ALLEN MARTIN MABRY. Radon-222 Concentrations in North Carolina Household Groundwater Supplies (Under the direction of JAMES E. WATSON, JR.)

A survey of randomly selected households served by groundwater was conducted to characterize radon-222 concentrations in groundwater-derived drinking water supplies in North Carolina. Groundwater sources in North Carolina had previously been analyzed for radon-222 by other researchers, but a random survey had never been attempted. The investigation included regional comparisons of radon-222 concentrations, characterization of the distribution of concentrations, and a comparison of the indoor airborne concentration to the waterborne concentration for each household.

One hundred and seventy-four homes were successfully surveyed. The statewide average concentration was 2,229 pCi/l. The eastern region of the state had a markedly lower average concentration of 337 pCi/l. Sixty-eight percent of the measured concentrations were above the U.S. Environmental Protection Agency's proposed maximum contaminant level of 300 pCi/l. The comparison of indoor airborne concentrations to waterborne concentrations revealed a weak linear relationship between them.

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INTRODUCTION

This project was undertaken to achieve two objectives: (1) to obtain a representative characterization of radon-222 concentrations of North Carolina groundwater sources used for drinking water, and (2) to compare radon-222 concentrations in groundwater sources to the airborne radon-222 concentrations in the homes served by them.

Physical Properties of Radon-222

Radon-222 (henceforth radon) is a radioactive noble gas that occurs naturally as a product of the decay of radium, a member of the uranium series of radionuclides, which is present in most soils (BEIR 1988). Radon decays by alpha particle emission with a half-life of 3.82 days to the solid daughter Po-218. Po-218 decays to Pb-214 by alpha emission; Pb-214 decays to Bi-214 by beta emission. Bi-214 then decays to Po-214 by beta emission; Po-214 decays almost instantaneously by alpha emission to the long-lived daughter Pb-210. This decay series is shown in Table 1. Equilibrium of the short-lived daughters with the parent is reached in about 3 hours (Evans 1969).

Occurrence of Radon in Drinking Water

Owing to the ubiquity of the uranium series radionuclides in the earth's crust, radon permeates the earth's groundwater in

Table 1. Principal Decays from U-238 to Pb-206 (ICRP 1983)

Isotope	Half-life	Principal radiation	Principal alpha energies (MeV)	Principal gamma energies (MeV)
U-238	4.5×10^9 y	alpha	4.198 (77%)	
			4.149 (23%)	
Th-234	24.1 d	beta		
Pa-234m	1.17 min	beta		
U-234	244,500 y	alpha	4.773 (72%)	
			4.721 (27%)	
Th-230	77,000 y	alpha	4.688 (76%)	
			4.621 (23%)	
Ra-226	1,600 y	alpha	4.785 (94%)	
			4.602 (6%)	
Rn-222	3.82 d	alpha	5.490 (100%)	
Po-218	3.05 min	alpha	6.003 (100%)	
Pb-214	26.8 min	beta		0.2952 (19%)
		gamma		0.3519 (37%)
Bi-214	19.9 min	beta		0.6093 (46%)
		gamma		1.120 (15%)
				1.765 (16%)
Po-214	1.6×10^{-4} s	alpha	7.687 (100%)	
Pb-210	22.3 y	beta		
Bi-210	5.01 d	beta		
Po-210	138 d	alpha	5.297 (100%)	
Pb-206	stable			

varying amounts (EPA 1984). The U.S. Environmental Protection Agency (EPA) estimates an average U.S. drinking water radon concentration in the range of 200 to 600 pCi/l for groundwater sources. The EPA estimates that the majority of water supplies served by groundwater have concentrations less than 2,000 pCi/l (Milvy and Cothern 1990). Radon is not typically found in surface water sources, and larger public groundwater systems usually have lower concentrations of radon than smaller systems and private wells (Milvy and Cothern 90). A concentration of 750,000 pCi/l has been measured in one public water supply (Milvy and Cothern 1990), and a concentration of $3x10^6$ pCi/l has been measured in a private well in Colorado (Lawrence et al. 1992).

An analysis of available radon concentration data performed by C.T. Hess et al. combined the results from 6,298 samples taken from U.S. public groundwater supplies and calculated a geometric mean of 130 pCi/l. In the same study, the results from 454 samples taken from private wells in the United States had a geometric mean of 920 pCi/l (Hess et al. 1985). The National Inorganics and Radionuclides Survey (NIRS) randomly surveyed 978 U.S. community groundwater supplies. Of the systems surveyed, 48% had radon concentrations greater than 200 pCi/l. Population-weighted averages of 249 and 2,277 pCi/l for the United States and North Carolina, respectively, were obtained from the survey. The smaller systems that were surveyed averaged higher radon concentrations. The population-weighted average for U.S. systems serving fewer than 1,000 people was 602 pCi/l (Longtin 1990).

North Carolina Data

Radon concentrations in N.C. groundwater sources have been reported by the EPA, the N.C. Division of Radiation Protection, and the University of North Carolina. A compilation of 437 sample results obtained from those sources has been prepared by Dale Dusenbury (Dusenbury 1992). Concentrations range from 0 to 55,900 pCi/l, with an average of 2,430 pCi/l. County averages computed from those concentrations are shown in Table 2. A high degree of variability throughout the state is evident. These samples were not randomly obtained, and not all of them were from drinking water sources.

Regional variations in average radon concentrations in water associated with different rock types have been reported (Loomis 1987). It has also been shown that geologic region is a good predictor of radon concentration in North Carolina (Loomis et al. 1987).

Health Risks

The presence of radon in groundwater presents a health risk to the public. Compared with all other naturally occurring radionuclides present in drinking water, radon presents the greatest health risk (Milvy and Cothern 1990). Two routes of exposure are possible from waterborne radon: ingestion of the radon-bearing water and inhalation of radon released into the home atmosphere from the radon-bearing water. More is known about the

Table 2. Average Concentrations for N.C. Counties Compiled from Data Supplied by Dale Dusenbury.

County	Avg. (pCi/l)	No. of samples	County	Avg. (pCi/l)	No. of samples
Alamance	413	6	Edgecombe	3609	5
Alexander	1017	3	Forsyth	2991	7
Alleghany	1472	1	Franklin	12414	5
Anson	1389	3	Gaston	41	4
Ashe	645	1	Graham	2335	1
Avery	1903	5	Greene	206	3
Beaufort	72	2	Guilford	2383	7
Bertie	139	3	Halifax	1395	3
Bladen	84	7	Harnett	30	2
Brunswick	269	7	Haywood	9071	2
Buncombe	2791	3	Henderson	8084	3
Burke	1153	3	Hertford	241	2
Cabarrus	423	2	Hoke	1483	2
Caldwell	22	1	Hyde	8	1
Carteret	121	8	Iredell	2224	9
Catawba	2092	10	Jackson	559	3
Chatham	1084	11	Johnston	3631	10
Cherokee	533	1	Jones	132	1
Chowan	60	2	Lenoir	55	6
Clay	3342	1	Lincoln	26	1
Cleveland	27475	7	Macon	229	1
Colombus	48	8	Martin	162	3
Craven	87	2	McDowell	11628	2
Cumberland	630	20	Mecklenburg	1903	14
Currituck	141	1	Moore	234	6
Dare	61	4	Nash	1611	11
Davie	613	3	New Hanover	49	8
Duplin	66	7	Northampton	494	6
Durham	990	19	Onslow	197	6

Table 2 (continued)

County	Avg. (pCi/l)	No. of samples	County	Avg. (pCi/l)	No. of samples
Orange	1118	8	Stanly	1198	5
Pamlico	40	3	Stokes	2264	4
Pasquotank	27	1	Surry	2067	16
Pender	29	2	Transylvania	8377	2
Perquimans	120	2	Tyrrell	95	2
Pitt	89	5	Union	1755	1
Polk	11	2	Vance	6797	2
Randolph	278	4	Wake	6540	30
Robeson	50	6	Warren	9580	6
Rockingham	4126	12	Watauga	1296	3
Rowan	1670	8	Wayne	610	10
Rutherford	5350	5	Wilkes	946	2
Sampson	71	3	Wilson	1310	6
Scotland	343	1	Yadkin	1167	2

lung cancer risk due to inhalation because of the experiences of uranium miners (NCRP 1984).

Risk estimates for the ingestion of radon are derived from calculations of the absorbed radiation dose delivered to specific body organs combined with published risk coefficients for absorbed radiation dose. The lifetime cancer fatality risk per pCi/l of radon for inhalation exposure is estimated to be greater than for ingestion. Due to its greater risk coefficient, inhalation is considered the most significant exposure pathway for risk from radon in water, even though more of the radon is ingested than

inhaled under typical conditions (Cross et al. 1985). However, risk comparisons based on calculations of absorbed dose vary, and it has been suggested that ingestion may be a significant exposure pathway for waterborne radon (Crawford-Brown 1990).

Proposed Regulation

Currently, the radon concentration of drinking water is not regulated. The EPA has proposed a maximum contaminant level (MCL) of 300 pCi/l based primarily on the inhalation risk from the contribution of the waterborne radon to the airborne radon concentration (EPA 1991). Previous studies indicate a waterborne concentration of 10,000 pCi/l would contribute an additional 1 pCi/l to the indoor air concentration of a typical household (Hess and Beasley 1990). The proposed MCL would affect an estimated 26,000 public water supply systems in the United States (EPA 1991). Private wells are not regulated by EPA drinking water regulations, but it is possible that the nation's estimated 13 million private wells will be affected by the regulation if public concern prompts the mortgage industry to adopt the MCL as a standard (Barron 1990). Removal of radon from water is achievable with currently available processess. Granular activated carbon (GAC) adsorption, diffused-bubble aeration and packed-tower aeration each have demonstrated the potential to remove 99% of the radon in water processed (Lowry 1988).

A radon concentration of 300 pCi/l in a household water supply will contribute 0.03 pCi/l to the indoor air concentration

of the household based on a water-to-air transfer factor of 10^{-4}. Lifetime continuous exposure to this concentration yields an additional lifetime risk of lung cancer mortality of 1.8×10^{-4} based on a risk factor of 350 cancer deaths per 10^{6} Person Working Level Months, assuming 50% equilibrium of the radon daughters with the radon and 70 years of exposure (BEIR 1988). A Working Level is a radon concentration unit equal to 100 pCi/l of radon in air at 100% equilibrium with the daughters.

By randomly surveying groundwater supplies, it was intended to investigate the scope and magnitude of radon contamination in N.C. drinking water supplies derived from groundwater. It was also intended to determine what percentage of households might be affected by the EPA's proposed MCL of 300 pCi/l. The comparison of airborne radon concentrations to waterborne concentrations was not intended to determine the rate of transfer of radon from water to air since there are overshadowing contributions to indoor air concentrations. Instead, the comparison was undertaken to investigate the possibility of an association between airborne and waterborne radon concentrations.

MATERIALS AND METHODS

Participant Selection

An address list of participants in the State/EPA survey of residential indoor air radon concentrations in North Carolina was obtained from Dr. Felix Fong of the N.C. Division of Radiation Protection. The State/EPA survey, completed in 1990, randomly sampled 1,290 residences throughout North Carolina. As part of the survey those homes served by well water were identified. Five hundred and eighty-four homes that used well water were included in the survey.

It was not certain at the beginning of the project whether it would be feasible to survey all 584 homes with well water. Therefore, an approach was employed in selecting participants from the list to preserve the randomness of the survey. Numbers representing a random ordering of the participants had been assigned to each participant of the State/EPA survey during the random selection process. Therefore, participants were chosen in ascending order according to these numbers.

Sampling was performed in groups of 25 homes each to keep the processing of samples manageable. Home owners were mailed letters asking them to participate in the survey. If they did not refuse the request, they were mailed a sampling kit. From November 1990 through February 1991, 250 home owners were surveyed in this fashion.

Sampling Procedure

The sampling kit consisted of a cardboard mailing tube containing two 20-ml scintillation vials containing 10 ml each of liquid scintillation counting (LSC) cocktail, instructions for collecting samples (see Appendix A), packing material, and a return address label with postage affixed.

The scintillation vials with LSC solution were preweighed and marked with unique identification numbers. The scintillation vial used was a polyethylene cone-capped, glass vial, available from Fisher Scientific (part no. VWR 66022-128), that had been found to be a suitable vial for containing radon gas (Hess and Beasley 1990). The scintillation cocktail used was a mineral oil-based cocktail available from E. I. du Pont NEN (High Efficiency Mineral Oil Scintillator part no. NEF 957A).

The participants were instructed to choose a faucet in the home that did not have any attachments, like an aerator, or to remove the attachment from a faucet if necessary. They were to let the cold water run for 5 minutes, reduce the flow, then fill each vial to the neck, capping it immediately. They were instructed to record the date and time the samples were taken on the instruction sheet and to return the samples and sheet promptly.

Sample Analysis

When samples were received at UNC, the volume of water collected was determined by weighing the samples and then subtracting their initial weights from their final weights,

assuming a density of water equal to 1 gram/ml. The dates and times of sample collections provided by participants were recorded. Each vial was shaken vigorously for 15 seconds to extract the radon from the aqueous phase into the organic scintillator phase of the mixture. After the extraction process, counting was delayed for at least 4 hours to allow the radon daughters to reach equilibrium with the radon. Counting was performed with a Packard Tri-Carb 300 liquid scintillation counter. The counter was programmed to count each vial for either 50 minutes or until 2 standard deviations of the gross count equaled 2% of the gross count, whichever came first. See Appendix B for details of the counting procedure.

Two background vials, each containing 10 ml of scintillator fluid and 10 ml of distilled water, were counted with each batch of samples. The two background count rates thus obtained were averaged for each batch of samples. The background values for the 39 batches counted during the survey are presented in Appendix C. The background values ranged from 29.83 to 32.50 cpm with an average value of 31.19 cpm and a standard deviation of 0.79 cpm (2.5%).

Two standard activity vials were counted with each batch of samples; they were sealed aqueous radium-226 standards of 714 and 952 pCi (Ladrach 1987). Before counting, the standards were shaken and allowed approximately 4 hours to reach equilibrium in the same manner as described above for samples. The 4-hour delay was accomplished by positioning the standards in the automated vial conveyor of the LSC so they would follow the two background vials

and three additional empty vials, which totalled 250 minutes. The two standard count rates thus obtained were used to determine an average calibration factor for each batch of samples. A decay correction was not necessary for this calculation because the standards were counted about 4 hours from the time they were shaken. Additionally, it was observed that the measured count rates of the standards did not decrease with time, suggesting that the transfer of the radon to the scintillation cocktail was continuous and independent of the shaking process previously described. For example, on one occasion the counter malfunctioned and counted the standards and samples for 13 repetitions over a 54-hour period, and no significant change in the count rates of the standards occurred. This phenomenon was also observed by EPA researchers (EPA 1990). The calibration factors for the 39 batches of samples processed during the survey are presented in Appendix D. The average calibration factor was 10.0 cpm/pCi, with a standard deviation of 0.14 cpm (1.4%). The calibration factors ranged from 9.68 to 10.26 cpm/pCi.

Radon concentrations in pCi/l were calculated from the net count rates by applying the calibration factor and correcting the results for decay. The following relationship was used:

$$Rn\text{-}222\ conc.\ (pCi/l) = (cpm_{gross} - cpm_{background})\ \frac{1}{K}\ \frac{1{,}000\ ml/l}{V}\ e^{\lambda t}$$

where:

K = calibration factor (cpm/pCi)
V = sample volume (ml)
λ = physical decay constant for radon (0.18 $days^{-1}$)
t = elapsed time between sample collection and analysis (days)

The concentrations of the two samples obtained from each home were averaged to determine the concentration for each home. These average concentrations were reported to the participants by mail. The standard deviation of the count rate (σ) for each result was calculated based on the standard deviations of the sample and background count rates using error propagation formulae.

It was necessary to determine the level below which a result was more likely to be due to statistical fluctuation of the background than to true radioactivity in the sample. The decision limit for nondetection was calculated using the relationship given in NCRP Report No. 58:

$$L_c = K\ \sqrt{2}\ \sqrt{B} = 1.64\ \sqrt{2}\ \sqrt{B} = 2.32\ \sqrt{B}$$

where:

L_c= decision limit, net counts (95% confidence level)
K = 1.64
B = background counts

The decision limit is the net number of counts at which there is 95% probability that any signal below it is false detection. The complement to the decision limit is the detection limit given in NCRP Report No. 58:

$$L_D = K^2 + 2 \quad L_c = 2.71 + 4.65 \sqrt{B}$$

where:

L_D= detection limit, net counts (95% confidence level)
K = 1.64
B = background counts
L_c= decision limit

The detection limit is the net number of counts at which there is 95% confidence that a signal above it will be detected.

The decision limit was calculated for each batch of samples using the background count for that day. For example, a background count rate of 32.0 cpm obtained over a 50-minute count (1,600 total counts) would yield:

$$L_c = 2.32 \quad \frac{\sqrt{1,600}}{50 \text{ min.}} = 1.86 \ cpm$$

For a typical 10 ml sample taken 4 days prior to counting and assuming a calibration factor of 10 cpm/pCi the decision limit

concentration would be determined using the previously given relationship for calculating concentration as follows:

$$L_c = (1.856\ cpm)\ \frac{1}{10\ cpm/pCi}\ \frac{1000\ ml/l}{10\ ml}\ e^{.72} = 34\ pCi/l$$

Results below the decision limit were so noted, but not discarded. Discarding values would introduce bias into calculated averages.

Determination of State and Regional Averages

State, regional, and county averages were determined after applying weighting factors to all results based on information supplied with the State/EPA survey data base. The weighting factors were necessary because the State/EPA survey used different sampling rates across the state to favor areas of greater interest. The weighting factors also incorporated other minor adjustments that resulted from the participant selection process (personal communication with Dr. Jane W. Bergsten of Research Triangle Institute).

The division of the state into the three regions used in this study is shown in Fig. 1. The counties that were sampled are shown in Fig. 2. The division of the state was based on geologic regions which have been shown to be predictors of radon concentration (Loomis et al. 1987). The eastern region represents the Coastal Plain; the central region is dominated by the Slate Belt, Charlotte

Belt, and Raleigh Belt, and the western region is composed of the Inner Piedmont and Blue Ridge Belt.

Figure 1. Map of the three regions of comparison.

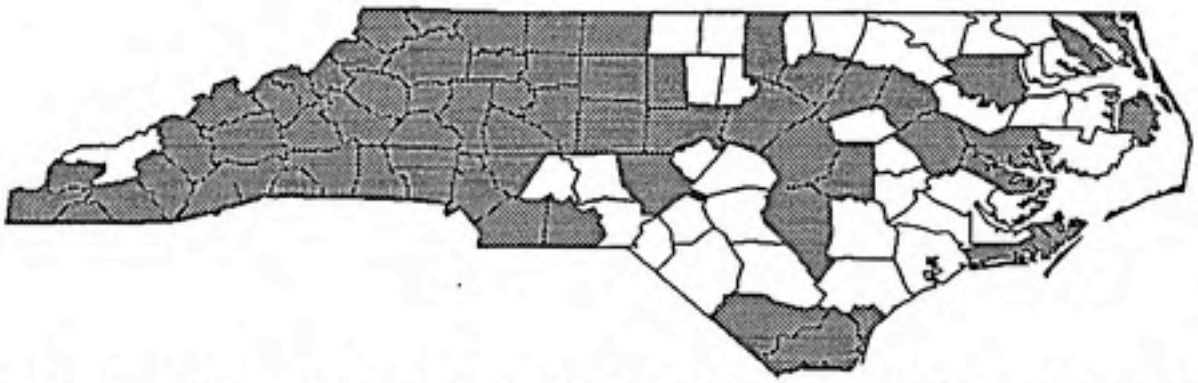

Figure 2. Map of the counties sampled. Counties sampled are shaded.

RESULTS

Two hundred and fifty homes were originally selected for sampling. Ten of those were eventually determined to be ineligible for the study. Ineligible homes included those that responded back that groundwater was not used and those for which the sample mailers were returned by the post office as undeliverable. At the conclusion of the sampling phase, 174 residential groundwater samples had been collected and analyzed. The collection success rate was 73% for eligible homes. Samples not collected from eligible homes were a result of no response by the home owner.

Duplicate samples were requested from each home owner. Of the 174 homes surveyed, 162 were successfully sampled in duplicate. Sample pairs received that had one broken vial resulted in singular samples for 12 of the homes surveyed. The concentration for each dually sampled home was determined by averaging the concentrations of the two samples.

The results are listed in Appendix E. The unweighted average concentration for all samples was 2,298 pCi/l. The weight-adjusted average concentration for the state was 2,228 pCi/l. The eastern region of the state had the lowest weight-adjusted average concentration, 337 pCi/l; the central and western regions had higher weight-adjusted average concentrations of 3,524 and 2,371 pCi/l, respectively.

A summary of the results is presented in Table 3. Measured concentrations ranged from 21 to 59,088 pCi/l. All results

presented in this section represent weight-adjusted values. The results listed in Appendix E are without any adjustments.

Table 3. Summary of Results

Region	Number	Minimum	Maximum	Weighted mean	Weighted median
Eastern	24	71	1,715	337	246
Central	31	55	19,558	3,524	945
Western	119	21	59,088	2,371	1,191
State	174	21	59,088	2,229	570

Distribution of Results

Ninety-five percent of the measured concentrations were between 0 and 10,000 pCi/l. Fig. 3 illustrates the distribution of the data in this range. It can be seen that the data are not distributed normally. Instead, the values are skewed toward the lower concentrations.

Fig. 4 is a plot of the distribution of all results on a log scale. The data appear to approximate a lognormal distribution more closely than a Gaussian distribution. Fig. 5, 6 and 7 show the distributions of data for each region of the state. Each of these distributions also approximates a log normal model. Note that since the horizontal scales of these figures are logarithmic, the midpoints between 10 and 100, 100 and 1,000, 1,000 and 10,000 and 10,000 and 100,000 correspond to values of 31.6, 316, 3,160 and 31,600 respectively.

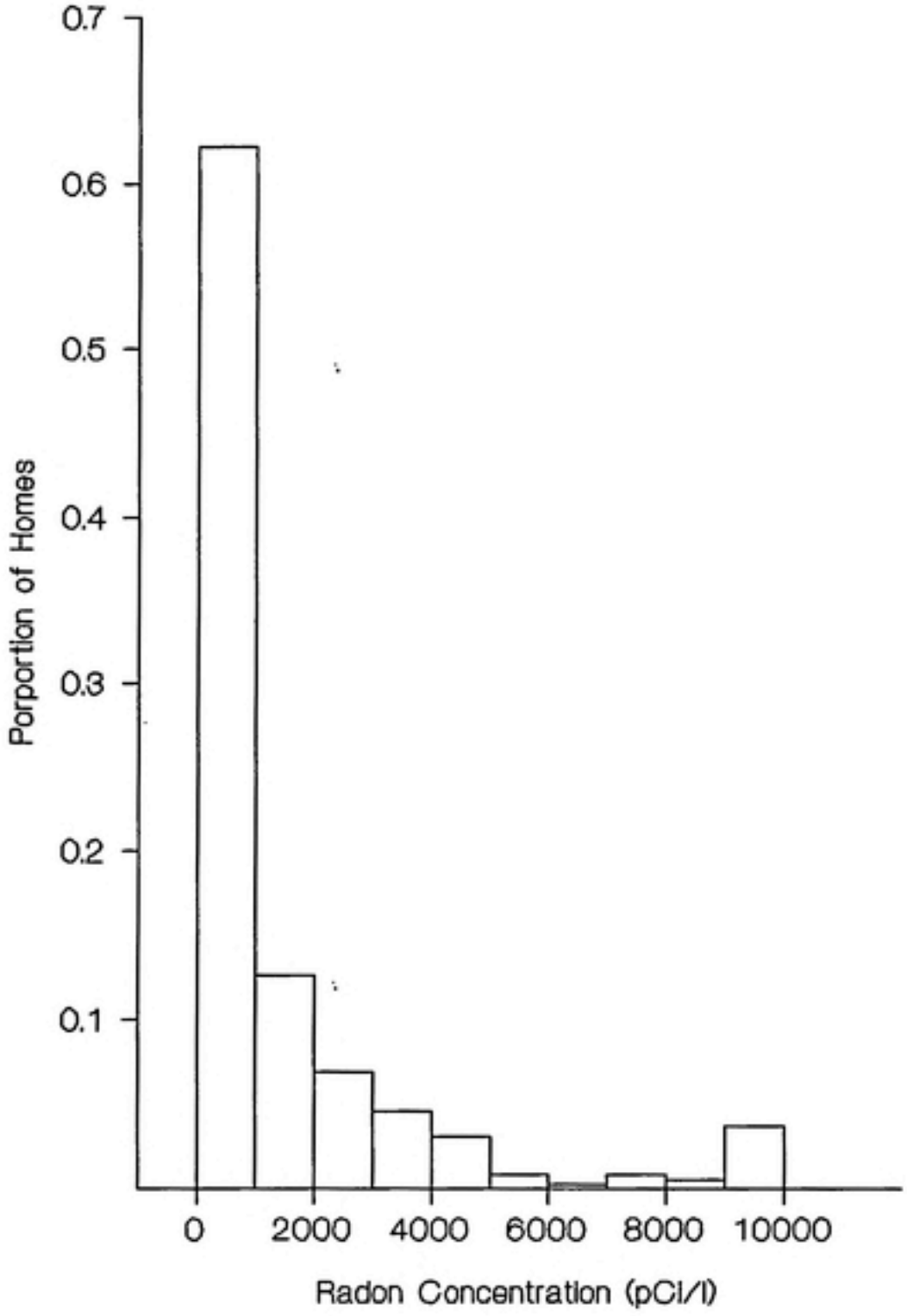

Figure 3. Frequency distribution of the concentrations between 0 and 10,000 pCi/l.

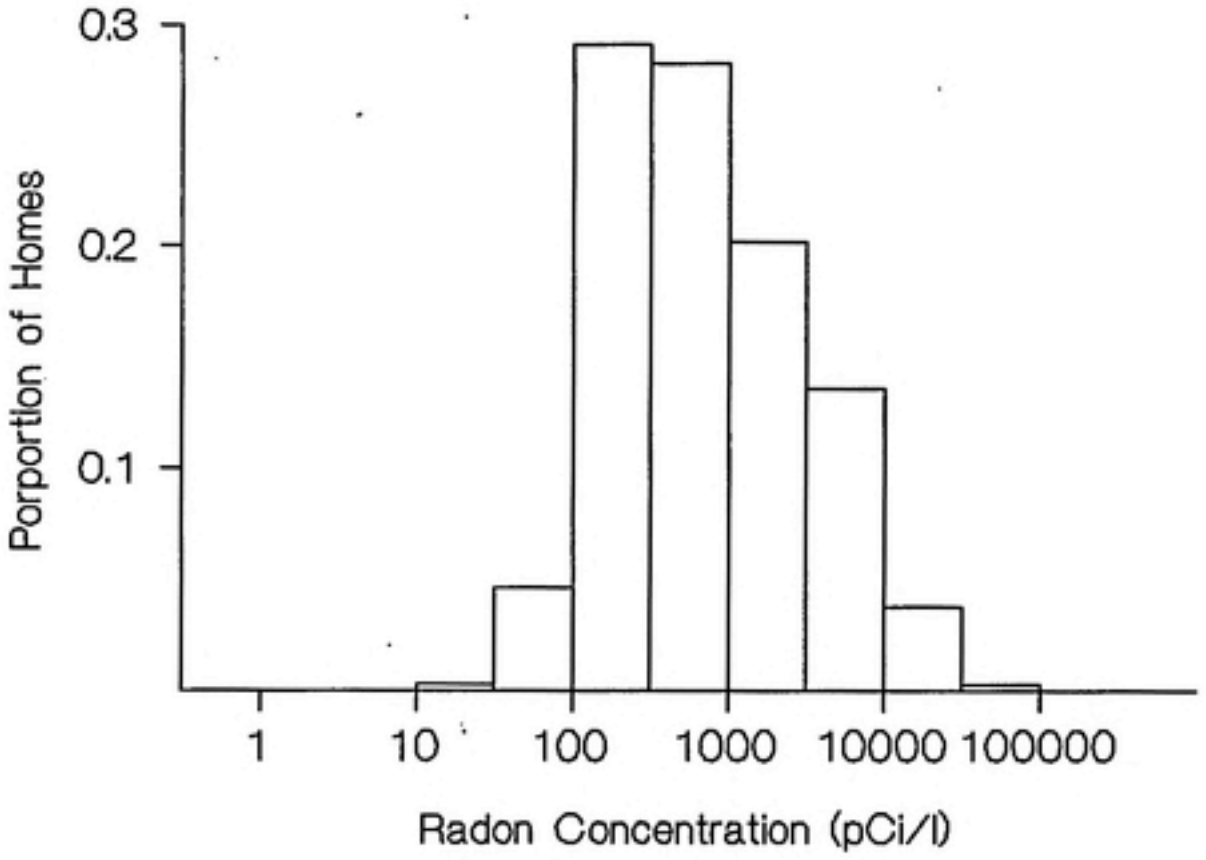

Figure 4. Frequency distribution of concentrations on a log scale.

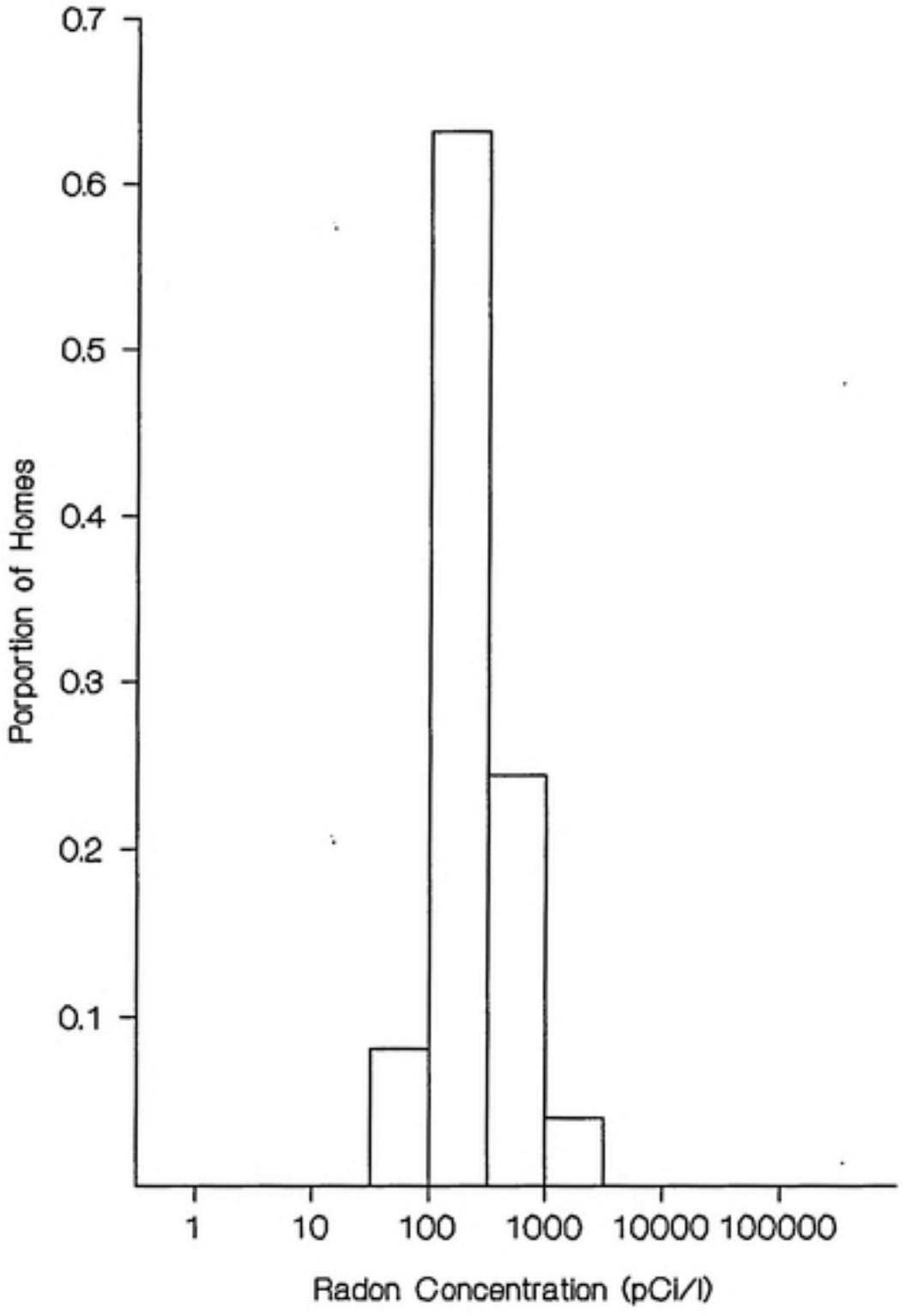

Figure 5. Frequency distribution of concentrations in the eastern region on a log scale.

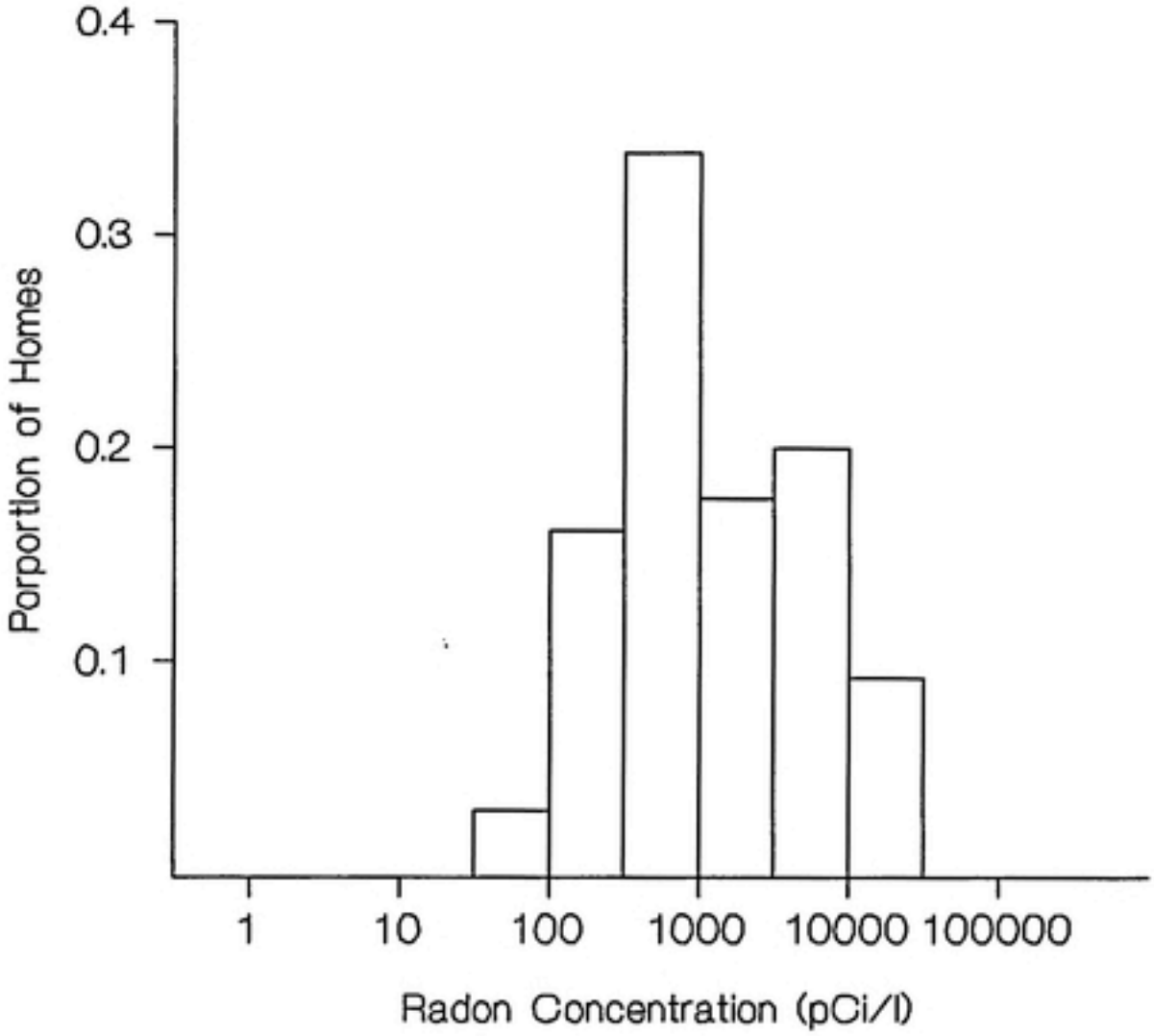

Figure 6. Frequency distribution of concentrations in the central region on a log scale.

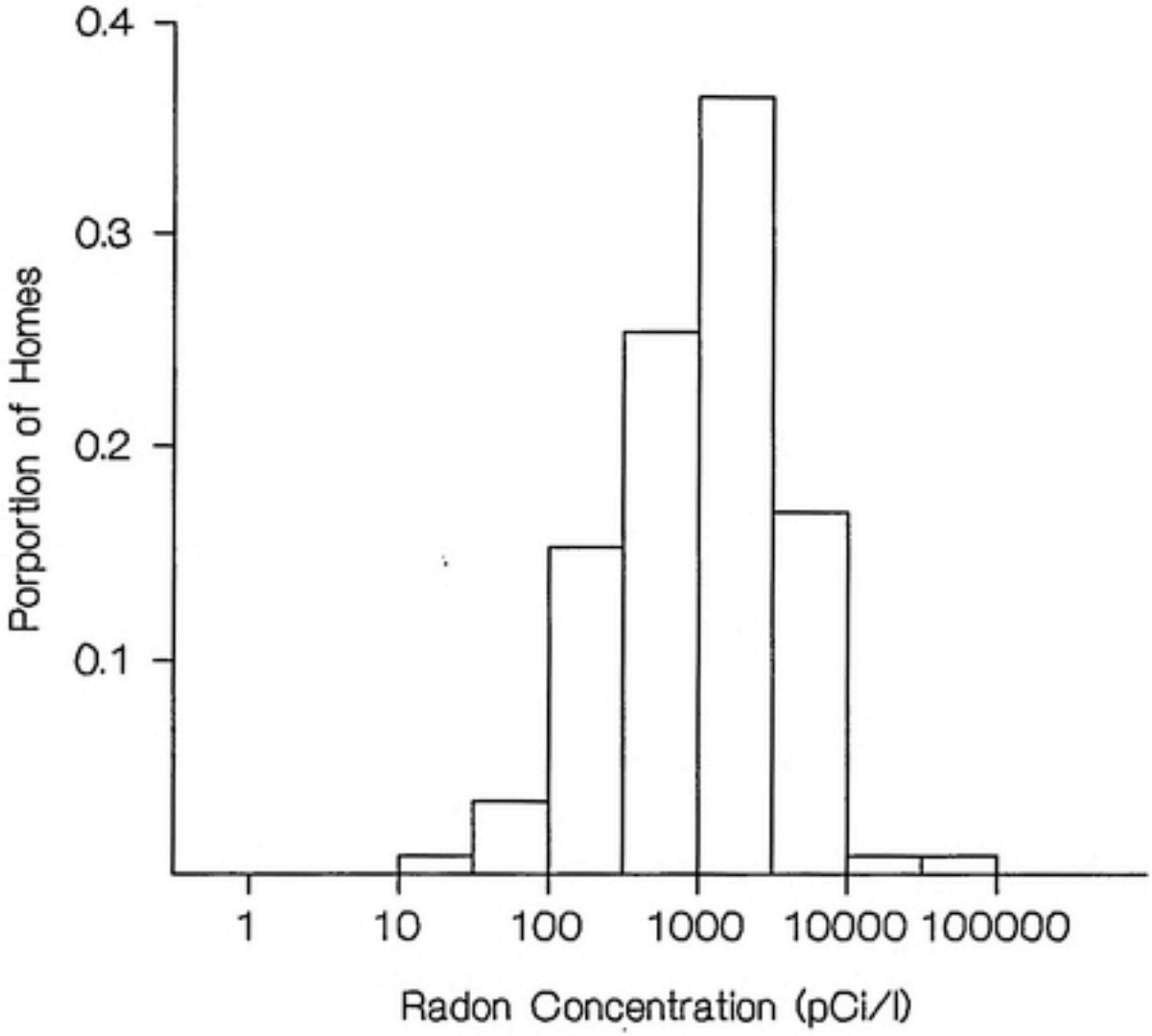

Figure 7. Frequency distribution of concentrations in the western region on a log scale.

Regional Comparisons

For the purpose of comparing the results by region, the medians in Table 3 are more useful than the means owing to the non-Gaussian distributions. The median value for the eastern region, 246 pCi/l, was significantly lower than the median values of the central and western regions (945 and 1,191 pCi/l respectively). However, the median values of the central and western regions were similar.

Fig. 8 illustrates the differences and similarities between the observations for the three regions. The horizontal boundaries of each box represent the range of the middle 50% of the results, or midrange, for its region. The horizontal line inside each box is at the sample median. Vertical lines attached to each end of each box model the normal range of the data. Each vertical line reaches to the most extreme result within a range defined as 1.5 midrange widths from the edge of the box. Results that fall outside this range are considered outliers. Outliers are represented by asterisks. The midrange for the eastern region lies below the midranges of the central and western regions with no overlap, signifying a meaningful difference between the eastern region and the remainder of the state. The results for central and western regions, however, appear quite similar.

A statistical analysis of variance between the log-transformed results for the regions confirms the preceding exploratory analysis. A comparison between results for the eastern region and results for the remainder of the state yields an *F* statistic of

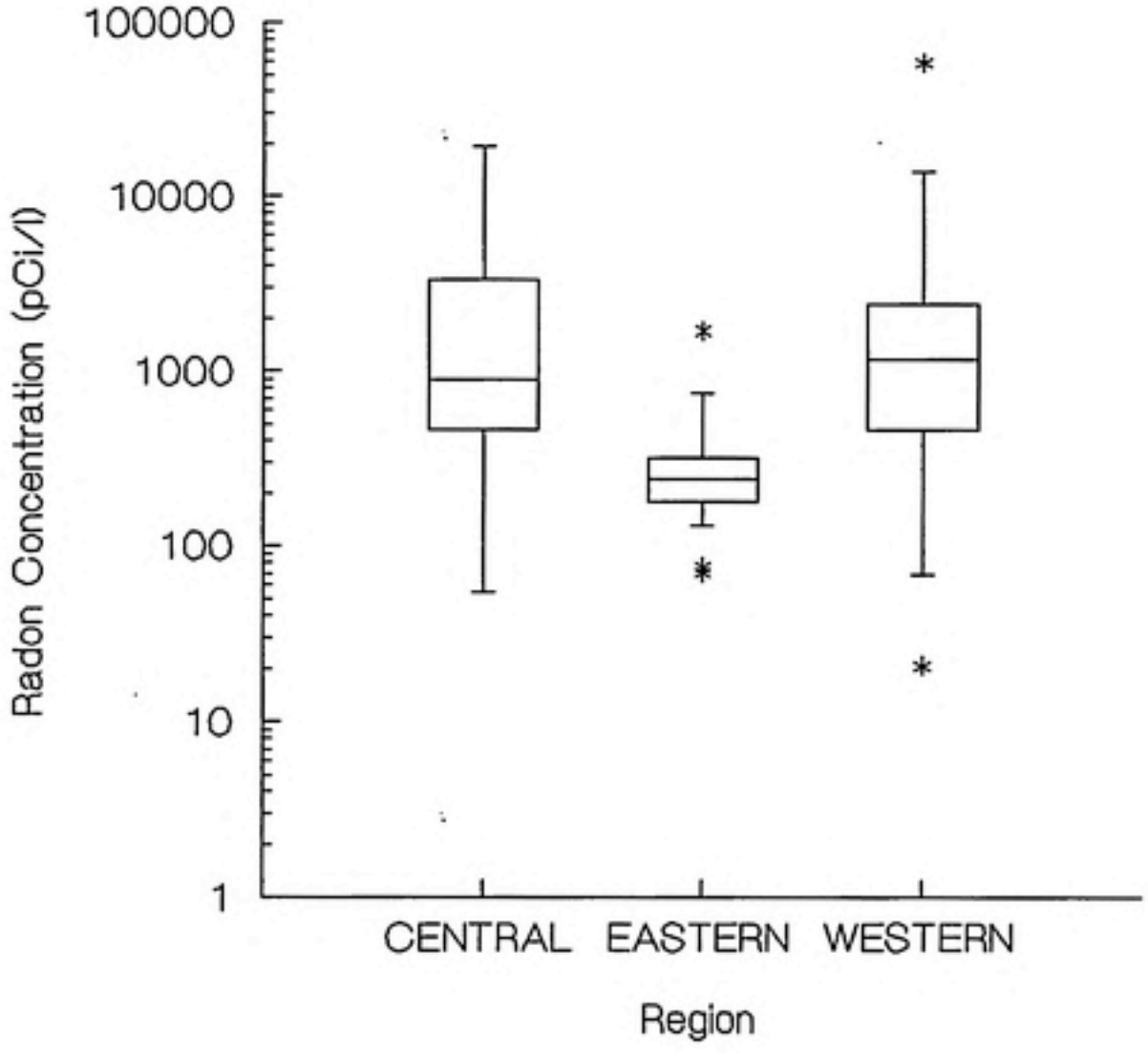

Figure 8. Box plots for the three regions. Each box shows the range of the middle 50% of the results, the sample median, and the normal range of the data. Outliers are represented by asterisks.

101, which is well above the critical value of 3.8 for the 95% confidence level, indicating a significant difference at the 95% confidence level. The *F* statistic for the comparison between results for the central and western regions is 1.4, which is below the critical value of 3.8 for the 95 % confidence level.

Comparison with the EPA's MCL

The eastern region also differed from the central and western regions in the percentage of observations above the EPA's proposed MCL of 300 pCi/l. Table 4 shows the percentages of results above cut points of 300; 1,000; 5,000; and 10,000 pCi/l for each region and the state as a whole. Thirty-three percent of the results in the eastern region were greater than the MCL, while in the central and western regions 84% and 81%, respectively, exceeded it.

Table 4. Distribution of Results (pCi/l)

Region	>300 (%)	>1,000 (%)	>5,000 (%)	>10,000 (%)
Eastern	33	4	0	0
Central	84	47	20	12
Western	81	55	9	2
State	68	38	10	4

Also of interest is the percentage of observations greater than 10,000 pCi/l, the waterborne concentration that will contribute approximately 1 pCi/l to the indoor air concentration in

a home. Statewide, 4% of the results exceeded this level. The highest regional percentage was 12% in the central region.

Air Concentration Versus Water Concentration

The measured water concentrations were compared with the available air concentration data from the State/EPA survey. Air concentration data were available for 164 of the 174 homes surveyed. Fig. 9 shows a semilog scatter plot of air concentration versus water concentration for all observations overlaid with a least-squares linear regression line. The least-squares line has a positive slope, indicating an increase in air concentration with water concentration. However, the coefficient of determination r^2, or model r-square, for the linear regression on the log-transformed data is 0.195, indicating a weak linear relationship between air concentrations and water concentrations.

Comparison of Duplicate Samples

Samples were collected in pairs for comparison as a measure of the precision of the water analysis technique employed. In 12 cases samples were received that had one broken vial. A total of 162 duplicates were compared.

The frequency distribution of percent difference between results for duplicate samples shown in Fig. 10 best summarizes the comparison of the duplicates. It can be seen that pairs differing by 10% or less accounted for the greatest proportion of pairs.

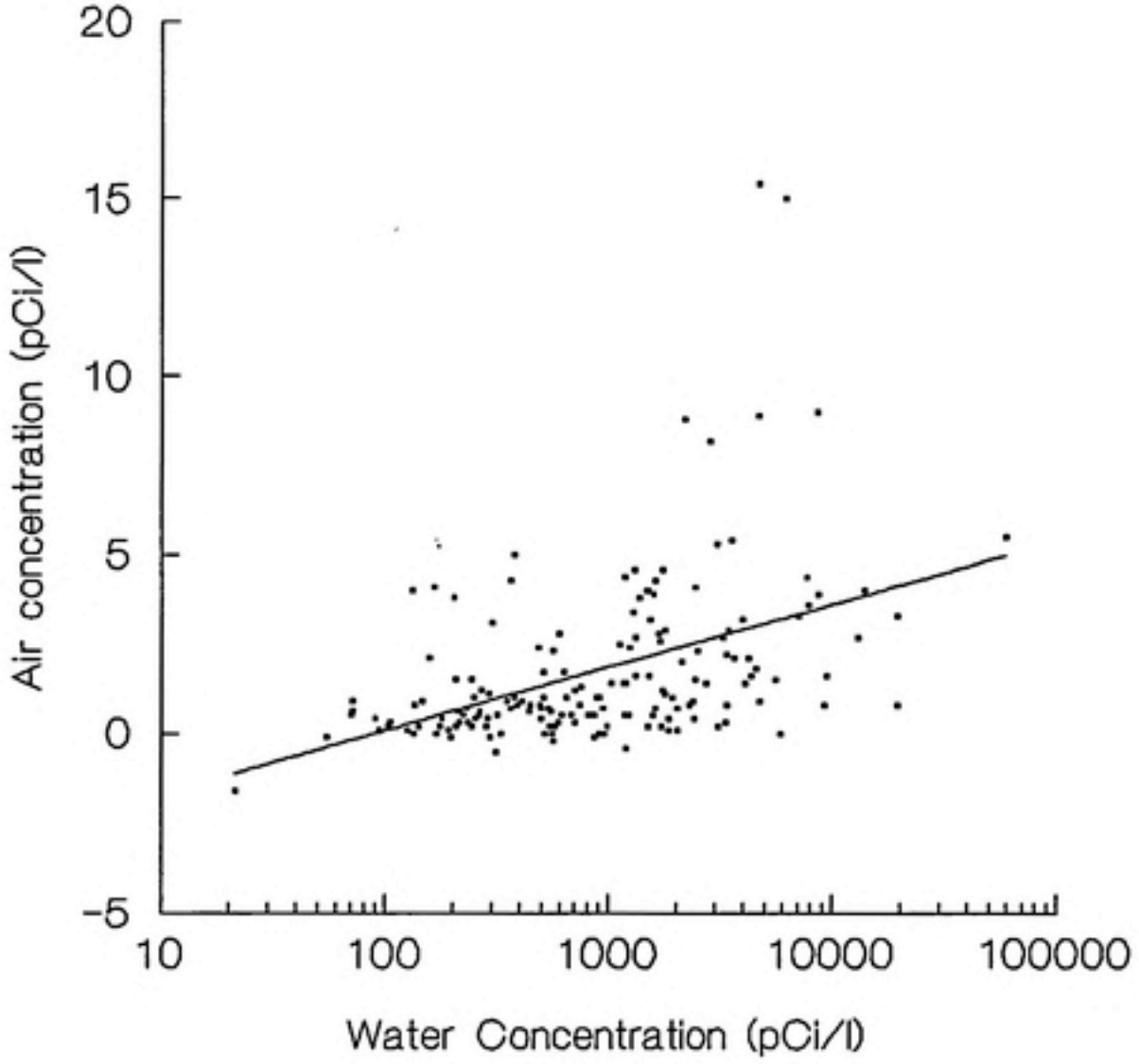

Figure 9. Scatter plot of air concentration versus water concentration with a linear regression overlaid.

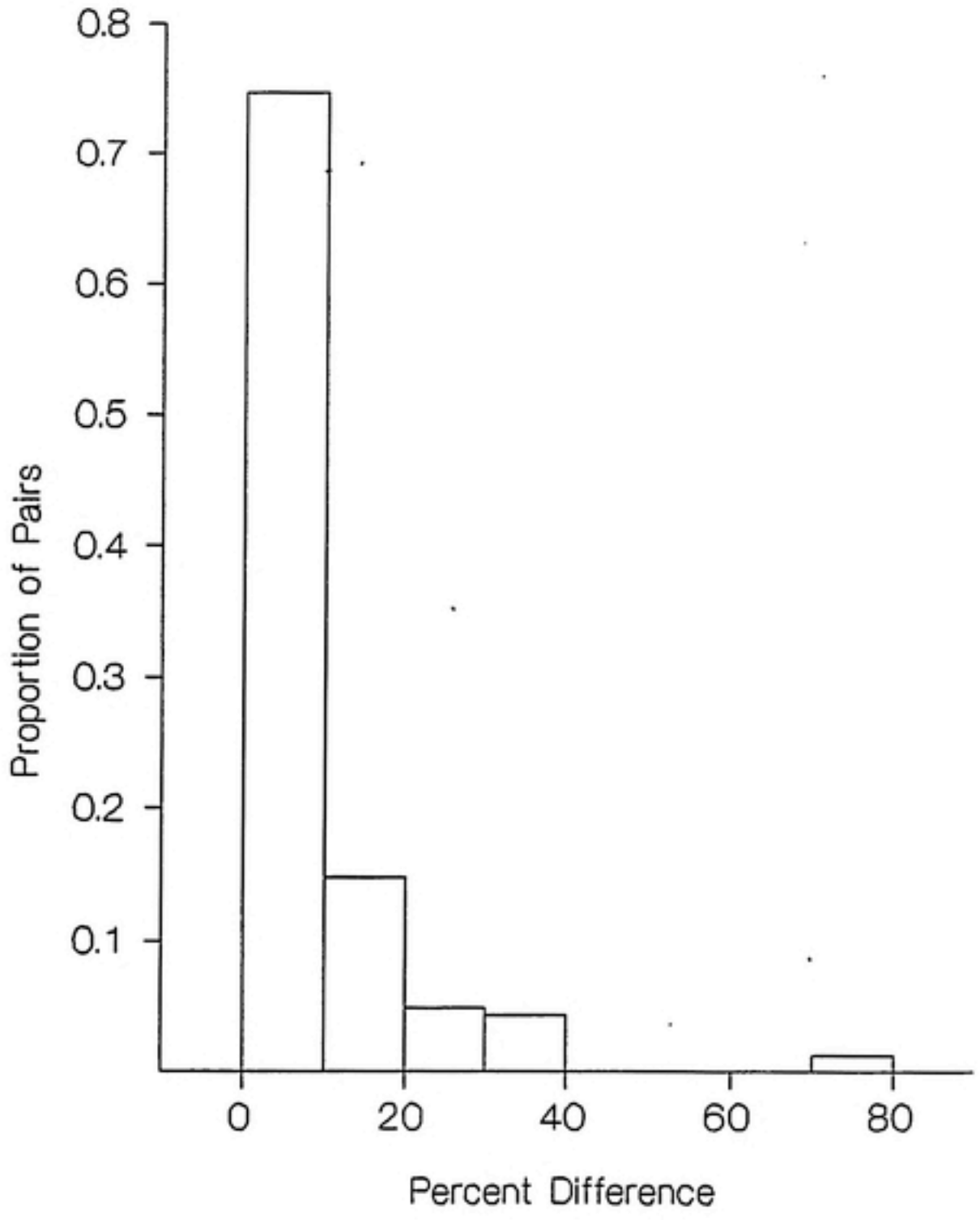

Figure 10. Frequency distribution of the percent differences of sample duplicates.

Approximately 75% of the pairs differed by less than 10%. The proportion of pairs differing by 20% or less, determined by adding the first two bars, was 0.9, or 90%.

Discussion

It is estimated that 55% of North Carolinians live in homes served by groundwater (personal communication with William C. Jeter, Groundwater Section, N.C. Division of Environmental Management). Therefore, based on the U.S. Census of 1990 which recorded over 6.5 million residents; approximately 3.8 million North Carolinians live in homes served by groundwater. The average radon concentration for groundwater of approximately 2,000 pCi/l found in this survey translates into a continuous radon inhalation exposure of 0.2 pCi/l. This waterborne radon contributes an additional 2×10^5 Person Working Level Months of exposure in the state each year. Based on the risk estimate of 350 cancer deaths per 10^6 Person Working Level Months, 70 additional cancer deaths per year would be estimated for this level of exposure. It should be noted that several variables can greatly influence this estimate, such as the time a person actually spends in the home, the transfer ratio of radon from water to air, and the degree to which the home retains radon.

The exposure to airborne radon originating in groundwater does not appear to present as great a risk as the exposure to radon from soil gases trapped by most homes. The ambient outdoor

airborne radon concentration is approximately 0.2 pCi/l, and the State/EPA survey of North Carolina homes found an average indoor concentration of 1.4 pCi/l.

It is not surprising that a strong association between airborne and waterborne radon concentrations was not observed in this investigation. Indoor air concentrations of radon are influenced by many factors that could not be controlled or accounted for by this survey. Waterborne radon contributes to indoor air concentrations, but the main source of airborne radon is soil emissions. There are also variables unique to each home that affect the indoor air concentration, such as the permeability of the ground floor to soil gases and the rate of air exchange. Even in the case where waterborne radon is the sole or main contributor, water usage activities such as showering, clothes washing, dish washing and the amount of hot water used are variables unique to each house that affect the rate of transfer of radon from water to air.

The observation that the eastern region of the state has lower groundwater concentrations of radon agrees with previous measurements in North Carolina. Loomis et al. (1987) observed that the geologic region known as the coastal plain, which comprises the eastern region delineated in this survey, had significantly lower radon concentrations in groundwater than the other geologic regions of the state. Also, the measurements compiled by Dusenbury (1992) show lower concentrations for most of the eastern counties when compared to the rest of the state.

Conclusions

One hundred seventy-four homes were successfully surveyed for groundwater radon concentrations. The statewide average concentration was 2,229 pCi/l. The eastern region of the state had a markedly lower average concentration of 337 pCi/l. Sixty-eight percent of the measured concentrations were above the U.S. Environmental Protection Agency's proposed maximum contaminant level of 300 pCi/l. The comparison of indoor airborne concentrations to waterborne concentrations revealed a weak linear relationship between them.

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APPENDIX A

INSTRUCTIONS

1. Preparation
   - Check the contents of the mailing tube. DO NOT THROW AWAY THE TUBE. You should have the following items:
     Reusable mailing tube
     Reusable packing material
     Return address label and postage
     2 glass vials with plastic caps (note: the liquid in the vials is mineral oil and is <u>not</u> hazardous)
   - You also need a pencil or pen and a clock.
   - Choose a faucet in your house that does not have an aerator or any other attachments. If this is not possible, then remove the aerator or attachment from a faucet.

2. Taking the samples
   - Turn the COLD water on all the way and let it run for five (5) minutes.
   - After five (5) minutes turn the water flow down to a <u>slow stream.</u>
   - Carefully fill each vial to the neck; try not to overfill the vials.
   - Immediately put the cap on each vial. Make sure the caps are tight.
   - Record the date & time below
     Date_____
     Month/Day/Year
     Time_____ AM PM (circle one)
     ID#_____

3. Returning the samples
   - Carefully wrap the vials in the packing material and place them in the mailing tube.
   - Place these instructions in the tube (be sure you recorded the date and time above).
   - Attach the return label to the tube.
   - Mail Immediately. Any delay will cause the samples to go bad.

APPENDIX B

PACKARD TRI-CARB 300 LSC PROGRAM SETTINGS

Terminators: minutes=50, 2σ % deviation=2
Radionuclide=manual
Windows: A: LL=0 KeV UL=2000 KeV
B: LL=5 KeV UL=1850 KeV
C: LL=0 KeV UL=5 KeV
QIP=yes
AEC=no
SCR=A/B
# vials/std=1, #vials/sample=1, #counts/vial=1
BKG=manual: A=0, B=0, C=0
% of standard=no
low cpm reject: A=0, B=0, C=0
Divide factor K=1
Data mode=cpm

Note: Gross counts are taken from window B (5 to 1850 KeV).

APPENDIX C

BACKGROUND VALUES

Background no.1 (cpm)	Background no.2 (cpm)	Average (cpm)
30.04	29.62	29.83
31.00	28.72	29.86
29.04	30.88	29.96
29.80	30.32	30.06
31.50	28.90	30.20
30.82	29.62	30.22
30.70	30.02	30.36
30.70	30.16	30.43
31.06	29.80	30.43
30.86	30.20	30.53
31.42	29.66	30.54
30.50	30.74	30.62
30.92	30.34	30.63
30.90	30.38	30.64
31.56	30.18	30.87
31.16	30.70	30.93
30.90	31.14	31.02
32.28	29.78	31.03
31.50	30.70	31.10
31.26	31.02	31.14
32.20	30.26	31.23
31.60	31.12	31.36
32.28	30.56	31.42
32.14	30.86	31.50
32.98	30.10	31.54
31.64	31.60	31.62

Background no.1 (cpm)	Background no.2 (cpm)	Average (cpm)
30.04	29.62	29.83
31.88	31.46	31.67
30.68	32.74	31.71
32.66	30.86	31.76
32.50	31.10	31.80
32.40	31.50	31.95
32.76	31.26	32.01
31.12	33.16	32.14
32.54	31.96	32.25
31.88	32.72	32.30
33.00	31.64	32.32
32.30	32.48	32.39
32.38	32.56	32.47
32.00	33.00	32.50

APPENDIX D

STANDARD COUNTS AND CALIBRATION FACTORS

714 pCi Standard (cpm)	952 pCi Standard (cpm)	Calibration Factor (cpm/pCi)
7058.39	9067.29	9.68
7045.25	9081.31	9.68
7147.41	9261.91	9.85
7227.61	9191.51	9.86
7091.18	9398.06	9.90
7239.55	9269.52	9.91
7170.37	9339.42	9.91
7203.70	9321.15	9.92
7070.80	9481.55	9.94
7367.67	9190.57	9.94
7239.85	9324.04	9.94
7301.50	9335.24	9.99
7211.94	9433.98	9.99
7182.96	9481.55	10.00
7261.94	9444.66	10.03
7327.07	9385.58	10.03
7307.52	9406.80	10.03
7292.48	9427.18	10.04
7384.85	9375.96	10.06
7231.34	9552.94	10.07
7318.04	9488.35	10.09
7283.58	9529.41	10.09
7261.19	9560.78	10.10
7255.97	9582.35	10.11
7332.58	9515.69	10.11
7421.37	9431.07	10.12

714 pCi Standard (cpm)	952 pCi Standard (cpm)	Calibration Factor (cpm/pCi)
7058.39	9067.29	9.68
7348.48	9508.74	10.12
7355.30	9510.78	10.12
7244.03	9630.69	10.13
7349.24	9529.41	10.13
7334.85	9561.76	10.14
7383.21	9516.67	10.14
7397.71	9524.51	10.16
7493.80	9431.07	10.16
7428.24	9535.29	10.18
7280.60	9726.00	10.21
7462.60	9550.98	10.21
7423.26	9639.60	10.24
7423.66	9670.30	10.26

APPENDIX E

INDIVIDUAL SAMPLE RESULTS

EPA Case no.	Result no. 1 (pCi/l)	Result no. 2 (pCi/l)	Average (pCi/l)	Standard Deviation σ
NC00163	N/A	377	377	18
NC00166	964	1001	983	17
NC00175	273	197	235	14
NC00176	486	535	510	31
NC00180	1454	1523	1489	22
NC00188	207	215	211	13
NC00198	554	643	598	19
NC00199	849	883	866	18
NC00203	193	209	201	11
NC00204	301	323	312	14
NC00207	587	528	558	16
NC00208	452	420	436	15
NC00228	356	402	379	27
NC00229	120	130	125	10
NC00231	125	85	105	15
NC00236	1553	1609	1581	33
NC00240	513	609	561	14
NC00250	1664	1691	1678	37
NC00254	296	191	243	60
NC00255	416*	111*	263	188
NC00257	225	273	249	10
NC00261	4795	4723	4759	212
NC00269	2109	2117	2113	23
NC00276	4026	4152	4089	32
NC00277	1845	1623	1734	125

EPA Case no.	Result no. 1 (pCi/l)	Result no. 2 (pCi/l)	Average (pCi/l)	Standard Deviation σ
NC00281	236	251	243	12
NC00282	22*	21*	21	14
NC00283	14193	13551	13872	100
NC00286	1809	1745	1777	25
NC00316	553	574	563	82
NC00329	241	172	207	23
NC00330	N/A	268	268	14
NC00333	537	558	548	15
NC00341	2349	2158	2298	19
NC00359	19450	19453	19451	156
NC00383	7099	8225	7662	57
NC00404	293	296	295	21
NC00418	536	500	518	17
NC00422	240	263	251	18
NC00423	3908	3349	3628	53
NC00428	1471	1576	1523	30
NC00439	1148	1089	1119	26
NC00441	498	480	489	12
NC00454	498	N/A	498	21
NC00465	496	N/A	497	20
NC00465	1728	1663	1695	17
NC00467	12937	13276	13106	96
NC00475	360	341	351	18
NC00485	1513	1529	1520	18
NC00492	900	872	886	21
NC00495	1111	1270	1191	45
NC00509	355	218	287	14
NC00512	3278	3396	3337	26

EPA Case no.	Result no. 1 (pCi/l)	Result no. 2 (pCi/l)	Average (pCi/l)	Standard Deviation σ
NC00521	247	228	237	23
NC00522	5592	N/A	5592	97
NC00533	97	109	103	11
NC00536	2616	2494	2555	21
NC00542	1431	1560	1496	64
NC00549	5583	5994	5789	50
NC00550	735	682	708	12
NC00556	201	192	197	22
NC00575	2360	2387	2374	23
NC00578	2393	2424	2408	20
NC00586	1610	1596	1603	26
NC00591	7806	N/A	7806	132
NC00600	963	943	953	30
NC00608	861	844	853	17
NC00618	268	334	301	10
NC00631	784	842	813	19
NC00636	681	673	677	20
NC00663	596	544	570	15
NC00668	1568	1571	1569	18
NC00670	740	670	705	14
NC00674	927	926	926	18
NC00676	1854	N/A	1854	90
NC00679	454	514	484	16
NC00680	1396	1332	1364	18
NC00683	754	740	747	71
NC00686	2875	2817	2846	31
NC00693	4643	4728	4685	41
NC00701	327	N/A	327	27

EPA Case no.	Result no. 1 (pCi/l)	Result no. 2 (pCi/l)	Average (pCi/l)	Standard Deviation σ
NC00704	396	240	318	52
NC00738	1796	1770	1783	26
NC00739	403	405	404	17
NC00742	3118	2954	3036	31
NC00745	1297	1269	1283	16
NC00752	204	224	214	17
NC00760	3358	3360	3359	44
NC00780	617	N/A	617	75
NC00790	2000	2043	2021	22
NC00798	858	1022	940	22
NC00800	79	63	71	9
NC00802	84	68	76	9
NC00808	40	70	55	12
NC00821	6270	5429	5850	46
NC00823	1196	1133	1164	21
NC00825	1751	1628	1690	17
NC00835	8538	8737	8637	66
NC00838	3597	3507	3552	29
NC00845	1189	N/A	1189	40
NC00877	58843	59333	59088	421
NC00880	3414	3464	3439	27
NC00892	354	377	365	26
NC00895	152	117	134	12
NC00900	1519	1443	1481	20
NC00907	81	62	71	10
NC00921	249	211	230	14
NC00923	915	899	907	25
NC00924	385	391	388	15

EPA Case no.	Result no. 1 (pCi/l)	Result no. 2 (pCi/l)	Average (pCi/l)	Standard Deviation σ
NC00931	150	164	157	12
NC00934	516	507	511	14
NC00936	2511	2509	2510	21
NC00945	3263	3209	3236	26
NC00948	2180	N/A	2180	26
NC00953	141	124	133	11
NC00963	167	172	169	19
NC00973	594	666	630	17
NC00975	1162	1199	1181	28
NC00977	634	555	595	22
NC00978	208	205	206	10
NC00989	1796	1692	1744	18
NC00996	1787	2060	1923	21
NC01004	894	825	859	16
NC01007	190	257	224	18
NC01022	92	88	90	10
NC01025	98	90	94	10
NC01051	291	275	283	19
NC01057	19664	19452	19558	142
NC01083	1860	1846	1853	23
NC01084	1654	1578	1616	27
NC01095	4004	3940	3971	32
NC01098	2536	2347	2442	28
NC01104	174	157	166	12
NC01120	892	919	906	13
NC01135	280	247	264	21
NC01136	157	105	131	15
NC01139	590	702	646	13

EPA Case no.	Result no. 1 (pCi/l)	Result no. 2 (pCi/l)	Average (pCi/l)	Standard Deviation σ
NC01141	428	463	445	17
NC01147	8242	8724	8483	64
NC01157	141	141	141	11
NC01175	241	165	203	16
NC01181	280	303	292	11
NC01187	68	73	70	8
NC01211	2039	1986	2012	25
NC01212	156	137	146	14
NC01229	4277	4148	4212	35
NC01232	4560	4801	4680	39
NC01235	7107	7071	7089	53
NC01238	1265	1366	1316	30
NC01241	3537	3207	3372	27
NC01250	1065	983	1024	23
NC01251	1735	1694	1715	22
NC01254	194	187	191	12
NC01267	2465	2410	2438	21
NC01279	407	315	361	13
NC01289	4333	4318	4325	35
NC01293	1382	1223	1302	23
NC01297	178	180	179	11
NC01304	161	189	175	19
NC01308	9197	N/A	9197	96
NC01312	9007	9231	9119	67
NC01325	1193	1258	1225	19
NC01326	1257	1214	1236	21
NC01329	762	721	741	16
NC01331	568	518	543	17

EPA Case no.	Result no. 1 (pCi/l)	Result no. 2 (pCi/l)	Average (pCi/l)	Standard Deviation σ
NC01340	1283	1352	1317	21
NC01343	2747	2695	2721	25
NC01352	717	778	748	24
NC01362	9352	9429	9391	73
NC01388	1198	1166	1182	26
NC01389	4575	4539	4557	36
NC01396	3122	3058	3090	33
NC01399	6305	5997	6151	47
NC01402	537	530	534	13

N/A No sample available for analysis.
* Result below the decision limit (L_c).