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Report to the Chairman, Committee on Science, Space, and Technology, House of Representatives

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AIR POLLUTION

Uncertainty Exists in Radon Measurements

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Resources, Community, and
Economic Development Division

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October 16, 1989

The Honorable Robert A. Roe
Chairman, Committee on Science,
Space, and Technology
House of Representatives

Dear Mr. Chairman:

Radon—a colorless, odorless gas formed by the decay of radium and uranium—has been shown to cause lung cancer. The Environmental Protection Agency (EPA) and the Public Health Service have advised residents to test their homes for radon and take action when elevated levels are found. To help ensure that the radon measurements homeowners obtain are accurate, EPA has issued procedures for taking radon measurements and established the voluntary Radon Measurement Proficiency (RMP) program. The RMP program assesses the proficiency of radon measurement devices and the capabilities of the companies that analyze these devices after they are exposed to radon.

In your letter of December 13, 1988, you expressed concern about the accuracy of the current methods and practices used to measure radon gas. In meetings with your office, we agreed to provide information on (1) the ability of radon measurement devices and the companies that analyze the devices to record radon levels accurately, (2) the extent to which homeowners are following EPA's recommended testing procedures, and (3) the extent to which the RMP program provides assurance to homeowners that radon measurements are accurate.

Results in Brief

EPA estimates that about 2 million homes have been tested for radon. Overall, through the RMP program, EPA has made progress in improving homeowners' assurance that radon measurements are accurate. Participation in this voluntary program by firms providing measurement services to homeowners has grown from 40 in 1986, when the program began, to over 700 in 1989; 87 percent of the devices tested in the program during the test round completed in 1988 passed. Despite this progress, however, we found that radon measurements, which are used to assess health risks and determine the need for action to reduce indoor levels, are uncertain because (1) the ability of the devices that measure radon and the companies analyzing the devices to accurately record radon levels varies and (2) homeowners may not be following EPA's recommended testing procedures.

Opportunities exist through the RMP program to reduce some of the uncertainty in radon measurements and provide homeowners with more assurance that measurements are accurate. For example, the RMP program is voluntary and allows companies to market devices that have not been tested or that failed the test. The program also does not include verification procedures; consequently, it allows companies to participate without their meeting requirements contained in EPA's measurement protocols.[1] In addition, the RMP program does not require companies to have quality control procedures; as a result, it cannot ensure that companies' measurement devices and results are consistently accurate.

A follow-up review we are conducting is designed to determine changes that can be made in the RMP program to provide homeowners with more assurance that radon measurements are accurate. As part of that work, we are gathering information on (1) state radon programs, (2) areas in radon testing where state officials believe more emphasis is needed, and (3) efforts EPA and states are using to communicate with homeowners on radon testing.

Background

In September 1988, on the basis of the results of radon measurements in 17 states, the EPA Administrator and the Assistant Surgeon General issued a national health advisory on radon, recommending that most homes be tested and action be taken when elevated levels are found. While EPA maintains that there is no safe level of radon, it recommends action whenever annual average radon levels are greater than about 4 picoCuries per liter (pCi/l) of air.[2]

Several different devices can be used to measure radon in the home. One popular short-term device, called the activated charcoal adsorption detector (commonly known as the charcoal canister), measures radon for 2 to 7 days. Another popular device, the alpha track detector, measures radon for periods, such as 3 months or 1 year. A third device, the electret ion chamber, can measure radon for either short or long periods,

[1]Protocols outline procedures for taking radon measurements, specify the standardized house conditions that should exist at the time of the measurement, and describe the appropriate steps to follow and the equipment to use for each EPA-approved measurement method. To date, the following protocols have been issued: "Interim Indoor Radon and Radon Decay Product Measurement Protocols," February 1986 (revised and issued in final form, Feb. 1989); and Interim Protocols for Screening and Followup Radon and Radon Decay Product Measurements," February 1987.

[2]The concentration of radon in air is measured in units of picoCuries per liter of air; 1 pCi/1 represents the decay of about two radon atoms per minute in a liter of air.

such as 1 week or 1 year. To date, EPA has approved nine methods for measuring radon (see app. III).

EPA recommends a two-step strategy for identifying hazardous radon levels in homes. First, a short-term screening measurement is taken under conditions and in locations most likely to yield the highest reading. The aim is to ensure that dangerous concentrations of radon are not overlooked. If this first reading signals elevated levels, a follow-up measurement is taken. EPA advises homeowners to use only this second measurement as a basis for taking corrective action. (See app. II for a more detailed discussion of EPA's testing procedures and supporting research.)

EPA's responsibilities for radon have evolved since 1984, when radon began receiving national attention. In 1985, without specific legislative direction, EPA established the radon action program. The program represents a nonregulatory approach, which EPA believes to be most suitable for dealing with a naturally occurring health hazard. Under the program, EPA (1) conducts radon surveys to assess the radon problem, (2) carries out radon mitigation research projects, (3) provides state and private company personnel with radon training, (4) develops and distributes public information on radon, and (5) operates the RMP program.

The RMP program tests the capabilities of companies measuring indoor radon. Companies voluntarily submit radon measurement devices to EPA for testing. The devices are exposed to known levels of radon at EPA's facilities and then returned to the company for analysis. After analyzing the exposed devices, the company reports the radon levels for each device to EPA. If the results are within 25 percent of the known concentrations, the company passes the proficiency test for that device. There is no generally accepted standard on what constitutes a good accuracy rate for radon devices. According to EPA officials, the 25-percent criterion was developed primarily for screening measurement results. Since February 1986, EPA has conducted five testing rounds; round 6 is underway. Participation in the program has grown substantially, from about 40 companies in 1986 to over 700 primary and 9,000 secondary companies in round 6.[3]

[3]Primary companies either have laboratory capabilities to analyze radon measurement devices after they have been exposed to radon or measure the radon levels and analyze the results with their own instrumentation and operators. Secondary companies provide services ranging from distribution of radon devices to home inspection and consultation. Secondary companies must use a primary company to analyze the radon devices.

Since initiation of the radon program, two pertinent laws have been enacted. The Superfund Amendments and Reauthorization Act of 1986 requires EPA to (1) conduct a national assessment of radon and (2) establish a research and development program that will address indoor pollution problems. More recently, the Indoor Radon Abatement Act of 1988 directed EPA to undertake a variety of activities to address the radon problem. A number of these activities, such as radon surveys and the proficiency program for firms providing radon measurement services to the public, were already underway as part of the radon action program. The act also authorized new activities, such as a state grant program, a federal buildings study, regional radon training centers, and a proficiency program for radon mitigation contractors.

RMP Program Test Data and Research Show That the Accuracy of Radon Measurements Varies

Our analysis of data from EPA's proficiency testing completed in September 1988 shows that the overall accuracy of the different measurement methods varies. For the eight measurement methods included in this test round, the average error ranged from 18 to 40 percent. The average error for a particular method is based on the difference between the readings of individual devices and the known concentrations for all such devices.

The RMP program data also show that the accuracy of different companies using the same measurement method varies. For example, the average company error for the alpha track detector method ranged from 11 to 55 percent; the average company error for the charcoal canister ranged from 1 to 133 percent. The average company error is the mean of the errors for all devices of a particular type submitted by an individual company. For this test round, companies generally submitted five devices for each method, but one was used as a control and not exposed during the test. (See app. III for the results of our analysis for the eight methods tested.)

Through bibliographic searches and information provided by experts recommended by EPA, we identified 15 studies evaluating the accuracy of radon measurement devices. These studies also show differences in the accuracy of radon measurement devices. (See app. IV for details on the studies.) For example, in exposing electret ion chamber devices to known levels of radon, one study found that the overall accuracy was between 91 and 109 percent of known concentrations. (See study 4, app. IV.) Another study, which exposed two groups of alpha track detectors to different levels of radon, found that the devices' readings varied from 91 to 101 percent of the known levels at low concentrations and from 76 to 115 percent at high levels. This study also exposed groups of charcoal canisters to different levels of radon. It found that the readings of these devices ranged from 57 to 94 percent of the known values for low radon levels and from 72 to 101 percent for high levels. (See study 3, app. IV.)

Several factors may affect the accuracy of radon measurements. Radon concentrations are highly variable—from hour to hour, day to day, and month to month, as well as season to season. Radon levels also are known to fluctuate rapidly, with low-point to high-point changes of more than 100 percent. In addition, most devices being marketed today are relatively new, developed since the mid-1980s, according to one expert. Further, another expert told us, a large number of inexperienced companies are providing radon measurement services and the accuracy and precision of nearly all of the devices in use have never been evaluated to determine the impact of such things as normal variations in temperature, wind velocity, and humidity. Finally, the extent to which measurement companies have implemented quality control procedures can affect the accuracy of the radon measurement results provided to homeowners.

Evidence Indicates That Homeowners May Not Be Following EPA's Testing Procedures

Information we obtained during this review provides some indication that homeowners may not be following EPA's testing procedures. (See app. II for a discussion of EPA's testing procedures.) An EPA-sponsored study of homeowners in the Washington, D.C., area who had tested their homes for radon found that over 85 percent of the respondents to a questionnaire had not performed a second follow-up measurement even though their measurement results were above 4 pCi/l of air.[4] EPA recommends follow-up measurements whenever the initial screening measurement is greater than 4 pCi/l of air.

In addition, representatives of mitigation firms told us that homeowners were taking mitigation actions on the basis of results of a single short-term measurement. For example, three of the seven mitigation firms that we contacted in Pennsylvania, New Jersey, and Rhode Island told us that most of the mitigation work they had done was based on the results of a single short-term test. A representative of one firm told us that, in several cases, the measurement was less than 20 pCi/l of air. If screening measurements are greater than about 4 pCi/l but less than about 20 pCi/l of air, EPA recommends a yearlong follow-up. In addition,

[4] J. K. Doyle, S. R. Elliott, G. H. McClelland, G. W. Russel, and W. D. Schulze, An Evaluation of Policies for Solving the Radon Problem (draft) (Boulder, Col.: University of Colorado, January 1989).

one company told us that it has taken mitigation action with less than 4 pCi/l of air.

Generally, EPA has not collected data to determine whether homeowners understand and are following testing procedures because of funding constraints. In addition, according to an EPA program official, because the radon program is nonregulatory, it is not clear whether EPA can require testing firms to report test results.

RMP Program Could Provide Greater Assurance That Radon Measurements Are Accurate

EPA's program for assessing the proficiency of radon measurement companies provides some assurance to homeowners that radon measurement results are accurate. However, the program could provide greater assurance to homeowners. The program is voluntary, and not all firms that market radon measurement services or devices participate. In addition, the program does not (1) include verification procedures to make sure that the companies follow EPA requirements or (2) require companies to implement quality control programs to make sure they maintain a minimum level of performance.

The RMP program is designed to assist states and the public in selecting companies that have demonstrated competence in measuring indoor radon and to provide assurance to the public that radon measurements made by companies are accurate. To pass the RMP program and be listed in the proficiency report, EPA requires a primary company to (1) follow the appropriate measurement protocols, (2) demonstrate the ability to get measurement results to the proper homeowner, and (3) demonstrate the ability to measure radon to within 25 percent of actual levels.

To meet the first requirement, EPA generally relies on a company's statement in the application that it follows the protocols. To meet the second and third requirements, companies must pass the proficiency test, which includes correctly analyzing devices exposed to known levels of radon and reporting the results to EPA.

Overall, 87 percent of the devices tested in the RMP program during the 1988 test round were listed as passing. Our review of primary companies that participated in the 1988 test round showed that companies listed as passing the RMP program did meet, for the most part, EPA's 25-percent criterion for passing the proficiency test (see app. III). However, we identified firms that were marketing devices that either were not tested or did not meet program requirements.

Firms Market Devices Without Meeting Program Requirements

In our sample of the 11 large primary companies and 100 of the 347 small primary companies that participated in round 5, we found the following:

- One device that was being marketed by one of the large radon measurement companies did not meet the RMP program's requirements. EPA advised the company that the device could not be part of the RMP program until EPA had evaluated and developed a protocol for it, but agreed to test the device. The device failed both the initial test and the retest.
- One large company and an estimated seven small companies were marketing devices that had not been tested in the RMP program (small company sample results are given as estimates to the universe of 347).
- An estimated 24 small companies that failed round 5 are marketing devices.
- An estimated three small companies that tested some of their devices in the RMP program have been marketing other devices that had not been tested in the program.
- Some secondary companies listed are not using the approved laboratory of the large primary company they listed in their applications to meet the program's requirements.

We identified a company, not in our sample, that continues to analyze devices in its laboratory under another name after they failed the round 5 proficiency test. In addition, we found that 10 companies were listed as passing the program with a charcoal canister but were actually using another device called a charcoal liquid scintillation device. EPA only recently issued a protocol for this device. Eight of these companies were using equipment for reading the devices that did not meet the protocol for the charcoal canister method. Without verification procedures, EPA has no way of knowing whether companies are complying with its measurement protocols.

Quality Assurance Not Required by RMP Program

Although EPA recommends certain quality control procedures for measurement companies, quality assurance is not a requirement of the RMP program. Consequently, companies may be providing homeowners with inaccurate test results.

In its protocol, EPA states that the objective of quality assurance is to ensure that data are scientifically sound, precise, and accurate. One quality assurance procedure EPA recommends is that companies calibrate their measurement devices. To ensure that accurate test results are being obtained, companies need to calibrate the measurement devices in a known radon environment, such as in a calibration chamber. One of the companies in our review that did not calibrate its equipment failed round 5 testing with a 100-percent error, but it had been marketing the device for a full year before round 5 testing. After calibrating its equipment, the company retested and passed EPA's test.

In round 6, EPA is implementing a procedure called "blind testing," which it believes will encourage companies to implement quality control procedures. Blind testing consists of EPA's acquiring devices without a company's knowledge, exposing the devices to known levels of radon, and returning the devices to the company for analysis. If the company's analysis does not meet the 25-percent criterion, it will not be listed as passing the RMP program.

Summary

Radon has been identified as a national problem, and homeowners have been directed to test for radon and take action to reduce dangerous levels. To help ensure that homeowners receive accurate measurements so that they can decide on the need to reduce radon levels, EPA issued procedures for taking radon measurements and established the RMP program. While these steps provide homeowners with some assurance that radon measurements are accurate, uncertainty still exists in the measurements.

Accordingly, we are conducting a review to determine changes that can be made in the RMP program to reduce the uncertainty and to provide more assurance to homeowners that radon measurements are accurate. We will investigate the possibility of applying the requirements of other federal laboratory accreditation programs. As we reported to you recently, those requirements generally fit into certain common categories, including organizational information, quality control, personnel, facilities and equipment, test methods and procedures, records and recordkeeping, and test reports and proficiency testing.[5]

Detailed descriptions of various aspects of our work can be found in the appendixes. Appendix I describes our objectives, scope, and methodology. Appendix II describes EPA's recommended testing procedures and supporting research. Appendix III describes the extent to which companies met the RMP program's 25-percent criterion in round 5 testing.

[5]Laboratory Accreditation: Requirements Vary Throughout the Federal Government (GAO/RCED-89-102, Mar. 28, 1989).

Appendix IV presents detailed descriptions of the studies we reviewed. Appendix V provides the confidence intervals associated with specific estimates in this report.

We discussed the factual information in this report with EPA officials and have incorporated their comments where appropriate. However, as you requested, we did not obtain official agency comments on a draft of this report.

As arranged with your office, unless you publicly release its contents earlier, we plan no further distribution of this report until 30 days from the date of this letter. At that time, copies will be sent to the appropriate Congressional committees, the Administrator of EPA, and other interested parties.

If you have any questions regarding this report, please contact me on (202) 275-6111. Major contributors to this report are listed in appendix VI.

Sincerely yours,

Richard L. Hembra
Director, Environmental
Protection Issues

Contents

Tables

Abbreviations

ATD	alpha track detector
CC	activated charcoal adsorption detector
EPA	Environmental Protection Agency
EIC	electret ion chamber
pCi/l	picoCuries per liter
RMP	Radon Measurement Proficiency

Objectives, Scope, and Methodology

In a December 13, 1988, letter, the Chairman, House Committee on Science, Space, and Technology, asked us to review a series of questions concerning the accuracy of radon measurements. In meetings with his office, we agreed to provide information on (1) the extent to which the Environmental Protection Agency's (EPA) program for assessing the proficiency of radon measurement companies provides assurance to homeowners that radon measurement results are accurate, (2) the ability of radon measurement devices and companies that analyze the devices to accurately record radon levels, and (3) the extent to which homeowners are following EPA's recommended testing procedures.

To determine whether EPA's program was providing assurance to homeowners that radon measurement results are accurate, we discussed the program with EPA and contractor officials responsible for implementing it and reviewed instructions and procedures for determining a company's proficiency. To determine whether testing procedures were being followed, we took a statistical sample of the companies that participated in the latest completed test round (round 5), reviewed their files and test results, and recalculated tests scores for all companies participating in the program.

Our sample was a stratified sample of 111 of the 358 primary radon companies participating in round 5. We defined "large" primary companies as those with 30 or more secondary companies during round 5 testing and "small" primary companies as those with fewer than 30 secondary companies. In the first strata, we reviewed all 11 large primary companies. The second strata contained the remaining 347 small primary companies, from which we took a random sample of 100. Our sample estimates are representative of the 347 small primary companies in round 5 testing. Our evaluation was conducted at EPA's RMP program contractor, the Research Triangle Institute, in Research Triangle Park, North Carolina, and EPA's headquarters, Washington, D.C.

For each company selected, we reviewed the contractor's file to (1) determine the test scores submitted by the company, (2) verify that the test scores met the 25-percent criterion, and (3) verify that the test scores were entered correctly from the testing forms to the contractor's database. We also reviewed the files to determine whether all relevant information was included and whether files contained any conflicting information. In either case, we conducted follow-up inquiries. We also followed up on any company having at least one device that failed round 5 testing. We attempted to conduct follow-up interviews with 5 large and 20 small primary companies. Four of the small companies were not contacted because they had gone out of business and/or we could not find a current telephone listing for the company. We completed follow-up telephone interviews with 5 large and 16 small primary companies to gather information on questions related to the companies' files and on whether the companies were marketing instruments that had failed testing or had not been tested in round 5.

In addition, we recalculated all test scores for devices tested during round 5 using the contractor's database in order to determine the accuracy of the contractor's calculation of test results. Further, to determine whether the 25-percent passing criterion was met, we applied the criterion to the test results for all 594 devices tested during round 5 and compared our list of companies that passed with EPA's list.

On the basis of additional information gathered during our review, we conducted telephone interviews with 10 firms to determine which measurement method they were using and whether they followed EPA's protocol.

To determine the ability of radon measurement devices and companies to accurately record radon levels we conducted computerized bibliographic searches and requested citations from selected EPA and private sector experts in order to identify studies related to radon and radon testing.[1] This search yielded over 1,300 studies. From these, we focused on studies that satisfied at least one of the following criteria:

- The study compared different radon testing devices and/or different measurement periods.
- The study investigated EPA's assumptions for screening measurements. For example, the study compared radon level readings taken in the basement with readings taken at other household levels.
- The study was conducted in either a laboratory or a residential setting.

These criteria relate to either the accuracy of the radon measurement devices or the assumptions underlying EPA's screening protocols. EPA assumes that measurements in the lowest livable area (basement) under closed-house conditions will generally yield higher radon levels than measurements in areas other than the basement.

[1]The following databases were searched for keywords, including indoor air pollution, radon, radon testing, and mitigation: SCORPIO, CIS, Environmental Bibliography, Pollution Abstracts, ENVIROLINE, INSPEC, DOE Energy, and NTIS.

Using these screening criteria, we selected 78 studies for further review. Each of these was examined, with the study methodology being a key determinant in whether we reviewed the study in detail. Methodological items of interest included whether the study contained a description of the methodology, whether the research was conducted within the last 10 years, the extent (or lack) of projectability of study results, etc. We focused our research on three radon measurement devices—the alpha track detector, the charcoal canister, and the electret ion chamber.

We selected 23 studies for a detailed review. The results of this review were organized in terms of the following basic issues:

- the accuracy of radon measurement devices,
- research related to EPA's screening procedures, comparing (1) basement and upper-floor measurements, (2) summer and winter measurements, and (3) the effects of different measurement periods.

In addition, we analyzed all 695 test results of EPA's RMP round 5 testing completed in May 1988. Our analysis included computing average error among the different measurement methods as well as the range of company errors using the same measurement method.

We conducted our audit work between November 1988 and June 1989 following generally accepted government auditing standards. We discussed with EPA officials various aspects of the radon measurement process and have included their comments where appropriate. However, as requested, we did not obtain agency comments on the report.

Description of EPA's Recommended Testing Procedures and Supporting Research

EPA recommends a two-step strategy for identifying hazardous radon levels in homes. First, a short-term screening measurement is to be taken under conditions and in locations that EPA assumes will yield the highest reading. The aim is to ensure that dangerous concentrations of radon are not overlooked. Second, if this first reading is over 4 pCi/l of air, EPA recommends either long-term or short-term follow-up measurements.[1] Information on this strategy, as well as information on the procedures for taking radon measurements in the home and evaluating the risks when elevated levels are found, are contained in EPA's publication A Citizen's Guide to Radon. EPA distributes this guide to consumers through the states.

EPA recommends that the screening measurement be made (1) in the lowest livable area in the house and (2) in a room or area with as little ventilation as practicable. According to EPA, the data indicate that concentrations in the basement tend to be two to three times higher than concentrations elsewhere. According to EPA, information also indicates that indoor radon concentrations are generally higher in winter than in summer. Thus, winter is a good time to take screening measurements.

In general, research studies showed that higher radon concentrations are more likely to occur in the basement or the level closest to the underlying soil—the source of most radon in homes—and when little or no ventilation exists. Some studies were consistent with EPA's findings, and others were not. (See studies 16 through 26, app. IV.) For example, studies showed that differences in radon concentrations in the basement were anywhere from slightly higher to more than three times higher than concentrations elsewhere. In addition, some studies supported the assumption that radon levels are usually higher in winter than in other seasons, while others studies did not.

Further, getting consistent high readings with screening measurements can be a problem, as illustrated by one of the studies. The study compared screening and long-term measurements and concluded that the screening measurement failed to detect 20 percent of the houses with radon concentrations over 4 pCi/l. (See study 21, app. IV.)

[1] EPA's recommended steps are the following: (1) If the result is less than 4 pCi/l, follow-up measurements are probably not required, (2) If the result is between 4 pCi/l and 20 pCi/l, perform follow-up measurements of 1 year or no more than one week duration during each of the four seasons, (3) if the result is between 20 pCi/l and 200 pCi/l perform follow-up measurements of no more than 3 months, and (4) if the result is greater than 200 pCi/l perform follow-up measurements of no more than one week as soon as possible.

Finally, studies also showed that radon concentrations in the same house can vary widely over time. For this reason, short-term measurements may not accurately reflect one's annual average rate of exposure, the basis EPA recommends for making most mitigation decisions. Five studies that discussed the use of short-term measurements to estimate average annual exposure rates were identified (see studies 27 through 31, app. IV). With the exception of one study, these studies showed that short-term measurements generally are not good indicators of annual average exposure rates. For example, in one study, measurements with charcoal canisters for a period of up to 7 days were compared with the average of four measurements with 3-month alpha track detectors (the annual average concentration). Results showed that the short-term measurement should carry a ±90-percent uncertainty factor. This means that if a short-term charcoal canister reading of 3 pCi/l were used to estimate an annual radon concentration, accounting for the uncertainty factor would mean that 9 times out of 10, the annual radon concentrations would be between 0.3 and 5.7 pCi/l. (See study 30, app. IV.)

Analysis of Companies' Compliance With the RMP Program's 25-Percent Criterion and Test Results

Background

To assist states and the public in selecting companies that are capable of measuring indoor radon, EPA established the national Radon Measurement Proficiency (RMP) program. The program assesses the proficiency and capabilities of companies offering radon measurement services to the public. Participation in the program by such companies is voluntary. The program's long-term objectives are to promote standard measurement procedures among measurement companies and to establish quality assurance procedures for all measurement companies. In April 1987, EPA reported to the Congress that the program was also designed to provide assurance to the public that radon measurements made by commercial firms are accurate.[1]

Since February 1986, EPA has conducted five testing rounds. Round 5 was completed during the summer of 1988; round 6 is in progress. Participation in the RMP program has grown from about 40 companies in 1986 to over 700 primary and 9,000 secondary companies in round 6.

After every round is completed, EPA publishes a list, by measurement method, of firms that passed the RMP program. To date, EPA has approved protocols for nine measurement methods: the activated charcoal adsorption detector, alpha track detector, radon progeny integrating sampling unit, charcoal liquid scintillation device, electret ion chamber, grab sampling-radon, grab sampling-working level, continuous radon monitor, and continuous working level monitor. The first five methods are called passive because they do not require a skilled operator and can be sent through the mail, while the remaining are called active because they do require a skilled operator.

To successfully participate in the RMP program, a primary company must meet the following requirements:

- It must follow the appropriate measurement protocols.
- It must demonstrate management tracking capability, that is, the ability to get measurement results to the proper homeowner.
- It must demonstrate the ability to measure radon within the established measurement criterion of the RMP testing program.

The protocols (1) describe standardized house conditions that should exist when measurements are taken, (2) list information that should be recorded with the measurement, and (3) specify types of equipment

[1] U.S. Environmental Protection Agency Report to Congress on Indoor Air Pollution and Radon Under Title IV Superfund Amendments and Reauthorization Act of 1986.

needed to complete the measurement process, such as a sodium iodide gamma scintillation detector to count the gamma rays emitted from a charcoal canister.

A secondary company, to successfully participate in the RMP program, is required to meet only the first and second requirements. Since secondary companies do not provide laboratory analysis, they were not tested during round 5. However, secondary companies must provide the names of all primary companies that analyze their measurement devices. These primary companies must have been successful participants in round 5 in order to be listed by a secondary company.

For round 5, EPA instructed primary companies with passive methods to submit five detectors. One detector was used for control purposes, while four detectors were exposed to known levels of radon in EPA's radon chambers either at its Eastern Environmental Radiation Facility in Montgomery, Alabama, or at its Las Vegas Facility in Nevada. EPA returned the detectors to their companies without revealing the radon levels to which they were exposed. Participating companies analyzed all detectors and reported their measurements to EPA.

EPA compared the companies' reported measurements with the EPA-documented levels of radon exposure. If the results were within the program's established measurement criterion (25 percent), the company met the proficiency requirements for the test round with that method and was listed in EPA's report of companies passing round 5 testing. Primary companies with active detectors also had to meet the 25-percent criterion, but they brought their instruments to EPA's radon chambers and measured chamber levels on-site.

RMP Program's Proficiency Test Requirements Met

We found, with only minor exceptions, that companies listed as passing the RMP program met EPA's 25-percent criterion. Specifically:

- Of 695 test score results (594 for initial tests and 101 for retests) for 358 primary testing companies, 694 were calculated correctly. The one error was only .022 and increased the company's error by a very small percentage that did not affect the company's passing status.
- All test scores for the 11 largest radon companies had been entered correctly. From our sample of 100 small primary companies, we verified that the results for all devices in 98 companies were entered correctly.

We were unable to verify the results for all devices for two of the companies because we could not locate two test results in their files.[2]

- The contractor's application of the 25-percent (.250) passing criterion was in accordance with procedures in 692 of the 695 test scores. Three devices slightly exceeded the .250 passing criterion and yet were passed and listed in EPA's round 5 performance test report. According to the contractor's project manager, the decision to round down the three test scores (.255, .251, and .251) and give the three devices passing scores was based on an EPA headquarters decision made during round 4.

Analysis of the RMP Program's Test Results

Our analysis of EPA's proficiency testing results from round 5 showed that accuracy varied both among the various types of devices and among companies using the same type of device. In the table below, the variation among devices is shown by the average error. Similarly, the variation among companies is shown by the range of company error.

Table III:1 Radon Measurement Methods for 695 Tests Performed During Round 5—Average Error and Range of Company Error

Method	Number of tests	Average error (percent)[a]	Range of company error (percent)[b]
Alpha track detectors	10	25	11–55
Activated charcoal adsorption detector	256	19	1–133
Continuous radon monitor	99	25	0–658
Continuous working level monitors	75	40[c]	0–1353[c]
Electret ion chamber	127	31	5–486
Grab sampling-radon	66	18	3–75
Grab sampling-working level	58	29	3–328
Radon progeny integrating sampling unit	4	27	1–80

[a]We computed the average error by taking the mean of all errors of the individual devices of a given type.

[b]We computed the average error for devices of a given type for each company for the test and also for the retest. The range represents the low and the high average company error.

[c]If the company whose average error was 1,353 is excluded, the average error becomes 22 percent and the range of company error becomes 0-518 percent.

[2]From the sample of small primary companies, we estimate that, at the 95-percent confidence level, the data entry errors were between 0 and 2.8 percent. This range represents the low and high estimates of the data entry error rates for small primary companies whose files included analysis reporting forms for all of their devices.

Research Relating to the Accuracy of Radon Measurements

We examined research data to determine (1) the accuracy of radon measurement devices, (2) the extent to which research supports EPA's assumptions for screening measurements, and (3) the effect of different measurement periods on radon level measurements. The following describes the studies we reviewed under each of the basic issues. Under each study, we discuss its methodology, the results, and the limitations of the conclusions. The limitations cited are methodological details that should be considered when the results are interpreted. Throughout the appendix, we use the abbreviations ATD, CC, and EIC for alpha track detectors, charcoal canisters, and electret ion chambers, respectively.

Accuracy of Radon Measurement Devices

Study 1

George, A.C., "Passive, Integrated Measurement of Indoor Radon Using Activated Carbon," Health Physics, Volume 46, Number 4, April 1984, pp. 867-872.

Methodology: Two types of activated carbon canisters were tested to determine their adsorption and retention characteristics for radon. Canisters were exposed to a constant radon concentration inside a chamber, with the level of radon in the chamber continuously monitored by a scintillation monitor. These tests were performed under various laboratory conditions of temperature (18-27 degrees Centigrade) and relative humidity (15-100%). At different intervals, six canisters were removed and sealed, and the radon level was measured 3 hours after the end of the exposure period. Exposed canisters were left open, and radon levels were measured periodically to determine the amount of radon desorption. Two tests were conducted to determine the maximum error that would be encountered with varying radon levels. The first test held the radon level constant at 26 pCi/l for 9 hours and then reduced it to 0.6 pCi/l for the next 63 hours. In the second test, the order of these exposure conditions was reversed. The mean concentration of radon measured with the canisters was compared with the known time-weighted mean concentration measured with a continuous radon monitor. Tests were also conducted in the radon chamber and in a residential building. The radon concentration in the chamber was varied deliberately by as much as a factor of 10 (from 5-55 pCi/l). In the residential building, the ambient radon concentration varied by a factor of 2. Two field tests were performed. In the first, pairs of carbon canisters were exposed in the cellars of 12 buildings in eastern Pennsylvania that had been monitored earlier with ATDs. The second field experiment was conducted in early 1982 in 35 buildings in Maryland with pairs of carbon canisters exposed for 60-70 hours in the cellar and first floor of each residence.

Results: Canisters exposed in the radon chamber for 3 days at 35 pCi/l showed a desorption rate of 50% in 36 hours when they were left open after being transferred into ordinary room air with radon concentrations of 0.2-0.3 pCi/l. When exposed to varying levels of radon, the mean concentration of canisters exposed to high followed by low radon concentrations was 60% of the known time-weighted mean. The mean concentration of canisters exposed to low and then high radon concentrations was 250% of the known time-weighted mean. On the basis of previous experience in measuring radon in residential buildings, the author estimated that in most practical situations the use of the standard calibration factors with corrections for humidity should yield results accurate within ±20%. The field experiment with carbon canister and ATD measurements in 12 cellars produced differences of less than 10% between paired canisters, and the average value indicated concentrations similar to those measured previously by the ATDs.

Limitations: Full details of the study methodology were not provided. The author noted that the conclusions were based on preliminary field data. The comparison between the carbon canister and ATD measurements for 12 cellars is hard to interpret, since the samples were taken at different times and radon levels are known to vary over time.

Study 2

George, Joan L., and G. Harold Langner, Jr., Field Study of Indoor Average Radon-Daughter Estimation Methods, GJ/TMC—26 UC—70A, Technical Measurements Center, U.S. Department of Energy, Grand Junction Projects Office, Grand Junction, CO, August 1986.

Methodology: An indoor field study was conducted in the Grand Junction, CO, area from January 1984-April 1985 to evaluate yearlong measurement methods used to estimate annual average indoor radon-daughter[1] concentrations in occupied structures. Structures were volunteered by their owners, and the selection criteria placed special emphasis on structures where data had been previously collected. The study involved 28 structures (with 44 sampling stations) and 8 devices, which included ATDs and 2 models of EICs. An evaluation criterion of 15% was

[1]The term "radon daughter" refers to any combination of the short-lived decay products of radon.

chosen as the maximum acceptable coefficient of variation, and the 2 EIC models were tested in the lab prior to field use to determine whether they could meet this criterion. The original coefficients of variation as tested in the lab for both models of EICs were 39 and 69%, respectively. After modifications, the first model's coefficient of variation was reduced to 9%. Even after fairly extensive modifications, the coefficient of variation for the second model EIC was 20% (although this was above the 15% criterion, this EIC was deemed marginally acceptable for use in the field study). The EICs were then calibrated in a radon chamber. They were exposed for 24 to 168 hours to a known radon concentration and relative humidity. The EIC calibration factor for the field study was determined by the 168-hour exposure at 35-40% relative humidity. The ATDs and unexposed controls were returned to the manufacturer "blind" (i.e., no locations were given) for calibration. The ATDs were also exposed under known conditions in the lab to test the accuracy of the manufacturer's calibration. Generally, in homes with habitable basements, one station was located in the basement and another was in a ground-floor room; otherwise, there was one station on the ground floor. Except for deviations in some stations, one or two ATDs were left for about 1 year, and at every third station one or two additional ATDs were changed every 4 months. The planned duration of each intermittent measurement with the EIC was 1 week. Measurements of less than 100 hours were considered invalid. The planned spacing from the beginning of one EIC measurement to the next was 2 months. The minimum spacing from the end of one EIC measurement to the beginning of the next was 4 weeks. Comparisons between ATD and EIC measurements and between the triannual and yearlong ATD measurements were made.

Results: The results of the calibration exposures for the EICs indicated that calibration factors increased (i.e., sensitivity decreased) with increasing relative humidity and that the calibration factors for 168-hour exposures were higher than for 24-hour exposures (at the same relative humidity). The calibration exposures of the ATDs indicated that the manufacturer's calibration factors were correct, but that the ATDs were acquiring excess background during handling. However, this background corresponded to a bias of less than 2% for a yearlong exposure at 4 pCi/l; consequently, correction was thought to be unnecessary. The coefficients of variation at 4 pCi/l were computed (based on the results of chamber exposure) as 6% for the first model EIC, 38% for the second model EIC, and 10% for the ATD. Based on duplicate field measurements, the coefficients of variation, similarly computed to the 4 pCi/l standard, were 18, 20, and 7%, respectively. ATD and EIC measurements were compared (1) over 1 year and (2) over 4 months. Paired t-tests indicated that the difference (30%) between these two devices was highly significant. This difference could have been due to the calibration of the EICs in the lab at 35-40% relative humidity, since it was found that the sensitivity of EICs depends on humidity, and the actual indoor relative humidity was probably lower (although it was never measured) than the humidity in the lab. On the basis of a paired t-test, there was good agreement between the time-weighted mean triannual (4-month) ATD results and the yearlong ATD results. On the basis of a plot of the ratios of triannual results to annual averages, it was determined that, on average, 4-month ATD exposures centered approximately around April 14 and October 13 reported the same average radon concentration as yearlong ATD exposures. To test this hypothesis, triannual exposures within 2 weeks of being centered around one of these dates were compared with annual averages. There was an 11% difference. Paired t-tests at the 0.05 level of significance could not detect a statistically significant difference between the two estimates of yearlong radon concentration. However, at the 0.10 level of significance, there was a statistically significant difference. The question could not be adequately answered because of gaps in the data near the two dates.

Limitations: The results were based on measurements from a self-selected sample of 28 structures in the Grand Junction, CO, area and, therefore, may not be representative. The EICs were modified prior to use in the field study. Comparisons between ATD and EIC results may not be valid, since the EICs were modified and calibrated under conditions that possibly differed from actual field conditions.

Study 3

George, A.C., et al., Intercomparison and Intercalibration of Passive Radon Detectors in North America, EML-442, Environmental Measurements Laboratory, New York, NY, May 1985.

Methodology: In a lab, the study compared different types of passive radon measurement devices, including ATDs (four participants) and activated carbon monitors (four participants). Each participant contributed at least four of each type of detector. The devices were exposed to two known levels of radon—one high (about 68 pCi/l) and one low (about 2-7 pCi/l). For both exposure levels, the radon, temperature, and relative humidity were monitored continuously, and the accuracy of the continuous monitors was verified with samples analyzed in pulse ionization chambers. The evaluation included quality controls. The carbon monitors were exposed for 1 to 4 days at both low and high concentrations. The ATDs were exposed for 58 days at the low concentration, except for one participant for which the exposure time was 14 days (although the recommended exposure time is 60 days). The ATDs were exposed for 7 days at the high concentration. After exposure, the devices were returned to the participating laboratories, which then reported the radon concentrations as measured by their detectors.

Results: The devices tested produced varied results. Activated carbon monitors: Reproducibility among detectors from individual participants was very good, with the mean participant result ranging from 57-94% of the known concentrations for low radon concentrations and 72-101% for high concentrations. ATDs: The reproducibility of results among detectors was mixed. The mean participant results ranged from 91-101% of the known concentrations for low concentrations and from 76-115% for high concentrations.

Limitations: The study involved a very small number of activated carbon canisters and ATDs.

Study 4

Kotrappa, P., John C. Dempsey, and John R. Hickey, Development of an Electret Passive Environmental Radon Monitor, NYSERDA-86-13, New York State Energy Research and Development Authority, Olean, NY, April 1987.

Methodology: One study objective was to develop and test an EIC that could accurately measure radon gas levels in homes. In a lab, three EIC designs were standardized and evaluated—a 1-week EIC and two varieties of EICs suitable for exposures of up to 1 year. Three test chambers were used to expose the EICs to known concentrations of radon, and the readings were analyzed.

Results: The sensitivity of the short-term EIC was adequate for measuring radon in homes over a 1-week period. Six 1-week EICs exposed to the same radon concentration at the Environmental Measurement Laboratory gave a coefficient of variation of only ±2.5%. Two groups of 12 3- to 12-month EICs exposed at the Bureau of Mines (Denver) gave a coefficient of variation of ±7-8%. The overall random error in the EIC's radon response at the present stage of development was estimated to be ±9%, as determined by analyzing and combining individual error components by the method of quadrature addition. These components and their associated error estimates were statistical counting error (small), electret thickness (±7%), electret area exposed (±2%), volume of EIC chamber (±2%), surface potential inaccuracies (less than ±2%), and calibration errors (±5%). The statistical counting error in EICs is relatively small because of the large number of alpha events which they integrate over the usual week exposure period.

Limitations: This was a demonstration/feasibility study. The study noted that more work is needed to establish a sound scientific basis for a family of accurate, field-worthy, and cost-competitive EIC home monitors.

Study 5

Martz, D.E., et al., Validation of the Diffusion-Barrier Charcoal Canister Method, UNC/GJ—47(TMC), Technical Measurements Center, U.S. Department of Energy, Grand Junction Projects Office, Grand Junction, CO, May 1989.

Methodology: The objective of the study was to determine whether diffusion-barrier CCs can be used to reliably estimate the annual average indoor radon-daughter concentration. A subset of 16 occupied homes, selected from a list of 34 structures in and around Grand Junction, CO, that had been measured extensively during previous studies, was monitored for 6 months—April to October 1988. Triplicate sets of four types of ATDs from three vendors were placed in the 16 homes for the full 6 months to establish the average radon concentration during the study period. As quality controls, eight additional ATDs from each of the four types were exposed to known radon levels in the lab, and four of each type were placed in a radon-free atmosphere for the 6-month test period. A single canister was placed adjacent to the ATDs for 1 week during each of the 26 weeks of the study, with a second canister deployed during 1 or more of the 26 weeks to provide duplicate measurements. An additional 150 canisters were exposed to known levels of radon in the lab for calibration and quality control. Also, a scintillation-chamber monitor was placed at each station for 1 week every other month to provide hourly readings. Through the use of bias correction factors and background adjustments (based on controlled exposures of ATDs in the lab and on the blank monitors), it was determined which of the 4 types of ATDs gave the most accurate estimate of the true integrated radon concentration at each of the 16 homes. These "best" measurements were used for comparison with the canister measurements. Also, a test was conducted to determine the adequacy of using 3 weekly canister samples, selected at random from the 6-month data set, to estimate the integrated 6-month radon concentration for each of the 16 homes. The data were divided into three 2-month intervals. Three readings for each station were selected randomly, one from each of the 2-month intervals, with no two readings selected within any 28-day period. Two hundred of these random choices were used from the database. The means and standard deviations were calculated.

Results: The summed canister readings for the total 26-week study period, divided by 26, provided the integrated average radon concentration for 6 months to be compared with the mean ATD measurements at each station. These integrated averages agreed well with the integrated ATD measurements and the integrated hourly measurements made by the scintillation chamber for 1-week periods. The least-squares-fitted regression lines had near-zero intercepts with slopes near unity. From a regression plot of the observed standard deviations against the associated exposure levels (based on the duplicate exposures of the canisters), the standard deviation at 4 pCi/l was calculated. The resulting coefficient of variation, adjusted to a standard radon concentration of 4 pCi/l, was 7.0% for the canisters. Similarly, an adjusted coefficient of variation at 4 pCi/l was determined for the 200 measurements randomly selected to test the adequacy of using an intermittent sampling to estimate a 6-month average. The resulting coefficient of variation was 17.8% (this includes instrument precision errors, calibration and handling errors, and errors due to the intermittency of sampling).

Limitations: The study was conducted in 16 homes in the Grand Junction area. The details of the selection of these homes were not included. The study period did not include any winter months.

Study 6

Matuszek, J.M., et al., "Standardization of Radon Measurements," Environmental International, Volume 14, Pergamon Press, 1988.

Methodology: The study objective was to evaluate, in a lab, the performance of ATD and charcoal detectors (charcoal-loaded paper bags and CCs). Four sets of three of each type of screening device were exposed at a constant radon concentration for 1, 3, 5, and 7 days. For the ATDs exposed simultaneously with the bags and canisters, the combination of radon concentrations and exposure times of 1, 3, 5, and 7 days in the lab's chamber would correspond to 30 days of exposure of each set of ATDs at 1.1, 3.8, 6.3, and 8.8 pCi/l, respectively. The charcoal bags and canisters were also tested for desorption by selecting one detector from each set of three and following the chamber exposure with exposure to radon-free tank air. The 1- and 3-day exposure detectors underwent 4 days of desorption, and the 5- and 7-day exposure detectors underwent 1 day of desorption. Following exposure, the charcoal bags and canisters and the ATDs were sent to company laboratories for counting and measurement.

Results: The three systems tested would provide equally poor results when used for screening measurements at radon concentrations up to tenfold greater than regulatory guidelines—the charcoal bags and canisters because of inherent sensitivity to fluctuations in radon concentrations, and the ATDs because of inherently poor detection efficiency and processing inconsistencies. Charcoal bags and canisters: The test for desorption showed that charcoal bags lost radon about as rapidly as they adsorbed it. After 1 day of desorption only 20% of the adsorbed radon remained, and after 4 days of desorption the retained fraction was 7-10% of that originally adsorbed. The CCs were not as greatly affected by desorption. After 1 day of desorption about 90% of the adsorbed radon remained, and after 4 days about 75% remained. The large number of false negative values expected due to desorption makes measurements using charcoal detectors unsuitable as the only measurement performed in a house. ATDs: The level of accuracy with ATD measurement was poor, and the bias appeared to vary in sign from day to day. The mean value for each set fell outside EPA's control limits requiring agreement to within ±25% of the reference value (only 2 of 12 were within 25%). Sets of ATDs exposed for 3, 5, and 7 days each averaged low by a factor of 2 or more. The mean value of each set (3-, 5-, and 7-day exposures) were 60, 42, and 44% of the known concentration, respectively. The precision of ATDs appeared to be inconsistent from detector to detector as well as from batch to batch.

Limitations: This was a preliminary study, and conclusions were based on only a few devices of each type.

Study 7

Michaels, L.D., A.S. Viner, and T. Brennan, "A Comparison of Laboratory and Field Measurements of Radon," Proceedings of the Technical Exchange Meeting on Passive Radon Monitoring, CONF-8709187, Technical Measurements Center, U.S. Department of Energy, Grand Junction Projects Office, Grand Junction, CO, September 1987, Section B.

Methodology: The radon concentration in the basements of 10 homes in Clinton, NJ, was measured over 5.5 days with continuous radon monitors during the spring of 1986. Diurnal variations of over 1 or 2 orders of magnitude were commonly seen. A chamber experiment with standard open-faced EPA charcoal type canisters was conducted to simulate these variations for exposures ranging from 24-96 hours. The radon concentration, temperature, and relative humidity were held constant in the chamber. Some canisters were continuously exposed in the chamber, and others were moved from the chamber to an adjoining room (where the radon concentration was monitored with a continuous radon monitor) in 12-hour cycles. The ratios of measured concentration to average continuous monitor results were calculated.

Results: Canisters exposed to varying levels of radon greatly underestimated the radon concentration for exposure times greater than about 48 hours. The canister results for the varying concentrations ranged from 40-105% of the average continuous monitor results. Canisters exposed to constant radon concentrations performed within EPA guidelines (± 25%) for all but the longest sampling period. The canister results ranged from 75-125% of the average continuous monitor results for constant concentrations.

Limitations: The field study was based on 10 homes in Clinton, NJ. Full methodological details of the laboratory study were not included.

Study 8

Office of Radiation Programs, "Operational Evaluation of Electret Passive Environmental Radon Monitor (E-PERM)," U.S. EPA, Las Vegas Facility, September 1987.

Methodology: The study evaluated two different EICs: A short-term EIC with a range of 200 pCi/l-days and a long-term EIC with a range of 2,000 pCi/l-days. The radon concentration in the chamber varied from 3.6-102.1 pCi/l. Two calibrated radon gas monitors sampled the radon concentration hourly.

Results: The EICs were subjected to various relative humidity (25-60%) and temperature (40-96 degrees Fahrenheit) with no noticeable effect on sensitivity or accuracy. The average coefficient of variation for short-term EICs was 4.9%, with a range of 1.6-10.8%. The average coefficient of variation for long-term EICs was 11.1%, with a range of 5.5-15.5%. The average percent difference between the EIC measurement and that of the radon gas monitor was 6.3% for short-term EICs and 8.5% for long-term EICs. A two-tailed t-test with a 95% confidence level was used to determine whether the EICs (both short- and long-term) and the radon gas monitor produced equivalent results. In the five short-term exposures examined and in two of the three long-term exposures, no statistical difference was detected between the radon gas monitor and EIC results at the 95% confidence level.

Limitations: The study was a controlled lab experiment, and the devices underwent modifications during the course of the study. Some evidence was noted that the EICs may make "low biased" measurements, but the study did not produce enough results to confirm this as a definite trend.

Study 9

Pearson, Mark D., "A Comparison of Four Types of Alpha-Track Radon Monitors," Proceedings of the Technical Exchange Meeting on Passive Radon Monitoring, CONF-8709187, Technical Measurements Center, U.S. Department of Energy, Grand Junction Projects Office, Grand Junction, CO, September 1987, Section L.

Methodology: A test series—24 exposures of 4 brands of ATDs in a radon chamber—was designed to evaluate the sensitivity of the devices to environmental parameters, including nonuniform radon concentrations. The ATDs were exposed in groups of six to eight to radon concentrations of about 40 pCi/l for 3 days. The integrated exposures ranged from 99-165 pCi-d/l, with one low concentration test at 26 pCi-d/l. The study design included the use of unexposed controls. The concentration in the chamber was measured by a continuous radon monitor. The uncertainty in the average concentration was ±3%. The reported radon concentrations were the net radon concentrations, which were determined by subtracting the integrated exposures of the unexposed controls from the exposed monitors and then dividing the results by the length of time in the chamber. The frequency distribution and theoretical coefficient of variation for an absolutely perfect set of ATDs would depend only on the Poisson statistics associated with the purely random distribution of tracks on the detectors. This theoretical coefficient of variation was estimated and compared with the observed coefficient of variation for the study's detectors.

Results: The results from all exposure groups ranged from 67-132% of the known concentrations. The difference between observed and expected coefficients of variation ranged from 0-44%. The study concluded that although the alpha track monitor occasionally performed to theoretical expectations, it more often showed much greater variation in response than could be attributed solely to Poisson counting statistics.

Limitations: The study involved only four types of ATDs, and the conclusions were related to the study's exposure protocol.

Study 10

Pearson, Mark D., Evaluation of the Performance Characteristics of Radon and Radon-Daughter Concentration Measurement Devices Under Controlled Environmental Conditions, UNC/GJ—44(TMC), Technical Measurements Center, U.S. Department of Energy, Grand Junction Projects Office, Grand Junction, CO, April 1989.

Methodology: The study was designed to evaluate (in a laboratory) the response of radon monitors to environmental parameters. EICs, CCs, and four models of ATDs were among the devices tested. Pretest operational checks were performed, and some devices and exposure designs were modified. The EICs underwent fairly extensive mechanical modifications. It was determined that the ATDs would be placed in a relatively low-radon environment for approximately 12 hours after being removed from a radon chamber to allow radon to diffuse out of the plastic cup and that one manufacturer's ATDs would be stored in an atmosphere of aged air in a pressure cooker to minimize the accumulation of background tracks. Although most tests were planned so that only a single environmental parameter varied, several times throughout the program devices were operated in a standard set of environmental conditions. The standard radon concentration was about 40 pCi/l, except for two tests at low concentrations and three tests that involved varying the radon concentrations. The EICs were placed in groups of 3 or 4 in all 24 tests, and a mean response was calculated for each test. The canisters were placed in groups of 5 for 20 tests. Typically, 6 ATDs of each type were exposed for all 24 tests, and 2 ATDs of each type were returned for analysis unexposed. For each ATD, the results were analyzed in the form of net radon concentration, calculated as the concentration reported by the manufacturer minus a background radon concentration (the overall average of the unexposed ATDs).

Results: EICs: The EICs responded linearly to radon concentration. A correlation coefficient of 0.95 was calculated from a plot of mean EIC response against radon concentration. The EICs also accurately measured radon in tests with varying concentration. For the three tests with varying radon concentrations included in the analysis, a correlation coefficient of 0.96 was calculated. The average coefficient of variation for the EICs was 10.2%. CCs: No conclusions could be reached concerning the linearity of the canisters, since they were not exposed to a wide range of radon concentrations for equivalent lengths of time. The canisters without diffusion barriers did not appear to accurately report radon levels when exposed to strictly increasing or decreasing concentrations. In tests under conditions of increasing radon concentration, the canisters overestimated the actual radon level by almost 40%. Under conditions of decreasing radon levels, the canisters underestimated the known levels by 30%. The canisters seemed to accurately report the radon concentration for a test during which the radon levels cycled upward and downward, but this could not be rigorously proven with statistical methods because of insufficient data. The average coefficient of variation for the canisters was 11.7%. ATDS: The coefficients of variation, calculated as the average coefficient of variation of the exposures of each group of six ATDS, ranged from 13-69% for the different models of ATDS examined. The 3-5% uncertainty in the actual radon concentration in the chamber made an insignificant contribution to this observed variability; consequently, the uncertainty could be attributed entirely to the variability in the ATDS. The net radon concentration reported by the manufacturer ranged from 72-137% of the known radon levels. For one model of ATD, the response to varying radon levels was difficult to determine because of the large variability of responses. For two other models, there was no statistically significant difference (based on t-tests at the 95% confidence level) in response among ATDS exposed to varying levels of radon and those exposed to uniform concentrations. For the fourth ATD model, the results of t-tests were inconclusive.

Limitations: The EICS underwent extensive modifications prior to the study. It was not possible to adequately answer all of the study questions concerning CCS because of insufficient data.

Study 11

Rector, Harry, and William Schoenborn, "Operational Experiences in Statewide Radon Surveys," Proceedings of the Technical Exchange Meeting on Passive Radon Monitoring, CONF-8709187, Technical Measurements Center, U.S. Department of Energy, Grand Junction Projects Office, Grand Junction, CO, September 1987, Section G.

Methodology: A study of radon concentrations in 6,500 homes in Florida was conducted to identify areas where the state's environmental radiation rule should be applied. Two parallel surveys were conducted: a land-based survey (keyed to inhabited land areas in each county) and a population-based survey (scaled to the number of housing units in each county). Both surveys were restricted to houses with slab-on-grade foundations. The land-based survey was conducted by technicians who placed CCs in the homes for 72-hour exposures. In 10% of the homes, technicians placed ATDs for 30-day exposures. In the population-based survey, CCs were mailed to the homeowners for placement. In both surveys, the detectors were returned by the homeowners for analysis, with a 97.4% return rate of CCs for the land-based survey and a 82.4% return rate for the population-based survey. Quality control for the study included participation in EPA's RMP program for both the canister and ATD companies.

Results: The accuracy and precision of the canisters and ATDs, as measured in the RMP program, were near 5 and 10%, respectively. The precision of canisters exposed side-by-side in homes with radon levels greater than 2 pCi/l averaged ±5% for the land-based survey and ±8% for the population-based survey. The precision of the ATDs in the field was poor, averaging near ±40%. CCs were located beside ATDs in 232 homes in the study, with a correlation of 0.7 between the two sets of test results (average canister measurement of 0.76 pCi/l and average ATD measurement of 0.95 pCi/l).

Limitations: Participation in both surveys was restricted to Florida residences with slab-on-grade foundations. CCs in the population-based survey were placed by the homeowner, whereas all other devices in both surveys were placed by technicians, a difference that may have affected the radon measurements. All study results were based on devices returned by the homeowner; nothing is known about the devices not returned. The poor field performance of the ATDs was attributed to the relatively low radon concentrations measured and the short exposure period.

Study 12

Ronca-Battista, M., and D. Gray, "The Influence of Changing Exposure Conditions on Measurements of Radon Concentrations With the Charcoal Adsorption Technique," Proceedings of the Technical Exchange Meeting on Passive Radon Monitoring, CONF-8709187, Technical Measurements Center, U.S. Department of Energy, Grand Junction Projects Office, Grand Junction, CO, September 1987, Section E.

Methodology: A study of the activated carbon adsorber included tests to determine the effects of desorption and the effect of exposure to two radon concentrations. To test for desorption, four canisters were exposed to high radon levels—first to 100 pCi/l for 72 hours and then to 10 pCi/l for 3 days, during which they were periodically analyzed (the daily change in efficiency of the analysis system varied less than 3%).

This test was repeated twice, once with a relative humidity of 20-25% and a second time with a relative humidity of about 50%. To study the effects of varying concentrations, duplicate sets of canisters were exposed to two radon concentrations, with total exposure times of 48 and 96 hours (with half of the exposure period at one radon concentration and the other half of the period at the other radon concentration). The ratios of the two radon concentrations ranged from 2:1 to 10:1, as well as the reverse. The radon concentration in the chamber ranged from 10-100 pCi/l.

Results: In a 20-50% relative humidity environment with radon levels decreasing by a factor of 10, only about half of the radon initially in the carbon bed remained after approximately 20-25 hours in the low concentration. The larger the decrease in radon concentration was, the faster the rate of desorption. In the tests with varying radon concentrations, the differences between the canister result and the average radon concentration ranged from -75 to +64% (for the 10:1 concentration ratio and the 1:10 concentration ratio, respectively, both with 96 total hours of exposure). The differences between the canister results and the average radon concentrations were smaller for total exposure times of 48 hours than for those of 96 hours at the same radon concentration ratio. The result of canister analysis was greater than the average radon concentration when the carbon was exposed to higher concentrations in the latter part of the exposure and less when exposed to lower concentrations in the latter part of the exposure.

Limitations: This was a draft version, and the results were based on a relatively small number of devices.

Study 13

Savage, E.D., Evaluation of Track-Etch Detectors, EPA 520/5-83-020, Eastern Environmental Radiation Facility, Montgomery, AL, Report for Office of Radiation Programs, EPA, Washington, DC, September 1983.

Methodology: The study objective was to evaluate the precision and accuracy of ATDs in a laboratory. Four configurations of the ATDs--filter cup, membrane cup, open cup, and bare badge—were exposed to known concentrations of radon in a radon chamber for various exposure regimes and then sent to the company for processing and readout. The study's protocol required two series of exposures at high concentrations, each series consisting of one run for 10 days at 100 pCi/l, one run for 20 days at 50 pCi/l, and one run for 40 days at 25 pCi/l. The study design focused on the monitors' reliability (the extent to which different detectors from the same production lot yield similar results when exposed together), lot-to-lot variability (differences in detector response between two production lots), and linearity of response (consistency of detector response over a range of total exposures). As a quality control measure, detectors exposed together during the first exposure series were divided into two groups, each submitted for processing and readout at a different time. Approximately 6 months separated the processing of the two groups.

Results: Groups of detectors exposed and processed together had similar responses. Groups exposed and processed at different times did not always agree with each other or with the company's published calibration numbers. The calibration factor is given with an error term equal to one standard deviation. The variation in calibration factors for the first series of runs ranged from a relative standard deviation of 6.9-31.2%. The variation in the second series of runs was higher, ranging from 9.7-34.1%. Comparing the calibration factors for the first series with those of the second series shows that the first series was higher in five of eight cases—ranging from 2-57%. In the remaining three cases, the first series' averages were lower—ranging from 20-38%. Twenty detectors exposed together during the first run were divided into two groups and processed 6 months apart. The calibration factor for the first group was 0.0359 ± 0.0016, and the calibration factor for the second group was 0.0224 ± 0.0057—a decrease of about 38%. The author noted that the study results were similar to results previously reported by the manufacturer in that results within a run were very consistent, but results between runs were not.

Limitations: The study involved only one company's ATDs, and the results may be relevant only to exposures at high radon concentrations, as in the study's protocol.

Study 14

Sextro, Richard G., and Daniel D. Lee, "The Performance of Charcoal-Based Radon Detection Under Time-Varying Radon Conditions: Experimental and Theoretical Results," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 2—Symposium Poster Papers, EPA-600/9-89-006b, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 2-81 to 2-91.

Methodology: The purpose of the study was to develop a model for predicting the response of various types of charcoal-based detectors to time-variant radon concentrations. As part of the model-building effort, experiments were conducted to compare CC readings with radon levels measured with continuous radon monitoring instrumentation. Two examples of each of the two basic types of charcoal sampler (open-face-type devices and devices with a diffusion barrier) were used. Several canisters (ranging from two to six) of each type were placed in the two rooms of the chamber. One room had a high radon concentration (ranging from 50-250 pCi/l), and the other room had a low radon concentration (ranging from 5-50 pCi/l). The 4-day experiment was divided into four approximately equal exposure periods. At the end of each period, some of the canisters were switched from one room to the other to vary the radon level of exposure. Also tested was the effect of varying exposure times.

Results: The open-face devices had a pronounced response to the changing radon concentrations to which they were exposed. For diffusion-limited samplers, the response was attenuated considerably. For open-face canisters, the results ranged from 10-105% of the actual integrated average concentrations based on the continuous data. The largest variations were found when the radon concentration changed from high to low because of desorption. The responses of the diffusion-limited devices ranged from 77-115% of the integrated average concentration. The authors concluded that charcoal-based detectors are heavily influenced by the most recent exposure conditions; therefore, results of readings over short periods of time when the actual radon concentration is changing could either under- or overpredict actual concentrations.

Limitations: The study results were based on only two examples of each of two basic types of charcoal canisters, with readings taken from two to six canisters of each type.

Study 15

White, S.B., et al., "Performance of Methods for Measuring Radon and Radon Decay Products," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 1—Symposium Oral Papers, EPA-600/9-89-006a, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 4-41 to 4-53.

Methodology: The purpose of the study was to characterize relative bias, measurement error, and precision for seven measurement methods—including ATDS, CCS, and EICS—by using data from both laboratory and field studies in 1987 and 1988. The data were generated in the RMP program (to measure relative bias and relative measurement error) and the state indoor radon surveys (to measure precision). The RMP program exposes detectors to a known concentration in a federal radon chamber, requiring a sample of five passive devices (one to be used as a control) and four active devices. The state indoor radon surveys were conducted in 17 states using CCs for a 48-hour exposure period. Duplicate measurements from a subset of sample households were used to estimate the relative precision. Relative bias was calculated as the average of the percent errors of the measurements in relation to the true radon concentration, relative measurement error was the standard deviation of the percent errors, and relative precision was the coefficient of variation.

Results: The overall (based on medians) relative bias for each method was under 10% (ignoring sign) with two exceptions: the 1987 CC method median bias was +17%, and the 1988 EIC method median bias was +22%. For most methods, 30-60% of the companies had bias estimates of less than 10% (ignoring sign). On the other hand, for most methods at least 10% of the companies had bias estimates greater than 30% (ignoring sign), and for some methods this percentage was much higher (for 1988 EICs, approximately one-third of the tested companies had an estimate of absolute bias greater than 30%). The median relative measurement error was 13% or less for most methods. All three methods showed 8% or more of the companies with relative measurement errors greater than 30% in 1988. The coefficients of variation (of the canisters used in the state surveys) were mostly less than 15%. However, they were slightly higher and less stable at low concentrations.

Limitations: The RMP program's 1987 testing included both primary companies (those with analysis capability) and secondary companies (those without analysis capability). The 1988 testing included only primary companies.

Comparison of Basement and Upper-Floor Measurements

Study 16

Dudney, C.S., and A. R. Hawthorne, "Seasonal and Annual Average Radon Levels in 70 Houses," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 1—Symposium Oral

Papers, EPA-600/9-89-006a, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 3-75 to 3-88.

Methodology: A yearlong indoor air study of 70 homes in 4 states (7 cities in Alabama, Georgia, Mississippi, and Tennessee), all with partial or complete basements, was conducted from 1985-87. Study houses constituted a self-selected sample—residents volunteered, and those satisfying study requirements (e.g., block wall construction in lowest level, at least one higher level, and multiple visits by study staff) were chosen. At the beginning of the study, a pair of ATDs was placed both on the main floor and in the basement of each home. One ATD on each level was left in place for a year. The other ATD on each floor was retrieved after 3 months and replaced by a new detector for the next quarter. The study compared (1) seasonal and annual averages, (2) summer and winter averages, and (3) short- and long-term measurements.

Results: Basement results were consistently higher, with the basement overestimating the main floor concentration in all seven cities by a factor ranging from 1.1 to 1.7. The difference between the basement and main floor was not as great as the difference between the seven cities in the study. Another striking pattern in the study results was the absence of markedly elevated winter radon levels in many of the cities.

Limitations: The study sample was self-selected and, therefore, may not be representative. All of the study sites were in the southeast United States, where winters are relatively mild.

Study 17

George, A.C., "Passive, Integrated Measurement of Indoor Radon Using Activated Carbon," Health Physics, Volume 46, Number 4, April 1984, pp. 867-872.

Methodology: See study 1.

Results: The field experiment involving canister measurements on different floors in 35 Maryland homes indicated that the average radon concentration in cellars was 250% greater than the average first-floor concentration.

Limitations: Full details of the methodology were not provided. The author noted that the conclusions were based on preliminary field data.

Study 18

George, Andreas C., and Lawrence E. Hinchliffe, "Measurements of Radon Concentrations in Residential Buildings in the Eastern United States," Radon and Its Decay Products: Occurrences, Properties, and Health Effects, American Chemical Society Symposium No. 331, April 1986, pp. 42-62.

Methodology: The purpose of the study was to test the feasibility of using a modified activated carbon device to measure radon levels. Radon concentrations in 380 buildings were measured with the latest version of the passive activated carbon device developed at the Environmental Measurements Laboratory. The buildings were located in six states in the eastern United States. Building characteristics were determined from a questionnaire returned by the occupant. Most of the buildings were single-family residences with full basements, with the exception of several plant buildings. In the residential buildings, one detector was placed in an area of the home where the occupants were likely to spend most of their time (living area), and a second detector was placed in the basement if there was one. The detectors were exposed for four days during the winter (October to April) and the summer (May to September). Homeowners returned the detectors to the lab for analysis. More than 90% of the devices were analyzed successfully. Most of the unsuccessful measurements were due to delays or losses caused by the participants. An estimation of the annual mean radon concentration was determined in each building, based on the winter and summer exposures. Results were grouped by nine locations in the six states, with the number of residential buildings at each location ranging from 20 to 52.

Results: Based on the winter exposures, the mean basement measurements ranged from 1.6-3.4 times the mean living area measurements. During the summer exposures, the mean basement concentrations ranged from 2.7-5.3 times those of the living areas. Analysis of the data with the Mann-Whitney nonparametric test concluded that there were significant differences (at the 95% confidence level) between radon concentrations in the living areas and basements for all locations and both seasons.

Limitations: Details of the building selection were not included. All study results were based on devices returned by the homeowners; nothing is known about the devices not returned. There were no details of the exposure protocol for the plants in which radon concentrations were measured. For one of the nine locations, the results included data from plant buildings as well as residential buildings. For this location, no results were given for residential basement exposures during the summer season. The number of residences at each of the nine locations was relatively small.

Study 19

Granlund, Carl, and Michelle Kaufman, "Comparison of Three Month Screening Measurements With Yearlong Measurements Using Track Etch Detectors in the Reading Prong," Proceedings of the Technical Exchange Meeting on Passive Radon Monitoring, CONF-8709187, U.S. Department of Energy, Technical Measurements Center, Grand Junction, CO, September 1987, Section M.

Methodology: Of the roughly 18,000 radon screening measurements made in the Reading Prong radon screening program, yearlong follow-up measurements were made in a sizable fraction of those homes with screening levels above 4 pCi/l. The purposes of the study included evaluation of (1) the relationship between yearlong follow-up measurements in living areas and basement screening measurements using ATDs and (2) the use of a 3-month basement screening measurement to estimate a yearlong first-floor average. Free radon detectors were mailed to every house in the Reading Prong area in October 1985. Homeowners were instructed to place the ATD in the lowest possible living space in the house, including the basement if the house had one. The ATDs were exposed for at least 3 months. If the result of the screening was greater than 4 pCi/l, another detector was mailed to the homeowner to be exposed for a period of 1 year in an area where the family spent the majority of its time. The majority of the screening measurements were begun in November 1985. The median exposure time for the screening measurement was 88 days, and the median exposure time for the annual measurement was 365 days.

Results: In 728 participant homes, the average 3-month wintertime basement screening measurement overestimated the first-floor annual average concentration by a factor of 3. No remediation was taken between the measurements.

Limitations: The sample was drawn totally from the Reading Prong screening program participants and was largely self-selected. All Reading Prong residents were mailed free ATDs from one manufacturer. Residents who returned these devices and whose readings were greater than 4 pCi/l were mailed additional free ATDs from the same company for a subsequent round of measurement. The study results were based on ATDs returned in both measurement rounds.

Study 20

Ranney, Colleen, et al., "Seasonal Variability and Bilevel Distribution of Radon and Radon Progeny Concentrations in 200 New Jersey Homes," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 1—Symposium Oral Papers, EPA-600/9-89-006a, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 3-59 to 3-73.

Methodology: To provide data necessary to assess the health risks of the radon problem in New Jersey, concurrent radon and radon-daughter measurements were made in 200 homes on the 2 lowest levels in 2 different seasons. Because indoor radon levels tend to vary depending on season and house characteristics, homes were divided into categories based on their substructure, heat distribution system, and the degree of air flow between the basement and the first floor. The level I sampling in fall 1986 consisted of a sample of over 6,000 residences and approximately 170 institutional facilities throughout the state. The level II sampling was designed to translate the 6,000 lowest-level radon screening results from the level I sampling into annual average working levels of radon decay products (progeny) for all levels of a house. The level II sampling focused on houses having a level I measurement of at least 8 pCi/l, housing types representative of the New Jersey housing stock (especially in relation to substructure and heat distribution type), houses that had not instituted remediation, and homes with a geographic sampling distribution similar to that of the level I sampling. The level II sampling was initiated in fall 1987 on a subset of 200 homes previously included in the level I sampling. Sampling devices mailed to participants included a 4-day CC and a radon progeny integrated sampling unit. The two measurement seasons were from September 30, 1987, to March 13, 1988, and from January 13, 1988, to July 16, 1988. Most of the participant houses were located in the three N. J. provinces with high radon levels—Highlands, Valley and Ridge, and Southern Piedmont. Equilibrium coefficients were calculated and compared:

Equilibrium coefficient = 100(annual average working level)/radon

The "annual average working level" refers to measurements of the short-lived decay products of radon for each of the two measurement seasons. "Radon" refers to the actual radon concentrations measured by the CCs.

Results: For houses with basements, the radon levels for the basement overestimated those of the first floor by a factor ranging from about 2 to 3.

Limitations: The study results were related to areas of New Jersey with previous measurements of at least 8 pCi/l and housing stock representative of New Jersey. Participants were concentrated in three N.J. provinces with high radon levels.

Study 21

Steck, D.J., "Statewide Radon Surveys: Screening vs Long-Term Measurements," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 2—Symposium Poster Papers, EPA-600/9-89-006b, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 1-67 to 1-80.

Methodology: The study objective was to compare EPA screening survey results with a survey of long-term average radon concentrations in Minnesota and Wisconsin. Two EPA-designed screenings were used. The Wisconsin Department of Health and Social Services surveyed 1,191 houses during the 1986-87 heating season, and the Minnesota Department of Health surveyed 1,001 houses during the 1987-88 heating season. In both screening surveys, radon concentrations were measured in the lowest level of the house by CCS left in place for 2 days. Houses were selected randomly within regions, with the number of houses sampled in each region weighted by population and/or geological factors. The long-term survey was conducted from 1983-87 in the 2 lowest levels of each of 250 houses (215 in Minnesota, 25 in Northern Wisconsin, and 10 in the Upper Peninsula of Michigan). ATDs were left in place for 8-12 months (houses monitored less than 12 months were monitored during the heating season—October to June—and radon concentrations were adjusted for seasonal variation). Nearly 100 houses were measured separately in winter and summer. The yearly average radon concentration in the living spaces was calculated from the individual measurements as either the average of all above-grade-level concentrations, or, if the below-grade level was used as a living space, 80% of the above-grade concentrations and 20% of the below-grade concentrations. To compare the 2 measurement protocols (screening and long-term), a "combined" survey of 74 homes was conducted in Minnesota from late March to early April 1988. Along with a canister and an ATD, a continuous radon monitor was used to examine the effects of daily variations during a short-term sampling period. Statistical analysis suggested that the "combined" survey was representative of both the screening and the long-term Minnesota surveys, and so further analysis was based on the "combined" survey.

Results: The median of the screening results was only 20% higher than that of the long-term survey, and the average values were almost the same. This finding contradicted the assumption that a closed-house, winter measurement in the lowest level of the house is a "worst case." In the "combined" survey, the screening measurement failed to detect 20% of the houses with radon concentrations in excess of 4 pCi/l (false negatives) and produced a false positive result for 30% of the houses whose radon concentration was below 4 pCi/l.

Limitations: All sampled houses were from Minnesota, Wisconsin, and Michigan. Different segments of the study were based on subsets of the state surveys. Details of the selection of some subsets were not provided.

Comparision of Summer and Winter Measurements

Study 22

Dudney, C.S., and A.R. Hawthorne, "Seasonal and Annual Average Radon Levels in 70 Houses," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 1—Symposium Oral Papers, EPA-600/9-89-006a, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 3-75 to 3-88.

Methodology: See study 16.

Results: Over the seven cities, the average winter measurements ranged from 67-350% of the summer measurements in the basement and the living areas.

Limitations: The study sample was self-selected and, therefore, may not be representative. All of the study sites were in the southeastern United States, where winters are relatively mild.

Study 23

George, Andreas C., and Lawrence E. Hinchliffe, "Measurements of Radon Concentrations in Residential Buildings in the Eastern United States," Radon and Its Decay Products: Occurrences, Properties, and

Health Effects, American Chemical Society Symposium No. 331, April 1986, pp. 42-62.

Methodology: See study 18.

Results: Based on the exposures in the living areas, the mean winter measurements ranged from 164-500% of the mean summer measurements. For the basement exposures, the mean winter measurements ranged from 97-195% of the mean summer measurements. The Mann-Whitney nonparametric test showed that most living area radon concentrations were statistically different from winter to summer, while the test failed to show a statistical difference between most basement concentrations at the 95% confidence level.

Limitations: Details of the building selection were not included. All study results were based on devices returned by the homeowners; nothing is known about the devices not returned. There were no details of the exposure protocol for the plants in which radon concentrations were measured. For one of the nine locations, the results included data from plant buildings as well as residential buildings. For this location, no results were given for residential basement exposures during the summer season. The number of residences at each of the nine locations was relatively small.

Study 24

Hess, C.T., R.L. Fleischer, and L.G. Turner, "Field and Laboratory Tests of Etched Track Detectors for 222Rn: Summer-vs-Winter Variations and Tightness Effects in Maine Houses," Health Physics, Volume 49, Number 1, July 1985, pp. 65-79.

Methodology: The study examined the effects of homes being airtight on indoor radon concentrations in 70 homes in Maine. A group of houses was selected—details of the selection were not described—from nearly 1,000 houses that had been tested for radon in water during 1972-78. Because radon concentrations vary hourly, daily, and seasonally, the study defined specific measurement periods. In the first measurement period from October 1980 to May 1981 (fall and winter exposures), ATDS were provided by EPA. The detectors were placed five to a house—in the kitchen or living room, bedroom, bathroom, and basement and outside in a protected area. A second group of ATDs was installed in spring 1981, continuing the same measurements for those still participating. At the same time, a different type of ATD (with filtered cups) was installed at the same locations. These two types of ATDs produced spring and summer exposures. Ratios of winter to summer measurements were analyzed.

Results: The winter 1981-82 measurements ranged from 45-780% of the summer 1981 measurements, with an arithmetic mean of 200% ±140%. The mean winter 1980-81 measurement was 160% ± 130% of the mean summer 1981 measurement.

Limitations: The study sample was small, and selection details were not included. All of the participants were in Maine.

Study 25

Mose, Douglas G., George W. Mushrush, and Stephen Kline, "Realistic Uncertainties for Charcoal and Alpha-Track Radon Monitors," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 1—Symposium Oral Papers, EPA-600/9-89-006a, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 4-25 to 4-39.

Methodology: The study objective was to compare charcoal and ATD measurements, particularly the length of time required to get an estimate of annual radon concentration. (See study 30 for results comparing annual estimates with short-term exposures.) It was assumed that the two devices were equally accurate and unbiased so that the pattern of deviation of a single measurement from annual measurements was considered to be due to natural variations in radon concentrations. Also, it was assumed that the annual radon concentration could be adequately estimated by averaging a series of four ATD measurements, each over 3 months. The study was conducted predominately in Fairfax County, VA, and Montgomery County, MD, between 1986 and 1988. The participants constituted a self-selected sample. Participation required purchasing four ATDs and completing a series of questionnaires; the purchase of CCs was optional. Monitors were to be placed in the basement level if the house had one (about 90% of the homes had basements). A single charcoal measurement and an estimate of the annual radon concentration using the average of four seasonal ATD measurements were done at 152 homes. A charcoal measurement and an ATD measurement were done during the same season at 329 homes (winter was Nov.-Jan., spring was Feb.-April, summer was May-June, and fall was Aug.-Oct.). The charcoal measurements were from each month, though most of the available measurements were from the summer interval (homeowners were instructed to use closed-home conditions). The entire sequence of four 3-month ATD measurements was done in 828 homes.

Results: Winter ATD measurements tended to be greater than the annual concentration, summer measurements tended to be less, and spring and fall ATD measurements were less biased toward higher or lower measurements. The median radon reading from a single, seasonal ATD expressed as a percentage of the annual average of four 3-month ATDs was 112% for winter, 98% for spring, 83% for summer, and 104% for fall.

Limitations: The study sample was self-selected and, therefore, may not be representative. The sampled houses were predominately from Fairfax County, VA, and Montgomery County, MD.

Study 26

Ranney, Colleen, et al., "Seasonal Variability and Bilevel Distribution of Radon and Radon Progeny Concentrations in 200 New Jersey Homes," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 1—Symposium Oral Papers, EPA-600/9-89-006a, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 3-59 to 3-73.

Methodology: See study 20.

Results: For basement houses, the interfloor radon ratio was consistently higher in winter than in other seasons. The winter measurements ranged from 103-333% of the nonwinter measurements.

Limitations: The study results were related to areas of New Jersey with previous measurements of at least 8 pCi/l and housing stock representative of New Jersey. Participants were concentrated in three N.J. provinces with high radon levels.

Effect of Different Measurement Periods

Study 27

Dudney, C.S., and A.R. Hawthorne, "Seasonal and Annual Average Radon Levels in 70 Houses," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 1—Symposium Oral

Papers, EPA-600/9-89-006a, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 3-75 to 3-88.

Methodology: See study 16.

Results: For ATDs, the time-weighted averages of four measured seasonal (3-month) average radon levels ranged from less than 40% to more than 200% of the measured annual average level, with typical results being 125% of the measured annual average level.

Limitations: The study sample was self-selected and, therefore, may not be representative. All of the study sites were in the southeastern United States, where winters are relatively mild.

Study 28

George, Joan L., and G. H. Langner, Validation of the Prompt Alpha Track Method, UNC/GJ—33 (TMC) (DOE/ID/12584—6), U.S. Department of Energy, Technical Measurements Center, Grand Junction, CO, August 1987.

Methodology: Because indoor concentrations of radon vary over the period of a year, the study evaluated the reliability of using short-term exposures of ATDs to estimate annual average radon-daughter concentrations in structures in Grand Junction, CO. The study was conducted from July 1985-July 1986. ATDs were exposed at 50 stations in 34 structures where previous annual average radon and/or radon-daughter concentration data were collected. Two sets of data were collected, each consisting of 2-, 3-, 4-, 5-, and 6-month-long exposures of the ATDs. October 2 was selected as the midpoint of the fall set, and April 2 as the midpoint of the spring set. Two ATDs were placed at each station for each short-term exposure. Three additional annual ATDs were placed at each station for the 6-month fall exposure. ATDs were also placed at each station for the 2- and 3-month spring exposures. Exposed and unexposed controls were submitted with each group of field detectors processed. At the end of the exposure period, the appropriate ATDs were retrieved and submitted to the manufacturer for processing. All the detectors were submitted "blind"; that is, no location numbers were provided.

Results: All results were based on the use of October 2 and April 2 as the midpoints of the fall and spring exposures, respectively. The authors concluded that short-term ATD measurements can reliably estimate the average indoor radon concentration in structures in the Grand Junction, CO, area. The coefficient of variation for the ATD estimation of annual average radon concentration using the 2- to 6-month exposures was less than 25% at 4 pCi/l. Paired t-tests at the 0.01 level of significance could not detect a statistically significant difference between a short-term measurement and an annual measurement for most short-term exposures. The authors noted that more than 10 control detectors were required to normalize results for variations due to the processing of ATDs, a requirement that might be cost prohibitive for many programs. Six to ten control ATDs should be included with each group of field ATDs submitted for processing to monitor the results reported by the vendor.

Limitations: The study results applied only in the Grand Junction, CO, area.

Study 29

Granlund, Carl, and Michelle Kaufman, "Comparison of Three Month Screening Measurements with Yearlong Measurements Using Track Etch Detectors in the Reading Prong," Proceedings of the Technical Exchange Meeting on Passive Radon Monitoring, CONF-8709187, U.S. Department of Energy, Technical Measurements Center, Grand Junction, CO, September 1987, Section M.

Methodology: See study 19.

Results: The 3-month wintertime basement measurement with an ATD overestimated the yearlong basement measurement by about 1.4 times. The 3-month wintertime first-floor measurement overestimated the annual first-floor measurement by a factor of 2.

Limitations: The sample was drawn from the Reading Prong Screening Program participants and was largely self-selected. All Reading Prong residents were mailed free ATDs from one manufacturer. Residents who returned these devices and whose readings were greater than 4 pCi/1 were mailed additional free ATDs from the same company for a subsequent round of measurement. The study results were based on ATDs returned after both screening and follow-up measurement rounds. Only 45 homeowners made both screenings and yearlong measurements in the basement level. Only 54 homeowners made both measurements on the first floor.

Study 30

Mose, Douglas G., George W. Mushrush, and Stephen Kline, "Realistic Uncertainties for Charcoal and Alpha-Track Radon Monitors," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 1—Symposium Oral Papers, EPA-600/9-89-006a, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 4-25 to 4-39.

Methodology: See study 25.

Results: Deviations of single charcoal measurements commonly occurred that were more than 50 percent higher or lower than the seasonal ATD measurement. At the 90% confidence level, a single activated charcoal measurement (up to 7 days) should carry a ±90% uncertainty factor when the annual radon concentration is estimated. Similarly, a single ATD measurement (3-months) should carry a ±50% uncertainty factor when the annual radon concentration is estimated. The study noted that the observed deviations were to some extent due to inaccuracies in the charcoal and ATD measurements, although such analytic variations were thought to be random. The uncertainties found in the study exceeded the manufacturer's estimates for the measurement interval (by a few days for the charcoal measurement and a few months for the ATD) by about ±25% at the 90% confidence level.

Limitations: The sample was self-selected and, therefore, may not be representative. The sampled houses were predominantly from Fairfax County, VA, and Montgomery County, MD.

Study 31

Steck, D.J., "Statewide Radon Surveys: Screening vs Long-Term Measurements," Proceedings: The 1988 Symposium on Radon and Radon Reduction Technology, Volume 2—Symposium Poster Papers, EPA-600/9-89-006b, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, March 1989, pp. 1-67 to 1-80.

Methodology: See study 21.

Results: Although the median of the screening results was only 20% higher than that of the long-term survey, the two measurement protocols gave quite different results in individual houses. The long-term measurement had a 95% chance of being between 0.25 and 2.5 times the screening measurement. An analysis of the concurrent measurements at six sites in the "combined survey" showed the failure of either the 2-day average (charcoal screening or continuous radon monitor) or the monthly average (track registration) radon measurements to reliably predict the annual average radon concentration for small sample populations.

Limitations: All sampled houses were from Minnesota, Wisconsin, and Michigan. Different segments of the study were based on subsets of the state surveys. Details of the selection of some subsets were not provided.

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