fluctuating radon gas concentrations during the last 48 h of exposure during EPA Test 1 and the Field Test and the higher relative humidity noted for these two test periods.

Despite the obvious differences in the relative radon concentrations, the magnitude of the temporal radon fluctuations, and the environmental factors (e.g., relative humidity, absolute humidity, temperature) during the three test periods, examining the performance of each company's detectors performance during the three study settings (Fig. 4) provides some interesting trends. For instance, detectors from companies C, D, F, and H tended to consistently under-report the actual reference radon concentration; while for company G, detectors tended to consistently over-report the radon concentration as compared to the reference radon concentrations. In addition, as mentioned above, the detectors from companies B and C are distributed and analyzed by the same company, but marketed under different names. Surprisingly, the detectors from company C consistently reported lower radon concentrations for the tests performed at the EPA Laboratory as compared to the results from company B (Fig. 4). The reason why the results from company C are less accurate and precise than the results from company B is unknown (Table 2).

The trend of under-reporting by several of the companies was not expected as it was believed that a rise in radon gas concentration above the mean exposure concentration, especially over the last 24 h, would tend to cause the measurements results of charcoal-based detectors to exhibit a high bias. It is possible that the elevated absolute humidity during EPA Test 1 may have affected the ability of the charcoal-based detectors to adsorb radon gas, although this does not explain the bias observed during the more moderate relative humidity conditions of EPA Test 2. Nonetheless, the observed trends are suggestive of systematic biases in those companies that consistently over- or under-reported results and merit further investigation.

Another noteworthy observation was that for EPA Test 1, company H reported they did not receive any of their 20 detectors (15 exposed and 5 blanks) in time to provide valid analysis results. All of the detectors in the study were mailed individually back to their respective laboratories from a U.S. Postal Office within 24 h after exposure. This procedure was consistent with testing

instructions supplied by each company. Inconsistencies were also noted in company H in other areas of the tests. For example, detectors from company H exhibited good precision (COV 6.6%) during the Field Test (Sun et al. 2006), but had the largest mean deviation from the reference value of all of the companies tested. In contrast, of all the companies tested in all three studies, company H exhibited the largest COV (22.3%) during the steady state conditions of EPA Test 2.

Overall, the detectors from most companies performed better under a moderate relative humidity of 50% and a fairly steady radon gas concentration, encountered during EPA Test 2, with 3 companies obtaining an IRE >25% for at least one of their detectors. The higher humidity and fluctuating radon gas concentrations encountered during the Field Test and EPA Test 1 appear to have negatively influenced the accuracy and precision of the detectors. Under these conditions 5 companies failed to obtain an IRE ≤25% for all of their detectors during the Field Test with three companies (D, F, and H) reporting an IRE >25% for a third or more of their detectors. Similarly, 5 companies failed to obtain an IRE ≤25% for all of their detectors during EPA Test 1 with one company (C) reporting an IRE >25% for approximately 83% of their detectors (10 out of 12 detectors).

The consistent over-reporting or under-reporting trends in the overall results for all three tests suggest a potentially widespread systematic bias for some of the companies that requires further investigation. However, it is important to note that these findings represent just a "snapshot" and may or may not reflect the accuracy and precision of detectors from these companies over time. In addition, the exposures were made at higher radon concentrations than both the estimated median annual basement radon concentration of 76 Bq $m^{-3}$ found in U.S. single family homes (Marcinowski et al. 1994) and the EPA recommended action level of 150 Bq $m^{-3}$, which generally favors the ability of the detector to perform well. Nonetheless, the accuracy and precision of some companies, even under a moderate relative humidity environment with high and fairly constant radon gas concentrations, suggest that the implementation of a systematic blind testing program for commercially available radon detectors may be appropriate. Furthermore, the inability of several of the companies tested to obtain a COV ≤10% in this study may also be indicative of a need for a more robust internal quality assurance program and possible external auditing. Another interesting observation is, with the exception of company C during EPA Test 1 and company H (which reported no results), all the companies would have passed the original EPA MARE criteria for both EPA Test 1 and EPA Test 2. The results of this study lend support to EPA's previous tightening of performance testing criteria from the use of the MARE to the IRE.

Because large numbers of short-term radon measurements are performed each year under varying field conditions, commercial detectors need to be able to perform reliably under a wide range of environmental conditions. If a particular type of detector is not robust enough to perform reliably under certain conditions, then the conditions under which it can perform reliably should be clearly noted on the instruction sheet. Assessing the accuracy and precision of commercially available radon detectors, under controlled conditions and in the field, is an important step for discovering and documenting the impact of environmental factors that affect the performance of the short-term radon detectors. Equally critical is the need for manufacturers and measurement providers to understand and control for the potential adverse affects of environmental factors at time of detector construction or analyses. It is EPA's recommendation that stakeholders revisit the issue of what the structure and content of radon measurement proficiency should be, and how the available Federal, state, and private market resources might be better coordinated to raise the general level of measurement proficiency.[††]

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