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PERFORMANCE OF METHODS FOR MEASURING RADON AND RADON DECAY PRODUCTS

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ABSTRACT

The tremendous growth in the number of companies providing radon measurement services over the past three years has strengthened the need to examine the performance of measurement methods. Seven methods -- Alpha Track, Charcoal Adsorption, E-Perm, Grab Sample-Radon and Working Level, Continuous Radon, and Continuous Working Level -- were evaluated on the basis of bias and measurement error derived for companies participating in the National Radon Measurement Proficiency Program during 1987 and 1988. For most methods, the median bias was between -10 and +10 percent and the median measurement error was less than 13 percent. For most methods, 10 percent or more of the companies had absolute bias estimates greater than 30 percent and 8 percent or more of the companies exhibited measurement errors greater than 30 percent. Effects of bias and measurement error on false positive and false negative error rates are discussed.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTRODUCTION

It has been almost four years since Stanley Watras activated a radiation monitor on entering a nuclear power plant where he was employed as an engineer. This alarm led to the discovery of very high concentrations of radon (up to 2700 picocuries per liter, pCi/L) in his family home in Boyertown, Pennsylvania (1,2). Since then, tens of thousands of radon measurements have been made throughout the United States, several states have completed or are conducting indoor radon surveys, a nationwide assessment of radon has been initiated, the Environmental Protection Agency (EPA) has established a Radon Action Program, and there has probably been a hundred-fold increase in the number of companies offering radon measurement services. The intensive focus of attention on indoor radon, as reflected by these activities, creates a need to examine the performance of methods currently employed in measuring radon and radon decay products. This paper characterizes relative bias, relative measurement error, and relative precision for seven measurement methods using data from both laboratory and field studies.

MEASUREMENT METHODS

Performance measures were derived for seven of the eight methods for which the EPA has interim measurement protocols (3); E-Perm is included in (3) via an attachment. The radon progeny integrating sampling unit (RPISU) method was excluded because of insufficient data. A brief description of each method is given below (4). Each method must be calibrated in a calibration facility to determine factors for converting count and voltage drop data to concentrations.

Alpha Track (AT). Radon measurement by alpha track detection use the damage tracks caused when a special type of plastic is exposed to alpha particles emitted by the decay of radon or some of its short-lived decay products. Usually the alpha track detector consists of a small sheet of a special plastic mounted inside a cup with a filter cover. A radon proof bag, or other containers are used to store the detectors except during the measurement period. After a measurement period of one month to one year, the detector is returned to the laboratory where the sheet of plastic is treated with a chemical solution to enhance the damaged tracks. Using a high power microscope, the tracks within a determined area are counted.

Charcoal Adsorption (CC). Radon detection by charcoal adsorption utilizes the ability of activated charcoal to adsorb radon. Detectors consist of a variety of containers filled with from 20 to 100 grams of activated charcoal held in place by a screen or other perforated material. Some systems use a filter to prevent radon products in the surrounding air from entering the canister containing the charcoal. Other systems use a filter bag to contain the charcoal. All detectors are sealed except during sampling. Sampling time is from 2 to 7 days depending on detector configuration and calibration. Analysis is accomplished by counting the gamma radiation emission rate from radon decay products generated by the radon adsorbed on the charcoal.

E-Perm (EP). E-PERMs (Electret Passive Environmental Radon Monitor) detect ions as a measure of radon. The only E-PERM presently approved for the National Radon Measurement Proficiency Program consists of an electrostatically charged material, the eletret, mounted inside a plastic canister about 300 cubic centimeters in volume. The outside of the canister is coated with aluminum foil. During exposure, filter covered holes permit entry by radon but not its decay products. Ions generated during the continuous decay of radon and radon decay products inside the canister, move to the surface of the electret and reduce the surface voltage. Therefore, the amount of voltage reduction is directly related to radon concentration and length of exposure. By varying the thickness of the electret material, E-PERM detectors can be designed to make integrated measurements from 2 days to one year.

Grab Sample - Radon (GR). Determining radon concentrations by grab sampling usually entails drawing a sample of air into a scintillation cell. The cell is a special flask from 100 to 2000 cubic centimeters in volume coated on the inside with a zinc sulfide phosphor and fitted with valves to permit air sample collection. One end of the cell is a window which is put in contact with a photomultiplier tube to count pulses of light (scintillations) created when alpha particles from the decay of radon and radon decay products interact with the phosphor coating. After the grab sample is taken, about four hours are required for the short-lived radon decay products to reach equilibruim before the cell can be analyzed.

Grab Sample - Working Level (GW). Determining the radon decay product concentrations (working level) in air is typically accomplished by using a filter for collecting the decay products and then counting the alpha energy on the filter using a scintillation-type counter. Up to 100 liters of air are usually filtered in about five minutes sampling time. Using the Kuenitz procedure the total alpha activity on the filter is counted any time between 40 and 90 minutes after sampling.

Continuous Radon (CR). Continuous radon monitors are capable of recording radon levels over times ranging from a few hours to several days. These monitors sample by pumping air through, or by diffusion of air into, a scintillation cell. With typical equipment, air passes through a filter into the cell where alpha particle emissions from the continuous decay of radon and radon decay products interact with the zinc sulfide phosphor coating on the cell walls producing pulses of light. A photomultiplier tube detects the pulses and generates an electric signal. The signals are processed electronically to compute radon concentration which are printed on paper as the continuous measurements are made or stored for retrieval at the end of the test.

Continuous Working Level (CW). Continuous working level monitors are capable of measurements over times ranging from several hours to several days. These monitors typically sample by continuously drawing air through a filter at a low flow rate (less than 1 liter per minute). An alpha detector placed in close proximity to the filter counts alpha particle emissions from the radon decay products deposited on the filter surface. The counts are directly proportional to radon decay product concentration (working levels) in the air being sampled. A microprocessor stores the number of counts and elapsed time. Additional electronic processing converts the counts to working levels.

DATA SOURCES

Measures of performance were derived from data generated in the National Radon Measurement Proficiency (RMP) Program and the State Indoor Radon Surveys.

National Radon Measurement Proficiency Program. The National RMP Program was developed by the EPA to assist state, county and local governments, and the public in selecting companies which can adequately measure radon and/or radon decay products. With the rapid growth in the number of companies offering measurement services, guidance in selecting a competent firm is a vital service. Briefly, the program works as follows. Initially, a company submits an application to participate in the program. If the application is acceptable, the company provides a designated number of detectors to the EPA. The detectors are exposed in a Federal radon chamber to a known concentration according to the company's operating procedure e.g., charcoal canisters may be exposed for a company-designated period of five days. If the measurement device requires an on-site operator, the operator is supplied by the company. At the end of the exposure period, detectors are returned to the company for analyses. Laboratory measurements are then returned to the EPA where comparisons are made with the chamber concentration(s). Companies meeting all program requirements are listed in a report that is sent to each state and subsequently made available to the public.

It should be noted that the National RMP Program is totally voluntary. Companies are not asked to participate and can freely withdraw from the program at any time. Also, the program does not certify, recommend or endorse participating companies. Rather, it simply provides a listing of companies that have demonstrated a capability for measuring radon and/or radon decay products.

The National RMP Program currently requires a sample of five passive devices (4 are exposed in a chamber and 1 serves as a control) and four active devices. If, however, a company owns fewer than four instruments, a single measurement is required of each instrument.

State Indoor Radon Surveys. Over the past two years the EPA has provided assistance to the design and conduct of indoor radon surveys in seventeen states and Native Americans in EPA's Region 5. The method used in these surveys to measure radon was Charcoal Adsorption with the canisters exposed for a 48-hour period. One design element of these studies was the side-by-side placement of canisters in a subset of sample households. Duplicate measurements from these field studies enable estimates of relative precision to be derived that cover a wide range of radon concentration levels.

RESULTS AND DISCUSSION

Definitions. Estimates of relative bias, and relative measurement error (RME) for companies that participated in the National RMP Program during the last two performance rounds of testing are summarized in this section. Results of retests of companies failing the performance test are not included. Also,

fifteen participants are not included because of data availability. Estimates of relative precision or coefficient of variation are given for charcoal canisters used in the state indoor radon surveys. Before presenting the results, these performance measures will be defined and their calculations illustrated with an example.

Define M_i as the measured radon concentration for the i^{th} detector, T_i as the true radon concentration (i.e., chamber level concentration) to which the i^{th} detector is exposed, and Z_i as the percentage error associated with the i^{th} detector. Assume that a company obtained the following measurements, M_i, on four detectors, $i = 1, \ldots, 4$, exposed to two concentration levels. The percentage error, Z_i, and the performance measures can then be calculated as shown below.

Detector i	M_i (pCi/L)	T_i (pCi/L)	$Z_i = 100\ (M_i-T_i)/T_i$ (%)
1	16.4	12.7	29.134
2	14.5	12.7	14.173
3	16.0	17.8	-10.112
4	18.7	17.8	5.056

Relative Bias = $\bar{Z}$ = 9.6% RME = s_Z = 16.4%
where $\bar{Z}$ is the arithmetic mean and s_Z is the standard deviation of the Z_i.

Suppose the true concentrations are unknown but it is known that detectors 1 and 2 were in the chamber at the same time and detectors 3 and 4 were together in the chamber but at a different time. Two estimates of relative precision can be derived -- one for detectors 1 and 2 and another for detectors 3 and 4.

Detectors 1 and 2:

Relative Precision = $100\ s_M / \bar{M}$ = 8.7%
where $\bar{M}$ is the arithmetic mean and s_M is the standard deviation of detectors 1 and 2.

The same procedure is followed for estimating relative precision for detectors 3 and 4.

Relative Bias. The estimated distributions of relative bias for companies participating in the National RMP Program during 1987 and 1988 are characterized, by year and method, in Table 1. Included in Table 1 are the number of companies tested (see footnote in table), the range of exposure levels used, the percentiles [10th, 50th (median), 90th] of relative bias, the average relative bias, and the minimum and maximum values. It should be noted that 1987 testing included both primary companies (companies with analysis capability) and secondary companies (companies without analysis capability); however, the 1988 testing included only primary companies. This explains the sharp decline in the number of alpha track companies evaluated in 1988.

Within each method, some companies showed a negative bias while others exhibited a positive bias. Thus, the overall bias tended to be rather small for each method (under 10 percent, ignoring sign). This is based on medians rather than means since the latter are affected by some very large biases (see maximum values in Table 1). There are two exceptions. One is the CC method in 1987 in which the median bias was +17 percent and the other is the EP method in 1988 in which the median bias was +22 percent.

Additional characteristics of the distributions of relative bias are shown in Table 2. These include the percentage of companies with absolute relative bias less than 10, between 10 and 20, between 20 and 30, and greater than 30. For most methods, 30 to 60 percent of the companies had bias estimates (ignoring signs) less than 10 percent. A notable exception was the EP method in 1988; only 7 percent of the companies had absolute bias estimates under 10 percent. On the other hand, for most methods, at least 10 percent of the companies had bias estimates (ignoring signs) greater than 30 percent and for some methods this percentage was much higher. In particular, the 1988 tests of the EP and the GW methods showed that approximately one out of every three companies tested had an estimate of absolute bias greater than 30 percent. If devices with this magnitude of bias are employed in making single-measurement screening tests in homes with concentrations near 4 pCi/L, the false positive and the false negative error rates become large. This is discussed further in the next section.

Relative Measurement Error (RME). The estimated distributions of RME for companies tested in the National RMP Program during 1987 and 1988 are characterized, by year and method, in Table 3. Included in Table 3 are the number of companies tested (see footnote in table), the range of exposure levels used, the percentiles [10th, 50th (median), 90th] of RME, the average RME, and the minimum and maximum values. Additional characteristics of the distributions of RME are shown in Table 4 for each method. These include the percentage of companies with RME less than 10, between 10 and 20, between 20 and 30, and greater than 30. Relative bias and RME are calculated from the same set of detectors/instruments. In some instances the number of companies providing estimates of RME is smaller than the corresponding number for relative bias. This occurs when the sample size is one and RME cannot be estimated.

The median RME was 13 or less for most methods. An exception was the AT method which had a median RME of 21 in the 1988 tests. Medians are more meaningful statistics than means in this case since the latter are affected by some very large values of RMEs (see maximum values in Table 3). On the other hand, most methods (5 out of 7 in 1988) showed 8 percent or more of the companies with RMEs greater than 30.

Short-term tests for determining if there is a potential radon problem are now commonplace. People are concerned about the level of radon where they live and prospective home-buyers are requesting radon testing as a pre-sale condition. Federal guidelines on radon testing suggest that additional measurements be taken when a single-measurement screening test gives a reading greater than 4 pCi/L (5). Bias and measurement error are important in determining how well a device performs in screening tests; they govern the

false positive and false negative error rates. Effects of bias and measurement error on error rates are given in Table 5 for true concentrations in the vicinity of 4 pCi/L. The estimated error rates in Table 5 are conservative in that all components of variance other than measurement error that may contribute to the total variability of a single measurement were assumed to be zero. The pronounced increases in error rates resulting from increases in RMEs and biases (positive and negative) clearly support the need to control these parameters in the National RMP Program.

Relative Precision. The state indoor radon surveys used charcoal canisters for measuring radon levels in owner-occupied homes with listed telephone numbers. The canisters were exposed for 48 hours, then mailed to EPA's Eastern Environmental Radiation Facility in Montgomery, Alabama, for analysis. Two canisters were placed side-by-side in a randomly selected subsample of test houses. This provided a means for monitoring the precision of canisters used in the surveys.

The surveys provided radon measurements on 480 "pairs" of canisters located in homes across fifteen states. Each pair of canisters was located in the same room and exposed over the same time period. Homeowners were instructed to place the canisters side-by-side in the same room. Each pair of concentration measurements furnishes an estimate of relative precision or coefficient of variation (CV). The estimated CVs for all pairs of canisters with means above 0.1 pCi/L were divided into five groups according to the average of the two readings. The number, mean, and standard deviation of the CVs in each group are shown in Table 6. Although the CVs are slightly higher and less stable at low concentrations, the vast majority of the CVs were less than 15 percent. The pattern exhibited in Table 6 suggests that a concentration level in the vicinity of 4 pCi/L should be included as one of the levels used in the National RMP Program.

CONCLUSIONS

Estimates of relative bias and relative measurement error were derived for companies participating in the National Radon Measurement Proficiency Program during 1987 and 1988 and summarized by measurement method. The results support the following conclusions.

- For most methods, the median bias was between -10 and +10 percent and the median measurement error was less than 13 percent.
- For most methods, 10 percent or more of the companies had bias estimates (ignoring sign) greater than 30 percent and 8 percent or more of the companies had measurement errors greater than 30 percent.
- The magnitude of bias and measurement error estimates confirm the need for a National RMP Program to identify companies capable of measuring radon and radon decay products.

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TABLE 1. SUMMARY STATISTICS ON RELATIVE BIAS BY YEAR WITHIN METHOD

Method	Year	Number of Companies	Exposure Levels*	Percentiles* 10th	50th	90th	Mean*	Min*	Max*
AT	1987	77**	38-42	-23	-8	6	-9	-100	55
	1988	10**	5-21	-50	5	23	1	-54	24
CC	1987	258**	38-42	-2	17	36	18	-100	291
	1988	224**	7-36	-27	0	16	-3	-64	101
CR	1987	15	37-43	-21	6	53	8	-23	108
	1988	85	13-36	-23	-3	35	10	-47	658
CW	1987	40	.14-.21	-17	4	30	4	-35	68
	1988	66	.03-.15	-26	-5	21	16	-86	1353
EP	1987	5	41-43	---	1	---	1	-2	5
	1988	96	5-21	9	22	47	31	-97	479
GR	1987	40	25-48	-36	-2	27	-1	-75	146
	1988	57	12-32	-30	-8	16	1	-54	475
GW	1987	46	.05-.25	-50	-4	21	-7	-69	37
	1988	44	.02-.21	-37	-2	43	6	-58	328

* Unit of measure is pCi/L or WL depending on the measurement method.
** Includes different "types" of detectors submitted by the same company as separate entries in the National RMP Program.

TABLE 2. DISTRIBUTION OF ABSOLUTE RELATIVE BIAS BY YEAR WITHIN METHOD

Method	Year	Number of Companies	Percentage of Companies with Absolute Relative Bias			
			≤ 10.0	10.1 - 20.0	20.1 - 30.0	> 30.0
AT	1987	77*	49	29	17	5
	1988	10*	40	40	10	10
CC	1987	258*	26	31	21	22
	1988	224*	54	21	13	12
CR	1987	15	60	20	13	7
	1988	85	47	23	14	16
CW	1987	40	60	25	3	12
	1988	66	50	24	14	12
EP	1987	5	100	0	0	0
	1988	96	7	37	25	31
GR	1987	40	43	22	15	20
	1988	57	39	38	11	12
GW	1987	46	41	22	20	17
	1988	44	30	14	22	34

* Includes different "types" of detectors submitted by the same company as separate entries in the National RMP Program.

TABLE 3. SUMMARY STATISTICS ON RELATIVE MEASUREMENT ERROR BY YEAR WITHIN METHOD

Method	Year	Number of Companies	Exposure Levels*	Percentiles* 10th	50th	90th	Mean*	Min*	Max*
AT	1987	76**	38-42	5	10	23	14	0	125
	1988	10**	5-21	10	21	84	33	9	84
CC	1987	257**	38-42	1	4	10	6	0	126
	1988	224**	7-36	2	6	27	10	0	61
CR	1987	5	37-43	---	7	---	33	1	145
	1988	32	13-36	2	8	30	12	1	94
CW	1987	15	.14-.21	2	6	13	7	1	16
	1988	30	.03-.15	1	5	15	7	0	30
EP	1987	5	41-43	---	5	---	4	3	6
	1988	96	5-21	5	13	39	26	2	394
GR	1987	40	25-48	1	6	22	8	0	35
	1988	56	12-32	3	6	29	13	1	172
GW	1987	46	.05-.25	2	5	20	8	1	36
	1988	44	.02-.21	5	13	26	23	3	383

* Unit of measure is pCi/L or WL depending on the measurement method.
** Includes different "types" of detectors submitted by the same company as separate entries in the National RMP Program.

TABLE 4. DISTRIBUTION OF RELATIVE MEASUREMENT ERROR BY YEAR WITHIN METHOD

Method	Year	Number of Companies	Percentage of Companies With Relative Measurement Error			
			≤ 10.0	10.1 - 20.0	20.1 - 30.0	> 30.0
AT	1987	76*	47	41	5	7
	1988	10*	10	30	20	40
CC	1987	257*	91	6	0	3
	1988	224*	68	17	8	8
CR	1987	5	80	0	0	20
	1988	32	59	16	16	9
CW	1987	15	87	13	0	0
	1988	30	77	17	6	0
EP	1987	5	100	0	0	0
	1988	96	36	33	15	16
GR	1987	40	73	15	10	2
	1988	56	64	23	4	9
GW	1987	46	80	11	2	7
	1988	44	30	43	23	4

* Includes different "types" of detectors submitted by the same company as separate entries in the National RMP Program.

TABLE 5. EFFECTS OF BIAS AND MEASUREMENT ERROR ON ERROR RATES IN SCREENING TESTS

True Concentration (pCi/L)	False Positive Error Rate		False Negative Error Rate	
	Bias = +30% RME=30	Bias = +10% RME=10	Bias = -30% RME=30	Bias = -10% RME=10
3.0	.47	.02	NA	NA
3.5	.66	.35	NA	NA
6.0	NA*	NA	.44	<.01
6.5	NA	NA	.34	<.01

* Not applicable.

TABLE 6. COEFFICIENTS OF VARIATION VERSUS RADON CONCENTRATION LEVEL

Range of Average Readings	Number of CVs	Coefficient of Variation	
		Mean	Standard Deviation
0.11- 2.0*	278	14.7	18.6
2.1 - 4.0	99	7.8	9.1
4.1 - 7.0	52	7.7	19.0
7.1 -10.0	28	7.2	8.1
>10.0	23	4.5	2.7

* CVs with means less than 0.11 pCi/L were excluded because of instability.