♻EPA # METHODS, OCCURRENCE AND MONITORING DOCUMENT FOR RADON FROM DRINKING WATER

PUBLIC COMMENT DRAFT

Acknowledgments

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1. INTRODUCTION

1.1 Purpose of This Document

This Methods, Occurrence, and Monitoring (MOM) Document has been developed by EPA in support of the rulemaking process for radon in drinking water. The Agency is proposing a Maximum Contaminant Level Goal (MCLG) and National Primary Drinking Water Regulations (NPDWR) for radon-222 in public water supplies (EPA, 1999a). The purposes of this document are:

- Identification of available analytical methods for monitoring radon in groundwater sources and in drinking water,

- Discussion of the patterns of occurrence of radon in groundwater and drinking water, and

- Explanation of alternative monitoring schemes for assuring compliance with the proposed rule.

1.2 Statutory Requirements

The 1996 Amendments to the Safe Drinking Water Act (PL 104-182) establish a new charter for public water systems, states, tribes, and EPA to protect the safety of drinking water supplies. Among other mandates, Congress amended Section 1412 to direct EPA to take the following actions regarding radon in drinking water.

Withdraw the 1991 Proposed Regulation for Radon

Congress specified that EPA should withdraw the drinking water standards proposed for radon in 1991.

Arrange for a National Academy of Sciences Risk Assessment.

The amendments in § 1412(b)(13)(B) require EPA to arrange for the National Academy of Sciences (NAS) to conduct an independent risk assessment for radon in drinking water and an assessment of the health risk reduction benefits from various mitigation measures to reduce radon in indoor air.

Set an MCLG, MCL, and BAT for Radon-222

Congress specified in § 1412 (b)(3)(C) that EPA should propose a new MCLG and NPDWR (an MCL, BAT, and monitoring, reporting, and public notification requirements) for radon-222 by August, 1999. EPA is also required to finalize the regulation by August, 2000. As a preliminary step, EPA was required to publish a radon health risk reduction and cost analysis

(HRRCA) for possible radon MCLs for public comment by February, 1999. This analysis must consider seven topics: (1) health risk reduction benefits that come directly from controlling radon; (2) health risk reduction benefits likely to come from reductions in contaminants that occur with radon; (3) costs; (4) incremental costs and benefits associated with each MCL considered; (5) effects on the general population and on groups within the general population likely to be at greater risk; (6) any increased health risk that may occur as the result of compliance; and (7) other relevant factors, including the quality and extent of the information, the uncertainties in the analysis, and factors with respect to the degree and nature of the risk.

Set an Alternative MCL (AMCL) and Develop Multimedia Mitigation (MMM) Program Guidelines

The amendments in § 1412(b)(13)(F) introduce two new elements into the radon in drinking water rule: (1) an Alternative Maximum Contaminant Level (AMCL) and (2) radon multimedia mitigation (MMM) programs. If the MCL established for radon in drinking water is more stringent than necessary to reduce the contribution to radon in indoor air from drinking water to a concentration that is equivalent to the national average concentration of radon in outdoor air, EPA is required to simultaneously establish an AMCL. The AMCL would be the standard that would result in a contribution of radon from drinking water to radon levels in indoor air equivalent to the national average concentration of radon in outdoor air. If an AMCL is established, EPA is to publish guidelines for state multimedia mitigation (MMM) programs to reduce radon levels in indoor air. Section V describes what a state or public water system must have in their multimedia mitigation program.

Evaluate Multimedia Mitigation Programs Every Five Years

Once the MMM programs are established, EPA must re-evaluate them no less than every five years. [§1412(b)(13)] EPA may withdraw approval of programs that are not expected to meet the requirement of achieving equal or greater risk reduction.

DevelopMonitoring Requirements and Characterize Contaminant Occurrence

Under every SDWA rule, EPA is required to develop monitoring requirements to assure compliance with the rule. Water systems are responsible for conducting monitoring of drinking water to ensure that it meets all drinking water standards. To do this, water systems and states use analytical methods developed by government agencies, universities, and other organizations.

EPA is responsible for evaluating analytical methods developed for drinking water and approves those methods that it determines meet Agency requirements Laboratories analyzing drinking water compliance samples must be certified by the EPA or the state. Chapter 2 of this document reviews the available analytical methods for radon in drinking water and their performance and costs.

EPA must also characterize the sources of drinking water contaminants, their fate and transport properties, and how they relate to potential exposures. Available data related to the occurrence of contaminants must be evaluated, and the patterns of occurrence across different regions of the country, different types of water systems (community and non-community) and in water systems of different sizes, must also be evaluated in order to develop a national picture of the distribution of contaminants. The degree to which the occurrence of the contaminant is correlated with that of other contaminants must also be evaluated. Chapters 3 through 7 of this document address these issues.

Whether addressing a regulated or unregulated contaminants, EPA establishes requirements as to how often water systems must monitor for the presence of the subject contaminant. Water systems serving larger populations generally must conduct more monitoring (temporally and spatially) because there is a greater potential human health impact of any violation, and because of the physical extent of larger water systems (e.g., miles of pipeline carrying water). Small water systems can receive variances or exemptions from monitoring in limited circumstances. In addition, under certain conditions, a state may have the option to modify monitoring requirements on an interim or a permanent basis for regulated contaminants, with a few exceptions. Chapter 8 of this document discusses monitoring strategies for determining compliance with the proposed rule.
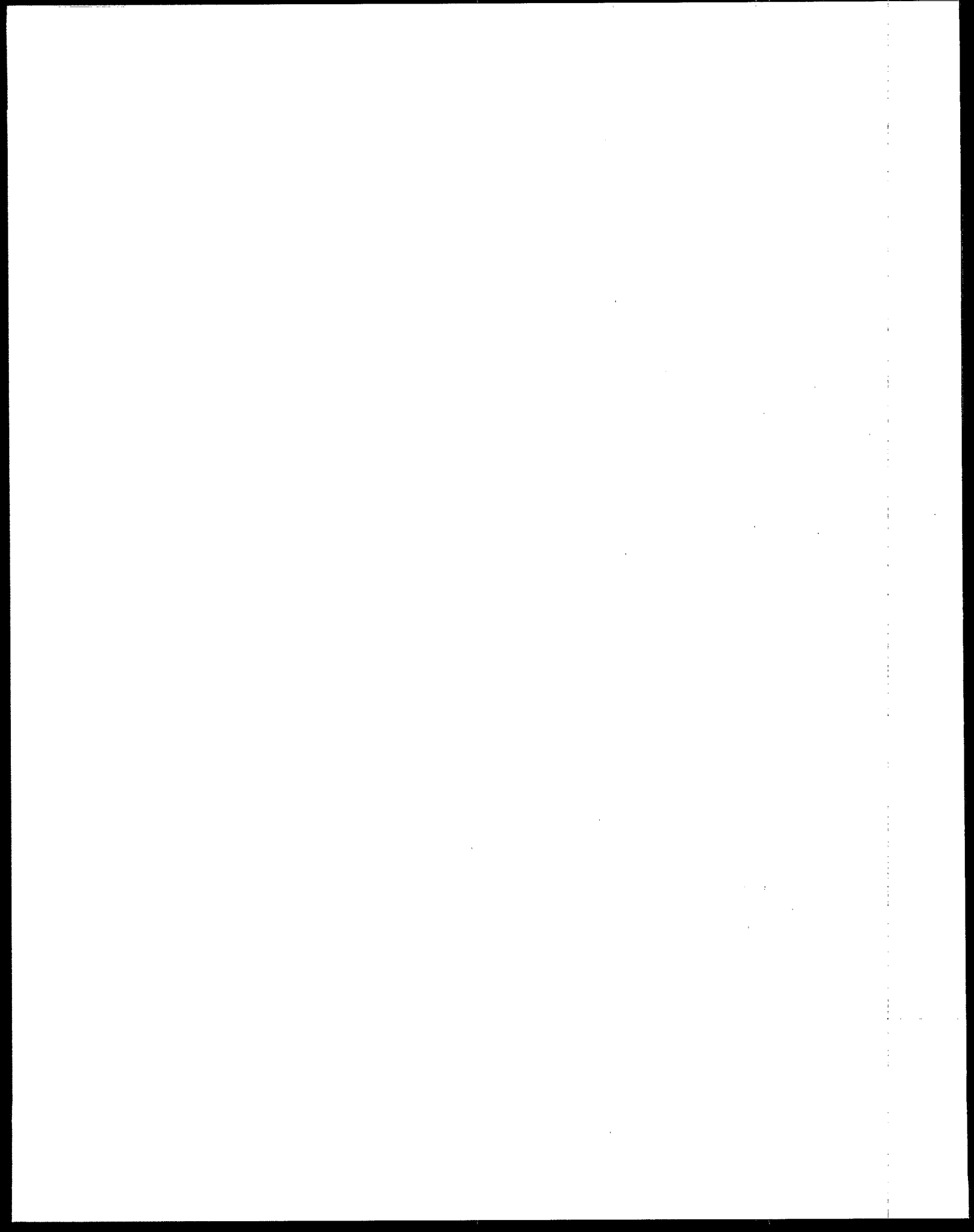
2. ANALYTICAL METHODS

2.1 Introduction

This chapter addresses the analytical methods that may be applicable to the measurement of radon in drinking water samples. It does *not* recommend a specific method for radon analyses, but rather, identifies possible candidate techniques and evaluates the extent to which the performance of those techniques has been demonstrated.

As part of its overall responsibility for regulating the nation's drinking water supplies, in 1991 EPA proposed regulations on various radionuclides under 40 CFR Parts 141 and 142 (July 18, 1991, FR 56 [138]: 33050-33127). Although eventually withdrawn, part of that proposal addressed the regulation of radon (^{222}Rn or radon-222). Among other topics, the proposal discussed methods for the analysis of radon in drinking water.

As EPA prepares to propose new regulations for radon in drinking water, the Agency has reviewed and updated the information on the analytical techniques that appeared in the 1991 proposal (EPA 1991). Specifically, in 1998, at EPA's direction, SAIC reviewed the information in the 1991 proposal and also conducted an electronic literature search to identify additional analytical techniques that might be used to measure the concentration of radon in drinking water. The focus of the 1998 effort was to determine if new monitoring techniques had become available since the 1991 proposal. The techniques identified by that search were further evaluated to determine their performance capabilities and possible costs. The remainder of this chapter addresses the following aspects of the techniques:

- Inventory of methods
- Performance capabilities of the methods
- Skill requirements
- Practical availability of methods
- Anticipated unit costs
- Practical performance and analytical uncertainties
- Degree to which each method meets EPA's regulatory needs

This last section summarizes the results of the review of the analytical techniques relative to EPA's need for a method for a nationwide compliance monitoring program. The focus of this section is on techniques for the analysis of radon in drinking water, and as such, does not attempt to review information relevant to the analysis of other environmental matrices.

2.1   Inventory of Methods

The 1991 EPA proposal focused on two techniques for the analysis of radon in drinking water: liquid scintillation counting and the Lucas cell. The 1991 discussion of these techniques is summarized in Sections 2.1.1 and 2.1.2, below.

Five newer techniques, or combinations of techniques, were identified in an electronic search of the open literature. Because EPA had reviewed older analytical techniques prior to proposing the radionuclides rule in 1991, the search was constrained to identify publications that have appeared since 1990, in an effort to identify newer techniques that may not have been considered in conjunction with the 1991 proposed rule on radionuclides. The discussion of the five newer techniques is presented in Sections 2.3.1 to 2.3.5.

2.1.1   Liquid Scintillation Counting

Radon is an alpha-emitting radionuclide and is just one of 14 radionuclides in what is known as the "uranium series," the term used to describe the chain of 15 elements that begins with ^{238}U and ends with ^{206}Pb, a stable (non-radioactive) element. ^{222}Rn is the seventh element in the series, created as a decay product of ^{226}Ra. Radon undergoes radioactive decay itself, forming ^{218}Po through the loss of an alpha particle. Polonium decays through the emission of a beta particle to form ^{214}Pb. The portion of the decay series from radon onward is illustrated in the Exhibit 2-1, and includes the manner of the decay (alpha or beta particle) and the half-life of each element.

Exhibit 2-1. Radon Decay Series

Element	Decay Emission	Half-life
^{222}Rn	alpha	3.8 days
^{218}Po	alpha	3 minutes
^{214}Pb	beta	27 minutes
^{214}Bi	beta	20 minutes
^{214}Po	alpha	1.6×10^{-4} seconds
^{210}Pb	beta	22.3 years
^{210}Bi	beta	5 days
^{210}Po	alpha	138 days
^{206}Pb	beta	stable

Radon's alpha particle emissions can be used as the basis for measuring radon in a variety of environmental media. The principal technique for radon analysis considered by EPA in the 1991 proposal was liquid scintillation counting.

Scintillation counting refers to the measurement of the light emitted when an alpha particle from the sample strikes some form of scintillating material. The two most common forms of scintillators are the scintillation disk, with is a planchet or metal disk coated with zinc sulfide, and a liquid scintillation fluid or an organic phosphor. The light emitted from the scintillator strikes the surface of a photomultiplier tube that is placed next to the sample in a light-proof container, releasing electrons from the photocathode in the tube at levels proportional to the intensity of the emitted light. The electrical pulses that result are counted to determine the number of disintegrations per minute (dpm) that occur, which can be related to the concentration of a given radionuclide.

In liquid scintillation counting, a volume of sample is mixed with the organic phosphor contained in a mineral oil solution or "cocktail" in a glass container which is then placed in the instrument, where it is held against the photomultiplier for counting.

As noted in the 1991 proposal, radon can be measured through a direct, low-volume liquid scintillation technique in which approximately 10 ml of water is added to a vial with the scintillation cocktail, mixed, and placed in a liquid scintillation counter. The sample can be left in the counter for periods ranging from several minutes to several hours, depending on the level of radon in the sample.

The energy of the alpha particles released by radioactive decay is characteristic of the radionuclide. In the case of liquid scintillation counting techniques, the counting apparatus can be configured to measure the scintillations is narrow energy ranges across the emission spectrum. In the case of radon analyses the counter can set to look in the portion of the energy spectrum that represents the alpha particles emitted by ^{222}Rn and as well as ^{218}Po and ^{214}Po, the next two alpha-emitting daughters in the series. Given the short half-lives of these two daughters, their alpha particle emissions can be measured along with that of the radon itself in less than an hour of counting time. From a practical standpoint, the emissions of three alpha particles can be measured and related back to one radon atom, thereby amplifying the signal from that single radon atom's decay.

It is important to distinguish between an analytical technique and a specific analytical method. Liquid scintillation counting is a technique. EPA's 1991 proposal stated that the Agency planned to establish a specific analytical method, EPA Method 913, based on the liquid scintillation technique.

2.1.2 The Lucas Cell Technique

The second technique that EPA considered in the 1991 proposal involved the Lucas cell, a specially constructed 100- to 125-ml metal cup coated on the inside with zinc sulfide (a scintillator) and fitted with a transparent window. The Lucas cell replaces the scintillation disk or planchet in the counting instrument. The analysis of radon in a water sample is accomplished by purging a volume of the sample with radon-free helium or "aged" air (air in which the radon has already decayed). The purge gas removes the dissolved radon from the sample and carries it into a Lucas cell that has been evacuated of any air. After an equilibration period of three to four hours, the Lucas cell is placed in the counter and the scintillations resulting from the alpha particles striking the zinc sulfide are counted through the transparent window.

The Lucas cell technique is a modification of other scintillation counting techniques and was considered by EPA because it can permit the measurement of lower levels of radon than in the liquid scintillation technique. However, the Agency noted that the method is more difficult to use than the liquid scintillation method, in particular, requiring specialized glassware and greater skill on the part of the analyst. It was the Agency's intent to include procedures for the Lucas cell technique in Method 913, as an adjunct to the liquid scintillation procedures.

2.2 Major Analytical Methods

2.2.1 Liquid Scintillation Counting and Lucas Cell Methods

Subsequent to the 1991 proposal, EPA published a report on its method validation efforts in fiscal year 1992 (Pia and Hahn 1992). That report described the results of collaborative studies for the analysis of radon in drinking water and provided performance data on both the direct low-volume liquid scintillation technique and the Lucas cell technique that the Agency planned to incorporate into Method 913.

The 1992 study evaluated both the liquid scintillation technique and the Lucas cell technique for the analysis of performance evaluation samples spiked with radon at levels of 111 and 153 picoCuries per liter (pCi/L).[1] The 1992 study also investigated two means of spiking the samples. The first sample was spiked with radium (^{226}Ra), which produces radon as a decay product. The second sample was produced using a "radon generator" in which ^{226}Ra was bound to a strong cation exchange resin. The decay of the radium released radon into the water, while the remaining radium was still bound to the resin and therefore not present in dissolved form in

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[1] The Curie is a measure of a quantity of radioactive material. Specifically, a Curie is defined as the quantity of a radioactive nuclide which produces 3.7×10^{10} atomic disintegrations per second. The prefix "pico" stands for one trillionth (10^{-12}), thus, a picoCurie would be 3.7×10^{-2} atomic disintegrations per second.

the sample. The data from the 1992 study are summarized Exhibit 2-2, for both techniques, both radon concentrations, and both sources of radon.

Exhibit 2-2. Summary of EPA 1992 Collaborative Study Data

Technique [1]	Spike Conc. (pCi/L)	Mean Conc. Found (pCi/L)	Mean Recovery (%)	Precision within Lab (pCi/L)	Reproducibility (pCi/L)	% Bias
LSC Ra	111	112	101	9	12	0.7
LCS Rn	111	112	101	14	24	1.1
LC Ra	111	114	102	9	12	2.3
LC Rn	111	127	114	16	23	14.5
LCS Ra	153	156	102	10	18	2.3
LSC Rn	153	154	101	17	28	0.9
LC Ra	153	158	103	10	16	3.4
LC Rn	153	174	114	17	28	13.7

1 LSC Ra = Liquid scintillation counting of samples spiked with ^{226}Ra
  LSC Rn = Liquid scintillation counting of samples spiked with radon generator
  LC Ra = Lucas cell counting of samples spiked with ^{226}Ra
  LC Rn = Lucas cell counting of samples spiked with radon generator

Another important aspect of the EPA 1992 collaborative study were the findings with regard to sampling, sample containers, and sample handling. EPA conducted single-laboratory studies that were designed to evaluate factors related to sampling methods for proficiency testing of radon laboratories. Such performance evaluation (PE) samples have been used as an important aspect of EPA's certification program for laboratories performing analyses under the Safe Drinking Water Act monitoring programs. The 1992 report describes studies of four sample collection techniques (displacement, immersion, catch, and grab sampling). EPA also evaluated the effectiveness of two types of scintillation vial cap materials (polypropylene and PTFE-lined caps) at maintaining the integrity of the samples. The effects of headspace or bubbles in the sample containers were also evaluated.

The analysis of sampling techniques found that the four techniques were statistically equivalent, in that no systematic error was introduced into the results by any of the four techniques. The report stated that displacement sampling and immersion sampling were the most conservative sampling approaches, requiring only that the flow of water from which the sample is collected not be aerated or turbulent.

With regard to the vial cap materials, EPA found that as much as 10-15% of the radon in the sample may be lost by its sorption into the polypropylene cap itself. The loss appeared to occur within the first four hours after the sample was collected. Caps equipped with PTFE liners did not show this loss of radon over time.

As with volatile organic constituents, radon in water samples may be lost into the headspace of the sample container. Although careful sampling techniques should result in the sample container being filled to the top and sealed with no headspace, changes in sample temperature will affect the solubility of *all* gases dissolved in the sample, including air and radon. As the temperature of the sample in the sealed container increases, the solubility of all gases will decrease and they may come out of solution, forming bubbles at the top of the container. It is not uncommon to observe air bubbles in a container that form as a result of such a temperature increase. Given the typical levels of radon in water, it is highly unlikely that a visible bubble of pure radon would form. However, the concentration of air is much higher and if radon is present in the sample, then the radon can partition into the headspace created by a bubble of air and the radon in the headspace would be lost from the sample when the container is opened.

EPA compared the radon concentrations measured in samples containing six air bubble volumes ranging from 0 - 5 ml in 63-ml sample bottles. The results of this study indicate that for bubbles up to 0.25 ml in volume, there was no significant loss of radon from solution. At a bubble volume of 0.5 ml, the loss of radon was 12%, with even larger losses for larger bubbles. Based on the solubility of air at 20°C and 24°C, EPA concluded that the headspace resulting from the formation of air bubbles as the sample warmed did not present a problem with respect to the loss of radon from the sample.

In the 1992 report, Pia and Hahn noted that there was a relatively large positive bias for the Lucas cell technique when using the radon generator approach (13.7 and 14.5% for the 111 pCi/L and 153 pCi/L sample, respectively). They attributed this bias to a problems with transferring the radon standard supplied by EPA and calibration of the instrument in the Lucas cell procedure. They indicated that the systematic error could be addressed by standardizing the technique used to transfer the sample and the radon standard, and that this issue would be addressed in EPA Method 913.

2.2.2   Standard Method 7500: Radon Liquid Scintillation Counting

This method is published in *Standard Methods for the Examination of Water and Wastewater*, (APHA 1996). The method is specific for ^{222}Rn in drinking water supplies from groundwater and surface water sources. This method grew out of EPA efforts in connection with the 1991 radionuclides proposal. In that proposed rule, EPA discussed the development of EPA Method 913, a liquid scintillation technique for radon analysis. Subsequent to the 1991 radionuclides proposal, EPA submitted the draft procedure to APHA and it was published in

Standard Methods as SM 7500-Rn. Having been published by a consensus organization (APHA), there was no need for EPA to pursue the promulgation of a separate EPA method.

In Standard Method 7500-Rn, the radon is partitioned selectively into a mineral-oil scintillation cocktail that is immiscible with the water sample. The sample is held in the dark for three hours. This "dark adaptation" serves two purposes. First, exposure to light can cause the cocktail to scintillate and this period in the dark allows this light-induced scintillation to dissipate before sample analysis, thereby reducing the background count. Secondly, the decay of the radon creates a number of short-lived daughter products. Compared to the half-lives of its daughter products, the half-life of radon is relatively long, 3.8 days (see the table in Section 2.1). Thus, during this equilibration period, the alpha emissions due to the daughter products ^{218}Po and ^{214}Po become equal to that of the radon itself and the signal from the radon is essentially amplified by a factor of three. After the equilibration period, the alpha particle emissions from the sample are counted in a liquid scintillation counter using a region or window of the energy spectrum optimal for the alpha particles from the three radionuclides. The results are reported in units of pCi/L. The diffusion of radon is affected by temperature and pressure. Therefore, it is important to allow the samples to equilibrate to room temperature before processing.

The precision of the method is affected by the background signal in the counting window used for analysis. A procedure is provided for selection of the analytical window to minimize the background contribution to the measurement. An important aspect of SM 7500-Rn is that it does *not* include any mention of the Lucas cell technique that EPA had planned to include in EPA Method 913.

The performance data in SM 7500-Rn shown in Exhibit 2-3 were incorporated from the 1992 EPA collaborative study cited earlier, which included 36 participants. However, the EPA 1992 study data were incorporated without differentiation between the liquid scintillation counting and Lucas cell techniques, even though, as previously noted, SM 7500-Rn does not ever mention the use of the Lucas cell.

Exhibit 2-3. Standard Method 7500-Rn Performance Data

Sample Conc. *pCi/L*	Accuracy *%*	Repeatability *pCi/L*	Reproducibility *pCi/L*	Bias *%*
111	101 - 102	9	12	0.7 - 2.3
153	102 - 103	10	16 - 18	2.3 - 3.4

The significance of the inclusion of the Lucas cell data is probably not great. As can be seen by comparing the data above with that in Exhibit 2-2, the accuracy data reported by EPA differ only by one percent between the two techniques. At each sample concentration, the reported precision within a laboratory (repeatability in the table above) is the same for both

techniques and differs by only 1 pCi/L between the two radon activity levels. The most notable differences are in the reproducibility figures, where the lower value in the 16 - 18 pCi/L range, and the higher value in the 2.3 - 3.4% bias range both come from the Lucas cell technique.

SM 7500-Rn incorporates other important information from the EPA studies as well. For example, the method specifies the use of glass sample containers or glass scintillation vials with PTFE- or foil-lined caps, avoiding the problems associated with the loss of radon into the polymer caps. The method describes the sample collection and employs the immersion procedure, although the method does not use that term by name.

2.3   Other Radon Measurement Techniques

As noted in Section 2.1, EPA's literature search identified several other recently developed radon measurement techniques, which are discussed in turn in the following sections

2.3.1   Delay-Coincidence Liquid Scintillation Counting System

The literature search performed in 1998 identified a report of an automated liquid scintillation counting system for determination of ^{222}Rn in ground water (Theordorsson 1996). The focus of the report was on the use of radon activity levels for earthquake prediction in Iceland. The report describes an automated radon detection system intended for mostly unattended operation.

The technique involves a two-part system which includes a prototype assembly for transferring radon (^{222}Rn) from water to toluene and a single phototube liquid scintillation counter. The radon in the toluene is detected by liquid scintillation counting, using a method known as delayed coincidence counting. Delayed coincidence counting takes advantage of the fact that the next four daughter products of radon all have short half-lives. As shown in Exhibit 2-1, the half-lives of ^{218}Po, ^{214}Po, and ^{214}Bi are all under 30 minutes, and the half-life of ^{214}Po is only 0.16 milliseconds. The delayed coincidence counter is programmed to respond to the beta particle decay of an atom of ^{214}Bi. Upon detecting that beta particle from ^{214}Bi, the system waits about 5 microseconds and then opens an electronic "gate" to the detector channel that corresponds to the energy of the alpha particle decay of ^{214}Po and holds that gate open for about 1 millisecond. The result is that the background count measured by the detector is greatly reduced because the detector is only looking for ^{214}Po scintillations in the very narrow time interval immediately after the beta particle decay of ^{214}Bi. The detection efficiency for the delayed coincidence counting of ^{214}Po is about 95%.

Most of the other aspects of the technique are modifications of those used in liquid scintillation counting and the Lucas cell techniques. For example, the transfer of the radon from the water sample by purging is employed in the Lucas cell, though in this case, the final reservoir is an organic liquid not unlike that used in liquid scintillation counting.

This technique is designed to permit the use of a much larger water sample than any of the previously described techniques. The use of a larger sample compensates for the fact that the percentage of radon transferred from the water to the toluene is only about 40%. In addition, delayed coincidence counting essentially ignores the alpha decay of the parent radon and ^{218}Po, thereby reducing the technique's sensitivity by a factor of three. Theodorsson anticipates this concern, arguing that although the ability to count multiple pulses for each disintegration of a radon atom is generally considered to increase the sensitivity and accuracy of measurements, that assumption is in error because the pulses are *"not statistically independent."* He states that the delayed coincidence counting

> *"hardly effects [sic] the resulting accuracy and sensitivity, compared to counting in a broad alpha-beta window, although the latter may give a pulse rate almost five times higher."*

Unfortunately, Theodorsson does not present any performance data to substantiate this statement.

At the time of the report, the author had only constructed a prototype system that was designed for primarily unattended operation in the field. This technique may be attractive for various types of low-level environmental radon measurements since it is relatively simple, very sensitive, and well protected from disturbances. However, no multiple laboratory data describing such performance characteristics as sensitivity are provided in the article. Thus, it is not possible to evaluate this technique more fully.

2.3.2 Activated Charcoal Passive Radon Collector

A technique that measures ^{222}Rn in river water using an activated charcoal passive radon collector has been described by Yoneda, et al. (1994). Unlike other radon methods that require the collection of a discrete water sample, the passive radon collector is immersed in the river by means of a string.

The radon collector used in this study consists of a sealed polyethylene bag containing a thin layer of activated charcoal. As water passes through the collector, the radon is adsorbed onto the charcoal and retained there. After a suitable period of immersion in the water of interest, the bag is removed and sealed in an air-tight plastic container and allowed to stand overnight until secular equilibrium among the decay products was achieved. The radon on the charcoal is determined by gamma-ray spectral analysis of its ^{214}Pb and ^{214}Bi daughter products.

The author describes experiments that evaluated the performance of the passive collector, including an evaluation of bag thickness, amount of charcoal used in the collector, immersion time and, most importantly, the use of dry and wet charcoal. This method claims to have the advantage of simplicity, low cost, and the ability to measure the average radon activity in flowing water over a specified period of time.

The author reported that:

- The mean amount of ^{222}Rn adsorbed by the collector was about reached a maximum when the quantity of charcoal reached 20 grams. and that the quantity of radon did not appear to be proportional to the amount of charcoal in the collector. Also, the charcoal should be fully spread out in a single layer within the bag.

- The thickness of the polyethylene bag did have an impact on the final results (a thin film collects more ^{222}Rn), but it was noted that when wet charcoal was used, the effectiveness of the polyethylene film decreases. The general recommendation was that a relatively thick polyethylene film, 0.005 cm, be used because it is stronger and less likely to tear.

- Collectors containing dry charcoal collected more ^{222}Rn than those containing wet charcoal. However, given the difficulty in keeping the charcoal dry during the immersion phase, it was concluded that, in order for efficient quantitative measurement of radon, wet charcoal should be used in the collectors. A revised radon absorption equation was developed to indicate the amount of ^{222}Rn collected in the wet charcoal collector.

The principal advantage of this method is that a discrete sample is not required, as the passive collector is immersed directly in the body of water. This method does not measure radon directly, rather it measures the decay of the daughter ions. An equation is given that allows the user to quantify the total ^{222}Rn absorbed by fully wet-activated charcoal sealed in a polyethylene bag in water.

The study report includes data for a variety of tests of the collection device. While some tests were conducted at lower radon levels, the majority of the performance data were generated from waters containing greater than 100 Bq/L of ^{222}Rn (>2700 pCi/L). Thus, it is not clear how well the method would perform at the levels of interest to EPA. The available performance data described in the article are limited to a single laboratory.

Because of the way that the monitoring is conducted, e.g., immersing the collector in the water body and monitoring the average radon concentration over a long time period (6-10 days), it may not be a particularly useful technique for monitoring compliance with a Maximum Contaminant Level (MCL). Low radon levels over a portion of the monitoring period could mask higher levels that would violate the MCL. However, if performance data were available for radon levels near the likely MCL (300 pCi/L), this technique might be useful as a screening method. If used as a screening method, long-term sample results that averaged over the MCL could be expected to violate the MCL if a grab sample were analyzed using a method such as Standard Method 7500-Rn, so no additional testing would be needed. In contrast, long-term sample results below the MCL would still require confirmation using another technique on a grab sample. However, such screening might not be cost-effective.

In addition, the need to leave the collector in a container of running water for 6-10 days imposes some practical limitations in comparison to other methods that employ some a sample collected over a short period (e.g, a few minutes). The adsorption coefficient of radon from water onto the charcoal can be defined as:

$$adsorption\ coefficient\ (k) = \frac{Bq\ radon\ per\ gram\ of\ charcoal}{Bq\ radon\ per\ mL\ of\ water}$$

where Bq, the Becquerel, is the SI unit of radioactivity corresponding to 1 disintegration per second (approximately 27 picoCuries). It may be possible that the adsorption coefficient reaches a constant during the exposure period of the collector. However, the study does not provide sufficient data to determine if that is the case. If the adsorption coefficient is not found to constant, it would be necessary to determine the total volume of water passing over the collector during that 6-10 day period. In some monitoring situations, such measurements would likely be more difficult than the measurement of the radon itself.

No collaborative data were available for this method.

2.3.3   Degassing Lucas Cell

A paper by Mullin and Wanty (1991) compares the use of a "degassing Lucas cell" (DLC) technique with liquid scintillation counting This paper describes the degassing Lucas cell technique in general terms, noting that a paper by Reimer in the same volume of the USGS Bulletin provides greater detail. The paper by Reimer was not reviewed directly, as the comparisons conducted by Mullin and Wanty provided more useful information.

As noted in Section 2.2., the Lucas cell technique is a well-established method for the analysis of radionuclides in water, including radon. In the degassing Lucas cell technique, a water sample is agitated in a closed vessel to extract the radon. The air in the headspace of the vessel is sampled with a gas-tight syringe and injected into a Lucas cell for counting. The principal advantage of this technique is that the results can be obtained in the field, at each site, which was the apparent reason for developing the technique.

The primary disadvantage of this method is that unless the sample is analyzed immediately, the radon level can be biased low by radon diffusing out of the syringe containing the air sample. Increased lag time from sampling to analysis via the DLC leads to greater uncertainty and usually lower radon measurements, both of which were attributed to loss of radon from the syringes in which the samples were stored. The loss of radon through radioactive decay during the lag time between sample collection and measurement was accounted for by using an exponential formula that corrects for the decay of the radon in the sample. However, that correction factor does account for the diffusion losses of radon from the syringe.

In addition, as written, this method does not expressly include the three-hour equilibrium period, in an effort to speed the use of the technique for field measurements. The lack of the equilibration period presents concerns as well. In particular, ^{218}Po, one of the short-lived progeny of ^{222}Rn, closely approaches secular equilibrium with ^{222}Rn in about 10 minutes, and may not be accounted for adequately in the calibration scheme. Finally, because the DLC analyses is performed at a time when the net alpha activity of ^{218}Po is rapidly building, large errors in apparent radon levels may result.

The authors of the study concluded that the liquid scintillation technique was more accurate than the degassing Lucas cell technique, but that the degassing Lucas cell may have utility for reconnaissance sampling, where the results can be used to design sampling schemes for use of the more accurate liquid scintillation technique. However, field measurements may not be an important factor relative to SDWA compliance monitoring for radon.

2.3.4   Electret Ionization Chamber System

Several articles were found that discuss the use of an electret system for the measurement of radon (Tai-Pow 1992, Sabol et al. 1995). Additional information was provided to EPA by the US manufacturer of the electret device, Rad Elec Inc., of Frederick, MD.

An electret is a device which has been treated to hold a stable electrostatic-field potential (initially 700 to 750 volts). In the case of these two studies, the electret is made of a wafer of Teflon that is housed in a chamber made of electrically-conducting plastic. The device is called an electret passive environment radon monitor (E-PERM) by the manufacturer of the device.

The decay products from the radon gas enter the chamber through the filtered inlet at the top and the alpha particles striking the electret discharge the static charge on the electret. The surface charge of the electret is measured before and after exposure by using a specially designed voltage reader. This electric field sensor can detect small changes on the electret. The electret is designed to handle exposures of two to seven days at levels of 0.04 to 1.85 Bq/L (1 to 50 pCi/L) of radon in air.

Electret ionization chambers are simple, portable, and easy to use. They are also well-suited for field measurements, since more than one measurement can be made from the same electret. Drawbacks to this simple and relatively inexpensive method include poor reproducibility at lower radon levels, uncertainty in the use of manufacturer-suggested gamma correction factors, and limited reusability. The electret device lacks specificity for radon. The surface charge of the electret will change with exposure to gamma radiation from within the sample chamber or from an external gamma source. It will also change in response to the alpha decay of other volatile radionuclides that enter the chamber headspace from the water.

When measuring radon concentrations in air, the gamma radiation can be subtracted through the use of voltage-dependent correction factors, resulting in improved accuracy. In the

studies cited above, the end results showed that a higher concentration of radon in water may result in elevated airborne radon concentration in the surrounding areas, including increased radon activity in buildings served by a hot spring water. For routine waterborne radon monitoring, including use in field conditions, the technique based on electret ion chamber technology may sometimes be a suitable choice.

In a 1990, a survey of laboratories conducting radon analyses in drinking water was performed by Wade Miller Associates, under contract to EPA. The goals of that study were to identify the types of certification programs that exist for radon analyses in drinking water, to identify laboratories capable of performing the analyses, and to determine the daily analysis capacity of each identified laboratory. Of 45 commercial and state laboratories contacted in 1990, only one listed the electret method.

Recent information provided by the US manufacturer included cited three additional studies that were not directly reviewed by SAIC. These include the following papers and presentations:

- Kotrappa, P. and Jester, W.A.,"Electret Ion Chamber Radon Monitors Measure Dissolved ^{222}Rn in Water," *Health Physics,* 64: 397-405 (1993)

- Colle, R. Kotrappa, P., and Hutchinson, J.M.R., "Calibration of Electret-Based Integral Radon Monitors Using NIST Polyethylene-Encapsulated ^{226}Ra/^{222}Rn Emanation (PERE) Standards," *Journal of Research of National Institute of Standards and Technology,* 100: 629-639 (1995).

- Budd, G, and Bentley, C., "Operational Evaluation of the EIC Method for Determining Radon In Water Concentrations," 1993 International Radon Conference, Hosted by AARST.

Those studies provide precision and bias data on the electret technique over a wide range of concentrations. According to the manufacturer, the electret technique has recently been certified by the States of Maine and New Hampshire for monitoring radon in water.

As summarized by the manufacturer, the precision of the electret technique ranged from 4 to 10% across all three of the studies. The bias of the technique was estimated by the manufacturer to be from -17% to +1% in these three studies, following the application of a correction factor of 1.15 to the initial sample results. Prior to the use of this correction factor, the bias ranged from -27% to -9% across these three studies. SAIC contacted the manufacturer and obtained information on the ranges of radon concentrations that were used in these studies.

According to the manufacturer, the Kotrappa and Jester study examined five radon activity levels, ranging from a low of about 220 pCi/L to a high of 73,200 pCi/L, and found no significant change in precision and bias across the range. The Colle *et al.* study examined only

one radon level of 10 Bq/g, which equates to approximately 270,000 pCi/L. The Budd and Bentley study examined a variety of activity levels, ranging from about 350 pCi/L to 46,000 pCi/L. The first and third studies included at least some activities near the levels of interest to EPA.

The correction factor recommended by the manufacturer is intended to relate the electret results to those expected by the liquid scintillation counting method, although the manufacturer points out that the liquid scintillation method may not be *"accurate with traceability to NIST."*

As is the case for the activated charcoal collector method described in Section 2.3.2, the electret method requires a long exposure of the detector to the sample. The range of exposure times in the papers reviewed by SAIC is 2-7 days. However, unlike the charcoal collector technique, the electret is exposed to a discrete sample container in a sealed vessel. Thus, although the measurement may take up to 7 days to complete, the results represent the concentration of radon in the discrete water sample.

Although the manufacturer's literature indicates that electret technique performed well in a 1994 US Department of Energy (DOE) "intercomparison" study, those data appear to be for the measurement of radon in air. No collaborative data for water samples have been identified.

2.4   Performance Capabilities of the Methods

The performance capabilities of these methods for the analysis of radon were difficult to evaluate in a consistent manner, in part, because many of the methods were developed in university settings for purposes other than those envisioned by EPA, i.e, not for compliance monitoring. Wherever possible, SAIC has reviewed the information on the sensitivity (detection limit) and precision of these methods. The selectivity of the procedures for ^{222}Rn is generally excellent and consistent across most of the methods. This is because most of the methods measure the alpha particle decay of ^{222}Rn and/or its daughter products, and these particles are released at discrete alpha energies. In the case of ^{222}Rn, the energy of the alpha particle is 5.49 MeV. The exception is the electret method described by Tai-Pow *et al.*, which measures the change in the electrical potential of the circuit containing the electret. This technique is less selective for radon than the other techniques, in that it will respond to both gamma radiation and other volatile radionuclides in the water sample.

As noted earlier, most of the methods lack data from collaborative studies. The two exceptions are the liquid scintillation method (SM 7500-Rn) and the Lucas Cell method. Both of these method were evaluated as part of the 1992 EPA collaborative study. The accuracy, reproducibility, repeatability, and bias data for Standard Method 7500-Rn and for the Lucas Cell method are shown in Section 2.3, above.

As noted above, the performance capabilities of some of the other techniques have not been demonstrated for relatively low activities of ^{222}Rn. Several of the techniques were

described as having poorer performance as low radon activities. A number of the papers did not present data on the sensitivity of the techniques, and in those cases no attempts were made to estimate the sensitivities. Rather, the radon levels at which performance was demonstrated were noted in the discussion.

Based on the information provided by the manufacturer, the performance of the electret method has also been relatively well-characteristics. While the summary information suggests that the bias is greater than that reported for Standard Method 7500-Rn, even the -17% figure is not so severe as to rule out this procedure, since methods for some organic analytes can be shown to have similar bias. However, as noted earlier, no collaborative study data on water samples were identified.

2.5   Skill Requirements

The two major techniques employed in most of these methods are liquid scintillation and Lucas cell counting. Neither of these techniques is technically difficult. Liquid scintillation counting has been used in medical laboratories and environmental research laboratories for over 30 years. The skills required are primarily the ability to remove an aliquot of the sample from the original vial and adding an aliquot of the scintillation cocktail, sealing the vial, and placing it into the counter. The counting process is highly automated and the equipment runs unattended for days, if needed.

The Lucas cell methods described in the papers considered for this report requires somewhat more manual skill. As noted in the 1991 proposed rule, EPA expects that this technique would require greater efforts to train technicians than the liquid scintillation technique. The Lucas cell technique requires that the counting cell be evacuated to about 10 mTorr pressure. Then, a series of stopcocks or valves must be manipulated to transfer the radon that is purged from the sample into the counting cell. Potential problems with the analysis, such as a high background level of radon that can develop over the course of the day, or aspirating water into the counting cell, can be minimized by a well-trained analyst. However, as EPA concluded in 1991, the Lucas cell technique is not expected to form the sole basis of a compliance monitoring program for radon in drinking water.

The electret method is relatively simple to perform. The water sample (<150mL) is transferred to a larger, leak-tight container housing the electret device. The radon escapes from the water into the air in the container. The electrical potential (voltage) of the electret must be measured before and after the analysis, using a specially designed sensor.

Overall, although the requirements vary across the techniques, the skills required to measure radon using the techniques described here are generally comparable to those required used to perform gas chromatographic or atomic absorption analyses, methods that EPA has identified for use in quantifying common organic and inorganic contaminants in water samples.

In discussions between EPA and the water utility industry, concerns have been expressed about the difficulties in collecting samples and the skills that may be required to do so in a reproducible fashion. As noted in Section 7.0, the ability to generate useful analytical results for radon is dependent in an important way on the sample collection process. The 1992 EPA collaborative study evaluated four sample collection techniques and found them all equally good at providing equivalent results. The State of California has developed a sampling protocol for radon in water that employs one of the four techniques evaluated by EPA, namely the immersion technique. SAIC has reviewed a copy of that protocol that was provided to EPA (Jensen, 1997).

As described in the California protocol, the well is purged for 15 minutes to ensure that a representative sample is collected. Purging simply means that the water is withdrawn from the well for this period of time. After purging, a length of flexible plastic tubing is attached to the spigot, tap, or other connection, and the free end of the tubing is placed at the bottom of a small bucket. The water is allowed to fill the bucket, slowly, until the bucket overflows. The bucket is emptied and refilled at least once.

Once the bucket has refilled, a glass sample container of an appropriate size is opened and slowly immersed into the bucket in an upright position. Once the bottle has been placed on the bottom of the bucket, the tubing is placed into the bottle to ensure that the bottle is flushed with fresh water. After the bottle has been flushed, the tubing is removed while the bottle is still on the bottom of the bucket. The cap is placed back on the bottle while the bottle is still in the bucket, and the bottle is tightly sealed. As noted in the California protocol, the choice of the sample container is dependent on the laboratory that will perform the analysis, and will be a function of the liquid scintillation counter that is employed. If bottles are supplied by the laboratory, there is no question of what container to employ.

Once the sealed sample bottle is removed from the bucket, it is inverted and checked for bubbles that would indicate headspace. If there are no bubbles, the outside of the sealed bottle is wiped dry and cap is sealed in place with electrical tape, wrapped clockwise. After the sample bottle is sealed, a second (duplicate) sample is collected in the same fashion from the same bucket. The date *and time* of the sample collection is recorded for each sample.

As described above, the sample collection procedures are not particularly labor-intensive. Most of the time is spent allowing the water to overflow the bucket. Likewise, there are no significant manual skills required. Personnel who can manage to slowly fill a 1-liter glass bottle to collect a sample for analysis of semivolatile organics, or fill a 40-mL VOA vial without headspace, can certainly collect samples for radon, using the method described above.

2.6   Practical Availability of the Methods

In order to determine the practical availability of the methods, SAIC considered two major factors. First, the availability of the major instrumentation was reviewed. Secondly,

several laboratories performing drinking water analyses were contacted to determine their capabilities to perform radon analyses.

The major instrumentation required for Standard Method 7500-Rn is a liquid scintillation counter. Automated counters capable of what that method terms "automatic spectral analysis" are available from at least a dozen suppliers. The Lucas cell apparatus is the same as has been used for radium analyses for many years. The electret system is used for the measurement of radon in air as well as in water. Information provided by the manufacturer of the electret system suggests that there are more than 600 users in the US, of whom, the manufacturer estimates, 10% measure radon in water.

In order to evaluate the availability of laboratory capacity to perform radon analyses, in early 1998 SAIC contacted the drinking water certification authorities in the states of California, Maryland, and Pennsylvania. These states were chosen based on SAIC's knowledge of radon problems associated with the "Reading Prong" that stretches through parts of Pennsylvania and Maryland, and the overall status of California's laboratory certification program. A total of eight commercial laboratories were contacted during this initial survey. Each laboratory was advised that SAIC was simply collecting information on the availability and relative costs of radon analyses for drinking water. SAIC was limited in its ability to perform a broader survey, since an upper limit of nine was placed on the survey, in order to abide by the Federal information collection regulations.

Six of the eight laboratories that were contacted in the initial survey perform radon analyses. All the laboratories were certified in one or more states to perform radiochemical analyses, though it was unclear if the certifications were specifically for radon or the more general radiochemical analysis category.

When asked what specific methods were used, the laboratories responded with either the technique (liquid scintillation counting) or a specific method citation. EPA Method 913 was cited by two of the six laboratories. As noted earlier, this method is the precursor to the current Standard Method 7500-Rn. EPA Method "EERF Appendix B" was cited by another laboratory. The remaining three laboratories indicated that they performed liquid scintillation analyses and could accommodate requests for methods employing that technique.

When asked about capacity, the laboratories indicated that they perform between 100 and 12,000 analyses per year. The latter figure came from a laboratory that is currently involved in a large ground water monitoring project in the western US. The next largest estimate was 300 samples per year. However, SAIC expects that like any other type of environmental analysis, given a regulatory driver to perform the analysis, the laboratory capacity would develop quickly.

The 1992 EPA collaborative study on radon analysis (Pia and Hahn, 1992) included 51 laboratories with the capability to perform liquid scintillation analyses. This suggests that there already exists a substantial capacity for these analyses. Further, the liquid scintillation apparatus is used for other radiochemical analyses, including tritium. Information from EPA regarding the

performance evaluation program for tritium analyses suggests that there are approximately 100-200 laboratories with the necessary equipment. Much of the capacity for tritium analyses could also be used for radon (EPA 1997). As of September 1997, 136 of 171 participating laboratories achieved acceptable results for tritium. Both the total number of participants and the number achieving acceptable results vary from study to study, but these data indicate that there is already a substantial capability for liquid scintillation analysis nationwide.

Recent information provided by the manufacturer of the electret indicate that the States of Maine and New Hampshire are certifying laboratories for drinking water analysis using the electret method. Several months after the initial laboratory survey, based on information from the manufacturer, SAIC contacted a laboratory in New Hampshire that uses the electret method and obtained information on the analysis price for water samples. The laboratory charges $30 per sample for drinking water analyses. They have been certified for drinking water analyses using the electret method in New Hampshire for at least three years and in Maine for one year. They have a current capacity of at least 40 samples per week (2000 per year), and indicated that they could easily increase that capacity to meet demand.

The availability of laboratories is also dependent on laboratory certification efforts in the individual states with regulatory authority for their drinking water programs. A major component of many of these certification programs is continued participation by the laboratory in the current EPA Water Supply (WS) performance evaluation (PE) program. Efforts are underway at EPA that will lead to the privatization of all of EPA's PE programs, including the WS studies. Those efforts will affect laboratory certifications for all analytes regulated under the SDWA, including radiochemicals such as radon. Any delays in implementing a private PE program will affect not only radon, but the certification status of laboratories for all regulated analytes.

Because of the issue involved with safe handling of radiochemical standards, there will likely be fewer laboratories seeking certification for radon than for other non-radiochemical parameters. However, there is no fundamental regulatory reason that a radon laboratory in one state cannot receive certification in another state. Even for more commonly performed analyses, there are numerous commercial laboratories that are certified in multiple states. Given the regulatory requirement for radon analyses, one can expect that those laboratories with the capability for radon analysis will pursue certifications in as many states as practical.

The National Environmental Laboratory Accreditation Conference (NELAC) is also evaluating the issues surrounding privatization of the SDWA PE program through its proficiency testing committee. NELAC serves as a national standard-setting body for environmental laboratory accreditation, and includes members from both state and Federal regulatory and non-regulatory programs.

The short holding time for radon, 4 days in Method 7500-Rn, presents a concern relative to the practical availability as well. The 4-day holding time was also the focus of a number of

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comments that EPA received in response to the 1991 proposed rule. Many commenters stated that if a local laboratory is not available, the only alternative would be to send the samples by overnight delivery to a laboratory elsewhere. Again, this situation is not unique to the analysis of radon. Several large commercial laboratories already account for a sizable share of the market for SDWA analyses for non-radon parameters, including organics, for which the holding times are often 7 days. Given that a day would be required for shipping the samples, only three days would remain for the laboratory to perform the radon analysis (the day on which the sample is collected being "day zero"). Some commenters argued that for a large commercial laboratory serving the water utilities, this short holding time will make it difficult if not impossible to perform the necessary analyses within the holding time. However, through common-sense scheduling efforts between the utility and the laboratory, such as not collecting samples on Thursdays and Fridays, the holding time issue should be able to be accommodated with relative ease. At worst, some laboratories may choose to offer analytical services over the weekend, perhaps at an increased cost.

For the vast majority of other analytes for which EPA has established formal holding times in its various regulatory programs, the holding times are specified in "days." This is typically understood to mean "calendar days" with the day of sample collection being "day zero." Because of the relatively short half-life of radon, the holding time is expected to be proposed as 4 days, beginning at the time of collection. SAIC strongly urges EPA to publish this holding time as "96 hours" instead of just "4 days," in an effort to reinforce how the holding time is to be calculated.

2.7   Anticipated Unit Costs

As part of its 1991 proposal, EPA conducted a limited survey of laboratories providing radon analyses. Four laboratories provided price information to EPA regarding the analysis of a single SDWA compliance monitoring sample, employing liquid scintillation counting as the analytical technique. The data from the 1991 survey are in Exhibit 2-4.

As part of the 1998 review of analytical methods for radon, SAIC contacted nine laboratories that perform radiochemical analyses. Of those nine, seven perform radon analyses. The prices from the those seven laboratories are shown in Exhibit 2-5. None of the laboratories contacted were among those contacted by EPA in 1991, but to avoid any confusion, the arbitrary numbers assigned to each laboratory begin where the 1991 numbers left off.

There was no clear correlation between the estimated price and the method cited by the laboratory. One of the laboratories that provided an estimate of $40 per sample is certified by the States of Maine and New Hampshire to perform radon analyses of drinking water using the E-PERM electret device. The other laboratory that quoted a price of $40 employs liquid scintillation counting. The 1998 range of prices brackets those collected by EPA in 1991.

Exhibit 2-4. 1991 Radon Cost Survey Data

Arbitrary Lab Number	Cost Estimate	Descriptive Statistics	
1	$30	Mean	$49.80
2	$44	Median	$47.00
3	$50	Std. Dev.	$18.80
4	$75	Range	$45
		Minimum	$30
		Maximum	$75

Exhibit 2-5. 1998 Radon Cost Survey Data

Arbitrary Lab Number	Cost Estimate	Descriptive Statistics	
5	$75	Mean	$54.29
6	$50	Median	$50.00
7	$40	Std. Dev.	$15.12
8	$75	Range	$35.00
9	$45	Minimum	$40.00
10	$55	Maximum	$75.00
11	$40	NA	NA

As noted above, one possible response to concerns about the effect of the short holding time on laboratory capacity would be for some laboratories to offer analyses over the weekend. The increased cost of such services would likely be due to increased labor costs, particularly if overtime were paid to the analysts. Assuming a 1.5 multiplier for overtime (e.g., "time and a half"), the unit cost might rise to the range of $60 to $112 per sample, but only for those utilities that could not arrange to sample at more convenient times.

2.8 Practical Performance and Analytical Uncertainties

The available information on the performance of the various methods is greatest for the liquid scintillation procedure, SM 7500-Rn, and the Lucas Cell technique. The data from the 1992 EPA collaborative study cited earlier indicate excellent precision and accuracy for liquid scintillation. The Lucas Cell technique yielded slightly less accurate and less precise results, but

still within the realm of performance that EPA has accepted for the measurement of other contaminants. Performance data for the electret method are incomplete, with no clear evidence of a collaborative study in drinking water.

As with many environmental measurements, an overall evaluation of the effectiveness of a monitoring method must also consider the practical aspects of collecting a representative sample. The analysis of radon presents two specific challenges. First, like many organic contaminants, radon is volatile, and some radon will come out of solution in a sample if exposed to the atmosphere for long periods. Secondly, being a radioisotope, ^{222}Rn undergoes radioactive decay.

The volatility of radon can be addressed in a fashion similar to that for the organic chemicals, namely careful sample collection techniques that minimize the disturbance of the sample, and the use of containers that can be sealed tightly.

The conclusions of the 1992 collaborative study indicate that while all four sample collection techniques examined in that study (displacement, immersion, catch, and grab sampling) can provide equivalent results, displacement and immersion sampling are the preferred approaches. Both can be accomplished with little or no specific expertise. Displacement sampling involves attaching a filling tube attached to the water source, inserting the other end into the sample container, and allowing the water to fill the container with no aeration until the container overflows. The filling tube is withdrawn while still running, so that water constantly overflows the container. The container is then quickly sealed with an appropriate cap (e.g., PTFE-lined).

Immersion sampling is somewhat similar, in that a sample container is placed in the bottom of a large container. The filling tube is then inserted into the sample container which is then filled to overflowing with the water to be sampled. The sample container is removed from the larger container with forceps and sealed. The use of immersion sampling further reduces the chances of leaving headspace in the sample container, by allowing the filling tube to be withdrawn while the sample container is still submerged in the larger container. However, as noted in the 1992 study report, there was little difference between the results from both sampling techniques. The sampling procedure developed by California that was described earlier in this document is an immersion technique. The losses of radon due to sorption on cap liners and in air bubbles that occur during transportation and storage appear to be minimal for this technique.

The radioactive decay of ^{222}Rn presents some concerns because the half-life of this isotope is approximately 3.82 days. However, even with this relatively short half life, it is both possible and practical to calculate the concentration of ^{222}Rn at the time of sampling with a high degree of accuracy. Depending on the regulatory action level (MCL or other level) that is specified, the sensitivity of the liquid scintillation method should be sufficient to be used for compliance monitoring even if the sample is held for several days. Method 7500-Rn currently specifies a 4-day holding time. For this analyte, sampling documentation *must* include the time

of sample collection, as well as the date. However, this documentation requirement does not present any practical difficulty for this technique.

2.9   Degree To Which Each Method Meets EPA's Regulatory Needs

Of the six techniques for the measurement of radon that were evaluated in this report, only two appear to meet all of EPA's needs relative to compliance monitoring. SM 7500-Rn and the Lucas Cell technique can achieve reasonable standards for precision and accuracy, are readily available, and have been subjected to collaborative testing.

The four other techniques lack collaborative testing data, which is a significant problem in establishing methods for a nationwide compliance monitoring program such as the SDWA. Of those four other techniques, the electret technique shows greatest promise, and should collaborative data indicating acceptable performance in water matrices become available in the future, EPA may wish to consider this technique at a later date.

The other three techniques, the delayed coincidence liquid scintillation counting system, the activated charcoal passive collector technique, and the degassing Lucas cell technique may have some utility in screening samples or in field measurements. The activated charcoal procedure requires a lengthy exposure to running water and provides an average radon concentration over the entire sampling period. The extent to which such time-averaged measurements might be employed in SDWA compliance monitoring is a policy decision that goes beyond the scope of this evaluation.

In summary, the results of this most recent review of possible analytical techniques for radon in drinking water has reached the same conclusions as that of the 1991 EPA proposal. The liquid scintillation counting technique (SM 7500-Rn) is most able to support a SDWA compliance monitoring program, supported by the possible use of the Lucas cell technique.

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3. SOURCES OF RADON IN GROUNDWATER

3.1 Natural Sources of Radon Groundwater Contamination

Radon is produced in rock, soil and water by the decay of naturally occurring radioactive elements in minerals. This process transfers radon into air- or water-filled soil pore spaces by alpha recoil or diffusion. Radon is then transported by air or water until it decays to its progeny or reaches the atmosphere.

Radon is a member of the "uranium series" of radionuclides all the members of which are derived from the decay of uranium-238. Each radioactive isotope spontaneously decays to emit a radioactive particle, radiant energy, and forms "progeny" isotopes. This process continues until a stable isotope of lead is formed. Radon has three naturally-occurring isotopes, radon-222 (Rn-222), radon-220 and radon-219. Of the three radon isotopes, Rn-222 is the only one of environmental concern, because the other isotopes have much shorter half lives which limit their potential for causing human radiation exposure. Radon-222 decays into Polonium-318 with a half-life of approximately 3.82 days by alpha emission. The uranium decay series is shown in Exhibit 3-1.

EXHIBIT 3-1 Uranium Decay Series (Including Rn-222)

SOURCE		PRODUCTS	HALF-LIFE
Uranium 238	→	Thallium 234 + α	4.46 X 10^9 years
Thallium 234	→	Palladium 234 + β	24.1 days
Palladium 234	→	Uranium 234 + β	1.17 minutes
Uranium 234	→	Thorium 230 + α	2.45 x 10^5 years
Thorium 230	→	Radium 226 + α	7.5 x 10^4 years
Radium 226	→	**Radon 222 + α**	**1622 years**
Radon 222	→	**Polonium 218 + α**	**3.825 days**
Polonium 218	→	Lead 214 + α	3.11 minutes
Lead 214	→	Bismuth 214 + β	26.8 minutes
Bismuth 214	→	Polonium 214 + α	19.9 minutes
Polonium 214	→	Lead 210 + β	1.6 x 10^{-4} minutes
Lead 210	→	Bismuth 210 + β	22.3 years
Bismuth 210	→	Polonium 210 + β	5.01 days
Polonium 210	→	Lead 206 + α	138.4 days
Lead 206			Stable

3.1.1 Release and Transport Properties of Radon and Radium

On a microscopic scale, the release of radon into groundwater water is directly related both to the concentration of radium in the host soil or rock, which determines the amount of radon generated, and to the emissivity of the mineral (which determines the fraction or the generated radon that is released from the particle in which it is generated). The physical condition of the rock (particle size, pore structure) plays a large role in determining emissivity. Because of the importance of these physical factors in determining radon release, there is often no strong correlation between radium levels in rocks or soils and radon levels in adjacent groundwater. The dominant radon route of release into interstitial water is diffusion along microcrystalline fractures in the rock. However, in most cases (i.e., cases in which the percolation velocity is greater than 10^{-5} cm/sec), the mass transport of radon in groundwater water is governed more by advection than this diffusion (Hess, et al. 1985).

Radium-226 is the immediate radiologic precursor of radon-222. Radium can be released to groundwater by three routes: the dissolution of aquifer solids; by direct recoil across the liquid-solid boundary during its formation by radioactive decay of its parent; and by desorbtion. In contrast to radon, radium has very low solubility in water and very low mobility in groundwater. Also, radium does not exist as a gas, and vapor phase transport is therefore not important. Thus, as discussed below the transport patterns of radium generally do not greatly affect the transport of radon and radium concentrations in groundwater can be a poor predictor of radon levels.

3.1.2 Factors Affecting Distribution of Radon in Groundwater

The levels of radon in groundwater in specific areas or types of systems are affected by a number of factors. Geologic regime and geological parameters are strongly associated with radon levels in groundwater. A number of studies have examined the correlations among radon levels in groundwater and the occurrence of other elements, aquifer lithology, and the depth to the groundwater. Analysis has suggested, that for a defined geographic area, relative radon levels can be inferred from the dominant aquifer lithology and implied activity levels of the parent isotopes. Loomis (1985) has identified six geologic and hydrologic variables that together can be used to predict radon activity in groundwater at a regional level. Each variable, except meteorology, tends to be strongly correlated with lithology type.

- *Uranium-radium geochemistry.* As noted above aquifer minerals with high uranium or radium content may exhibit a relatively high rate of radon release.

- *Physical properties of source rocks.* The escape of radon from rocks into water varies according to the rock's grain size, degree of weathering, microfractures, and the distribution of radon's parent nuclides within the rock's mineral grains. Generally, the smaller the grain size and more pervasive the fracturing and weathering, the greater the amount of radon that escapes.

- *Dissolved radium.* The relationship between dissolved radium in the water and radon in water is inconclusive; several studies indicate there is little to no correlation in the co-occurrence of these two nuclides.

- *Aquifer properties.* The transfer of radon from rocks to the aquifer is largely determined by the flow characteristics of water through the aquifer. The transfer of radon from rocks to water is enhanced when the rocks are relatively permeable, weathered, and fractured and flow rates are relatively high. Given radon's relatively short half-life, groundwater flow must be relatively rapid for radon to reach water supply wells before it decays

- *Meteorologic factors.* Some studies have indicated that radon levels co-vary positively with precipitation. Moreover, there is some evidence that radon emanation from the rocks and soils is related to barometric pressure. Several studies that have looked for a relationship between radon in water and meteorologic factors have found none.

- *Well and water system design and use.* Several studies have reported that radon levels in water are inversely proportional to a groundwater system's number of customers and yield. Reasons for this consistently-seen relationship are not clear, although it may be that wells serving smaller numbers of customers may draw from less productive granitic aquifers with higher levels of radon precursor elements.

The aquifers with the highest radon concentration have a lithology profile that is dominated by granite and granite alluvia. These rocks tend to have higher levels of uranium and a physical structure that facilitates the release of radon into adjacent water. Radon levels are also often elevated near volcanic ash layers. Lower radon levels are found in basalts and sand aquifers. This relationship between lithology and radon concentration is illustrated by the regional differences in radon levels in groundwater between the southern Mississippi valley (a predominance of basalts and sand results in low radon levels) and Appalachian uplands (a predominance of granite results in high radon levels).

3.1.3 Large-Scale Geographic Patterns of Radon Occurrence in Groundwater

As noted above, groundwater radon levels in the United States have been found to be the highest in New England and the Appalachian uplands of the middle Atlantic and southeastern states. There are also isolated areas in the Rocky Mountains, California, Texas, and the upper Midwest where radon levels in groundwater tend to be higher than the U.S. average. The lowest groundwater radon levels tend to be found in the Mississippi valley, lower Midwest, and plains states. However, even in areas with generally very high or low levels of radon in groundwater, local differences in geology strongly affect observed radon levels (e.g., not all groundwater radon levels in New England are high; not all radon levels in the Gulf Coast region are low). For example, the presence of faults and shear zones in a geographic area characterized by low radon levels can produce localized areas of high radon levels (Gunderson, et al. 1992). It was found

that radon levels in groundwater were correlated with measured radioactivity of rocks and soils in the area, the prevalence of rock types know to produce radon in the area, and the area's soil permeability. The general pattern of groundwater radon occurrence across the US is shown in Exhibit 3-2. Data related to geographical patterns or radon occurrence are discussed in more detail in Chapter 5. The potential for radon to co-occur with other pollutants is discussed in Chapter 7.

3.2   Anthropogenic Sources of Radon Contamination in Groundwater

Radon in the environment is derived primarily from natural sources. Because of its short half life, there are relatively few anthropogenic sources of groundwater radon contamination. The most common manmade sources of radon groundwater contamination are wastes from phosphate or uranium mining or milling operations and from thorium or radium processing. These sources can results in high groundwater levels in very limited areas if, for instance, homes are located on soil contaminated with such wastes or tailings, or if a contaminated aquifer is used as a source of potable water (EPA 1999a). Otherwise, significant groundwater transport of radon is limited by its short half-life.

3.3   Distribution System Sources

3.3.1   Radon Sources in Distribution Systems

Radon levels in distribution systems are usually lower in distribution systems than in source water because radioactive decay and water treatments involving storage, aeration, or carbon filtration act to reduce radon levels. As will be discussed in more detail in Section 5.2, this is not always the case, however. In a number of systems in Iowa, for example, radon levels in finished water samples were found to be substantially higher than those from the wells supplying the systems. Detailed studies have shown elevated levels of radium in pipe scale in these systems. The decay of the radium increases radon levels over and above those already present in the influent water. The greater the length of old, scaled pipe through which the water passes, the greater the radon levels. The extent to which this is a general phenomenon is not known, but it suggests that care should be taken in estimating radon exposures on the basis of wellhead or point-entry-samples where iron-manganese scaling is likely to be a problem.

3.3.2   Radon Sources in Households

Except to the extent that pipe scale in residences sequesters radium, there are no radon sources that increase the levels of radon after water enters the household. Radon is released to indoor air during domestic water use, however, as discussed in Section 4.3.

3.4   Non-Water Supply Sources of Radon Exposures

It has been estimated that only between 1 to 3% of the total residential radon exposures results from radon in public water supplies (NRC 1998). The most important source of radon exposure (accounting for approximately 95 percent of exposures) is indoor air contaminated by radon released from rocks and soils and infiltrating into basements and living spaces. Other sources of radon exposures include ambient (outdoor) air, fuel gas, and construction material (primarily gypsum board).

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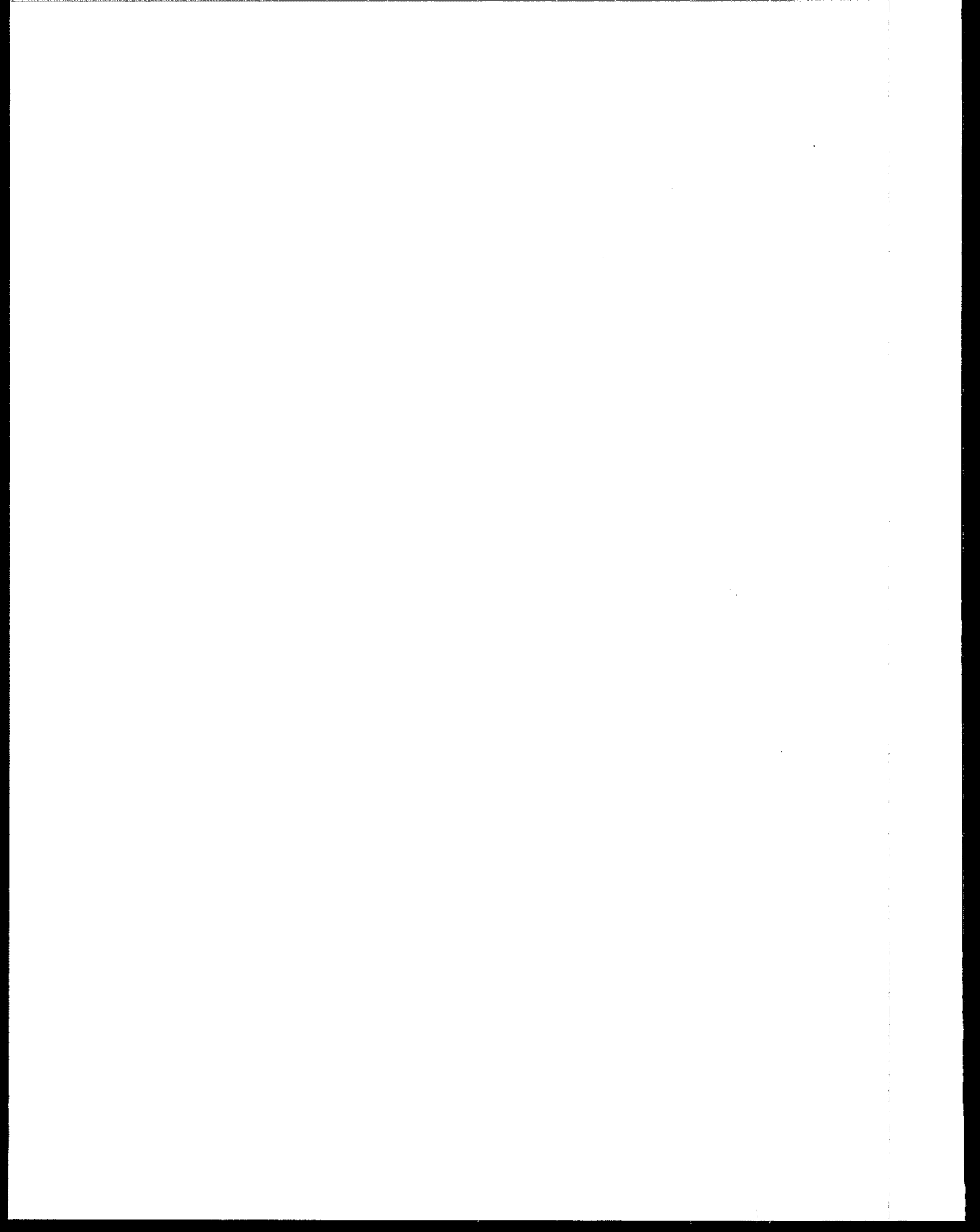
4. FATE AND TRANSPORT

4.1 Physical and Chemical Properties of Radon and Progeny

Radon, atomic number 86, is a "noble" and chemically inert gas. It does not react with other elements in the environment. Radon is soluble in water, but also very volatile. It has a high Henry's Law Constant ($>X10^{-3}$ m^3/l) , indicating a high potential to volatilize from water solution. Its melting point is -71°C and its boiling point is -61.8°C. It's solubility in water is 230 cm^3/liter at 20°C. Radon is adsorbed by activated carbon, and therefore presumably to some extent to other organic matter, although radon partitioning to organic matter in the environment has not been extensively studied.

As noted in Chapter 3, radon-222 has a half-life of 3.82 days. Radon's progeny radionuclides (primarily isotopes of lead, polonium, and bismuth) unlike radon, are not gases, and are less soluble in water than radon. When radon undergoes radioactive decay in water, the resultant nuclides tend to precipitate out onto suspended particulates or other surfaces. Similarly, radon progeny in air "plate out" onto airborne particles, and the bulk of radon-related radiation exposures through the inhalation pathway are often due to the deposition of progeny-bearing particulates in the respiratory tract.

4.2 Relationship of Fate and Transport Properties to Human Exposures and Intake

–Radon's chemical and physical properties, particularly its radioactive half-life and volatility, greatly effect its behavior in the environment, and human exposures from domestic water use.

Because of its short radioactive half-life, the distance over which radon can move in groundwater is severely limited. In just under four days, the activity of radon will be reduced about 50 percent, and it will be reduced another 50 percent in the following four days, etc. In an aquifer where typical horizontal flow velocities are on the order of 10-100 cm/day, this limits the distance over which radon can be transported and still cause significant exposure to a few meters or less. In bedrock aquifers, where water flow may be primarily through fractures, this distance might be larger. As noted in Section 4.1, when radon decays in water, the resulting progeny are much less soluble and mobile, and do not result in appreciable exposures.

Another consequence of radon's short half-life is that radon levels are reduced when water is stored for any appreciable time prior to use. Thus, water systems which use storage devices such as water towers, tanks or reservoirs, are already reducing radon levels in water. The amount of reduction achieved depends on the average residence time in the storage device, and whether the storage vessel is open to the atmosphere (see below)

When radon is released to surface water, its high volatility results in rapid release to the atmosphere. Radon levels in surface water bodies are almost always below measurable levels

(NAS, 1998). Systems that store water in contact with the atmosphere therefore achieve radon reduction both through radioactive decay and volatilization.

4.3. Exposures to Radon in Indoor Air After Release During Domestic Water Use

When water is heated or agitated during domestic use, radon is rapidly released to the air. NAS (1998) estimates that between 80 and 100 percent of the radon in tap water remains in solution to be ingested if the water is consumed immediately and is not heated. Between 60 and 80 percent of dissolved radon is released from water from showers, sinks, and washing machines. If water is heated to boiling (e.g., during cooking), essentially all of the radon is driven off.

The radon level in indoor air resulting from domestic water use is often estimated using a transfer factor (TF) approach. This transfer factor is defined as the average increase in long-term radon in air (pCi/L_a) due to a long-term increase of one pCi/L_w radon in water. The value of the transfer factor depends on three factors:

- Patterns of household water use (amount, timing, duration, agitation, and temperature);

- Volume and air exchange rate of the room in which the water is being used; and

- Volume and air exchange rate of the entire house.

Measured Transfer factors in typical American houses generally fall between 1:1,000 and 1:100,000, with the mean being between 1:10,000 and 1: 15,000. That is, the domestic water supply entering a house on average needs to have a radon level of approximately 10,000 pCi/l to increase the average indoor air level by 1.0 pCi/l. This value is estimated based on modeling studies, validated by some of the measurements described above.

More refined models are available for predicting radon levels as a function of water usage and building design parameters (e.g., "the three-compartment model"). Generally, it has been found that, while these models provide additional insights into short-term peak exposures in specific areas of the home (for, example, in the shower), they provide little improvement in the quality of long-term estimates of inhalation exposures compared to the simpler transfer factor approach.

4.4 Relationship of Fate and Transport Properties to Radon Behavior in Treatment and Distribution Systems

As noted above, radon undergoes spontaneous radioactive decay during storage and residence in distribution systems. Thus, radon levels in distribution systems and at the point of use are usually lower than in the source water (but see below). In addition, radon's chemical and physical properties mean that some technologies that are used to remove other contaminants also

result in reduced levels of radon. These properties have also been used to design treatment technologies specifically for removing radon from domestic water. Because radon is an inert gas, processes which involve chemical treatment of water (e.g., chlorination, iron/manganese sequestration, chemical coagulation) do not effect radon levels unless they cause it to volatilize or be removed bound to solids.

4.4.1   Aeration Technologies

Aeration technologies make use of radon's volatility to reduce radon levels in treated water. In the *Proposed Rule*, (EPA 1999), high-performance aeration has been selected as the Best Available Technology (BAT) for radon removal. The specific technologies which have been identified include packed-tower aeration, multi-stage bubble aeration, and shallow tray aeration. In addition, there are other aeration technologies that can also cost-effectively achieve radon reduction in commercial-scale use. All the technologies identified above are capable, under defined operating conditions, of achieving at least 99.9 percent radon removal from influent water. Capital and operating costs can be lower if lower removal efficiencies are required (EPA 1999b).

A significant proportion of community groundwater systems already employ aeration technologies to remove odors or organic chemicals, or as an adjunct iron/manganese removal. EPA estimates (1999b) that between approximately 16 and 24 percent of groundwater systems serving 1,000 or more customers currently employ some form of aeration treatment. A smaller proportion of smaller systems also employ aeration technologies. EPA estimates that these existing technologies are likely to achieve a 90 percent reduction in radon levels in the majority of cases.

4.4.2   Granular Activated Carbon Treatment

As noted above, radon also can be adsorbed onto granular activated carbon (GAC). EPA has indicated (1999b) that GAC technologies, while not BAT for most systems, may be appropriate for some very small systems where the capital costs of aeration technologies are prohibitive. Both point-of-entry (POE) and point-of-use (POU) GAC technologies can achieve up to 99 percent radon removal under certain conditions. However, the amount of carbon and contact time required to achieve high radon removal efficiencies are considerably greater than those required to achieve efficient removal of organic chemicals. Thus, at a minimum, changes in operating conditions would be required to adapt existing GAC systems (which EPA estimates to be present at about two percent of all small and very small systems) to address radon contamination.

4.4.3   Radon Release from Pipe Scale

As discussed in Section 3.3, there is evidence that radon can be released from pipe scale pipes in distribution systems. The best information regarding this phenomenon comes from

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studies of radon distributions in groundwater systems from Iowa. Information was provided concerning raw and finished water radon analyses from 150 water systems across the state, from systems of different sizes (Kelley and Mehrhoff, 1993). The geometric mean radon level in the raw data samples was 284 pCi/l. As expected, the geometric mean value of water radon levels from the finished water was lower, at 176 pCi/l. However, the ratio of the radon levels in the finished water to the raw water varied considerably. In a substantial proportion of the cases (Exhibit 4-1), the radon level in the finished water exceeded that from the raw water, by up to six-fold.

Exhibit 4-1. Ratios of Finished/Raw Radon Levels in 150 Iowa Water Systems

Ratio Finished/Raw Radon Levels	Number of Systems
Less than 1.0	107
1.0-1.5	29
1.5-2.0	6
2-5	7
>5	1

Radon levels that were higher in finished water than in raw water occurred with varying frequency across the types of geological formations. When water was drawn from alluvial aquifers, finished water levels increased over the wellhead levels only five percent of the time (3/60 systems). In contrast, this phenomenon was seen in 41 percent (9/22) of the wells finished in Cambrian/ Ordovician and 40 percent (2/5) of wells finished in Cambrian/ Precambrian units.

Although no specific geochemical data were provided for the systems where the increases in radon occurred after entry into the systems, the basis for this phenomenon has been previously described in studies of several of the systems included in the Iowa data (Field et al. 1994, Fisher et al. 1998). The increases in radon in the distribution system appear to occur as a result of the accumulation of iron pipe scale in the distribution systems. The scale sequesters radium, and the resultant buildup of radium results in the releases of radon into the water as it passes through the system. The ultimate outcome may be in-system radon levels that substantially exceed the levels seen in the aquifers from which the water is drawn.

There is little evidence concerning the frequency or severity of this phenomenon outside of Iowa, although there is no reason to think it would not occur wherever the geochemical conditions are similar. There would a lower likelihood of scaling and radon buildup in systems drawing from alluvial aquifers, and more potential for problems whenever iron levels are high

and eH levels low in the producing aquifer. Systems treating water to reduce iron and manganese might expect that radon levels would also be reduced in distribution systems.

4.5   References

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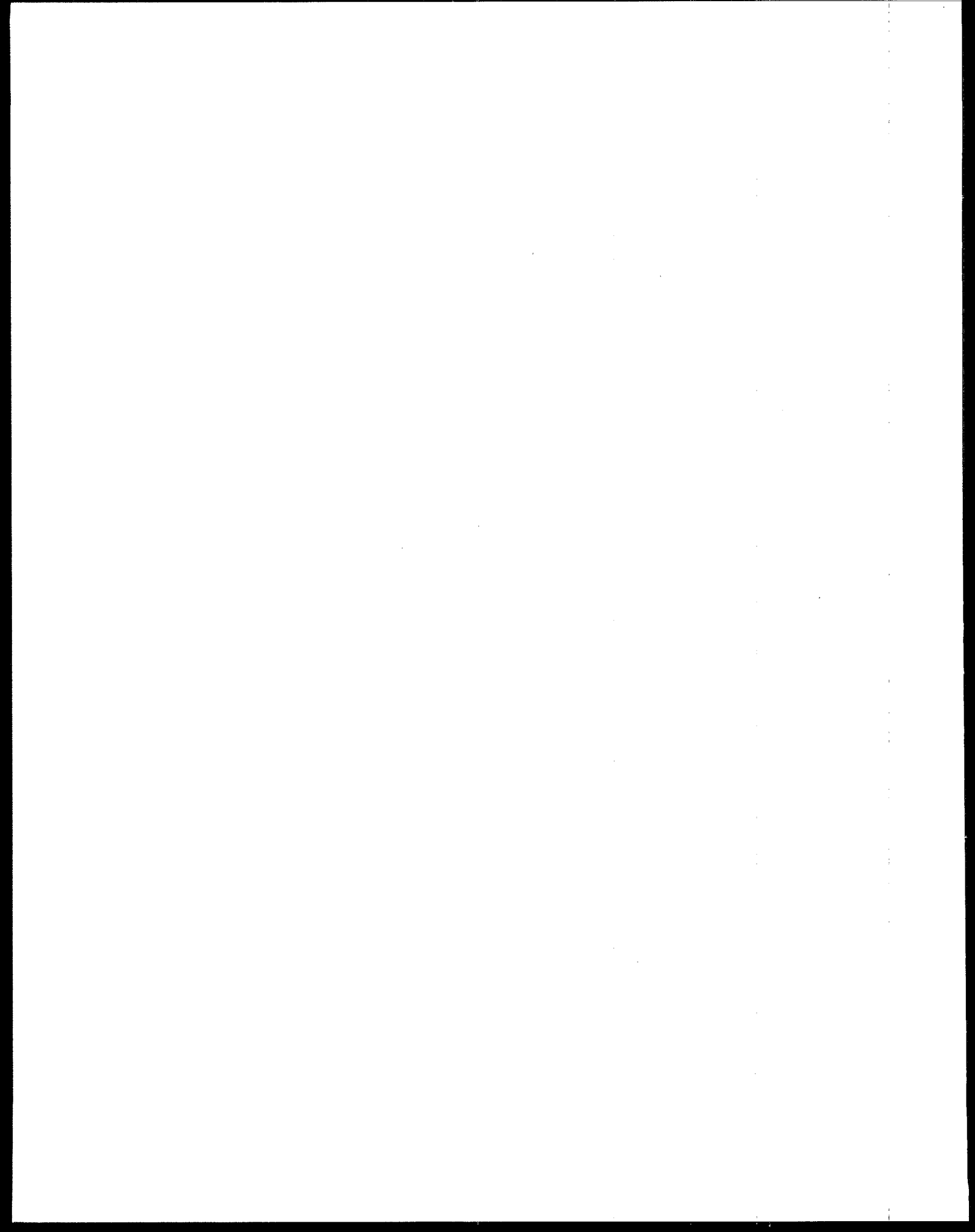
5. DISTRIBUTION OF RADON IN GROUNDWATER SOURCES

This chapter of discusses the available information related to the distribution of radon in groundwater sources in the United States and the numbers and proportions of groundwater systems with sources that could exceed potential regulatory levels. The following sections discuss the nature and quality of the available data related to radon distribution, the methods used to analyze and characterize the distributions of radon from the various data sources, the assumptions used to develop nationwide estimates of the occurrence of radon in groundwater sources. In addition, estimates of the proportions of systems that could exceed regulatory levels are presented, and the potential uncertainty associated with these estimates are discussed. The material in this chapter comes primarily from the *Re-Evaluation of Radon Occurrence in Groundwater Supplies in the United States: External Review Draft* (ICF, 1998). External peer reviewer comments on that document have been incorporated into the chapter.

5.1 Data Availability and Quality

This section begins with a chronological review of EPA's past efforts to develop data related to radon occurrence in groundwater. Relevant literature sources, including the Agency's previous radon occurrence analyses, are cited in the text. We then discuss the data sources that have been identified since EPA's previous rulemaking effort ended in 1993.

5.1.1 Previous EPA Data Gathering Efforts Related to Radon Occurrence in Groundwater Supplies

In 1978, EPA's Eastern Environmental Radiation Facility began a pilot study to determine the need for a nationwide study of radon in drinking water, to demonstrate the feasibility of such a study; and to develop a limited national database of radon levels in drinking water. In this pilot study, approximately 6,298 samples of raw and finished water were collected from private and public surface and groundwater supplies (Horton, 1983). Samples were collected by state or local personnel from water supplies serving more than 1,000 people in 40 states. Sampling or Quality Assurance/Quality Control (QA/QC) procedures were not defined in the study protocol, but were left up to the states. Data collected during the pilot study were analyzed to estimate representative radon levels in water in each state. Geometric mean radon levels were calculated for each state represented and for the entire U.S.[1] Analysis of these data lead to the following conclusions:

- radon levels in surface water are very low (geometric mean <2 pCi/l);
- radon levels in groundwater are highest in areas where water is drawn from granitic aquifers;

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[1] As will be discussed in Section 5.2, the distributions of radon levels in the various states and at the national levels were positively skewed, and the investigators thought that the geometric mean levels provided a better measure for comparison purposes than the arithmetic mean.

- higher levels occur in small systems than in larger ones; and

- higher levels of radon are observed in private wells than in public wells.

The pilot study findings were used to help plan a larger-scale survey in support of the *Nationwide Occurrence of Radon and Other Natural Radioactivity in Public Water Supplies* project (USEPA 1985a). This project, which began in November of 1980, was the first attempt to systematically sample water supplies in the US to characterize the distribution of radioactive contaminants. The objective of the study was to collect samples that were representative of actual exposures and thus only finished water was sampled.

More than 2,500 samples were collected. Although the study design called for samples from all 50 states, only 35 provided data.[2] In addition, only public water supplies serving at least 1,000 people were sampled. Thus groundwater supplies representative of the large majority of the groundwater systems in the US, many of which were likely to have potentially elevated radon levels (Hess 1985), were not sampled. The population-weighted arithmetic mean radon levels calculated for each state and for consumers of groundwater in the US as a whole are presented in the left-hand column of Exhibit 5-1.

Exhibit 5-1. Radon Levels in Public Groundwater Systems From Two Surveys

State	EPA Eastern Environmental Radiation Facility Study (USEPA, 1985)[1] Population-Weighted Arithmetic Mean, pCi/l	EPA National Inorganics and Radionuclides Survey (NIRS) (Longtin, 1987)[2] Population-Weighted Arithmetic Mean pCi/l
Alabama	160.7	420.1
Alaska	N/A	128.5
Arizona	329.3	1,435.1
Arkansas	N/A	100.0
California	N/A	228.4
Colorado	380.7	329.9
Connecticut	N/A	1,208.9
Delaware	126.4	123.3
Florida	148.5	127.3
Georgia	147.4	563.4
Hawaii	N/A	N/A
Idaho	256.6	437.4
Illinois	167.6	193.2

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[2] The states not submitting data were Alaska, Arkansas, California, Connecticut, Hawaii, Iowa, Louisiana, Maryland, Michigan, Missouri, Nebraska, New Jersey, Texas, Washington, and West Virginia.

State	EPA Eastern Environmental Radiation Facility Study (USEPA, 1985)[1] Population-Weighted Arithmetic Mean, pCi/l	EPA National Inorganics and Radionuclides Survey (NIRS) (Longtin, 1987)[2] Population-Weighted Arithmetic Mean pCi/l
Indiana	105.4	187.4
Iowa	N/A	136.4
Kansas	106.0	369.1
Kentucky	107.8	205.5
Louisiana	N/A	108.2
Maine	N/A	1,228.4
Maryland	N/A	266.1
Massachusetts	769.4	587.8
Michigan	N/A	185.2
Minnesota	210.3	388.7
Mississippi	82.0	104.3
Missouri	N/A	143.7
Montana	328.6	344.6
Nebraska	N/A	351.6
Nevada	550.8	743.2
New Hampshire	1,183.6	2,673.5
New Jersey	N/A	137.1
New Mexico	178.1	309.1
New York	132.1	223.7
North Carolina	278.6	2,277.7
North Dakota	148.8	114.0
Ohio	169.8	175.2
Oklahoma	160.0	158.0
Oregon	264.0	118.2
Pennsylvania	719.9	507.8
Rhode Island	1,511.1	1,170.0
South Carolina	276.9	557.7
South Dakota	289.2	281.6
Tennessee	23.8	113.7
Texas	N/A	150.5
Utah	360.9	226.8
Vermont	656.8	997.1
Virginia	447.8	485.4
Washington	N/A	432.5
West Virginia	N/A	263.6
Wisconsin	234.4	367.2
Wyoming	415.3	558.0
U.S.	232.1	249.0

Sources of Data:

1. *Nationwide Occurrence of Radon and Other Natural radioactivity in Public Water Supplies,* USEPA-520-5-85-008

2. Longtin, J.P., "Occurrence of Radon, Radium, and Uranium in Groundwater", *Journal of the American Water Works Association,* July, 1987, pp. 84-93.

In the mid-1980s, the need for additional representative and systematically collected occurrence information on radon and other radionuclides, especially in small systems, motivated EPA to undertake the National Inorganics and Radionuclides Survey (NIRS). The objective of NIRS was to characterize the occurrence of radon and other constituents present in community groundwater supplies in the U.S., its territories, and its possessions. The sampling program was carefully stratified to reflect the national distribution of community groundwater supplies by size, as measured in population served. The inventory of the community groundwater supplies contained the 1983 Federal Reporting Data Systems (FRDS) database was used to select the sites to be sampled. Non-community systems were not sampled . At the time of the survey, there were approximately 47,000 community groundwater supplies in the database, from which 1,000 sites, stratified into the four size categories on the basis of population served, were selected.[3] Within the size categories, an effort was made to develop samples that were geographically representative of the U.S. The relatively small numbers of medium and large systems in the sample, however, limited the extent to which this could be accomplished for these size categories. The four population categories and the number of sites sampled in each category are presented in Exhibit 5-2. The NIRS radon sampling effort was conducted between July 1, 1984 and October 31, 1986.

**Exhibit 5-2   Groundwater System Size Categories and
Selected Sites in the Design of NIRS**

Community Water Supply System Size	System Size (Population Served)	Number of FRDS Sites*	Number of Sites Selected for NIRS
very small	25-500	34,040	716
small	501-3,300	10,155	211
medium	3,301-10,000	2,278	47
large/very large	10,001->100,000	1,227	26

* Based on the FRDS inventory for Fiscal Year 1985.

Of the 1,000 sites selected in the study design, 990 were actually sampled. Although sampling occurred over a two-year period, only one sample was taken from each water system, and the NIRS data therefore provide a cross-sectional "snap-shot" of radon levels in drinking water supplies. The locations of these sampling sites are shown in Exhibit 5-3. Samples were collected from points in the distribution systems selected to as to represent typical radon exposures. Unlike previous studies, a rigorous QA/QC program was built into NIRS and all radon analyses were conducted in EPA laboratories. The QA/QC program included field duplicates, field blanks, split laboratory samples, blind laboratory standards, and laboratory spikes. Summary results of the NIRS were published in 1987 (Longtin, 1987). The results are presented in the right-hand column of Exhibit 5-1 and the results are mapped in Exhibit 5-3.

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[3] The size of the sample was limited to 1,000 because of constraints imposed by available resources and impending deadlines in the regulatory process.

Exhibit 5-3.: Sampling Locations and Geographic Patterns of Radon Occurrence in Groundwater from the NIRS, 1985-1986

Radon Concentration

- More than 1000
- 300 to 1,000
- 100 to 300
- Less than 100

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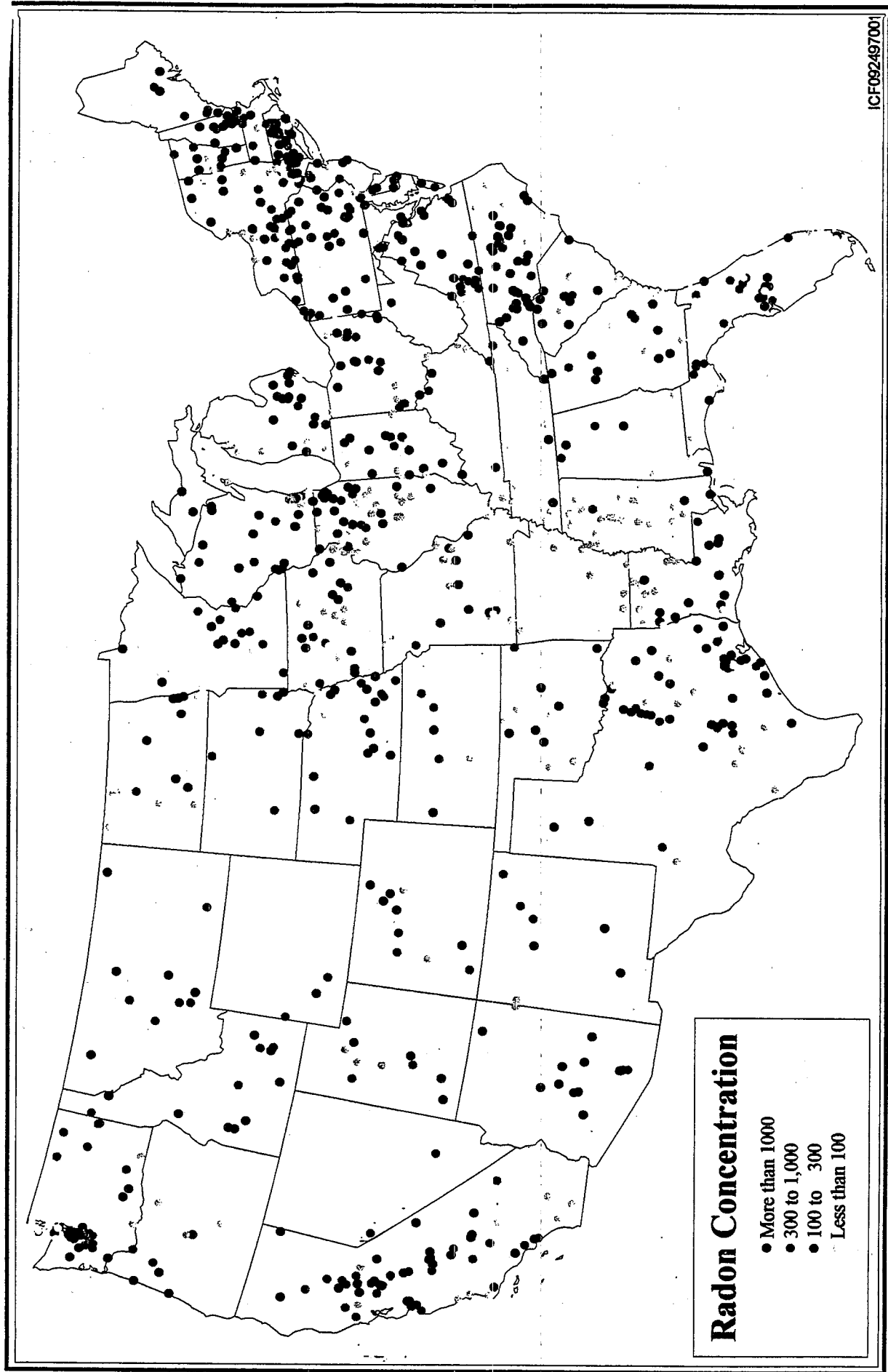
The extensive QA/QC program, the large number of samples collected, and the extensive geographical coverage across the nation (at least of the smaller systems) make the NIRS database the most representative and reliable source of national occurrence data for radon in public water supplies. EPA has relied exclusively on the NIRS data in its previous analyses of the occurrence of radon in groundwater supplies and to predict the proportions of groundwater systems that would exceed possible drinking water standards (Wade Miller 1990, 1993).

In response to the 1991 Proposed Rule, which included EPA's findings on radon occurrence, the Agency received a number of comments from stakeholders concerning the use of the NIRS as sole source of radon data for the occurrence analysis. The major concerns included:

- NIRS data represent water quality "at the tap," whereas the proposed rule would require systems to mitigate radon based on wellhead or point-of-entry levels. Since levels at the tap are generally lower than levels in source water, according to the commenters, this could underestimate the numbers of systems affected by radon regulations;

- NIRS samples were taken after blending of water from different sources in some distribution systems, further reducing radon levels and obscuring the variability among different sources ; and

- The numbers of systems sampled in the NIRS are very limited for some states, leading to a potential underestimation of non-compliance in those states. Also, radon occurrence in medium and large systems are poorly characterized.

In addition, commenters have raised a number of issues concerning how the cross-sectional nature of the NIRS data further limit its utility in estimating potential exceedences of regulatory levels. The limitations include (according to commenters):

- Using the NIRS data directly to estimate regulatory exceedences ignores the potential uncertainty in the NIRS radon levels introduced by sampling and analytical error. This uncertainty could result in underestimation of the numbers of systems exceeding regulatory levels;

- Additional uncertainty is introduced by failing to take into account variations in radon levels over time in individual wells and systems, which could also increase the proportion of systems exceeding regulatory levels above that predicted using the cross-sectional NIRS data.

Finally, as noted above, the NIRS did not attempt to characterize the occurrence of radon in non-transient non-community water systems (NTNCWS) that could be affected by radon drinking water standards. These systems, which serve schools, hospitals businesses, commercial and industrial buildings, and other institutions, could also be significantly affected by the regulation of radon in drinking water.

All of these considerations influenced EPA to seek additional sources of data related to radon occurrence in groundwater supplies. Therefore, in 1988, EPA began an effort to update its database on radon occurrence and to revise its estimates of radon occurrence in groundwater.

5.1.2 Data Gathering Efforts in Support of the Revised Occurrence Analysis

The data gathering effort related to radon occurrence was closely coordinated with EPA's outreach efforts in support of the development of the 1999 Proposed Rule for radon in drinking water. These efforts included three Stakeholders Meeting held in Boston, San Francisco, and Washington, DC in 1998 and 1999. Representatives from many water utilities and state regulatory agencies took part in the Stakeholders Meetings.

The first major source of data was EPA's files of comments and data submitted in response to the 1991 Proposal and subsequent efforts to revise the rule. When EPA ceased rulemaking efforts in 1993, many of these comments had not been fully evaluated or responded to. These files provided data and information related to individual and groups were involved in data gathering. Where significant data were provided, the authors of the studies were contacted to ascertain whether they could provide the raw data in electronic form. In addition, attendees at the Agency's Stakeholders' Meetings who stated that they had radon occurrence data that they were willing to share were contacted by telephone to facilitate the transfer of the data.

EPA also conducted a computer literature search of recent publications related to radon occurrence, and some useful information was identified through the searches. The United States Geological Survey representative to the Stakeholders Meetings also provided useful background information and data on radon occurrence.

At first, few new data sets were received from stakeholders, and EPA therefore contacted the American Society of Drinking Water Administrators (ASDWA) to ascertain whether any members of this group might have radon occurrence data that they wished to submit. In response to EPA's request, ASDWA conducted a survey of its members (water utilities and state water regulators, primarily) asking whether they had any radon occurrence data and whether they would be willing to provide it to the Agency in support of the revised occurrence analysis. Thirty-five responses to the survey were received, the majority of which indicated that radon occurrence data were available. ASDWA then followed up with the positive responders, and data were forwarded to ICF (EPA's contractor) under the auspices of the Association. In addition to the data received from ASDWA members, useful data related to radon occurrence was obtained from several academic researchers.

5.1.3 Results of the Data Gathering Effort

As noted above, supplementary data were sought primarily to:

- Increase the coverage and representativeness of the data, across geographic regions and system size strata;

- To support the investigation of systematic differences in radon levels between in-system and well-head or point-of-entry levels; and

- To support an assessment of the magnitude and impacts of sampling, analytical, and temporal variability on estimated radon distributions.

High priority was therefore given to obtaining data sets that provided information on radon distributions in a state or region sparsely covered by the NIRS, that provided both in-system and wellhead samples, and which provided the results of duplicate analyses or multiple samples over time. In addition, data sets were sought that reported radon levels in large groundwater systems and in non-transient non-community systems, which were poorly represented (the former) or absent (the latter) from the NIRS.

To be usable, the data had to be of acceptable quality and traceable back to a specific water system in a specific state and city. Because system size was a major stratification variable (see section 5.2), the ability to identify systems (and estimate the populations served) was a key element in the exploratory data analysis. Data had to come from community groundwater water systems (systems providing residential water on a year-round basis to 25 or more individuals) or from non-transient non-community systems (systems providing non-residential drinking water to 25 or more individuals exposed on a year-round or nearly year-round basis.) Data from residential wells (wells serving individual homes), transient systems (systems serving seasonal campgrounds, etc.), or monitoring wells were not included in the analysis. Characterizing the types and sizes of systems reporting data from a given state often presented a major challenge in the preliminary data analysis.

In addition, data sets were used only if it could be ascertained that the sampling and analytical procedures used were similar or identical to those recommended by EPA, and if there was evidence of an acceptable QA/QC program supporting the data gathering effort. In a few instances, QA/QC plans and/or results from QA/QC replicate analyses were provided, but for most data sets, only verbal descriptions of QA/AC procedures were provided by the individuals supplying the data. Finally, for a data set to be included in the analyses described in the analysis, there had to be a sufficient amount of data to allow meaningful statistical analysis. If only a few sampling results were provided, then a data set was given low priority or excluded from the data analysis.

The data gathering efforts resulted in the identification of 20 significant supplementary data sources related to radon occurrence[4]. The selected sources are identified in Exhibit 5-4, along with the general types of data they provide. The sources fall into two general categories.

The first category includes sixteen data sets that have been assembled by state regulatory agencies for the purpose of characterizing the state-wide distribution of radon in groundwater supplies. Most of these data sets greatly supplement the NIRS data in terms of the total numbers of systems sampled, the numbers of systems sampled in each size category, and the geographic representativeness of radon data. In addition, some of the data sets provided duplicate samples, which could be used to evaluate sampling and analytical variability, sampling results from more than one well in the same systems, and samples taken over time from single wells. These data could be used to characterize intra-system and temporal variability, as discussed in Section 5.7 Some of these sources (e.g, the data on radon distribution in Maine groundwater systems provided by Hess, et al, and the data from the New York Statewide Surveillance Study) were available when the previous occurrence analyses were performed, but were not formally evaluated by the Agency. Data from most of the states, however, has been collected more recently.

The second general type of source that we found report data specifically related to sampling, analytical, and/or temporal variability in radon levels, but that do not characterize geographical variability in radon levels. Data sources of this type include the duplicate samples (samples taken sequentially and analyzed separately) from Alabama rural water systems, the QA duplicate analytical results (duplicate analyses of the same sample) from the Southern California Water Survey, the study of radon levels in Missoula, MT municipal wells, and the study of temporal, sampling, and analytical variability in small-system wells in central North Carolina cited in Exhibit 5-4.

The only source that provided both raw and finished water data came from the Iowa Department of Natural Resources, which provided information on raw and finished water radon levels from 150 community systems. Finally, we identified only six data sources with significant data related to radon levels in noncommunity non-transient systems.

In the following sections, data from the NIRS and supplemental sources are used to evaluate radon occurrence in groundwater systems in the US, and to develop predictions of the proportions of systems that may exceed radon regulatory levels. Data management and QA/QC procedures are described in Appendix A.1. More detailed information concerning the individual supplemental data sets are provided in Appendix A.2

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[4] Approximately 10 additional source of radon occurrence data were identified but not included in the analysis because they failed to meet one or another of the requirements in this section. The data set for Missouri water systems was received too late to be used in the model for estimating national radon occurrence, but summary statistics for the Missouri data are presented in Section 5.2.

Exhibit 5-4. Summary of Major Supplementary Radon Occurrence Data Sources

Data Source	Geographic Coverage	Sampling Dates	Supplement NIRS Data Related to Geographic/ System Size Distribution	Direct In-System vs. Point-of-Entry Comparison	Data on Large Systems	Data on Non-Community Non-Transient Systems	Data on Sampling and Analytical Variability	Data on Temporal Variability
Duplicate Samples, Alabama Rural Water Systems (David Grey, USEPA, NAERL, Montgomery, AL)	Alabama	1992-1993	No	No	No	No	Yes	No
California Community and Noncommunity Water Systems (Dr. David Storm, CA Department of Health Services)	California	1987-1998	Yes	No	Yes	Yes	Yes	Yes
Southern California Radon Survey QA Duplicates (Metropolitan Water District of Southern California)	Southern California	1989	No	No	No	No	Yes	No
Connecticut Community and Noncommunity Systems (Nancy McHone, CT Dept. Of Environmental Protection)	Connecticut	?	Yes	No	No	No	No	No
Idaho Community and Noncommunity Systems (Janet Crockett, Idaho Department of Water Resources)	Idaho	1991-1993	Yes	No	Limited	Yes	No	No
Iowa Community Water Systems (Roy Ney, Iowa Department of Natural Resources)	Iowa	1992	Yes	Yes	Yes	No	No	No
Kansas Community Water Systems (Darrel Plummer, Kansas Department of Health and the Environment)	Kansas	1991-1997	Yes	No	Yes	No	No	No

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Exhibit 5-4. Summary of Major Supplementary Radon Occurrence Data Sources(Continued)

Maine (Charles T. Hess, University of Maine, Orono)	Maine	1979	Yes	No	No	Limited	Yes	No
Maryland (Charles Poreda, Maryland Department of the Environment)	Maryland	1993-1997	Yes	No	No	No	No	Limited
Michigan (E. Brown, Michigan Department of Public Health)	Michigan	1991-1992	Yes	No	No	No	No	Limited
Missoula, Montana (Robert Ward, Mountain Water System, Missoula)	Missoula, MT	1993-1994	No	No	Yes	Limited	Yes	Yes
New Hampshire Community and Noncommunity Systems (Bernie Lucy, New Hampshire Department of Environmental Services)	New Hampshire	1988-1977	Yes	No	Yes	Yes	No	Yes
New York Community Systems (New York Statewide Surveillance for Radon in Selected Community Water Systems, 1990)	New York	1989-1990	Yes	No	Yes	No	Yes	No
North Carolina Temporal and Sampling Analytical Variability Study (William Drane, Department of Environmental Sciences and Engineering, University of North Carolina)	Vicinity of Chapel-Hill, NC	1993-1995	No	No	No	No	Yes	Yes
Ohio Community Water Supplies (Kathleen Pinto, Ohio EPA Division of Drinking Water and Groundwater)	Ohio	1986-1988	Yes	No	Yes	No	No	No

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Exhibit 5-4. Summary of Major Supplementary Radon Occurrence Data Sources(Continued)

Data Source	Geographic Coverage	Sampling Dates	Supplement NIRS Data Related to Geographic/ System Size Distribution	Direct In-System vs. Point-of-Entry Comparison	Data on Large Systems	Data on Non-Community Non-Transient Systems	Data on Sampling and Analytical Variability	Data on Temporal Variability
Pennsylvania Community Water Systems (Jerry Rupert, PA Department of Environmental Protection)	Pennsylvania	1992-1993	Yes	No	Yes	No	No	No
South Carolina Community Water Systems (South Carolina Department of Health and Environmental Control)	South Carolina	1991	Yes	No	Yes	No	No	No
Texas Community and Noncommunity Systems (Ron Beardon, Texas Natural Resources Conservation Commission)	Texas	1995	Yes	No	Yes	Limited	No	No
Washington State Community and Noncommunity Systems (Jim Hudson, Washington Department of Health)	Washington	1992-1995	Yes	No	Yes	Limited	No	Limited
Wisconsin (Mark Wilson, Wisconsin Department of Natural Resources	Wisconsin	1990-1996	Yes	No	Yes	No	No	Limited
Missouri [1] Department of Natural Resources (Kenneth Duzan, Division of Environmental Quality, Public Drinking Water Program)	Missouri [1]	1998	Yes	No	Yes	Yes	No	Yes

Notes:

1. These data were obtained too late to be included in the development of the statistical model of the national distribution of radon in community and non-transient non-community water systems discribed in Section 5.3. Summary statistics for the Missouri data are provided, however, in Section 5.2.

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5.2   Methods Used in the Data Analysis

This analysis builds on previous studies of the NIRS and other data sets to estimate the distribution of radon activity in groundwater sources that are used to supply domestic and commercial water in the U.S. A second objective of the analysis was to estimate the proportions of systems that would exceed various radon levels, should they be proposed as regulatory limits by the EPA. This effort naturally employed a wide range of analytical and statistical tools. This section describes the approaches that were employed to evaluate the data and to answer specific questions regarding radon distributions.

5.2.1   Statistical Analysis of Radon Distributions

The specific QA/QC and data management methods used in this analysis are described in Appendix A. The following sections describe the statistical methods that were used in the evaluation of radon data from the final data sets that had been subject to QA review.

a.   *Treatment of Censored Data*

In most of the radon data sets, some proportion of the analytical results are censored, that is, reported as being "less than" some specific value, reflecting an inability of the analytical method used to measure the analyte in question at low levels. Depending upon the QA procedures used during the data gathering, the censoring value may constitute the limit of detection of the analytical method employed, or the lower limit at which analytes can be quantified. In the NIRS, a Minimum Reporting Limit of 100 pCi/l was employed. Values below the censoring limit are referred to as "non-detects". Where a non-detect is reported, it is likely that the analyte is present at some level greater than zero, but the problem remains as to how to incorporate these analyses into the calculation of summary statistics (such as mean or standard deviation).

If the proportion of censored observations is low and the censoring level is low compared to the levels that are of concern, the presence of censored data will have little effect on the calculation of summary statistics for the sampled population. However, if the censoring level is near the level of concern, or if a large proportion of the data are censored, the potential impact on such calculations may become significant. In the NIRS data set, approximately 27 percent of the data are reported as less than the MRL of 100 pCi/l. For larger system sizes, the proportion is larger. While this has the potential to affect calculations of the representative activity levels (e.g. the mean or geometric mean values), it has less impact on the utility of the NIRS data for generating predictions of the proportions of systems above the censoring level, or regulatory levels near the censoring level. In evaluating radon occurrence from the NIRS data, the censored data were retained, and subject to the graphical and statistical analyses described below.

As noted in Appendix A.1, the censoring limits could not be estimated accurately many of the supplemental databases. Censoring levels were not provided with most of the supplementary data sets, and it is likely that the quantitative limits varied over time and within the data sets.

Often, reported radon values were much lower than the NIRS MRL. In these case, we used professional judgement to estimate censoring levels. Values that were reported as "<" were provisionally included in their databases at one-half the reported "<" level. In addition, reported values that seemed unreasonably low (generally less than 10-20 pCi/l, depending on the database) were adjusted to one-half the estimated censoring level. Finally, if a database reported a relatively large proportion of values at a single lower bound (such as 50 or 100 pCi/l), it was assumed that all these values were "<", and the data were included in the database provisionally at one-half the reported levels.

The proportions of censored data in the various supplementary databases are shown in Exhibit 5-5. (These totals include the data that are reported as being censored and the additional data points which we identified as reflecting "<" values.) It can be seen that between 7 and 8 percent of the data from three states (Ohio, Pennsylvania, and Washington) are censored. Six additional state databases (California, Kansas, Maryland, Michigan, New Hampshire, and Wisconsin) had fewer than about 2.5 percent censored results, while the remainder of the states reported no censored data. On the whole, 237 of a total of 9,005 analytical results in the state databases (2.6 percent) were censored. At least one censored result was present among the radon analyses for about 4.7 percent of the 3,534 systems that were evaluated, and 1.6 percent of all systems reported only censored results. In almost all cases, these latter systems reported only one analytical result each. As will be discussed below, the censoring procedures that were employed appeared to have relatively little impact on the derivation of summary statistics from the various data sets.

b. Calculation of Summary Statistics for Uncensored Data

As discussed below, the lognormal distribution was the primary model used to characterize the distribution of radon in groundwater systems. The natural log of the geometric mean and the natural log of the geometric standard deviation are exactly comparable in their meaning, for lognormal distributions, to the mean and standard deviation of a normal (Gaussian) distribution. Thus, the **log mean** (natural log of the geometric mean) and **log standard deviation** (natural log of the geometric standard deviation) are the primary statistics that are used in the comparison of radon distributions.

For uncensored data, the log mean is simply equal to the arithmetic mean of the natural logarithms of the radon data, and the log standard deviation is the standard deviation of the natural logarithms. The relation ship between the geometric mean and standard deviation and the log mean and standard deviation is thus defined as:

$$\text{Log Mean} = \ln(GM) \tag{5-1}$$

$$\text{Log Standard Deviation} = \ln(GSD) \tag{5-2}$$

where GM and GSD are simply the geometric mean and standard deviation of the data, respectively.

EXHIBIT 5-5. SUMMARY OF CENSORED OBSERVATIONS AND CENSORING LEVELS FOR STATE RADON DATA

STATE DATA BASE	NUMBER OF SAMPLES VALID CWS SAMPLES	CENSORING LEVEL, pCi/l	NUMBER OF CENSORED RESULTS	TOTAL SYSTEMS	SYSTEMS WITH NON-DETECT RESULTS	SYSTEMS WITH ONLY NON-DETECT RESULTS	COMMENTS
CALIFORNIA	1,592	~10	13	75	7	0	Eight results < 10 pCi/l adjusted to 5 pCi/l, five values <100 adjusted to 50, one value > 200,000 pci/l excluded
CONNECTICUT	32	NA	0	32	0	0	All results > 1,000 pCi/l
IDAHO	74	NA	0	64	0	0	All reported results > 100 pCi/l
IOWA	150	NA	0	150	0	0	All reported results > 40 pCi/l
KANSAS	245	~25	10	169	9	6	Abilene has three of six results below censoring limit
MAINE	64	NA	0	64	0	0	Lowest result = 22pCi/l, next lowest ~200 pCi/l
MARYLAND	259	~20	3	107	2	1	--
MICHIGAN	186	~50	7	120	7	5	--
MISSOURI	1,184	~10	12	691	12	10	Two results < 0 pCi/l excluded, 10 results < 10 pCi/l adjusted to 5 pCi/l
NEW HAMPSHIRE	2,896	~100	70	725	53	2	Three medium systems with all results < 100 excluded
NEW YORK	425	NA	0	425	0	0	Lowest result = 14 pCi/l
OHIO	228	~25	18	228	17	17	--
PENNSYLVANIA	981	~100	64	488	31	7	--
SOUTH CAROLINA	121	~20	1	89	1	1	One censored sampled deleted because another sample from the same system was > 10,000 pCi/l
TEXAS	169	100	3	120	3	2	--
WASHINGTON	331	~20	25	68	14	9	--
WISCONSIN	1,252	~50	23	610	21	7	--
Total	10,189	--	249	4,225	177	67	
Proportion	100.0%	--	2.4%	100.0%	4.2%	1.6%	

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When data sets contained no censored values, or the frequency of censored values was low, (< about five percent), the log mean and log standard deviation were calculated as described above. This procedure was used with the large majority of data sets (see Exhibit 5-5). When the data contained a higher proportion of censored data, other methods were used to calculate the summary statistics.

c. Calculation of Summary Statistics for Censored Data (MLE Approach)

The NIRS data in particular, as well as some of the supplemental data sets, contained substantial proportions of censored observations. When analyzing these data sets, the log mean and log variance parameters were estimated by a maximum likelihood estimation (MLE) method, a procedure proven to provide estimators with good statistical properties for reasonably large samples. The specific approach that was used was the "EM algorithm" (Dempster,et al. 1979). This algorithm provides a convenient and robust approach to developing MLE estimates of distributional parameters. It involves the iterative calculation of log likelihood ratios while updating the estimates of the censored values of the data until the likelihood ratio is optimized within specified limits. A detailed discussion of the approach is given in Appendix B.1.

The EM algorithm was implemented on Excel® spreadsheets for each data set and system size stratum. The spreadsheets were designed to perform 20 iterations of the algorithm starting from user-specified initial estimates of the sample mean and variance. For all of the data sets and size strata, the EM estimates of the log mean and log variance converged very rapidly. Usually, estimates of the log mean and log standard deviation were stable to the fourth decimal place between the fifth and tenth iteration. The final estimates of log mean and log variance were quite insensitive to the initial estimates used as inputs to the first iteration of the algorithm. As discussed further below, the results of the EM algorithm were generally very consistent with the estimates of distributional parameters derived using other methods.

d. Calculation of Proportions of Systems Above Radon Levels and Confidence Limits on Proportions (Distributional Approach)

A major focus of this analysis was to predict the proportions of water systems or sources that would be above potential regulatory limits. Thus, methods had to be found for estimating the proportions of sources or systems that would exceed regulatory limits, given specified distributions of radon levels.

In each data set, it is clear possible to estimate the proportions of sources or systems above a given regulatory level simply by counting. In some data sets, the numbers of sources in a given range of activity levels may be quite small. Thus, another method may need to be found to provide an estimate of the number of sources exceeding some regulatory levels. Also, a method is needed to predict the proportions of sources above regulatory levels for derived distributions (e.g. for a lognormal distribution derived from NIRS data, adjusted for point-of-entry versus point-of-use sampling).

In these cases, the proportions of sources/systems above potential regulatory levels were estimated as:

$$p(>X) = \Phi[(LM-\ln(X))/LSD] \tag{5-3}$$

where:

p(>X)	=	The proportion of systems with radon levels exceeding (X) pCi/l
Φ	=	The standard normal cumulative distribution function
LM	=	Log mean radon (natural logarithm of geometric mean) for sources or systems being evaluated
LSD	=	Log standard deviation radon (natural logarithm of geometric standard deviation) for sources of systems being evaluated

This approach simply applies the known properties of the cumulative normal distribution to the estimated log mean and log standard deviation of radon occurrence in a given population of sources/systems to estimate the proportion that would be expected to be above the potential regulatory level, X pCi/l. The proportions can be calculated easily using the "NORMDIST" function in Excel®.

As noted above, the data used to estimate the log mean and log standard deviations of radon occurrence were quite limited for some data sets. Therefore, it was necessary to calculate the potential uncertainty in estimates of the proportions, and derive confidence limits for them. The classical approach to estimating confidence intervals in this case is to estimate the standard deviation of the estimated proportion, p(>X) , using the formula

$$SD(p(>X)) = \frac{p(>X)(1-p(>X))}{n}. \tag{5-4}$$

where:

SD	=	the Standard Deviation of the p(>X)
n	=	the number of observations upon which p(>X) has been estimated

The 95 percent confidence interval is then given by the large sample approximation

$$p(>X) \pm 1.96 \times SD(p(>X)). \tag{5-5}$$

This formula for SD(p(>X)) is exactly correct only when the observed fraction of sources exceeding the level (X) is used to estimate the population fraction (of all sources of the given size). Since the proportions of sources exceeding potential regulatory levels were usually estimated using a fitted log-normal distribution, the standard deviation of the estimated proportion will not be given by the above formula. Equation 5-4 will tend to overestimate SD(p(>X)) because the maximum likelihood estimates have smaller variances than the empirical estimates if sample sizes are relatively large. A more exact calculation uses the asymptotic distribution of the maximum likelihood estimators, since the EM algorithm was used to derive maximum likelihood estimates of the mean and variance of the log radon levels, which in turn were used to estimate the proportions exceeding potential regulatory levels. We therefore used a more exact calculation method for determining SD(p(>X)) and its associated confidence interval. This method, which is described in detail in Appendix B.2, does, in fact yield slightly narrower confidence limits for the proportions of systems and sources exceeding potential regulatory levels than does the classical approach.

e. *Estimation of Confidence Intervals on Proportions (Distribution-Free Method)*

Because the fits of the radon distributions to lognormal distributions were not always very good (see Section 5.4) estimates of confidence intervals on the proportions of systems exceeding specified radon levels were also estimated using a distribution-free (also termed "non-parametric") approach (Johnson and Katz, 1969). This method calculates the upper and lower confidence limits, P_u and P_l, respectively on p^*, the estimated proportion of systems above a certain level. (These parameters are often referred to as Clopper-Pearson confidence limits). This method, which is based on counts of actual systems/sources above specified levels, makes no assumptions about the underlying shape of the distribution of radon levels. Confidence intervals on the proportions developed with this method, which is described in detail in Appendix B.3, are compared to those derived using the distributional method in section 5.4.

5.2.2 Distribution Fitting and Goodness-of-Fit Testing

A number of approaches were employed to determine the extent to which the radon occurrence data were consistent with common probability distributions. As discussed will be seen in Sections 5.4 and 5.5, log-transformation of data from the NIRS and state databases (e.g., substituting the natural logarithm of the analytical result for the analytical result itself) results in distributions that closely approximate "normality." Thus, the primary candidate for the distribution of radon levels in these cases is the lognormal distribution, and the bulk of the effort at distribution fitting and goodness-of-fit testing is designed to determine whether, and how well, the radon data from the NIRS and supplemental data sets fit a lognormal model. Given the mixed results of our attempts to fit lognormal distributions to the data, we also explored other plausible distributions to see if the goodness-of-fit to the various data sets could be improved.

As is usual in such analyses, the first approach that is used is a qualitative graphical method, namely the development of "probability plots" for the data sets in question. This approach is also called the "regression on order statistics(ROS) approach" and has previously

been applied to the NIRS data by EPA (Barry and Brattin 1998). To develop a probability plot, the data are ordered in terms of increasing values of the independent variable(x) and plotted as (x(I), y(I)) pairs, and a regression line is fitted using the following equation:

$$\ln x_k = \mu + z_k = u + \sigma \cdot \Phi^{-1}(\frac{k}{N+1})$$

(5-6)

where:

k	=	the number of the ordered observation (including censored values)
N	=	total number of observations (including censored values)
μ	=	the intercept estimate from the regression model
σ	=	the slope estimate from the regression model
Φ	=	the cumulative normal distribution

If all of the data points fall on or near the estimated regression line, this is an indication that the data are consistent with a lognormal model. Curvature in the data in relation to the regression line can indicate that the lognormal model is not appropriate. Plotting the data against the regression line also can identify specific data points or groups of points that do not fit the model well, and additional analyses can be performed on these subsets of the data.

Probability plots provide mainly a qualitative test of the lognormal model. A common pattern in environmental data sets is that data points in the lower and middle ranges of concentration or activity fit the lognormal probability plot quite well, but that some data points at the upper end of the distribution deviate substantially by having log concentrations that are too high to fit the plotted relationship for the rest of the data (Ott 1998). This pattern holds true to some extent for the NIRS data, and this has lead one investigator (Burmaster 1998) to explore the use of mixed lognormal distribution models to better fit these data. While this approach does improve the modeled fit to the selected data sets, it adds a substantial level of complexity to the estimation of proportions of systems exceeding specific radon levels and estimating confidence limits around these proportions. Thus, the mixed models were not used in this analysis.

In addition to the qualitative measure of goodness of fit provided by the lognormal probability plot, we also employed two quantitative tests to determine the goodness of fit of the data to lognormal models. The first of these tests is the Shapiro-Wilk's W-test (Shapiro and Wilk 1965). This procedure calculates a statistic essentially equivalent to the correlation between the points in the probability plot described above. If the statistic is "significant," the hypothesis that the underlying data are lognormally distributed should be discarded. This test has some advantages over some other normality tests in that it is relatively powerful at small sample sizes, and it is not dependent on selection of appropriate test strata (unlike the conventional χ^2 test). When using the W-test, surrogate values equal to one-half the detection limits were substituted for non-detects when running this test. Thus, the results of this test must be interpreted cautiously.

The other goodness-of-fit test that has been used to test the hypothesis of lognormality is the Anderson Darling D-statistic. Like the Shapiro-Wilk W-test, a "significant" result on this test indicates that the hypothesis that the underlying data are lognormal should be discarded. This test has the advantages that it is comparatively sensitive to deviation from lognormality in the "tails" of the distribution. Also, the version of the test that we used (D'Agostino and Stephens, 1989) has been adapted so that it can accommodate left-censored data. It has the disadvantage, however, that critical values of the D-statistic have been calculated only for a situation in which the actual geometric mean and log standard deviation of the distribution from which the data are drawn are known. In the analyses which follow, these values are not known, but are estimated from the data. This again introduces some uncertainty into the interpretation of this test. In this case, using the critical values for the known distribution will probably be less likely to falsely identify a lognormal data set as not being lognormal, but more likely to falsely identify a non-lognormal data set as being lognormal. For these reasons, the Anderson-Darling statistic is used primarily to compare goodness-of-fit among data sets and distributions, rather than as a rigorous test of hypotheses regarding specific distributions.

5.2.3 Hypothesis Testing for Differences in Radon Activity Levels and Distributions

In Sections 5.4 and 5.5, we make a large number of comparisons of radon levels across states, size strata, and data sets. In some cases, formal statistical tests are used to evaluate the significance of the differences between radon levels. Because the various data sets that we evaluate (national NIRS data, state data, data from different system size strata), while generally consistent with lognormality, vary in their distributional characteristics, we use both classical "parametric" tests, as well as non-parametric tests of hypotheses.

a. Parametric Tests (Student's t)

For comparing two distributions using the classical Student's t-test, we applied the test to the natural logarithms of the data. The results of this test indicate whether the log geometric means of two lognormal distributions are significantly different (i.e., whether the hypothesis of their equality can be discarded with a given degree of certainty). The t-test is used primarily to compare data from the same system size strata between the NIRS and the radon data gathered by the states. The degrees of freedom used in the test is ($n_{(NIRS)} + n_{(state)} -2$). In implementing the t-test, we substituted one-half the quantitation limits for censored observations in both the state and NIRS data. The t-statistics for independent samples were calculated and the Levene test of homogeneity of variances was employed to confirm the independence of samples.

For some data sets, we also employed a stratified t-test procedure to test the difference between the weighted means of the NIRS and state data sets. Using this approach, we first calculated the weighted mean difference in log radon level:

$$\text{Weighted Mean Dif.} = \sum(w)_s \, [(\log \text{mean(NIRS)} - \log \text{mean(state)}] \qquad (5\text{-}7)$$

where $(w)_s$ is the weight for each stratum of the data and log mean denotes the logarithm of the geometric mean radon. Since the data are stratified by system size, these weights correspond to the proportions of the various size groundwater systems in various states. The variance of the weighted mean difference is:

$$\text{Var(Weighted Mean Dif.)} = \sum(w)_s^2 \, [\text{Var(log mean(NIRS)} + \text{Var(log mean(state))}] \qquad (5\text{-}8)$$

where the symbol "Var" indicates "the variance of".

The significance of the difference in means between the two data sets can then be evaluated using a conventional Z-test (all the comparisons involve more than 30 degrees of freedom), where Z is:

$$Z \text{ (two-sided)} = \text{Weighted Mean Dif.}/\sqrt{\{\text{Var(Weighted Mean Dif.)}\}} \qquad (5\text{-}9)$$

Critical values for Z corresponding to p = 0.1 (one-sided test) or p = 0.05 (two-sided test) come from standard statistical tables.

b.   Non-Parametric Test for Difference of Means (Mann-Whitney U Test)

In order to confirm the results of the t-test, we also employed a non-parametric test to evaluate the differences between means in the radon data sets. The Mann-Whitney U-Test was used to evaluate differences in means in all comparisons where the total number of degrees of freedom was less than 100, or where the number of samples from either stratum being compared was less than 10. (For larger data sets, it is generally recognized that the t-test is almost always more sensitive.) The U-test does not assume any specific distributional form of the data, and the impact of including the censored data can be expected to be lower than on the t-test results. As will be seen in Sections 5.4 and 5.5, the U-test and t-test results for the differences between the NIRS and state data were highly consistent.

c.   Test for Differences Between Distributions (Kolmorgorov-Smirnov Test)

The final test that we used to evaluate the differences between radon distributions was the Kolmorgorov Smirnov test. This procedure compares the entire distributions being evaluated, rather than estimating the significance of the difference of their mean values. This test was originally intended to compare known distributions, rather than distributions fitted to observational data. When used, as in this case, to compare fitted distributions, it is likely that the test is somewhat conservative, that is, less likely to underestimate the significance of differences in distributions.

d.   Bootstrap Confidence Limits for Ratios of Log Means and Log Standard Deviations and Numbers of Systems Exceeding Potential Regulatory Levels

The ratios of the log mean radon levels in the state and NIRS data sets, discussed in Section 5.6, were not expected to be normally distributed. Therefore, we used a numerical simulation method ("bootstrap") to estimate confidence limits for these ratios. The approach taken is that described by Davison and Hinkley (1997).

The individual ratios of state to NIRS radon levels are used as inputs to a Monte Carlo simulation model. For each statistic being analyzed, we took R = 200-500 samples of N values from the input data, where N is the number of data points. "Studentized" bootstrap confidence limits are then calculated as:

$$\mu^* - \sigma^* Z^*_{(1-\alpha)} \quad \text{and} \quad \mu^* - \sigma^* Z^*_{(\alpha)} \tag{5-12}$$

where:

μ^* = The mean of the R simulation estimates

σ^* = The standard deviation of the R simulation estimates

$Z^*_{(1-\alpha)}, Z^*_{(\alpha)}$ = The α or $1-\alpha$ percentile of the R ordered values of $(\mu_i - \mu^*) / \sigma^*$ calculated from the simulation, where μ_i is the "ith" ratio estimate from the simulation and α is the desired confidence level

5.2.5 Computing Methods

Spreadsheet data files were developed and managed using Microsoft Excel® Version 5.0. Larger data files were manipulated and analyzed using Microsoft Access® Version 2.0. Probability plots, box plots, multiple regression analyses, single-stratum t-tests, Mann-Whitney U-Tests, and Kolmorgorov-Smirnov tests were performed using the Statsoft, Inc. Statistica® program Version 5.0. Pearson rank correlation coefficients were also calculated using this package.

The Anderson-Darling goodness-of-fit tests, the E/M maximum likelihood algorithms, and the estimation of confidence limits on the proportions of facilities exceeding specific radon levels were implemented on Excel spreadsheets, as were the t-tests of the differences between weighted average radon levels. The Monte Carlo simulation modeling used in the evaluation of temporal and sampling and analytical variance and in the bootstrap analyses were performed using the Crystal Ball Pro ® package as an Excel add-in.

5.3 Analysis of Radon Occurrence Data: Approach to Stratification

This section provides a discussion of the methods used in the exploratory data analysis of the radon data obtained from the sources discussed in Section 5.1. The following sections discuss, in turn, the approach used to stratify radon data from groundwater systems, comparison of radon level data from the NIRS and supplementary sources, studies which directly evaluate radon in raw and finished water, and the use of the lognormal model to predict the proportions of systems exceeding potential radon regulatory levels.

5.3.1 Stratification by System Size

As discussed in Section 3.1, radon levels in groundwater systems are known to vary as a function of system size. As early as 1979 (Hess, et al., 1979), it was found that private wells in Maine generally had higher radon levels than larger public systems. An analysis of data from the National Uranium Resource Evaluation (NURE) project (Hess, et. al. 1985) confirmed the national pattern of generally higher radon levels in private wells compared to public wells, and also provided suggestive evidence that radon levels in smaller public groundwater supply systems were higher than those in larger systems. The NIRS sampling strategy, including as it did a high proportion of small and very small systems, was designed in part to more fully investigate the differences in radon levels across system sizes at the national level. The NIRS sampling strategy divided groundwater systems into four size categories (Very Small, Small, Medium, and Large) based on population served.

Data from the NIRS survey confirm that radon levels generally increase with decreasing system size, as measured by the number of individuals served (Longtin, 1987). EPA's Occurrence Analysis (Wade Miller 1990) also evaluated radon occurrence in the NIRS systems for these four size strata of systems. Subsequently, EPA received comments (RCG/Hagler Bailly, 1992) that the smallest size stratum evaluated in the occurrence analysis was heterogeneous enough (and that the number of systems in this category was large enough) to merit splitting again into two separate strata. In 1993, the revised occurrence analysis (Wade Miller, 1993) included evaluation of five strata rather than four, and in 1995, with its *Uncertainty Evaluation of Risks Associated With Exposure to Radon* (EPA 1995a), the agency also evaluated radon levels in the same five size strata of systems:

* Very Very Small (VVS) = serving 25 to 100 people;
* Very Small (VS) = serving 101-500 people;
* Small (S) = serving 501 to 3,300 people;
* Medium (M) = serving 3300-10,000 people; and
* Large (L) = serving more than 10,000 people.

The first two strata represent a subdivision of the original "Very Small" category. In this analysis, we likewise evaluate radon levels in these five system sizes.

5.3.2 Alternative Stratification Variables

Other stratification variables in addition to system size have been considered. These include stratification by region, by geological regime, and by other measures of system size, such as total production (the amount of water pumped per day) or the number of points of entry to the groundwater system (approximately equivalent to the number of wells). Based on a review of the NIRS and supplemental data, system size measured in population served was retained as the primary stratification variable. This decision was based on a number of considerations. Use of the geologic regime as a predictor of radon activity was ruled out by a lack of geological regime information for most of wells sampled in the NIRS and supplemental data sets. Alternative

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measures of system size, such as number of points of entry, or total production, were found to be less closely correlated to radon levels than population served in the NIRS data and not available for the bulk of the supplemental data. Geographical stratification was used, however, to characterize radon levels. In the first place, most of the supplemental data sets provided data on specific geographic areas (states), so this was a natural unit of comparison to the NIRS data. In addition, radon levels were found to vary substantially across different regions of the U.S. As will be discussed in more detail below, the NIRS data were stratified into eight regions when substantial variations in radon levels were seen across the country.

Stratification by sampling point was likewise impractical with the available data. The NIRS samples were all taken at or near the point of use in the distribution system. Almost all the data from the supplementary sources was taken at either the well head or at the point of entry into the distribution system.[5] Only one data set provided data from both the point of entry and point of use. As will be discussed in more detail in Section 5.3, data from the point-of-entry samples in the supplemental data sets were used to estimate the likely point of entry radon levels in groundwater sources for the systems sampled during the NIRS. To estimate exposure levels from the supplemental data, the point of entry radon levels were likewise adjusted downward to reflect the expected losses of radon in the distribution systems.

Because the great majority of the supplemental data were gathered from samples taken at the wellhead, it was also not possible to stratify these data according to the presence or type of in-place treatment. This may have resulted in an overestimation of the average radon levels to which consumers are exposed at systems having in-place treatments that might reduce radon levels (aeration, granular activated carbon filtration, storage). The NIRS database contained information on in-place treatments, but no significant relationships were found between the presence or absence of treatment and radon levels in the distribution system.

5.4   Distribution of Radon Level in the NIRS Database

Like the different radon levels in different size systems, the tendency for radon activity levels to fit lognormal distributions was noticed in the earliest systematic studies of its occurrence. Hess, et al. (1979) characterized groundwater levels from in the NURE data from individual states as being drawn from one or more lognormal distributions, and Longtin (1986) provided probability plots (see below) for radon levels in groundwater indicating approximate lognormality for the combined NIRS data from all states and size strata. In addition, there is good theoretical reason to expect radon levels to approximate such a distribution. Ott (1995), for example, has illustrated how random multiplicative dilutions of pollutants in the environment tend to produce concentration distributions that are asymptotically lognormal. In addition, many distributions of naturally occurring elements and man-made pollutants have been found to be approximate

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[5] Throughout this report, "point of entry", consistent with EPA policy is defined as the location just before water enters the distribution system. For many small and very small systems, the point of entry is the wellhead. "Point of use" refers to any samples taken in the distribution system or from the tap.

lognormality. However, since we intend to use the radon occurrence distributions to predict proportions of systems above specific radon levels, we conducted additional evaluations of the appropriateness of the lognormal model, and its utility in projecting radon levels.

5.4.1 Distribution of Radon in Nationally Aggregated NIRS Data

When the cumulative occurrence of radon in groundwater systems from the NIRS data is plotted, without stratification for system size or region, the result is a very broad distribution with a long "tail" extending to high radon activity levels. While the majority of radon values are less than 300 pCi/l, there are a substantial number of observations above 5,000 pCi/l. When the data are "log-transformed" (the natural logarithm of the radon levels are substituted for the raw values), the distribution becomes somewhat more regular (Exhibit 5-6.) The large group of systems at the left-hand end of the histogram are the 269 samples reported as being "less than 100 pCi/l". These are shown in the graph as having radon levels of 50 pCi/l (whose natural logarithm is 3.912.) The remaining values are distributed in a more or less smooth curve that is somewhat bell-shaped (it looks a little like a "normal" or Gaussian distribution), but the high-activity tail is still evident at ln(radon) values greater than 7.0 or so (corresponding to a radon activity of approximately 1,100 pCi/l.) If the data were "perfectly" lognormal, this histogram would look like a symmetrical bell-shaped curve. Thus, the evidence suggests that the NIRS data, viewed as a whole, are nearly, but not perfectly lognormal.

**Exhibit 5-6. Distribution of ln(Radon) in NIRS Data Set
(All System Sizes, All Regions)**
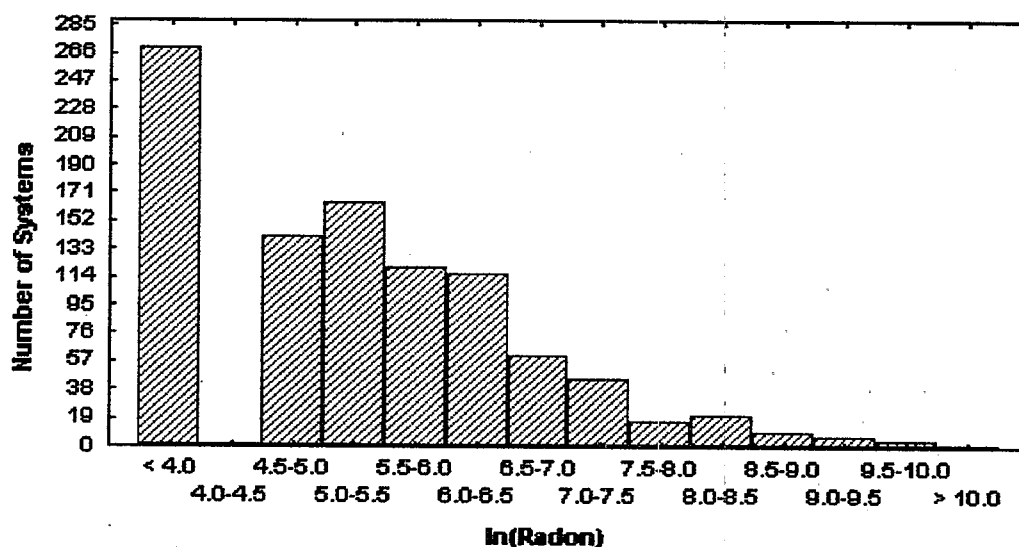
This impression is confirmed by other tests. Exhibit 5-7 shows a "probability plot" (as described in Section 5.2.2) of the data from the NIRS, transformed by graphing it on a log scale. A perfect straight-line fit would indicate a lognormal distribution of radon levels. There is some

Exhibit 5-7. Probability Plot of NIRS Radon Data
(All System Size Categories, All regions)

(Solid line indicates linear fit.)
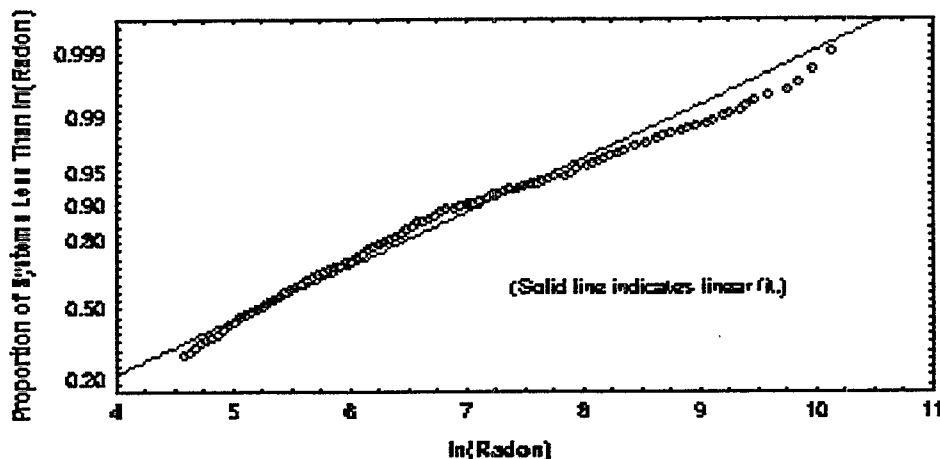
deviation from linearity, however, particularity near the high end of the data range, consistent with the long "tail" seen in the conventional histogram. The graph thus suggests that the data are not perfectly lognormal. In addition, statistical tests designed to test normality indicate that the data are not consistent with a simple lognormal distribution. Two of the goodness-of-fit tests discussed in Section 5.2, the Shapiro-Wilk W statistic and Anderson-Darling test, both indicate that the hypothesis of lognormality for the NIRS data taken as a whole can be discarded with greater than 95 percent certainty.

When the NIRS data are broken down by size strata, the linearity of the probability plots improves but is still imperfect (Exhibit 5-8). The W-test again indicates that the data from all five size categories depart from lognormality, although the larger systems come close to lognormality. The better goodness-of-fit statistics for the larger systems are more a function of the smaller number of systems in these categories (there are nine large and 11 medium systems with valid results altogether) than an inherently better fit to the data.

Exhibit 5-8. Probability Plots of ln(Radon) by System Size
(NIRS, All Regions)
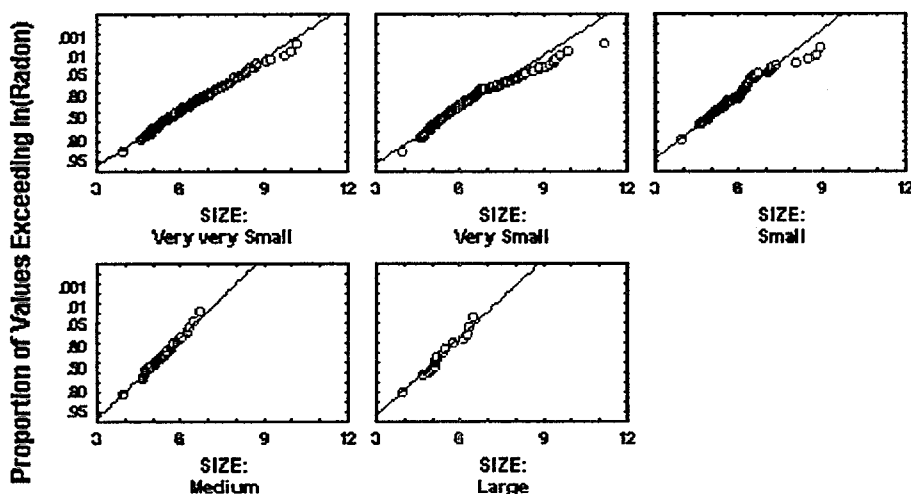
The very small systems have a particularly high proportion of observations falling below the linear plot of ln(radon) versus cumulative probability. Closer evaluation of these data indicate that the highest value (ln (radon)= 11.17, radon = 71,400 pCi/l) was more than five times the next highest radon level in the entire NIRS database, and that the 15 very small systems with the highest radon levels were concentrated in two states with high average radon levels (Connecticut and North Carolina). Further, three pairs of data points from these states were taken from water systems located within 10 miles of one another. Thus, it appears that the NIRS data are not perfectly representative of the geographic distribution of radon in very small systems, and that this has affected the goodness-of-fit to the lognormal model. In the estimation of geometric mean and standard deviations that are discussed below, the highest value in this stratum is omitted as unrepresentative.

Despite the fact that the probability plots do not show perfect linearity for the different size systems, the slopes and intercepts of the plots provide approximate estimates of the geometric mean and geometric standard deviations of the radon analytical results. These results are summarized in Exhibit 5-9, along with estimates of these statistics developed in previous analyses. Also included are estimates of the geometric means and standard deviations of radon levels in the various size strata of the NIRS data developed using the iterative maximum likelihood approach (EM algorithm) described in Appendix B-2. The different techniques arrive at generally similar estimates for the radon distributional parameters. The geometric mean values for the size strata decrease from about 270-285 pCi/l for the smallest systems (log mean ~ 5.65) to 125-135 pCi/l for the largest systems (log mean ~ 4.85). The corresponding arithmetic means range from approximately 795 pCi/l for the very very small systems to about 185 pCi/l for the large systems.

Compared to the other estimates, the EM algorithm consistently yields slightly higher log means and slightly lower log variances for all the size strata. The reasons for the differences in the results between the current study and the 1990 EPA occurrence analyses (Wade Miller Associates 1990) due to the use of the EM algorithm, but are more likely due to a different treatment of a few samples with irregular results ("non-detect" values greater than 100), or to the use of slightly different algorithms to calculate the order statistics for the probability plots. In addition, EPA's 1990 occurrence analysis did not disaggregate the very small and very very small strata. Similar factors probably explain the somewhat smaller differences between the results of EPA's 1995 *Uncertainty Analysis* (EPA 1995) and our results.

It can be seen from the data in Exhibit 5-9 that there is a clear trend (as expected) of increasing log radon levels with decreasing system size. The results of a one-way analysis of variance (ANOVA) indicates that differences in systems size explain a significant proportion of the overall variance in the data. (The f-statistic for inter-group differences is $=15.18$, $p = 0.000$, indicating a high degree of statistical certainty that system size is associated with log mean radon level). In addition, the ANOVA post-hoc comparison of means indicates that the log mean radon levels for the two smallest size strata differ significantly from those of the three larger system strata. However, the differences among the means of the three large-system strata (large, medium, and small) are not significant, nor were the differences between the means of the two

| EXHIBIT 5-9 | ESTIMATED DISTRIBUTIONAL PARAMETERS FOR RADON IN GROUNDWATER SYSTEMS, NIRS DATA, NATIONALLY AGGREGATED | | | | | |

1. Maximum Likelihood Estimates (This Study)

	All Systems	Large	Medium	Small	Very Small	Very Very Small
Log Mean Radon	5.325	4.871	4.924	4.856	5.469	5.645
Geometric Mean	205	130	138	129	237	283
Arithmetic Mean [1]	561	191	197	275	629	792
Log Standard Deviation Radon	1.417	0.872	0.847	1.234	1.397	1.435
Number of Systems	981	335	333	232	53	28
Number of Systems With Cenored Data	269	71	74	95	18	11

2. Regression Estimates (This Study)

	All Systems	Large	Medium	Small	Very Small	Very Very Small
Log Mean Radon	5.228	4.832	4.875	4.811	5.372	5.567
Geometric Mean	·186	125	131	123	215	262
Arithmetic Mean	572	181	199	278	699	796
Log Standard Deviation Radon	1.497	0.855	0.913	1.277	1.535	1.492

3. EPA Occurrence Analysis (Wade Miller, 1990)

	All Systems	Large	Medium	Small	Very Small	Very Very Small
Log Mean Radon [2]	—	4.897	4.895	4.822	5.490	—
Geometric Mean	—	134	134	124	242	—
Arithmetic Mean	—	205	206	284	758	—
Log Standard Deviation Radon	—	0.924	0.933	1.287	1.510	—

4. EPA Uncertainty Analysis (1995)

	All Systems	Large	Medium	Small	Very Small	Very Very Small
Log Mean Radon	—	4.910	4.889	4.835	5.373	5.586
Geometric Mean	—	136	133	126	216	267
Arithmetic Mean	—	199	200	281	677	831
Log Standard Deviation Radon	—	0.878	0.903	1.267	1.513	1.508

Notes:

1. Calculated from fitted lognormal distribution

2. Statistics for Very Small category include Very Very Small Systems

smallest size strata. Tests for differences between the distributions using the Kolmorgorov-Smirnov test (a procedure for testing the differences between distributions) showed the same pattern; the distributions of the three largest and two smallest size categories were significantly different from one another.

5.4.2 Distributions of Radon in Regionally Stratified NIRS Data

As noted above, the NIRS data were also stratified by region. This approach was originally suggested by commenters on EPA's 1990 and 1993 occurrence analyses (RCG/Hagler Bailly 1993), and adopted based on the finding that radon distributions varied significantly among regions of the U.S. The regional stratification proposed by the commenters was:

- New England (CT, ME, MA, NH, RI, VT)
- Appalachians (DE, GA, MD, NJ, NY, NC, PA, SC, VA, WV)
- Plains (AR, KS, KY, MI, MO, NE, ND, OK, SD, TN)
- Great Lakes (IL, IN, IA, MN, OH, WI)

- Gulf Coast (AL, FL, LA, MS, TX)
- Northwest (OR, WA)
- California (CA)
- Rocky Mountains (AZ, CO, ID, MT, NV, NM, UT, WY)

EPA had some reservations about adopting these regional divisions (placing Michigan in the "Plains" region, and Iowa in the "Great Lakes"). Subsequent analysis, however, suggested that these divisions, despite the counterintuitive assignment of some states to regions, capture important differences in radon levels, (see below) and, in combination with the data from individual states, provide a useful basis for predicting the proportions of systems exceeding potential regulatory levels. In addition, the regional stratification provides another opportunity to test the issue of lognormality.

Probability plots for the NIRS data stratified by region are shown in Exhibit 5-10. Subjectively, they appear to be more linear than the plots of radon data stratified by system size. However, the Shapiro-Wilk W statistic indicates that of all eight regions, the data from the Rocky Mountain regional is the only combined data set consistent with the lognormal distribution. Stratifying the data by both region and system size, as is illustrated for the data from the Appalachian Region in Exhibit 5-11, again seems to improve the linearity of the probability plots for the smaller size strata. However, this stratification does not significantly improve the goodness-of-fit test results, which still indicate that the hypothesis of lognormality may be excluded with $p < 0.05$ for the three strata (the smallest systems) with more than a few systems. Similar results are seen for the other regions.

Exhibit 5-10. Probability Plots of ln(Radon) by Region
(All Size Strata)
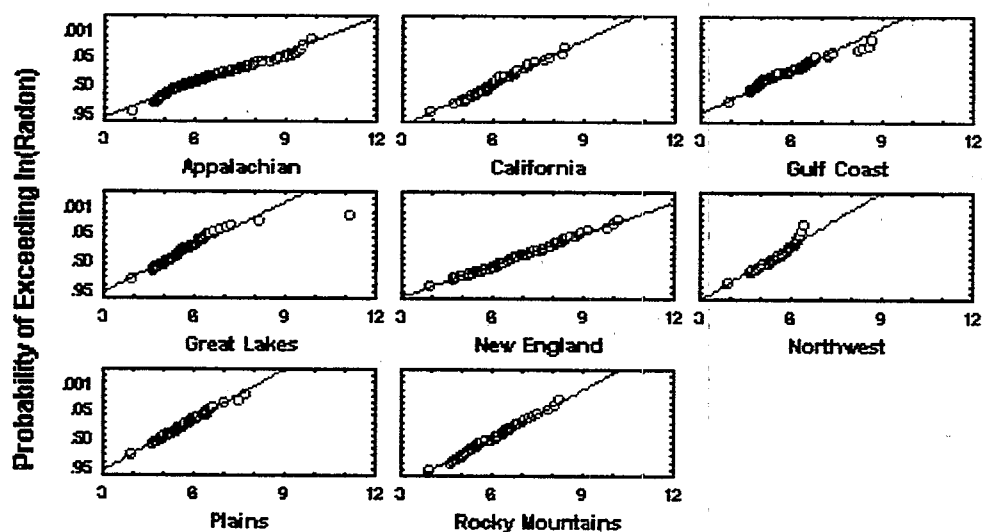
Exhibit 5-11. Probability Plots of ln(Radon) from NIRS Appalachian Region Data by Size Category
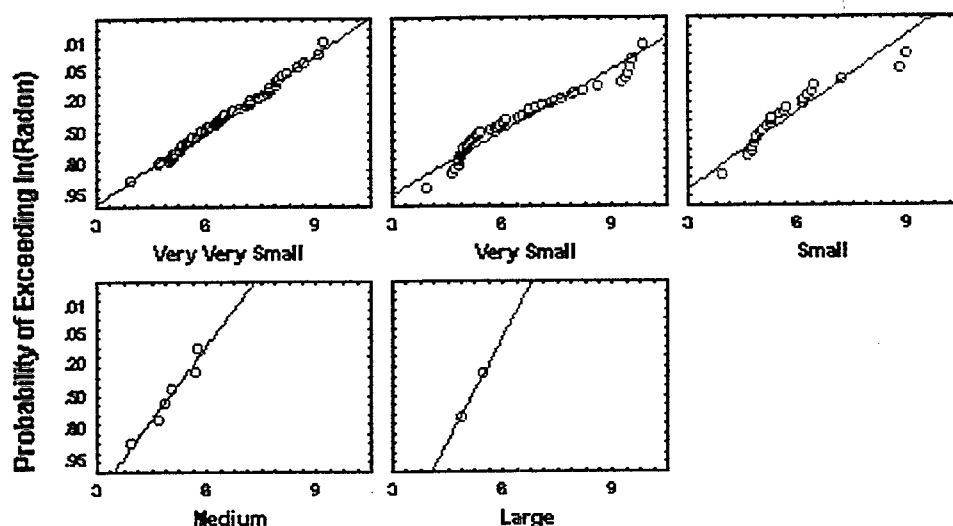
noted above, the regional stratification does appear to capture important differences in radon activity levels. Exhibit 5-12 shows the log mean and log standard deviation values estimated for the combined systems in the eight regions with statistically significant differences indicated. Most of the regional log means are significantly different from one another, using the t-statistic as a criterion. Exceptions include the plains region, whose mean is similar to that for the Gulf Coast, Great Lakes, and Northwest, and the Rock Mountain region, whose log mean is near that of the Appalachian region and California. The Kolmorgorov-Smirnov test gives the same radon distributions as being significantly different from one another (the Gulf Coast compared to the Great Lakes and Northwest regions) whose means are not significantly different based on the t-test.

5.4.3 Goodness of Fit Testing of Lognormal and Alternative Distributions of NIRS Data

Because the previous analyses indicated the possibility that the aggregated and dissagregated NIRS data might not fit lognormal distributions, we also employed goodness-of-fit testing to determine whether the lognormal provided the best overall fit to the data. The entire NIRS data set, and the data broken down by Region and size were fit to a number of analytical distributions and the Anderson-Darling statistic (see section 5.2) was used to estimate the relative

Exhibit 5-12. Differences Among Regional NIRS Log Mean and Standard Deviation Values

Regional Means Significantly Different?[1]

Region	Log Mean/Geometric Mean (Log Standard Deviation)	Appal-achian	California	Gulf Coast	Great Lakes	New England	North West	Plains	Rocky Mount.
Appal-Achian	5.71/302 (1.59)	--	-	++	++	++	++	++	-
California	5.81/334 (1.59)	NA	--	++	++	++	++	++	-
Gulf Coast	4.83/125 (1.22)	NA	NA	--	+	++	+	-	++
Great Lakes	5.02/151 (1.10)	NA	NA	NA	-	++	-	-	++
New England	7.10/1,211 (1.33)	NA	NA	NA	NA	-	++	++	++
North West	5.08/161 (0.80)	NA	NA	NA	NA	NA	--	-	++
Plains	4.84/126 (0.93)	NA	NA	NA	NA	NA	NA	-	++
Rocky Mount.	5.89/361 (1.02)	NA	NA	NA	NA	NA	NA	NA	-

Notes:

1. - = Not significant, ++ = one-tailed t-statistic significant at p , 0.05, Komorgorov-Smirnov test significant at p < 0.025, + = Kolmorgorov -Smirnov test significant at p< 0.025, t-statistic not significant results as the t-test except that it identifies two sets of As

fits of lognormal and other distributions that were tested.[6] The results of the goodness-of-fit testing are shown in Exhibit 5-13.

Using the relative magnitude of the Anderson-Darling (A-D) statistic as the indicator, the lognormal distribution provides the best fit to the data as a whole, and to most of the subsets of the NIRS data when they are stratified either by size or region. The lognormal provides the best fit to data from three smallest system categories, the third-best fit to the data from medium systems, and the second-best fit to data from the large system. For data as a whole, and for the three smallest size categories , the values of the A-D statistics for the lognormal distribution are such that, using the statistic alone, the lognormal could be discarded as an acceptable fit to the data ($p < 0.05$). However, the A-D statistics for the other types of distribution are even larger. Thus, it appears that the lognormal does as well or better than any of the distributions at describing the radon data for these data. In the case of the two largest size categories, the lognormal is not the best-fitting distribution, but the differences in A-D statistic values among the distributions are so small that there really is no basis to conclude that the lognormal is any worse then the other contending candidates.

When the NIRS data are stratified by region, the lognormal provides the best fit (as measured by the A-D statistic) for six of the eight regions. For three regions (California, New England, and the Rocky Mountains), the A-D value is low enough that the hypothesis of lognormality cannot be ruled out with any degree of statistical certainty. For another three regions (Appalachian, Gulf Coast, and Great Lakes), the A-D value could rule out the lognormal distribution, but the fit for the other distributions appears to be even worse.

In two regions, (the Northwest and Plains), the lognormal distribution apparently does not provide the best fit to the data. Data from the Plains regions do not fit any of the distributions very well. This is apparently because of the large proportion (41 percent) of censored observations in this stratum. The data from the Northwest region are characterized by low radon levels and low levels of variability, compared to other regions. This results in relatively low A-D statistics for a number of distributions, including the lognormal, even though the lognormal is not the best fit.

Taken together, we interpret these results to suggest that the lognormal distribution is, on the whole, the most practical model for describing and predicting radon levels in groundwater systems. The summary statistics for the radon data for all of the regions and size strata in the NIRS data are shown in Exhibit 5-14.

5.5   The Distribution of Radon in the Supplementary Data Sets

In this section, we describe the results of our analysis of radon occurrence data from some of the supplementary data sets obtained during the occurrence analysis. The focus is primarily on

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[6] The distribution types that were tested included the uniform, triangular, normal (Gaussian), lognormal, two- and three-parameter Gamma, Beta, Logistic, Type 1 Extreme Value, Pareto, exponential, and Weibull.

Exhibit 5-13. Goodness of Fit Test Results (Anderson-Darling Statistics) for NRS Data Stratified by System Size

ALL		Very Very Small		Very Small		Small		Medium		Large	
Distribution	ADStat.	Distribution	ADStat.	Distribution	ADStat.	Distribution	ADStat.	Distribution	ADStat.	Distribution	ADStat.
Lognormal	22.3	Lognormal	4.48	Lognormal	6.47	Lognormal	10.9	Exponential	2.09	Exponential	1.32
Gamma	38.6	Gamma	8.72	Gamma	14.7	Gamma	17.6	Beta	2.25	Lognormal	1.40
Pareto	51.3	Weibull	11.47	Extreme Value	4.82	Extreme Value	20.8	Lognormal	2.30	Beta	1.43
Weibull	59.6	Pareto	15.64	Logistic	5.38	Exponential	23.4	Extreme Value	2.96	Extreme Value	1.72
Extreme Value	125	Extreme Value	36.52	Pareto	61.7	Logistic	25.8	Logistic	3.07	Logistic	1.88

Goodness of Fit Test Results (Anderson-Darling Statistics) for NRS Data Stratified by Region

Appalachian		California		Gulf Coast		Great Lakes		New England		Northwest		Plains	
Distribution	ADStat.	Distribution	ADStat.	Distribution	ADStat.	Distribution	ADStat.	Distribution	ADStat.	Distribution	ADStat.	Distribution	ADStat.
Lognormal	3.94	Lognormal	1.02	Lognormal	8.86	Lognormal	5.42	Lognormal	0.62	Beta	1.27	Exponential	4.91
Weibull	4.11	Exponential	1.68	Gamma	13	Gamma	5.99	Weibull	1.933	Extreme Value	1.84	Beta	5.58
Gamma	8.71	Weibull	2.21	Extreme Value	20.4	Exponential	6.4	Gamma	2.45	Logistic	1.89	Lognormal	5.75
Pareto	32.2	Extreme Value	2.76	Exponential	21.9	Weibull	7.14	Exponential	2.73	Exponential	1.98	Extreme Value	6.97
Extreme Value	34.2	Logistic	4.27	Logistic	23.9	Extreme Value	8.48	Extreme Value	3.31	Lognormal	2.14	Logistic	6.98

Methods, Occurrence, and Monitoring Document for Radon

Exhibit 5-14. Summary Statistics for NIRS Data, Broken Down By Region[1]

Region	System Size				
Appalachian	ALL	VVS	VS	S	M
Geometric Mean, pCi/l	333	378	419	199	158
Geometric Standard Deviation	4.76	4.36	5.71	3.90	1.67
Arithmetic Mean, pCi/l	1,127	1,118	1,912	502	180
Log Mean	5.81	5.94	6.04	5.29	5.06
Log Standard Deviation	1.56	1.47	1.74	1.36	0.51
Number of Systems	179	84	56	31	6
Systems With Censored Data	31	16	7	7	1
California	ALL	VVS	VS	S	M
Geometric Mean, pCi/l	333	359	525	267	145
Geometric Standard Deviation	3.09	3.38	2.53	1.84	2.05
Arithmetic Mean, pCi/l	629	754	808	322	187
Log Mean	5.81	5.88	6.26	5.59	4.98
Log Standard Deviation	1.13	1.22	0.93	0.61	0.72
Number of Systems	60	29	16	7	6
Systems With Censored Data	10	5	1	1	2
Gulf Coast	ALL	VVS	VS	S	M
Geometric Mean, pCi/l	125	183	181	64	35
Geometric Standard Deviation	3.38	3.21	2.88	3.85	3.57
Arithmetic Mean, pCi/l	263	362	318	159	78
Log Mean	4.83	5.21	5.20	4.16	3.55
Log Standard Deviation	1.22	1.17	1.06	1.35	1.27
Number of Systems	189	48	68	53	10
Systems With Censored Data	75	11	18	32	8
Great Lakes	ALL	VVS	VS	S	M
Geometric Mean, pCi/l	151	168	182	121	140
Geometric Standard Deviation	3.01	2.43	3.54	2.88	2.43
Arithmetic Mean, pCi/l	278	250	404	212	208
Log Mean	5.02	5.13	5.20	4.80	4.94
Log Standard Deviation	1.10	0.89	1.26	1.06	0.89
Number of Systems	191	40	65	65	14
Systems With Censored Data	61	11	15	28	5
New England	ALL	VVS	VS	S	M
Geometric Mean, pCi/l	1,214	1,657	1,169	479	645
Geometric Standard Deviation	3.77	3.43	4.61	1.69	1.23
Arithmetic Mean, pCi/l	2,933	3,543	3,760	550	659
Log Mean	7.10	7.41	7.06	6.17	6.47
Log Standard Deviation	1.33	1.23	1.53	0.52	0.21
Number of Systems	59	26	24	6	2
Systems With Censored Data	4	1	3	0	0
Northwest	ALL	VVS	VS	S	M
Geometric Mean, pCi/l	161	160	167	111	112
Geometric Standard Deviation	2.23	2.14	2.12	3.73	1.00
Arithmetic Mean, pCi/l	222	214	222	265	112
Log Mean	5.08	5.07	5.12	4.71	4.72
Log Standard Deviation	0.80	0.76	0.75	1.32	0.00
Number of Systems	66	36	22	6	1
Systems With Censored Data	20	11	6	3	0
Plains	ALL	VVS	VS	S	M
Geometric Mean, pCi/l	132	172	127	83	142
Geometric Standard Deviation	2.65	2.77	1.75	3.32	1.74
Arithmetic Mean, pCi/l	213	289	148	170	166
Log Mean	4.88	5.15	4.84	4.42	4.96
Log Standard Deviation	0.98	1.02	0.56	1.20	0.56
Number of Systems	136	34	34	45	13
Systems With Censored Data	52	9	13	26	3
Rocky Mountains	ALL	VVS	VS	S	M
Geometric Mean, pCi/l	361	559	226	345	248
Geometric Standard Deviation	2.77	2.54	3.32	2.34	1.84
Arithmetic Mean, pCi/l	607	863	464	495	299
Log Mean	5.89	6.33	5.42	5.84	5.51
Log Standard Deviation	1.02	0.93	1.20	0.85	0.61
Number of Systems	68	24	22	18	3
Systems With Censored Data	6	0	6	0	0

1. Regions defined as described in text. Includes states with supplemental data.

those data sets which are intended to be representative of the radon distributions in individual states, and include the results of statewide radon surveys or ongoing radon monitoring programs. In Section 5.6, we compare the data from the supplementary data sets to the NIRS results from the same states and regions in order to develop national estimates of radon occurrence in groundwater supplies.

5.5.1 Distributions of Radon in Supplemental Data Sets

To more fully investigate the distribution of radon levels in groundwater, we examined the distributions of radon levels in data from 17 states who had submitted substantial amounts of data. The results of the analysis were quite variable. Aggregated data from community water systems in some states (Maine, for example) gave very nearly linear probability plots (Exhibit 5-15). On the other hand, data from some other states clearly depart from lognormality (data for Texas is given in Exhibit 5-16.) Goodness-of-fit testing was performed on the aggregated data from the individual state data sets, and on data from individual size categories when sufficient numbers of systems had been sampled. (Below about 10 systems, the ability of the Anderson-Darling statistic to distinguish among the goodness-of-fit for different distributions was found to be quite limited.)

Exhibit 5-15. Probability Plot of ln(Radon) Data From Maine Community Water Systems (Hess, 1979)
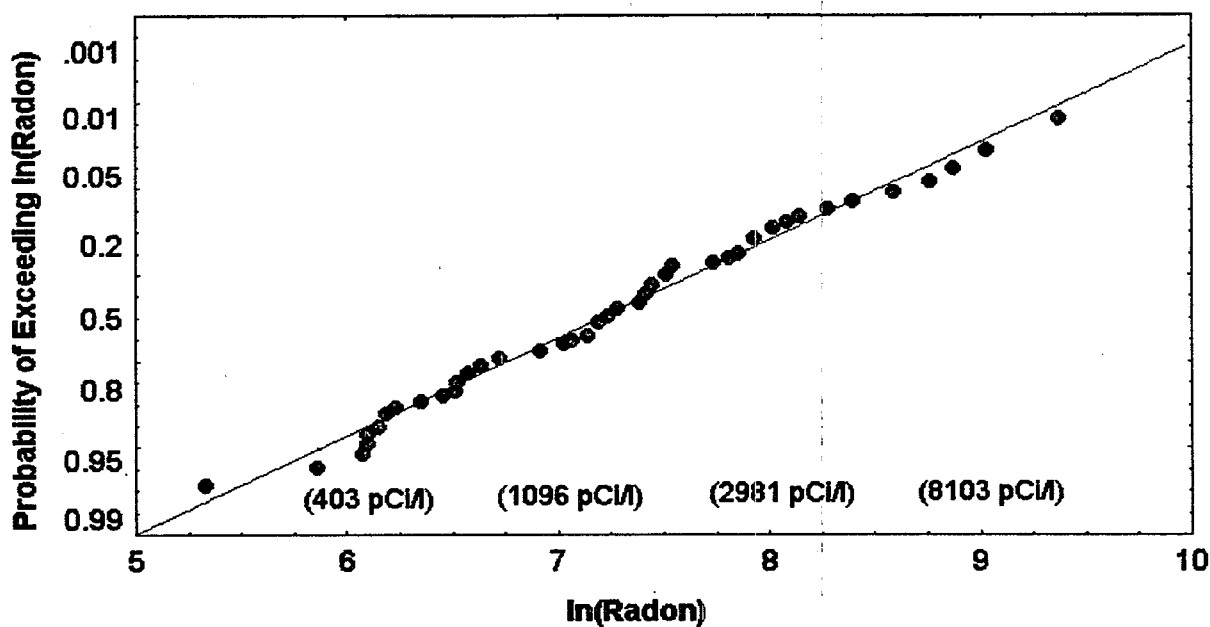
It can be seen from the data in Exhibit 5-17 that the lognormal distribution provided the best fit (as measured by the A-D statistic) for 14 out of 17 of the data sets evaluated. In seven of these cases, the value of the A-D statistic is judged to be consistent with lognormality. In the seven other statewide data sets where the lognormal is judged to be the best fit, the A-D statistic indicates that the data are not consistent with the lognormal distribution. In these cases, however, the other distributional forms that were tested fit the data even more poorly. For one data set

Exhibit 5-16. Probability Plot of Radon Concentrations from Texas Community Water Systems (NIRS Data)
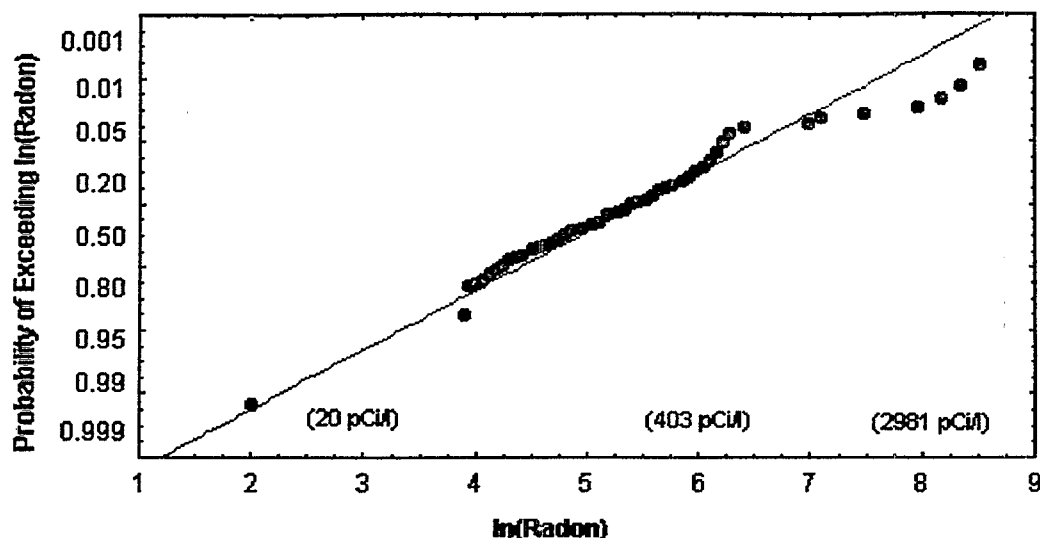
(Texas) the lognormal was the second-best fit to the data, but the A-D statistic indicated that the hypothesis of lognormality could not be discarded at $p < 0.05$. For two state data sets (Ohio and

Exhibit 5-17. Goodness of Fit Ranking of Lognormal Distribution Applied to State Radon Data Sets

State	All	Large	Medium	Small	Very Small	Very Very Small
			System Size			
California	1 + [1,2]	1 +	6 +	-- [3]	2 +	--
Connecticut	1 +	--	--	--	--	--
Idaho	1 +	--	--	--	--	--
Iowa	1 +	--	1 +	3 +	4 -	1 +
Kansas	1 -	2 +	3 +	6 -	1 +	--
Maine	1 +	--	4 +	7 +	2 +	--
Maryland	1 +	--	--	1 +	5 -	7 +
Michigan	1 +	7 +	4 +	2 +	1 +	1 +
Missouri	1 -	1 +	7 -	2 -	1 +	1 +
New Hampshire	1 -	1 +	3 +	2 -	1 +	1 +
New York	1 -	6 +	4 +	5 -	1 +	1 +
Ohio	5 -	4 +	6 +	4 -	--	--
Pennsylvania	1 -	3 +	2 +	1 +	2 -	1 +
South Carolina	1 -	2 +	3 -	1 +	1 +	8 +
Texas	2 +	2 +	1 +	1 +	2 +	1 -
Washington	8 -	9 -	8 +	8 +	8 +	--
Wisconsin	1 -	1 +	1 +	1 -	1 +	1 -

Notes:
1. Numbers in cells are ranking of lognormal among nine distributions tested, based on Anderson
2. A (+) indicates that the data are consistent a lognormal distribution at $p = 0.05$; a (-) indicates
3. (--) indicates not enough data to judge goodness of fit.

Washington), the lognormal was far down on the list of distributions, in terms of goodness of fit.

Sufficient data were available to allow goodness of fit testing on 64 individual size categories of data within the 17 state data sets (Exhibit 5-17). In 27 cases, the lognormal provides the best fit, and in another 11 cases, the lognormal is ranked second, in terms of goodness of fit. In an additional 19 cases, (mostly smaller data sets), the lognormal is ranked lower than second (e.g, it is at least the third best-fitting distribution), but the A-D statistic cannot rule out the data being consistent with the lognormal model. In ten of the dissagregated data sets, the lognormal is ranked worse than second, and the goodness of fit statistic indicates the data do no fit the lognromal model. In a total of 48 of the 64 cases, the data are indicated to be consistent with the lognormal distribution. In two of the state data sets (Ohio and Washington), the lognormal ranks low when the data as a whole nor any of the individual size strata are evaluated.

No specific distribution turned up more frequently in the supplemental data sets as providing a better fit than the lognormal. The other distributions providing the best fit the data included, in rough order of frequency, the Weibull, three-parameter Gamma, Type 1 Extreme Value, logistic, and exponential. None of these distributions appeared as frequently among the best-fitting distributions, or consistently had lower A-D values, than the lognormal. Thus, consistent with the pattern seen in the NIRS data, it was decided that the lognormal was the most suitable distribution for describing the supplementary data sets.

5.5.2 Radon Summary Statistics from Supplementary Data Sets

Exhibit 5-18 summarizes the distributions of system radon levels that were derived from the 17 supplemental data sets.[7] As noted in the previous section, some of the data sets provide significant information on radon levels in groundwater sources serving all size classes of systems. In some of the data, sets the number of systems in some strata (usually the larger systems) is relatively small, and in two state data sets (Connecticut and Idaho) system size data were not available. Departing from the general pattern, the data sets from California, Ohio, and Wisconsin, are composed of data predominantly from larger systems. The radon survey in South Carolina from which the state data were derived was intentionally designed to sample roughly equal numbers of systems in each size category.

The state-wide geometric mean radon levels seen in the data sets vary from a maximum of 8,973 (Connecticut) to a low of 139 (Texas). The geometric mean values for "all" systems in each state data set are shown in Exhibit 5-19 (except for Connecticut, which would be off the scale at the top.) Consistent with previous studies, radon levels in the New England states are seen to be very high, compared to the rest of the country. Only Connecticut, New Hampshire,

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[7] When more than one measurement was available from one or more sources in a system, the system geometric mean was calculated with each sample weighted equally. System arithmetic means are calculated from the derived lognormal distributions of radon levels. State-wide summary statistics are calculated with each system, irrespective of size, weighted equally. The radon distributions in Exhibit 5-17 are therefore not population-weighted.

STATE	SYSTEM SIZE					
CALIFORNIA	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	284	153	220	318	220	312
ARITHMETIC MEAN	473	–	1,065	373	528	426
LOG MEAN	5.65	5.03	5.39	5.76	5.40	5.74
LOG STANDARD DEVIATION	1.01	–	1.78	0.56	1.32	0.79
NUMBER OF SYSTEMS	74	1	9	6	8	49
CENSORED [1]	0	0	0	0	0	0
CONNECTICUT	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	8,973	–	–	–	–	–
ARITHMETIC MEAN	14,935	–	–	–	–	–
LOG MEAN	9.10	–	–	–	–	–
LOG STANDARD DEVIATION	1.01	–	–	–	–	–
NUMBER OF SYSTEMS	32	–	–	–	–	–
CENSORED	0	–	–	–	–	–
IDAHO	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	537	–	–	–	–	–
ARITHMETIC MEAN	716	–	–	–	–	–
LOG MEAN	6.29	–	–	–	–	–
LOG STANDARD DEVIATION	0.76	–	–	–	–	–
NUMBER OF SYSTEMS	64	–	–	–	–	–
CENSORED	0	–	–	–	–	–
IOWA	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	283	642	293	248	244	194
ARITHMETIC MEAN	436	3,245	397	356	364	194
LOG MEAN	5.65	6.46	5.68	5.51	5.50	5.27
LOG STANDARD DEVIATION	0.93	1.80	0.78	0.85	0.89	0.03
NUMBER OF SYSTEMS	150	10	67	56	15	2
CENSORED	0	0	0	0	0	0
KANSAS	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	299	303	363	271	274	300
ARITHMETIC MEAN	456	516	653	395	301	382
LOG MEAN	5.70	5.71	5.89	5.60	5.61	5.70
LOG STANDARD DEVIATION	0.92	1.03	1.08	0.87	0.43	0.70
NUMBER OF SYSTEMS	169	4	52	92	12	9
CENSORED	7	0	2	5	0	0
MAINE	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	1,300	871	2,516	950	1,179	628
ARITHMETIC MEAN	2,080	1,024	4,163	1,529	1,688	1,165
LOG MEAN	7.17	6.77	7.83	6.86	7.07	6.44
LOG STANDARD DEVIATION	0.97	0.57	1.00	0.98	0.85	1.11
NUMBER OF SYSTEMS	64	4	13	24	7	3
CENSORED	0	0	0	0	0	0

Exhibit 5-18. Summary of Radon Occurrence Data from 17 State-Wide Data Sets

Exhibit 5-18. Summary of Radon Occurrence Data from 17 State-Wide Data Sets (Continued)						
MARYLAND	ALL	VVS	VS	S	M	L
GEOMETRIC MEAN	440	675	517	281	667	214
ARITHMETIC MEAN	1,490	2,759	1,902	573	1,746	1,926
LOG MEAN	6.09	6.51	6.25	5.64	6.50	5.36
LOG STANDARD DEVIATION	1.56	1.68	1.61	1.19	1.39	2.10
NUMBER OF SYSTEMS	107	28	33	35	7	4
CENSORED	1	1	0	0	0	0
MICHIGAN	ALL	VVS	VS	S	M	L
GEOMETRIC MEAN	187	143	183	211	168	202
ARITHMETIC MEAN	253	202	288	273	205	244
LOG MEAN	5.23	4.96	5.21	5.35	5.12	5.31
LOG STANDARD DEVIATION	0.78	0.83	0.96	0.72	0.63	0.62
NUMBER OF SYSTEMS	120	14	30	42	20	14
CENSORED	5	1	3	0	1	0
MISSOURI	ALL	VVS	VS	S	M	L
GEOMETRIC MEAN	156	197	162	137	106	97
ARITHMETIC MEAN	217	254	219	201	159	151
LOG MEAN	5.05	5.28	5.09	4.92	4.67	4.58
LOG STANDARD DEVIATION	0.85	0.67	0.79	0.92	1.07	1.01
NUMBER OF SYSTEMS	691	209	197	208	56	21
CENSORED	5	0	0	3	2	0
NEW HAMPSHIRE	ALL	VVS	VS	S	M	L
GEOMETRIC MEAN	2,017	2,507	2,472	680	593	331
ARITHMETIC MEAN	4,911	5,032	5,251	2,452	841	1,270
LOG MEAN	7.61	7.83	7.81	6.52	6.39	5.80
LOG STANDARD DEVIATION	1.33	1.18	1.23	1.60	0.84	1.64
NUMBER OF SYSTEMS	788	386	279	91	16	16
CENSORED	32	3	6	17	1	5
NEW YORK	ALL	VVS	VS	S	M	L
GEOMETRIC MEAN	318	290	348	321	312	210
ARITHMETIC MEAN	657	605	1,016	532	459	298
LOG MEAN	5.76	5.67	5.85	5.77	5.74	5.35
LOG STANDARD DEVIATION	1.21	1.21	1.46	1.01	0.88	0.84
NUMBER OF SYSTEMS	424	82	141	163	22	16
CENSORED	0	0	0	0	0	0
OHIO	ALL	VVS	VS	S	M	L
GEOMETRIC MEAN	140	–	489	149	134	119
ARITHMETIC MEAN	228	–	492	235	211	218
LOG MEAN	4.94	–	6.19	5.00	4.90	4.78
LOG STANDARD DEVIATION	0.99	–	0.09	0.96	0.95	1.10
NUMBER OF SYSTEMS	228	–	2	115	65	46
CENSORED	23	–	0	10	6	7

Exhibit 5-18. Summary of Radon Occurrence Data from 17 State-Wide Data Sets (Continued)						
PENNSYLVANIA	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	500	465	489	546	493	575
ARITHMETIC MEAN	1,403	1,310	1,853	1,243	1,214	1,032
LOG MEAN	6.21	6.14	6.19	6.30	6.20	6.35
LOG STANDARD DEVIATION	1.44	1.44	1.63	1.28	1.34	1.08
NUMBER OF SYSTEMS	488	151	153	95	4	38
CENSORED	24	5	12	2	5	0
SOUTHCAROLINA	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	542	2,024	1,250	279	325	173
ARITHMETIC MEAN	1,767	3,206	4,240	680	941	299
LOG MEAN	6.30	7.61	7.13	5.63	5.78	5.15
LOG STANDARD DEVIATION	1.54	0.96	1.56	1.33	1.46	1.04
NUMBER OF SYSTEMS	89	22	13	20	18	16
CENSORED	1	0	0	1	0	0
TEXAS	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	139	194	142	152	138	91
ARITHMETIC MEAN	218	284	224	265	192	114
LOG MEAN	4.94	5.27	4.96	5.02	4.93	4.52
LOG STANDARD DEVIATION	0.95	0.87	0.95	1.05	0.82	0.66
NUMBER OF SYSTEMS	120	14	33	36	18	16
CENSORED	50	4	14	14	7	10
WASHINGTON	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	141	26	155	160	139	187
ARITHMETIC MEAN	279	86	296	244	262	325
LOG MEAN	4.95	3.27	5.04	5.07	4.93	5.23
LOG STANDARD DEVIATION	1.17	1.54	1.14	0.92	1.13	1.05
NUMBER OF SYSTEMS	68	6	15	11	15	21
CENSORED	10	3	2	0	2	3
WISCONSIN	ALL	WS	VS	S	M	L
GEOMETRIC MEAN	297	260	314	333	273	279
ARITHMETIC MEAN	416	380	456	468	340	304
LOG MEAN	5.69	5.56	5.75	5.81	5.61	5.63
LOG STANDARD DEVIATION	0.82	0.87	0.87	0.83	0.66	0.42
NUMBER OF SYSTEMS	610	176	140	197	67	30
CENSORED	7	0	0	0	0	0

Notes:

1. Indicates all samples from the systems are censored.

Exhibit 5-19. State-Wide Geometric Mean Radon Levels from Supplemental Data Sets
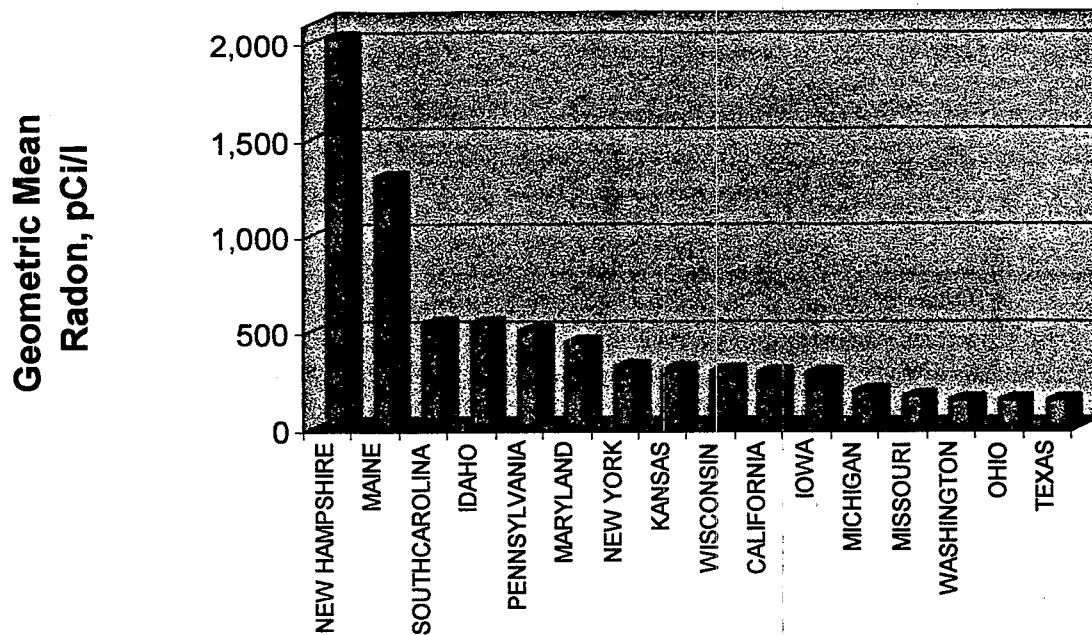
and Maine, have overall geometric mean radon levels that exceed 1,000 pCi/l in the supplemental data, with the next highest average value being 542 pCi/l for South Carolina.

Consistent with the pattern seen in the NIRS data, the geometric mean radon levels increase with decreasing system size for the majority of the data sets (Exhibit 5-20.) In 10 of the 15 supplemental data sets reporting radon values for multiple size strata, the very very small or very small systems had the highest geometric mean radon values. In the other data sets, the pattern varied, with the larger systems sometimes having the highest values. The data sets in which the larger systems had radon levels comparable to those small systems were generally from states where the average radon levels were low, and where the variation in radon levels among the size strata was also the lowest. Overall, the levels of radon seen in the supplemental data sets were similar to those seen in the NIRS data for the same regions (but see below).

Log standard deviations of the radon levels were also calculated for the various supplemental data sets and are tabulated in Exhibit 5-18. The log standard deviations of radon levels seen in the combined data sets (all systems sizes) vary from 1.56 for the data from Maryland to 0.76 for the data from Idaho. Much of the variance in these values comes from differences between radon levels in the different size strata, and, for most states, the log standard deviation values for the individual strata are substantially lower than those for the aggregated data sets.

Exhibit 5-20. Geometric Mean Radon Levels as a Function of System Size in Supplemental Data Sets
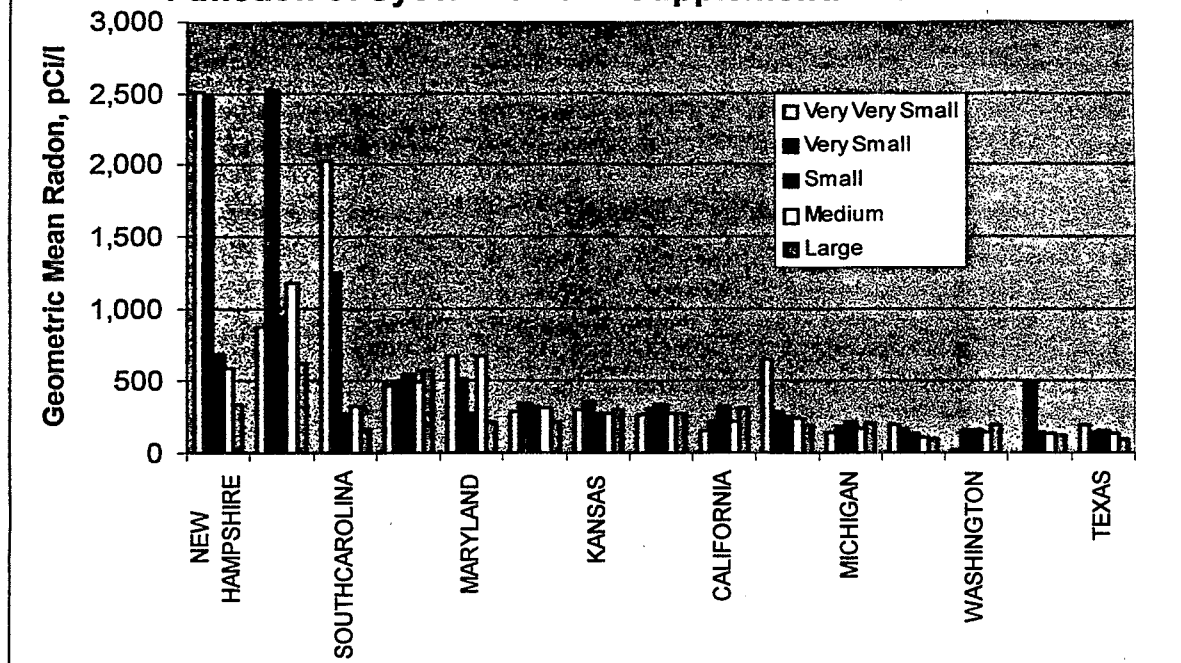
Unlike the geometric mean values, there is no consistent pattern in the log standard deviation with changes in system size. Similarly, the log standard deviation values in the supplemental data sets are only weakly correlated with the geometric mean values. This implies that the relative variability of radon levels is more or less constant across groups of systems with different geometric mean radon levels.

5.6   Comparison of NIRS and Supplemental Data Sets

As noted in Section 5.4, the NIRS data are derived from samples taken within water distribution systems. In contrast, all of the state supplemental data that we analyzed come from samples taken at the wellhead or at other sampling locations before the water enters the distribution system. Thus, we expect to see a systematic difference between the NIRS data and the supplemental data, with the supplemental data showing higher radon levels than the NIRS for the same state and system size categories. The magnitude of the difference would reflect the average reduction in radon that occurs as from existing treatment systems and as a results of storage and retention of water in the distribution systems. If residence time in the systems is significant, then a large portion of the influent radon would decay before reaching the consumer. Characterizing the differences (if any) between the NIRS and state supplemental data has important implications for estimating the national proportions of systems exceeding potential regulatory levels, as discussed in detail in Section 5.8.

5.6.1 Comparison of Log Mean Radon Levels Between NIRS and Supplemental Data Sets

We first compared the log mean radon levels estimated from the NIRS data with those estimated from the supplemental data sources for the same state and system size strata. In this analysis we used the log mean radon levels (the log of the geometric mean), rather than the geometric means, because, with the underlying lognormal distributions of the data, the log mean values provide a consistently-scaled basis for comparison. The ratios of the geometric means derived from the NIRS data to those derived from the supplemental data were calculated for all states and strata covered by both data sources.[1] The results of this analysis are summarized in Exhibit 5-21. For each size stratum, the individual NIRS/state log mean ratios are shown, along with the average ratios for all of the states. For all of the size strata, the average log mean ratio is close to 1.0. For "All" systems, the average ratio is 0.97 (the NIRS log means are lower than the corresponding state log means). The NIRS/state log mean ration for the very very small systems is very similar, at 0.98. The log mean ratios decrease further as system size increases, to 0.97, 0.95, and 0.93 for the very small, small, and medium systems, respectively. For the large systems (not shown) only one state had both sufficient NIRS data and state data to conduct a comparison. In this state (Texas), the ratio of NIRS to state geometric mean values was 1.08, reversing the

Exhibit 5-21. Ratios of Log Mean Values for Individual States
NIRS Versus Supplemental State Data

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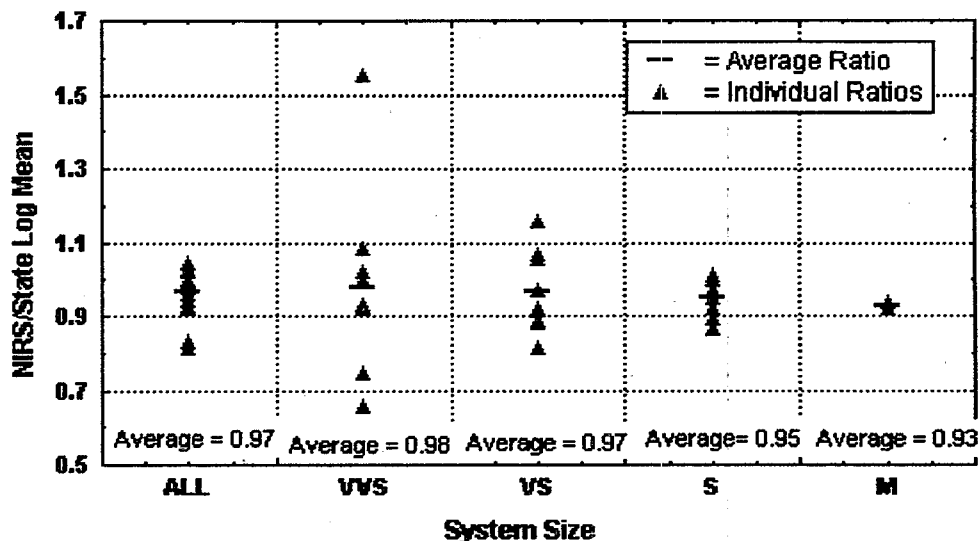
[1] In estimating the NIRS/state log mean and log standard deviation ratios for the individual states, we eliminated all states and size strata from which five or fewer systems reported radon values in either the NIRS or the supplemental data sets. The ratios for the strata with fewer data point tend to have a much higher degree of variability than those having more data and we did not consider the ratios calculated for these strata to be reliable.

pattern of the NIRS log means being generally lower than those from the supplemental data.
The average ratios of state to NIRS log mean radon levels are tabulated in the top row of Exhibit 5-22, along with the 95 percent confidence intervals on the ratios, derived using the bootstrap method described in Section 5.2.4. The ratios of the state to NIRS state-wide log means are significantly less than 1.0 at p = 0.05 when all systems are included in the calculation and for the very small, small, and medium strata. The state/NIRS ratios for very very small systems were considerably more variable, and the average state/NIRS ratio for this size category is not significantly different from zero.

Exhibit 5-22. Ratios of State Log Mean and Log Standard Deviation Radon Levels to NIRS Values (Confidence Limits on the Ratios)

	All	Very Very Small	Very Small	Small	Medium
State Log Mean Radon/NIRS Log Mean Radon	0.97 [1] (0.96 - 1.00)	0.98 (0.87 - 1.09)	0.97 [2] (0.92 - 1.01)	0.95 [1] (0.93 - 0.98)	0.93 [1] (0.92 - 0.93)
State Log Standard Deviation Radon/NIRS Log Standard Deviation Radon	1.05 (0.95 - 1.14)	1.04 (0.85 - 1.20)	0.82 [1] (0.65 - 0.96)	0.94 (0.78 - 1.10)	0.84 (0.51 - 1.17)

Notes:
1. Different from 1.00 at p <= 0.05
2. Different from 1.00 at p <= 0.10

The results in Exhibits 5-21 and 5-22 suggest that, on the whole, the geometric means estimated from the state data are similar to, but lower than, those estimated from the supplemental data. Within the limitations of the data, there seems to be a trend for the NIRS/supplemental log mean ratio to decrease with increasing system size. For very very small systems, the average ratio is close to unity (0.98), whereas the average ratio decreases consistently across the next three size strata to a value of 0.93 for the medium systems. This means that, as systems get smaller, the NIRS log means get progressively lower compared to the supplemental data. The continuation of this trend through the large systems cannot be confirmed (based on these data) because of the lack of data on NIRS/State ratios for this size system.

The pattern of differences between the radon levels seen in the NIRS and supplemental data is consistent with a simple physical explanation. First, the radon levels in the smallest systems (very very small and very small) would be the most similar across the two data sets because:

- The NIRS very very small systems would draw from the same relatively low-yield, high-radon aquifers as the very very small systems in the supplemental data sets;

- The NIRS very very small systems are less likely to have treatment systems in place to reduce radon levels than the larger systems; and

- The NIRS very very small systems would have short residence times, and relatively little radon decay would occur.

The combined effect of these factors would be to reduce the differences between the NIRS point-of-use samples and the wellhead and point-of-entry samples from the state supplemental data sets. This would explain why the average (and median) NIRS/state log mean should be close to 1.0 for the smallest systems.

In contrast, the radon levels in the larger NIRS systems would be lower than that seen in the state data sets for the same size systems because:

- A larger proportion of the larger NIRS systems would tend to have treatment in place; and

- The residence times in the larger NIRS systems is appreciable compared to the half-life of radon.

These factors would decrease the average ratio of the NIRS (in-system) to the supplemental (wellhead) radon log mean ratios, consistent with the observed pattern. These observed differences between the NIRS and state data are used in the development of national distribution of radon level in groundwater sources, as discussed in Section 5.8.

5.6.2   Comparison of Log Standard Deviations

The question also arises whether the NIRS data adequately capture the variability of the groundwater radon levels across the U.S. This issue was addressed by comparing the log standard deviations estimated from the NIRS data and those estimated from the state data. These comparisons are shown graphically in Exhibit 5-23, and their confidence limits are shown in the bottom row of Exhibit 5-22. For all systems combined, the average NIRS/state log standard deviation ratio was 1.05, indicating a similar average degree of variability in the two data sets. The average log standard deviation ratio for the very very small systems was also close to unity (1.04.)

For the larger system sizes, the average ratios of log standard deviations in the state and NIRS data sets are smaller and more variable. For very small, small, and medium systems, the ratios are 0.82, 0.94, and 0.84, respectively, indicating that the NIRS data are, on average, less variable than the state supplemental data for these size strata. For Texas, the only state for which a NIR/state log standard deviation ratio can calculated for large systems, the value is 0.37.

Exhibit 5-23. Ratios of NIRS to State Log Standard Deviations
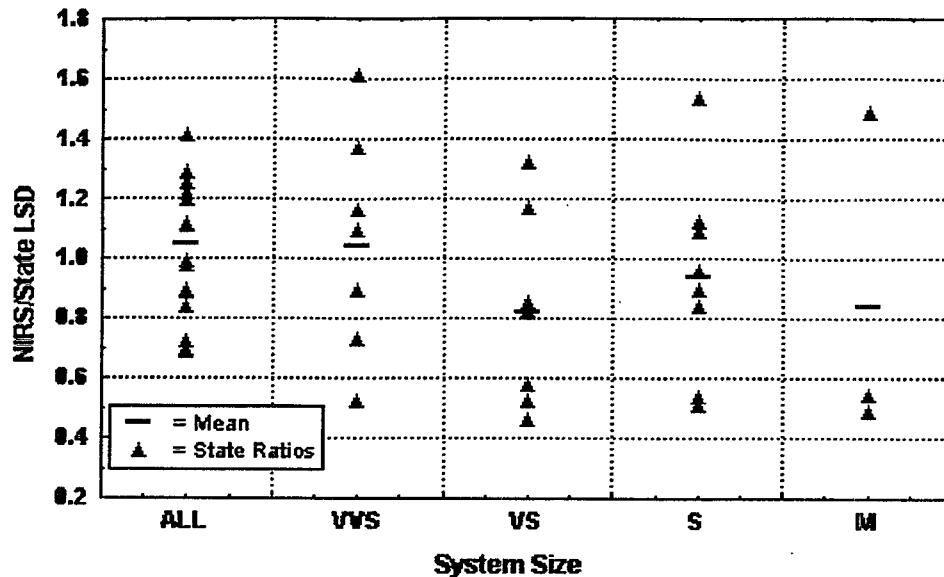
The degree of variability in state/NIRS log standard deviation ratios for the different size strata is greater than that seen for the log mean ratios. Although the average ratios are smaller than 1.0 for all three of the smallest size categories, only the ratio for very small systems achieves statistical significance at $p = 0.05$. These data are also used in the development of the national radon distributions for groundwater sources in Section 5.8.

5.7   Sources and Magnitude of Variability in Groundwater Radon Levels

Until this point, the focus has been on the variability of long-term radon levels in individual systems and in sources serving these systems. This has been the case for two reasons. First, the NIRS, which is far and away the most comprehensive data source on radon levels in U.S. water supplies, comes from a cross-sectional survey, designed to gather data typical of systems, rather than sources. Second, a primary goal of the occurrence analysis is to determine the proportions of systems that might be above potential regulatory levels, and the number of customers served by these systems, so that potential risks and risk reduction can be assessed.

However, as noted in Section 5.1, EPA has received numerous comments regarding the use of the NIRS data in the characterization of radon levels across the U.S. These comments point out that the previous occurrence analysis did not address important sources of variability in radon levels, which might strongly effect the estimates of the numbers of systems affected by radon regulation. The following sections discuss EPA's analysis of these issues using the NIRS and supplemental state data sets.

5.7.1   Identification of Sources of Variability in Radon Levels

When a radon measurements are taken from different sources and systems, the distribution of the results is affected by a number of factors. For purposes of this analyses, we use the following terms to identify these sources of variability:

- **Var(SYS)** -- This symbol represents the "true" inter-system variability in radon levels, for example the differences in radon levels due to differences in location, geologic setting, size, etc., between a small system in New Hampshire, and a large system in Nebraska.

- **Var(W)** -- This is the variability among different sources (wells) within a given system. Where a system obtains water from only one well (as do many of the smallest systems), this source does not contribute to the overall variability in radon observations. This source of variability is often referred to as "intra-system" variability, although variability in radon levels within a single system also includes contributions from the following sources as well.

- **Var(T)** -- This factor is the time (temporal) variability of radon levels in a given source or system. For purposes of this analysis, we use this symbol to refer to differences in radon levels seen of times scales of greater than one day.

- **Var(S)** -- Refers to all variability associated with the process of taking samples, transferring them to the laboratory, and performing any other manipulations up to the point at which the sample enters the scintillation counter. Often, it is not possible to separate this source of variability from analytical variability, below.

- **Var(A)** -- The last factor we address is variability associated with the analysis of radon samples themselves. This includes statistical counting error, as well as any other factors affecting the precision of the radon analysis. As will be discussed further below, the magnitude of this variability is measured by examining the differences in the results of duplicate analyses of the same sample.

By characterizing all of these sources of variability in a given data set, it is possible to predict the proportions of sources (wells) that would exceed regulatory levels over time, and the numbers of systems that would be affected by the variability in well radon levels.

5.7.2   Estimating Contributions to Variability

The sources of variability discussed above contribute to the total variability in different data sets in different ways. Sampling and analytical variability can only be estimated where duplicate samples are taken; intra-well variability only affects systems that obtain water from more than one well, etc. The following analysis makes use of a simple generalized model for the variability of radon to estimate contributions from each of these sources to the overall variability in radon levels.

The model that is employed is a additive variance model (also referred to as an ANOVA model). This model assumes that the sources of variability in any radon data set all act independently of one another. Under this assumption, it can be shown that the total variance in radon levels can be expressed as the sum of the contributions to variance from all the individual sources:

$$Var(Total) = Var(Sys) + Var(W) + Var(T) + Var(S) + Var(A), \qquad (5\text{-}13)$$

where the symbol Var( ) mean "variance due to" the sources which were defined above. An ideal data set (which does not exist) would consist of a large number of samples over time from a large number of wells in a large number of systems, with plentiful sampling and analytical duplicates. Such a database would allow the estimation of the contributions to variance from each source. Because none of the available data sets meet this ideal, it is necessary to develop estimates of the contributions to variance from different sources using different data sources. This analysis is described in detail in Appendix C. The results of the analysis of variance are discussed below.

5.7.3 Magnitude of Contributions to Radon Variability

Using the data from a number of studies, the relative contributions of the different sources to the overall variance in a "typical" radon data sets were estimated. The "typical" data set was defined as one which includes radon measurements from multiple systems and sources, sampled over a significant period of time (months to years) from systems located in a region with geological diversity equivalent to that of an average state data set.

As described in Appendix C, different studies were used to develop ranges of estimates of total variance, and of the contributions to variance from the individual sources and combinations of sources. The results of that analysis are summarized in Exhibit 5-24. The average total log variance seen in the radon data sets that were examined was on the order of 1.35 (top row of the Exhibit). Combined sampling and analytical variability, VAR(S+A) was found to be quite small in a number of data sets, typically contributing the equivalent of 0.6 percent to the total variance. Two estimates of temporal variability , Var(T) were developed using the equivalent of Equation 5-13 on the results from two different combinations of studies. One estimate was derived by subtracting estimates of sampling and analytical variability from estimates of combined sampling, analytical, and temporal variability, Var(S+A+T). The second estimate was derived by subtracting estimates of combined sampling, analytical, and between-well variance from estimates of combined sampling, analytical, between-well and sampling variance. In the first case, the estimated contribution of temporal variability to overall log variability was 0.19, while the second method resulted in an estimate for temporal variance of about 0.14.

Typical values for the individual contributions of variations among wells and among systems were also calculated using the relationships shown on the last two rows of Exhibit 5-24. Between-well variance was found to account for between 12 and 17 percent of the variance, while variations between systems, as expected, accounted for the bulk (69 percent) of the total variance.

Exhibit 5-24. Estimated Contributions to Variance in a Typical Radon Data Set

Source of Variance	Typical Magnitude of Contribution to Log Variance (Method of Estimation)	Typical Proportion of Total Variance, percent
Total (All Sources)	~ 1.35 (Measured)	100
Sampling and Analytical	~ 0.009 (Measured)	~ 0.6
Temporal	(S+A+T) - (S+A) ~ 0.19	13-18
	(S+A+T+W) - (S+A+T) ~ 0.14	
Among Wells	(S+A+W+T) - (S+A+T) ~ 0.16	12-17
	(S+A+W) - (S+A) ~ 0.23	
Among Systems	(SYS+S+A+W+T) - (S+A+W+T) ~ 0.93	~ 69
	(SYS+S+A+W+T) - (S+A) - (W) - (T) ~ 0.93	

These results are used in the following sections to help estimate the proportions of systems above specified radon levels and the effectiveness of monitoring programs in identifying non-complying sources.

5.8   Estimates of Numbers of Groundwater Systems Exceeding Potential Regulatory Limits

In this section, we use the distributional approaches discussed in the previous sections to estimate the proportions of community water systems exceeding potential regulatory levels. Radon distributional parameters are then developed for eight regions using NIRS data and for 7 states using data from the supplemental data sources. These distributions are combined to provide an estimate of the total numbers of systems exceeding potential regulatory levels in the U.S. Potential uncertainties associated with these estimates are then discussed, and the current estimates of radon exceedences are compared to the results of previous EPA occurrence analyses.

5.8.1   Characterizing Radon Distributions for States and Regions

This section describes the approaches used to estimate the proportions of systems with radon levels above potential regulatory levels. The focus of the section is on the development of estimates of log mean and log standard deviation values that can be used, at the end of the section, for estimating these proportions using the lognormal model. A large proportion of the discussion is centered on adjusting the calculated values to account for difference between samples taken in the distribution system (NIRS) and expected radon levels in influent water, and for differences in

variance that would be associated with different monitoring and averaging approaches to estimating system-wide radon levels.

The general process used to estimate the proportions of systems above potential regulatory levels (MCLs or AMCLs) is summarized in Exhibit 5-25. Radon occurrence data from NIRS or the state supplemental data systems (upper left corner of the Exhibit) form the basis for the occurrence estimates. The NIRS data are used to calculate regional estimates of log mean and log standard deviation radon levels for each size category of system.

The eight regions are those defined in Section 5.1, except that the radon data for the states with good supplemental data (see below) are excluded.[2] In these states (Michigan, New Hampshire, New York, Pennsylvania, South Carolina, Texas, and Wisconsin), "raw" state log mean and standard deviation values are also calculated from the supplementary data sets.

The first step in the process of estimating the proportions of systems above potential regulatory levels is to adjust the regional log means derived from NIRS data upward to take into account the difference between the in-system samples and point-of-entry samples discussed in Section 5.6 The ratios of the NIRS to state log mean and log standard deviation shown in Exhibit 5-21 and 5-23 are used to calculate adjusted log mean and log standard deviation values (corresponding to the estimated radon distributions in groundwater sources) for the region where the NIRS is the primary source of data. The "adjusted" NIRS regional log means are used as inputs to the lognormal model to estimate the proportions of systems above regulatory levels in the eight regions. Because the state data sets include only data from groundwater sources and points of entry, adjustment for in-system sampling is not necessary.

For all data sets where the estimates of log standard deviation are based on single samples from different systems (as in the NIRS and several of the state data sets), the log variance of radon levels needs to be reduced to provide a representative estimate of log standard deviation. This is because, when multiple samples are taken over time (as would be required under EPA's proposed monitoring scheme), the temporal, sampling, and analytical variance in radon levels would be canceled out to a large extent. The degree of adjustment in the log variance that is required to account for multiple sampling is derived from the analyses of variance discussed in Section 5.7

The output of these various adjustment processes are sets of log mean and log standard deviation estimates for the seven states and eight NIRS regions. These estimates form the basis for the estimates of the proportions of systems exceeding potential regulatory levels. The proportions are estimated using the assumption of lognormality of radon levels ("the lognormal model").

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[2] In addition, the 491 community groundwater systems in Alaska have been added to the Northwest region totals. Community water systems from Hawaii are excluded because no data related to radon levels in groundwater in Hawaii were identified.
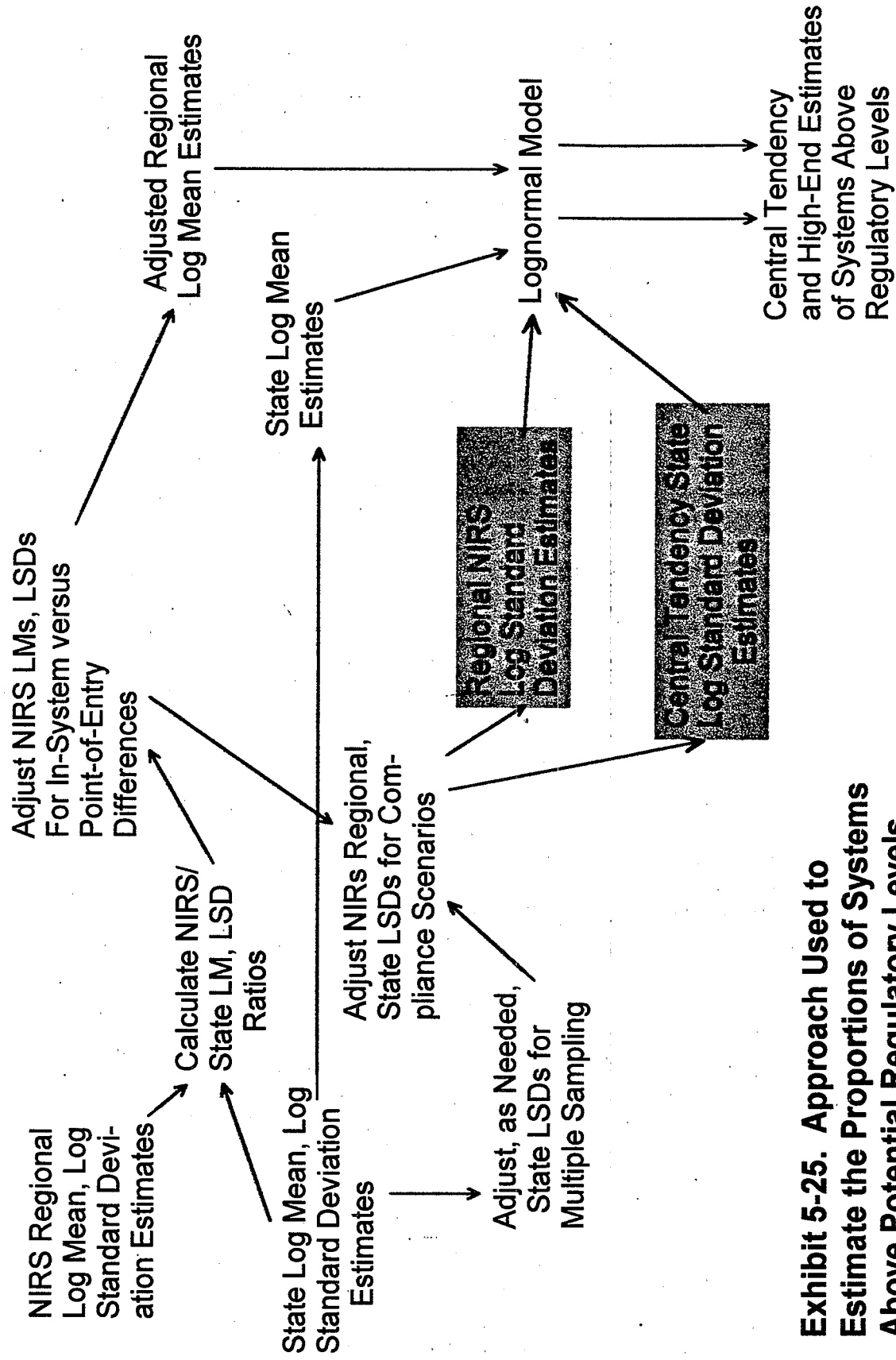
Exhibit 5-25. Approach Used to Estimate the Proportions of Systems Above Potential Regulatory Levels

The final step in the analysis is to multiply the proportions of systems above the various radon levels by the total numbers of systems in the various states, regions, and size strata. This process provides stratified estimates of the occurrence of radon in community water systems in the U.S.

a. Regional Estimates of Log Mean and Log Standard Deviations Using Adjusted NIRS Data

As noted in Section 5.6, the NIRS log mean radon levels in most states are slightly lower than those from the state data sets for the same size systems. The reason for the differences are most likely that the NIRS samples were taken from within the distribution systems, while the state data which we evaluated all came from wellhead or point-of-entry samples. Thus, for purposes of identifying water systems where influent radon limits are above potential regulatory levels, the radon levels seen in the NIRS data need to be adjusted to account for differences between in-system and influent water analyses.

To adjust the NIRS log mean values for the various regions and size strata, the average national NIRS/state log mean ratio for each size system was multiplied by the NIRS regional log mean. The NIRS/state ratios of the log geometric mean values are summarized in Exhibit 5-21. Log mean point-of-entry radon levels for given size system in a specific region was estimated as:

$$\text{Log Mean Radon}_{(Region,Size)} = \text{NIRS Log Mean}_{(Region,Size)} / \text{AF(LM)} \qquad (5\text{-}12)$$

where:

AF(LM) =   Adjustment factor for log means = national average ratio of NIRS to state log means for the system size category.

The same adjustment factor was thus used for all systems in a given size category across all regions. While the NIRS/state log mean ratios varied across the states and across regions of the country, there were insufficient data to allow the derivation of adjustment factors for each region.

The calculations to adjust the log means derived from the NIRS data are summarized in Exhibit 5-26. The adjustments increase the log means only slightly, since the adjustment factors are mostly close to 1.0. However, because these adjustments are carried out in "log space," they result in appreciable changes in the estimated geometric means. For example, as shown in the Exhibit, the unadjusted NIRS log mean for medium systems in the Appalachian region is 5.10, corresponding to a geometric radon level of 163 pCi/l. When the adjustment factor of 0.93 is applied, this value increases to 5.49, corresponding to a geometric mean radon level of 242 pCi/l, a 48 percent increase.

Owing to the small number of large systems sampled in some regions, the overall level of uncertainty associated with the log means in these regions is greater than that for the other systems. Because there are only 29 large systems in the entire NIRS database, there are no data for NIRS large systems in several regions. For this reason, the national NIRS log mean value for large systems was used as the estimate of the NIRS large system log mean in all the regions. Similarly, there are

only a few medium systems in the New England and Northwest regions. Thus the log mean for these regions is estimated as the national mean of the log means for this size category of system.

Exhibit 5-26. Adjustment Of NIRS Regional Log Means to Adjust for Point-of-Entry Versus In-Systems Sampling Using NIRS/Supplemental Radon Ratios						
Unadjusted Regional Radon Log Mean Values, NIRS Data						
Region	ALL	VVS	VS	S	M	L
Appalachian[1]	5.73	5.81	6.15	5.06	5.10	4.87
California	5.81	5.88	6.26	5.59	4.98	4.87
Gulf Coast[2]	4.69	5.49	5.10	3.78	3.65	4.87
Great Lakes[3]	4.91	5.04	5.14	4.66	4.94	4.87
New England[4]	7.00	7.28	7.03	6.17	6.47 [7]	4.87
Northwest	5.08	5.07	5.12	4.71	4.72 [7]	4.87
Plains[5]	4.84	5.07	4.99	4.31	5.04	4.87
Rocky Mountains	5.89	6.33	5.42	5.84	5.51	4.87
Adjustment Factor for Log Means[6]	0.97	1.00	0.97	0.95	0.93	0.94
Regional Radon Log Mean Values, Adjusted for NIRS/State Differences						
Region	ALL	VVS	VS	S	M	L
Appalachian	5.93	5.80	6.35	5.33	5.49	5.18
California	6.01	5.87	6.46	5.89	5.36	5.18
Gulf Coast	4.85	5.47	5.26	3.99	3.93	5.18
Great Lakes	5.08	5.03	5.30	4.91	5.32	5.18
New England	7.25	7.26	7.26	6.51	6.97	5.18
Northwest	5.26	5.06	5.28	4.97	5.08	5.18
Plains	5.01	5.06	5.15	4.54	5.43	5.18
Rocky Mountains	6.10	6.31	5.59	6.16	5.94	5.18

Notes:
1. Omitting Pennsylvania, South Carolina
2. Omitting Texas
3. Omitting Wisconsin
4. Omitting New Hampshire
5. Omitting Michigan
6. National average NIRS/state log mean rations from Exhibit 5-21
7. Log standard deviation for all large systems is used because of small number of data points.

In addition to the log mean, the log standard deviation also affects the proportions of systems above given MCL/AMCL levels. Consistent with the approach used for log means, we adjusted the NIRS log standard deviation values to be more consistent with those seen in the state databases. The latter presumably better reflect variability in groundwater sources than do the in-system NIRS data.

To adjust the NIRS regional log standard deviation values, we used the arithmetic average log standard deviation ratio as follows:

$$\text{Log Std. Dev. Radon}_{(Region, Size)} = \text{NIRS Log Std. Dev.}_{(Region, Size)} / \text{AF(LSD)} \quad (5\text{-}13)$$

where:

AF(LSD) = Adjustment factor for log standard deviation of in-system radon level = national average ratio of NIRS to state log standard deviations for the appropriate system size category.

As shown in Exhibit 5-23, the ratios of the NIRS to state log standard deviations are more variable than the rations of the log mean values ranging from as low as approximately 0.45 to greater than 1.6 across individual states. The adjustment factors used in this analysis are ranged between 0.82 and 1.05, however.

The application of the adjustment factors to the log standard deviations of the regional radon levels is summarized in Exhibit 5-27. The top panel provides the regional log standard deviations calculated directly from the NIRS data and the bottom panel of the table shows the adjusted log standard deviation values. The adjustments for many of the regions and system strata are proportionally larger than those for the log means, and result in both increases and decreases in the estimated variability in point-of-entry radon levels compared to in-system values.

Similar to the case for the log mean values, the national NIRS log standard deviation for large systems was used to estimate adjusted log standard deviations for all of the regions. In addition, the adjusted log standard deviations for medium systems in New England and the Northwest were estimated to be equal to the national average log standard deviations due to a lack of data.

The adjusted log standard deviations tabulated in the bottom panel of Exhibit 5-27 are those that would be expected to occur assuming single sample were taken from a single well in each system. As noted above, these values need to be further adjusted if compliance status is to be evaluated under a monitoring scheme involving multiple samples, because such a scheme reduces the variance in the estimated radon levels for a given system.

The general approach we have taken to adjusting the log variance estimates (and therefore

Exhibit 5-27. Adjustment Of NIRS Regional Geometric Standard Deviations for Differences Between Point-of-Entry and In-System values Using NIRS/Supplemental LSD Ratios

Unadjusted Regional Radon Log Standard Deviation Values, NIRS Data

Region	ALL	VVS	VS	S	M	L
Appalachian[1]	1.67	1.51	1.85	1.58	0.56	0.87[7]
California	1.13	1.22	0.93	0.61	0.72	0.87
Gulf Coast[2]	1.46	1.10	1.31	1.78	1.26	0.87
Great Lakes[3]	1.115	0.860	1.318	0.925	0.923	0.87
New England[4]	1.34	1.18	1.66	0.52	0.77[6]	0.87
Northwest	0.80	0.76	0.75	1.32	0.77[6]	0.87
Plains[5]	0.93	1.03	0.73	1.21	0.57	0.87
Rocky Mountains	1.02	0.93	1.20	0.85	0.61	0.87
Adjustment Factor for Log Means[8]	1.05	1.04	0.82	0.94	0.84	0.84

Regional Radon Log Standard Deviation Values, Adjusted for NIRS/State Differences

Region	ALL	VVS	VS	S	M	L
Appalachian	1.598	1.458	2.259	1.686	0.669	1.044
California	1.079	1.174	1.133	0.652	0.852	1.038
Gulf Coast	1.392	1.060	1.601	1.896	1.498	1.038
Great Lakes	1.066	0.829	1.608	0.987	1.098	1.038
New England	1.279	1.137	2.022	0.558	0.922	1.038
Northwest	0.767	0.734	0.917	1.404	0.922	1.038
Plains	0.885	0.990	0.886	1.296	0.680	1.038
Rocky Mountains	0.974	0.899	1.463	0.907	0.724	1.038

Notes:
1. Omitting Pennsylvania, South Carolina
2. Omitting Texas
3. Omitting Wisconsin
4. Omitting New Hampshire
5. Omitting Michigan
6. Log standard deviation is average of that for other regions (no data).
7. Log standard deviation for all large systems is used because of small number of data points.
8. National average NIRS/state log standard deviation ratio, from Exhibit 5-23

log standard deviation estimates) form multiple samples is illustrated in Exhibit 5-28. The three

Exhibit 5-28. Reductions in Variance Achieved by Combining Multiple Sample Results (Data from California, New York)

Log Variance vs Number of Samples

Legend:
- CA (S,A,W,T)
- CA (S,A,T)
- NY (S,A,T)

Data points:
- CA (S,A,W,T): ONE = 0.328, TWO = 0.160, THREE = 0.121, FOUR = 0.098, FIVE = 0.079
- CA (S,A,T): ONE = 0.194, TWO = 0.094, THREE = 0.068, FOUR = 0.055, FIVE = 0.044
- NY (S,A,T): ONE = 0.019, TWO = 0.010, THREE = 0.006, FOUR = 0.005, FIVE = 0.004
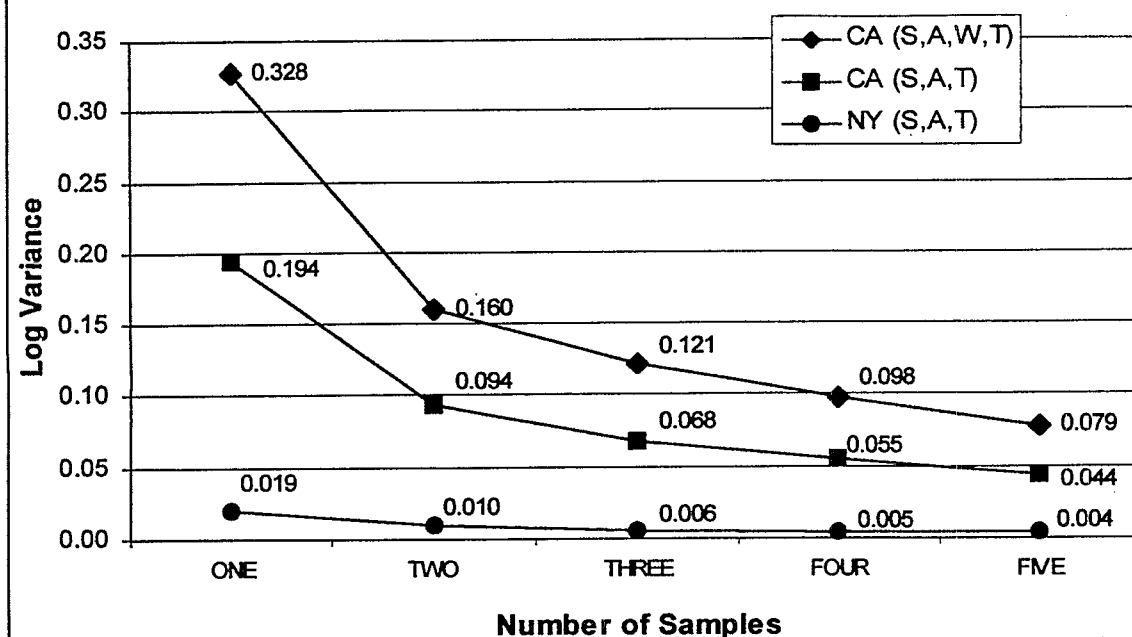
curves in the graph represent the estimated log variance contributions from some of the different sources discussed in Section 5.7, and how they would be reduced by taking multiple samples. These curves were derived by Monte Carlo simulation of sampling from the distributions of Var(S), Var(A), Var(W), and Var(T), or combinations thereof. In each iteration of the simulation, the results of one, two, three, four, or five samples were averaged (to simulate various potential monitoring schemes), and the log variance of the averages were calculated.

The upper curve represents the simulated results of taking one or more samples from a lognormal distribution with a variance equal to the average (S+A+W+T) variance for the California data discussed in Appendix C. Taking many single samples from this population of analyses will have a combined total (S+A+W+T) log variance of approximately 0.33. As more than one sample is taken (equivalent to taking multiple samples from randomly selected wells at random times), the variance is reduced, with a greater degree of reduction as more samples are taken and averaged together.[3]

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[3] If the system average log variance or log standard deviation were calculated by taking the geometric mean of multiple sample results instead of the arithmetic mean, then the residual log variance would be exactly equal to (1/n) times the population log variance, where n is the number of samples. In fact, the results come quite close to this ratio.

The middle curve on the graph is the similar procedure repeated again for supplemental data from California, but in this case starting with only the combined analytical, sampling, and temporal variance (S+A+T) Finally, the bottom curve is a simulation of multiple sampling of a population of radon analytical results with a combined log analytical and sampling (S+A)variance equal to that seen in the supplemental data from New York(Appendix C).

The first step in adjusting log variances for multiple sample averaging was to develop, implicitly, curves like those in Exhibit 5-28 for all of the data sets that were evaluated. After separating out the true system variability from the population of reported levels (Var(SYS)), the calculated log standard deviations (and variances) fall somewhere on one of the three curves shown in this Exhibit. The calculated log variance from the NIRS data, composed of single samples from multiple systems, fall at the upper left-hand end of the top curve. The summary statistics from some of the states, calculated from multiple analyses of multiple samples from multiple wells, correspond to points near the lower right-hand end of the upper curve.

The following specific rules of thumb were used to estimate state and regional log variances from the NIRS and supplemental data sets:

- NIRS regional average log standard deviations were derived assuming that averaging four samples would reduce the total (S+A+T+W) variance by 75 percent. Using the estimate from Appendix C that (S+A+T+W) variance accounts for an average of 30 percent of the total variance in a typical population of radon measurements, this means that the observed NIRS variances were reduced by 22.5 percent to give the adjusted estimates of variance assuming four samples. For the NIRS data, this works out to a reduction in overall variance of approximately 13.5 percent.

- For state data sets composed of single samples from multiple systems, the same approach used for the NIRS data was employed to estimate log standard deviation. For several of the states, minor corrections first had to be made to account for the variance reduction achieved by taking duplicate samples or conducting duplicate analyses.

- For state data composed of results from multiple wells and/or multiple samples over time from individual wells, the state log standard deviation estimates as calculated in Section 5.6 were used directly as estimates of log standard deviations. It is recognized that this approach captures different degrees of variance reduction for different states, depending on the designs of the sampling programs and numbers of samples taken from individual systems in the various states.

The resulting estimates of log standard deviations for the NIRS regions are shown in Exhibit 5-29. As noted above, the final log standard deviation values are approximately 13.5 percent lower than the total variances shown in Exhibit 5-27. The estimates of adjusted log mean values shown in Exhibit 5-26 and the doubly adjusted log standard deviation values shown in Exhibit 5-29 were used to estimate the proportions of systems above potential radon regulatory limits later in this section.

EXHIBIT 5-29. NIRS Regional Log Standard Deviation Estimates, Adjusted for Averaging of Multiple Samples						
	System Size					
Region	ALL	VVS	VS	S	M	L
Appalachian	1.407	1.284	1.989	1.484	0.589	0.914
California	0.950	1.033	0.997	0.574	0.750	0.914
Gulf Coast	1.226	0.933	1.410	1.670	1.318	0.914
Great Lakes	0.939	0.730	1.415	0.869	0.966	0.914
New England	1.126	1.001	1.780	0.492	0.812	0.914
Northwest	0.675	0.646	0.807	1.236	0.812	0.914
Plains	0.780	0.871	0.780	1.141	0.598	0.914
Rocky Mountains	0.858	0.792	1.288	0.798	0.638	0.914

b. ***Estimates of Log Mean and Log Standard Deviation Values for States With Sufficient Supplementary Data***

As noted in Section 5.8.1, seven of the state data sets provided sufficient data such that the state log mean and log standard deviation radon levels could be developed independent of the NIRS results. For these states, the proportions of systems exceeding potential regulatory levels were estimated from the state data sets.

All of the states that provided detailed and representative data reported sampling results from the wellhead or points of entry to the water distribution system. Thus, it was not necessary to adjust the state log mean radon levels as was done for the NIRS data. Thus, the log mean values that were used were the same as those shown in Exhibit 5-18, and summarized again in Exhibit 5-30.

Exhibit 5-30. Log Mean Radon Values from State Data Sets						
	System Size					
State	ALL	VVS	VS	S	M	L
MICHIGAN	5.23	4.96	5.21	5.35	5.12	5.31
NEW HAMPSHIRE	7.61	7.83	7.81	6.52	6.39	5.80
NEW YORK	5.76	5.67	5.85	5.77	5.74	5.35
PENNSYLVANIA	6.21	6.14	6.19	6.30	6.20	6.35
SOUTH CAROLINA	6.30	7.61	7.13	5.63	5.78	5.15
TEXAS	4.94	5.27	4.96	5.02	4.93	4.52
WISCONSIN	5.69	5.56	5.75	5.81	5.61	5.63

The state log standard deviations likewise do not need to be adjusted for the differences between in-system and point-of-entry sampling. However, they do need to be adjusted for the reduction in variance associated with the averaging of multiple samples. As was the case for the NIRS data, it was assumed that the arithmetic average of four samples would be used to determine compliance with potential regulatory levels. The adjustments that were made to the various state log standard deviations are shown in Exhibit 5-31. These, along with the log mean values shown in Exhibit 5-30, are used in Section 5.8.4 to develop estimates of the numbers of systems above potential regulatory levels in seven states.

Exhibit 5-31. Estimates of State Average Log Standard Deviations Adjusted for Multiple Sampling						
Log Standard Deviation (Unadjusted)						
	System Size					
State	**ALL**	**VVS**	**VS**	**S**	**M**	**L**
MICHIGAN	0.777	0.834	0.956	0.722	0.631	0.619
NEW HAMPSHIRE	1.334	1.180	1.228	1.602	0.836	1.640
NEW YORK	1.205	1.214	1.463	1.007	0.880	0.837
PENNSYLVANIA	1.437	1.438	1.632	1.282	1.343	1.082
SOUTH CAROLINA	1.537	0.959	1.563	1.335	1.458	1.044
TEXAS	0.947	0.872	0.953	1.053	0.815	0.657
WISCONSIN	0.821	0.870	0.865	0.825	0.660	0.417
Log Standard Deviation (Adjusted for Multiple Sampling)						
	System Size					
State	**ALL**	**VVS**	**VS**	**S**	**M**	**L**
MICHIGAN	0.778	0.839	0.960	0.724	0.633	0.622
NEW HAMPSHIRE	1.343	1.209	1.255	1.610	0.850	1.647
NEW YORK	1.205	1.214	1.463	1.007	0.880	0.837
PENNSYLVANIA	1.437	1.438	1.632	1.282	1.343	1.082
SOUTH CAROLINA	1.537	0.959	1.563	1.335	1.458	1.044
TEXAS	0.947	0.873	0.954	1.053	0.816	0.658
WISCONSIN	0.826	0.445	0.879	0.830	0.666	0.427

5.8.3   Numbers of Community Water Systems in the U.S.

All of the data sets evaluated thus far have been samples from larger population of groundwater systems. The NIRS is a representative sample of in-system water from approximately 1,000 of the approximately 40,000 community groundwater systems in the U.S, and the state data

sets, with one exception[4], likewise represent relatively small samples of the total populations of groundwater systems in the states. Therefore, it is necessary to extrapolate the proportions of systems across the states and the regions that are above regulatory levels to the entire populations of those states. Data regarding the total numbers of active community groundwater systems in the U.S. were taken from EPA's *Drinking Water Baseline Handbook* (EPA 1999), and are summarized in Exhibit 5-32. The numbers in this table represent the total groundwater systems in each size category in each state, excluding systems that purchase their groundwater.

The data in Exhibit 5-32 show that there are a total of 40,812 active groundwater systems in the U.S. (excluding Hawaii, for which radon levels were not estimated because no data on radon levels in groundwater were identified). Consistent with previous estimates, the great majority of the systems fall in the smallest size categories. The very very small and very small systems each account for approximately 34 percent of the national total (13,687 and 13,860, respectively). There are 39,389 systems serving less than 10,000 people, amounting to approximately 91 percent of the total systems. (For purposes of regulatory analysis, EPA defines these systems as "small entities".)

5.8.4 Numbers of Community Water Systems Exceeding Potential Regulatory Levels

Exhibit 5-33 provides estimates of the numbers of community groundwater systems that would be above potential regulatory limits, assuming the current distribution of radon levels and assuming compliance is judged based on the arithmetic average of four duplicate samples. The totals in this exhibit represent the summed results of calculations for the eight regions where NIRS data were used to estimate systems above regulatory levels (30,354 systems) and for the seven states (10,458 systems) where supplemental data sets were used to estimate the numbers of systems above potential regulatory levels. Calculations for the individual states and regions are shown in Appendix D.1 and D.2.

The national proportions of systems predicted to exceed regulatory levels ranges from 76.7 percent (100 pCi/l) to 3.2 percent (4,000 pCi/l). The corresponding numbers of systems exceeding these levels are 31,307 and 1,312, respectively. Approximately 42.5 percent (17,349) of the systems are predicted to exceed EPA's preferred regulatory limit of 300 pCi/l, while, as noted above, 1,312 systems (3.2 percent) are predicted to exceed the AMCL values estimated by NAS. Because of their generally higher radon levels, the two smallest system categories account for a disproportionate share of the systems exceeding the higher radon levels. Very small and very very small systems combined account for approximately 85 percent of the systems above 1,000 pCi/l, 91 percent of the total systems above 2,000 pCi/l, and 94 percent of the systems above 4,000 pCi/l.

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[4] The data set from New Hampshire appears to present an almost complete census of groundwater systems in that state. In fact, there are more systems reporting data from New Hampshire than are identified in EPA's *Baseline Handbook*, probably because some of the systems in the New Hampshire data are listed under more than one name or are no longer active.

System Size (Population Served)	25-100	101-500	500-1,000	1,001-3,300	3,301-10,000	10,001-50,000	50,001-100,000	100,001-1 Million	> 1 Million
Total [1]	13687	13860	4247	5260	2335	1222	135	64	2
Grand Total	40812								
Alabama	3	27	33	107	78	24	1	0	0
Alaska	231	187	44	20	6	3	0	0	0
Arizona	235	255	95	77	45	28	2	0	0
Arkansas	40	116	71	104	48	11	3	0	0
California	1098	851	193	213	164	178	47	21	0
Colorado	233	191	42	46	12	8	0	0	0
Connecticut	238	239	20	25	7	8	0	0	0
Delaware	89	82	24	20	7	2	0	0	0
Florida	509	633	181	263	130	132	32	19	1
Georgia	604	549	98	132	51	22	2	1	0
Idaho	340	196	41	38	23	10	0	0	0
Illinois	184	378	203	217	106	48	1	2	0
Indiana	200	185	120	168	87	33	2	1	0
Iowa	214	334	161	165	57	15	3	1	0
Kansas	82	212	83	111	20	14	0	0	0
Kentucky	32	29	6	22	12	5	1	0	0
Louisiana	235	392	135	240	118	32	3	2	0
Maine	171	79	20	29	8	2	0	0	0
Maryland	148	179	47	45	17	20	0	0	0
Massachusetts	115	70	19	37	62	46	0	0	0
Michigan	345	428	127	168	59	15	3	1	0
Minnesota	159	319	147	168	57	50	1	0	0
Mississippi	72	294	266	365	109	35	0	1	0
Missouri	380	333	128	154	72	22	2	1	0
Montana	256	203	31	33	11	2	0	0	0
Nebraska	112	265	88	81	24	9	0	1	0
Nevada	103	80	22	28	14	1	0	0	0
NewHampshire	325	219	29	31	9	4	0	0	0
New Jersey	113	124	44	71	68	65	4	0	0
New Mexico	189	238	54	48	25	16	1	1	0
New York	815	646	164	159	54	44	3	5	0
North Carolina	895	669	111	95	45	24	1	0	0
North Dakota	38	83	32	44	5	3	0	0	0
Ohio	260	326	117	170	82	57	6	3	0
Oklahoma	82	176	66	102	21	13	0	0	0
Oregon	317	221	38	54	17	12	1	0	0
Pennsylvania	683	616	162	177	70	25	0	0	0
Rhode Island	22	22	1	4	2	4	0	0	0
South Carolina	230	160	46	55	31	9	2	0	0
South Dakota	103	112	39	34	13	3	0	0	0
Tennessee	30	34	22	44	24	14	1	1	0
Texas	889	1185	429	607	262	60	5	0	1
Utah	81	124	35	51	23	10	1	0	0
Vermont	137	144	32	20	8	1	0	0	0
Virginia	528	482	81	62	13	7	0	0	0
Washington	942	735	114	142	57	40	3	2	0
West Virginia	100	84	38	39	11	6	0	0	0
Wisconsin	402	275	141	162	87	29	4	1	0
Wyoming	78	79	7	13	4	1	0	0	0

Exhibit 5-32. Number of Community Groundwater Systems By Size and State

Notes:

1. For purposes of this analysis, Hawaii has been omitted, because no data related to radon levels in Hawaii were identified.

Exhibit 5-33. Estimated Numbers and Proportions of Community Groundwater Systems With Long-Term Radon Above Potential Regulatory Levels								
System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	13,687	11,464	6,549	4,381	3,248	2,289	1,047	415
Very Small (101-500)	13,860	10,808	6,478	4,608	3,602	2,734	1,536	817
Small: 501-1,000	4,247	2,849	1,452	858	554	325	103	32
1,001-3,300	5,260	3,409	1,694	991	636	370	116	36
Medium (3,301-10,000)	2,335	1,728	769	384	227	128	40	11
Large: 10,001-100,000	1,357	999	388	178	95	45	9	2
>100,000	66	49	19	8	4	2	0	0
National Total	40,812	31,307	17,349	11,408	8,366	5,892	2,852	1,312
Proportion of Total Systems	100.0%	76.7%	42.5%	28.0%	20.5%	14.4%	7.0%	3.2%

5.8.5   Comparison of Predicted Exceedences For States and Regions

The proportions of systems exceeding potential regulatory levels were estimated differently for those states having good supplemental data from those that did not. Radon distributions in the former states were evaluated using the supplemental state data, while the distributions in the other states were estimated by adjusting the NIRS regional average values using the average NIRS/State ratios. Thus, a comparison between the two groups of predictions can help to confirm the consistency of the adjustment approaches for the two types of data.

The proportions of community groundwater systems predicted to be above regulatory levels using the two data sources are compared in Exhibit 5-34. The predictions of proportions exceeding regulatory levels derived using the state data are consistently somewhat higher than those derived from the regional NIRS data for all system sizes. For the lower regulatory levels the two estimates differ by about four to 4.5 percent, while the proportions predicted to be above the highest regulatory levels differ by about 2.0-3.5 percent.

The systematic differences between the two sets of predictions appear to indicate a bias in the approach used to adjust the NIRS data for the differences between raw and in-system data, or in some other part of the estimation methodology. However, it is likely that a substantial part, if not all, of the difference in exceedance proportions is driven by real differences in radon levels between the seven states and the rest of the regions in which they reside. This is because the seven states having supplemental data appear to be generally among those with above-average radon levels compared to the rest of the country.

Exhibit 5-34. Comparison of Proportions of Systems Above Potential Regulatory Levels Predicted Using NIRS and State Data Sets
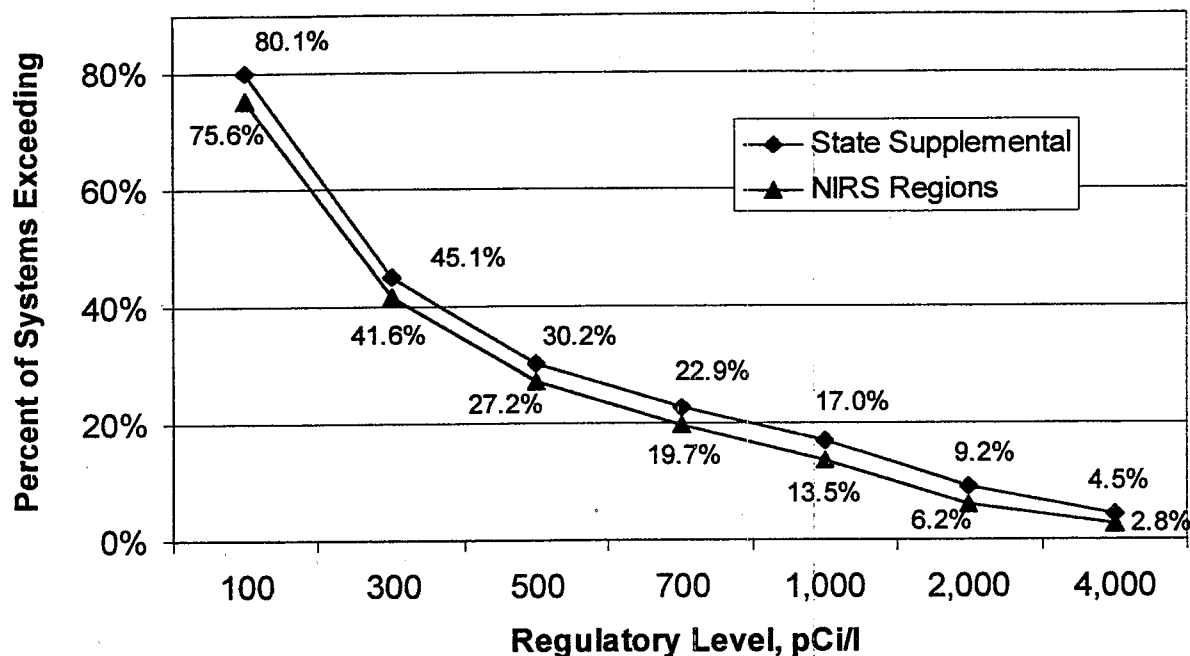
Exhibit 5-35 compares the log mean radon values for each of the seven states, calculated from the NIRS data (the only nationally representative source of radon data) to the regional log mean values calculated from the NIRS data for the entire region. It can be seen that the state NIRS log means for the remainder of the regions are less than the NIRS log means for the seven states having supplementary data. This confirms that the inconsistency between the predictions developed using state data and those developed using adjusted NIRS data are due to actual differences in radon levels, and is not artifactual.

5.8.6 Estimates of Non-Transient Non-Community Systems Exceeding Potential Regulatory Levels

In addition to community water systems, non-transient non-community systems (NTNCWS) would also be affected by the proposed limit on radon in drinking water. Therefore, the numbers and proportions of NTNCWS exceeding regulatory levels was also estimated. A detailed discussion of the process used to develop these estimates is provided in Appendix E, and only a summary is presented here.

Exhibit 5-35. Comparison of NIRS State Log Mean Levels to Corresponding Regional Log Means for Seven States

State	NIRS Data State Log Mean (all systems)	NIRS Regional Log Mean [1]
Michigan	5.13	4.84
New Hampshire	7.57	7.00
New York	5.41	5.73
Pennsylvania	5.98	5.73
South Carolina	5.82	5.73
Texas	4.93	4.69
Wisconsin	5.37	4.91

Notes:
1. Regional averages omit states with supplemental data. Thus, they are different from regional means in Exhibit 5-9.

Data concerning the numbers of NTNCWS active in the U.S. was obtained from EPA's *Drinking Water Baseline Handbook* (EPA 1999). Data from this source provide a national total of NTNCWS of 19,062 in 1998. A breakdown of the numbers of systems by state and size is given in Exhibit E-1. The distribution of radon levels in NTNCWS systems was estimated using supplementary data from five states (Maryland, Maine, New Hampshire, Texas, and New Hampshire). No other states provided information on radon levels in NTNCWS.

National geometric mean radon levels for each NTNCWS size category were estimated using the average ratios of the geometric mean levels in NTNCWS to the corresponding log mean levels in community water systems in the five states. Log standard deviations were estimated for each size category using the average of the log standard deviations seen in the state data sets for each size category.

The numbers and proportions of NTNCWS exceeding potential regulatory levels were estimated using the lognormal model, in the same manner as for the community systems. Only national totals were estimated, as the data were too limited to support detailed regional estimates. The results of the analysis are shown in Exhibit 5-36. The general pattern of results is similar to that seen for the community water systems, except that the proportions of NTNCWS exceeding the regulatory limits are greater, owing to the generally higher radon levels in the latter systems. The great majority of NTNCWS (over 91 percent) are predicted to have long-term radon levels above 100 pCi/l, and 64.9 percent of the systems would exceed EPA's proposed regulatory level of 300 pCi/l. The proportions of NTNCWS exceeding potential regulatory levels then decline rapidly, until

only about 3.1 percent are predicted to exceed the NAS AMCL value of 4,000 pCi/l.

		Exhibit 5-36. Estimated Proportions of Non-Community Non-Transient Groundwater Systems With Long-Term Average Radon Above Potential Regulatory Levels						

State/Region:	National							
System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	9,606	9,137	6,687	4,734	3,423	2,208	693	140
Very Small (101-500)	6,840	6,095	4,511	3,500	2,819	2,138	1,074	436
Small:								
501-1,000	1,891	1,550	842	503	325	187	48	8
1,001-3,300	665	545	296	177	114	66	17	3
Medium (3,301-10,000)	53	45	26	16	11	6	2	0
Large/Very Large:								
10,001-100,000	7	6	4	2	2	1	0	0
>100,000	0	0	0	0	0	0	0	0
Total	19,062	17,377	12,367	8,932	6,694	4,606	1,834	587
Proportion of Total Systems	100.0%	91.2%	64.9%	46.9%	35.1%	24.2%	9.6%	3.1%

5.8.7   Sensitivity Analysis of Estimates of Systems Exceeding Radon Levels

In this section, we describe a screening-level analysis of the uncertainty associated with the estimates of the numbers of systems exceeding potential regulatory levels. A one-dimensional Monte Carlo simulation method is employed to investigate the combined impacts of the various sources of uncertainty and variability that affect these estimates, and to develop quantitative estimates of the overall uncertainty of the estimated numbers of systems exceeding different regulatory levels.

To implement the Monte Carlo model, the log mean and log standard deviation of the various state/region/system size categories were modeled as independent random variables:

$$LM = LM_{(NIRS, State)} + N(0,SEM) \qquad\qquad (5\text{-}14)$$

$$LSD = LSD_{(NIRS, State)} + N(0,SESD) \qquad\qquad (5\text{-}15)$$

where:

$LM_{(NIRS, State)}$ = The log mean radon level for the category of systems being evaluated

$N(0,SEM)$ = A random normal variable with mean zero and standard

deviation equal to the standard error of the log mean radon

$\text{LSD}_{\text{(NIRS, State)}}$ = The log standard deviation in radon levels for the category of system being evaluated

N(0,SESD) = A random normal variable with mean zero and standard deviation equal to the standard error of the log standard deviation for the category

The approximate normality of the log mean and log standard deviation estimates follows from the central limit theorem. The approximate independence of these variables follows from standard statistical theory, which shows that the sample mean and sample variance for non-censored normal data are independent.

The log mean and log standard deviation values were estimated from the NIRS and state supplementary data shown in Exhibit 5-9 and 5-18. The standard errors of the log mean and log standard deviations of radon levels were estimated as:

$$SEM = \frac{\delta}{\sqrt{n}} \tag{5-16}$$

$$SESD = \frac{\delta}{\sqrt{2n}} \tag{5-17}$$

where:

δ = the log standard deviation for the state/region/system size category
n = the number of observations from which the log standard deviation was estimated.

This approximation (for the standard error of the log mean and the log standard deviation) follows from the standard large-sample approximation.

In performing the simulation, 5,000 estimates of log mean and log standard deviation were derived for each set of systems evaluated by random sampling. For each the log mean and log standard deviation estimates, the proportions of systems above regulatory levels were then estimated, as described previously, using Equation 5-3. The numbers of systems in each region/state/system size category exceeding regulatory levels were then estimated as the product of the proportion above the regulatory limit times the numbers of systems in the various regions and size categories, as described in Section 5.8.3.

Two sets of simulations were conducted. First, probability distributions were developed for the total numbers of CWS above the various regulatory levels . The results of that analysis are summarized in Exhibit 5-37. This Exhibit tabulates the percentiles of the cumulative probability

distribution of the estimated numbers of systems exceeding the regulatory levels from 100 pCi/l to 4,000 pCi. Looking at the second column of the table, for example, it can be seen that the average estimated number of systems exceeding 300 pCi/l is 17,349 systems (consistent with Exhibit 5-33), and that the 5th and 95th percentile estimates of total systems exceeding 300 are 16,713 and 17,999, respectively.

Exhibit 5-37. Distributions of Monte Carlo Estimates of Total Community Systems Above Radon Levels							
	Potential Radon Regulatory Level, pCi/l						
Percentiles	100	300	500	700	1,000	2,000	4,000
0%	30,123	15,982	10,119	7,272	5,173	2,365	939
5%	30,678	16,713	10,940	7,978	5,548	2,633	1,155
10%	30,802	16,860	11,059	8,083	5,651	2,701	1,199
15%	30,891	16,956	11,125	8,153	5,725	2,741	1,232
20%	30,954	17,030	11,186	8,210	5,769	2,778	1,255
25%	31,010	17,097	11,230	8,262	5,814	2,810	1,279
30%	31,064	17,158	11,285	8,312	5,854	2,832	1,301
35%	31,113	17,210	11,333	8,350	5,898	2,857	1,316
40%	31,158	17,263	11,374	8,389	5,932	2,879	1,332
45%	31,198	17,314	11,418	8,426	5,960	2,903	1,348
50%	31,239	17,362	11,460	8,463	5,988	2,925	1,364
55%	31,282	17,408	11,506	8,501	6,023	2,950	1,382
60%	31,323	17,455	11,543	8,541	6,060	2,977	1,398
65%	31,368	17,502	11,591	8,586	6,097	3,001	1,416
70%	31,419	17,561	11,656	8,626	6,135	3,027	1,429
75%	31,467	17,624	11,711	8,682	6,172	3,054	1,448
80%	31,524	17,689	11,763	8,738	6,222	3,086	1,470
85%	31,591	17,766	11,840	8,797	6,273	3,120	1,492
90%	31,676	17,857	11,923	8,855	6,341	3,168	1,524
95%	31,801	17,999	12,033	8,970	6,429	3,239	1,570
100%	32,362	18,766	12,726	9,569	6,968	3,594	1,853
Mean	31,307	17,349	11,408	8,366	5,892	2,852	1,312

On the whole, the spread in the distributions of the estimates are quite narrow. At 100 pCi/l, the difference between the 5th and 95th percentiles estimates is only about 3.5 percent. As the regulatory levels increase, the spread in the distributions increases, so that at 4,000 pCi/l, the 95th percentile estimate is about 36 percent greater than the 5th percentile estimate.

The second set of simulations looked at the distributions of the numbers of systems in different size categories above a regulatory limit of 300 pCi/l. The results of that analysis are summarized in Exhibit 5-38. In this case, the spread in the distributions are also relatively narrow, and inversely proportional to the average numbers of systems predicted to be above regulatory levels. For the very very small systems, the 5th and 95th percentile differ by approximately 12 percent around a mean of 6,552 systems above 300 pCi/l. The average number of large systems above 300 pCi/l, in contrast, is 409, and the 95th percentile is 31 percent higher than the 5th percentile.

Finally, confidence limits were derived for the mean numbers of systems exceeding 300 pCi/l, using the "bootstrap" method described in Section 5.2. The results of that analysis are summarized in Exhibit 5-39.

Exhibit 5-38. Distributions of Monte Carlo Estimates of Community Systems Above 300 pCi/l, by System Size Category						
Percentiles	System Size					
	VVS	VS	S	M	L	Total
0%	5,669	5,506	2,498	483	283	15,982
5%	6,179	6,051	2,866	645	355	16,713
10%	6,261	6,147	2,925	672	367	16,860
15%	6,315	6,206	2,967	691	375	16,956
20%	6,360	6,264	3,002	706	381	17,030
25%	6,400	6,304	3,030	719	387	17,097
30%	6,430	6,346	3,054	730	392	17,158
35%	6,463	6,382	3,076	742	396	17,210
40%	6,493	6,416	3,106	753	400	17,263
45%	6,521	6,448	3,129	763	404	17,314
50%	6,550	6,482	3,151	774	409	17,362
55%	6,576	6,512	3,171	784	413	17,408
60%	6,605	6,544	3,192	794	417	17,455
65%	6,634	6,575	3,215	805	422	17,502
70%	6,668	6,613	3,239	816	426	17,561
75%	6,706	6,649	3,266	830	431	17,624
80%	6,744	6,690	3,297	844	437	17,689
85%	6,791	6,735	3,326	861	444	17,766
90%	6,849	6,796	3,365	881	452	17,857
95%	6,931	6,887	3,421	913	465	17,999
100%	7,429	7,331	3,824	1,073	533	18,766
Mean	6,552	6,476	3,148	775	409	17,349

Exhibit 5-39. Confidence Limits on Mean Estimates of the Numbers of Systems Above 300 pCi/l

Estimate	System Size Category					
	All	Very Very Small	Very Small	Small	Medium	Large
5th Percentile	17,316	6,513	6,441	3,126	760	403
Mean	15,359	5,549	6,482	3,149	774	409
95th Percentile	17,396	6,528	6,528	3,175	790	415

The widest interval between the upper and lower confidence is approximately four percent for the medium systems. The interval for the large systems is approximately three percent, and the range between the upper and lower confidence limits for the other size categories are between approximately 1.0 and 1.6 percent. For all systems combined, the range between the upper and lower confidence limits is approximately 0.5 percent, or a difference of 80 systems, compared to an average of 15,359.

The estimates just discussed provide a rough estimate of the degree of uncertainty associated with the estimates of the numbers of systems above the different potential regulatory levels, the numbers of systems in different size categories above a regulatory limit of 300 pCi/l, and estimates of the uncertainty in the mean estimates of these values. On the whole, the distributions of the estimates are quite narrow, considering the magnitude of variability in radon levels in community water systems. A major reason for this is that, when averaged over large numbers of systems, much of this variability is "smoothed out" and the estimates of the overall proportions of systems above the regulatory levels are quite stable. The validity of these estimates depends on three major assumptions:

- That long-term radon levels in community water systems are well-represented by the lognormal models that have been derived for the various states and regions,

- That the potential errors in the summary statistics used to describe these distributions are normally distributed, and

- That the estimates of the numbers of active community systems in the various states are regions have been accurately estimated.

To the extent that these assumptions are not true, the uncertainty in the numbers of systems above potential regulatory levels may have been underestimated.

5.9 Comparison of Current Estimates of Radon Exceedences to Previous EPA Occurrence Analyses

The preceding analyses have employed the same general approaches as those used in EPA's previous occurrence analyses except that the data base of radon occurrence has been expanded to include additional data for seven states. In addition, the approaches used to estimate summary statistics for the radon distributions are slightly different than those employed n the previous occurrence analyses, and the NIRS data have been adjusted to compensate for differences between in-system and point-of-entry sampling. Finally, as will be discussed below, the estimated of the numbers of active community and non-transient non-community systems have changed since the previous effort. This section provides a brief comparison of the results of the current analysis with those of EPA's previous efforts.

The data for the 1993 occurrence analysis (Wade Miller Associates 1993) came from EPA's FRDS data base, current as of 1992. while the estimates used in this analysis come from EPA's Drinking Water Baseline Handbook. The current estimates are based on SDWIS data from mid-1998. There are considerable differences between the estimated numbers of community and non-transient non-community water systems derived from the two sources, as shown in Exhibit 5-40. In 1993, EPA estimated that there were a 45,626 community groundwater systems and 23,865 non-transient non-community groundwater systems that could be affected by a radon rule. Using the more recent data, EPA estimates that there are only 40,812 community groundwater systems active in the U.S., and 19,062 non-transient non-community systems.

Exhibit 5-40. Comparison of Estimated Numbers of Groundwater Systems from the 1993 Occurrence Analysis With Estimates from The Current Analysis								
System Size	Very Very Small	Very Small	Small		Medium	Large		
System Type	25-100	101-500	501-1,000	1,001-3,300	3,301-10,000	10,001-100,000	>100,000	Total
1993 Occurrence Analysis								
Community	16,634	15,422	4,691	5,261	2,302	1,257	59	45,626
Non-Transient Non-Community	13,842	7,512	1,817	627	63	4	0	23,865
Total	30,813	23,673	6,854	6,232	2,471	1,322	62	71,427
This Analysis								
Community	13,687	13,860	4,247	5,260	2,335	1,357	66	40,812
Non-Transient Non-Community	9,606	6,840	1,891	665	53	7	0	19,062
Total	23,293	20,700	6,138	5,925	2,388	1,364	66	59,874

The reasons for the differences between the earlier estimates and those derived from more recent data are not clear. Based on the data in Exhibit 5-40, it would appear that the bulk of the changes have been reductions in the numbers of the smallest systems, both community and non-transient non-community. It is possible that many of these systems have ceased operations, or merged with larger systems. Whatever the reasons, the number of community groundwater systems is estimated to have decreased by approximately 11 percent and the number of non-transient non-community systems decreased by approximately 20 percent between 1993 and 1998.

In addition to the number of systems affected, the current analysis differs substantially from the previous one in the proportions of systems predicted to be above the various regulatory levels (Exhibit 5-41.) The proportions of systems predicted to exceed the three lowest regulatory levels (100, 300, and 500 pCi/l) in this analysis are all higher than both the lower-bound and upper-bound estimates from the 1993 analysis. At regulatory limits of 1,000 and 2,000 pCi/l, the predictions of the current analysis fall between the lower- and upper-bound analyses from 1993, but are closer to the upper-bound estimates. The major reason for this difference is undoubtedly the upward adjustment made in the regional log mean values derived from the NIRS data to account for differences between in-system versus point-of-entry sampling.

Exhibit 5-41. Comparisons of Estimated Proportions and Numbers of Systems Exceeding Potential Regulatory Levels from 1993 Occurrence Analysis and the Current Study							
1. Estimated Proportions of Systems Exceeding Potential Regulatory Levels [1]							
1993 Occurrence Analysis [2]							
Regulatory Level, pCi/l	100	300	500	700	1,000	2,000	4,000
Lower Bound	63.5%	33.4%	21.4%	—	9.7%	3.1%	—
Upper Bound	75.7%	46.7%	33.8%	—	19.8%	10.4%	—
This Analysis							
Mean Estimate	81.3%	49.6%	34.0%	25.2%	17.5%	7.8%	3.2%
2. Estimated Numbers of Systems Exceeding Potential Regulatory Levels							
1993 Occurrence Analysis							
Regulatory Level, pCi/l	100	300	500	700	1,000	2,000	4,000
Lower Bound	44,115	23,201	14,898	—	6,763	2,185	—
Upper Bound	52,571	32,472	23,503	—	13,749	7,229	—
This Analysis							
Mean Estimate	48,684	29,716	20,340	15,060	10,498	4,686	1,900

Notes:

1. Includes community and non-transient non-community systems
2. Source: Wade Miller Associates 1993

As shown in the bottom panel of Exhibit 5-40, estimates of the numbers of systems above potential regulatory levels from the current analysis are generally comparable to the 1993 estimates. For all the regulatory levels where predictions have been made in both studies, the current analysis predicts that the numbers of systems exceeding regulatory levels will fall almost exactly half-way between the lower- and upper-bound estimates from the 1993 analysis. The higher proportions exceeding regulatory levels predicted in the current study are offset by the lower total number of systems that could be affected by a radon rule. Thus, despite the substantial differences in input data and estimation methods, this analysis arrives at roughly the same estimates of the numbers of systems that could be affected by the radon rule as were predicted in EPA's previous study.

5.10. References

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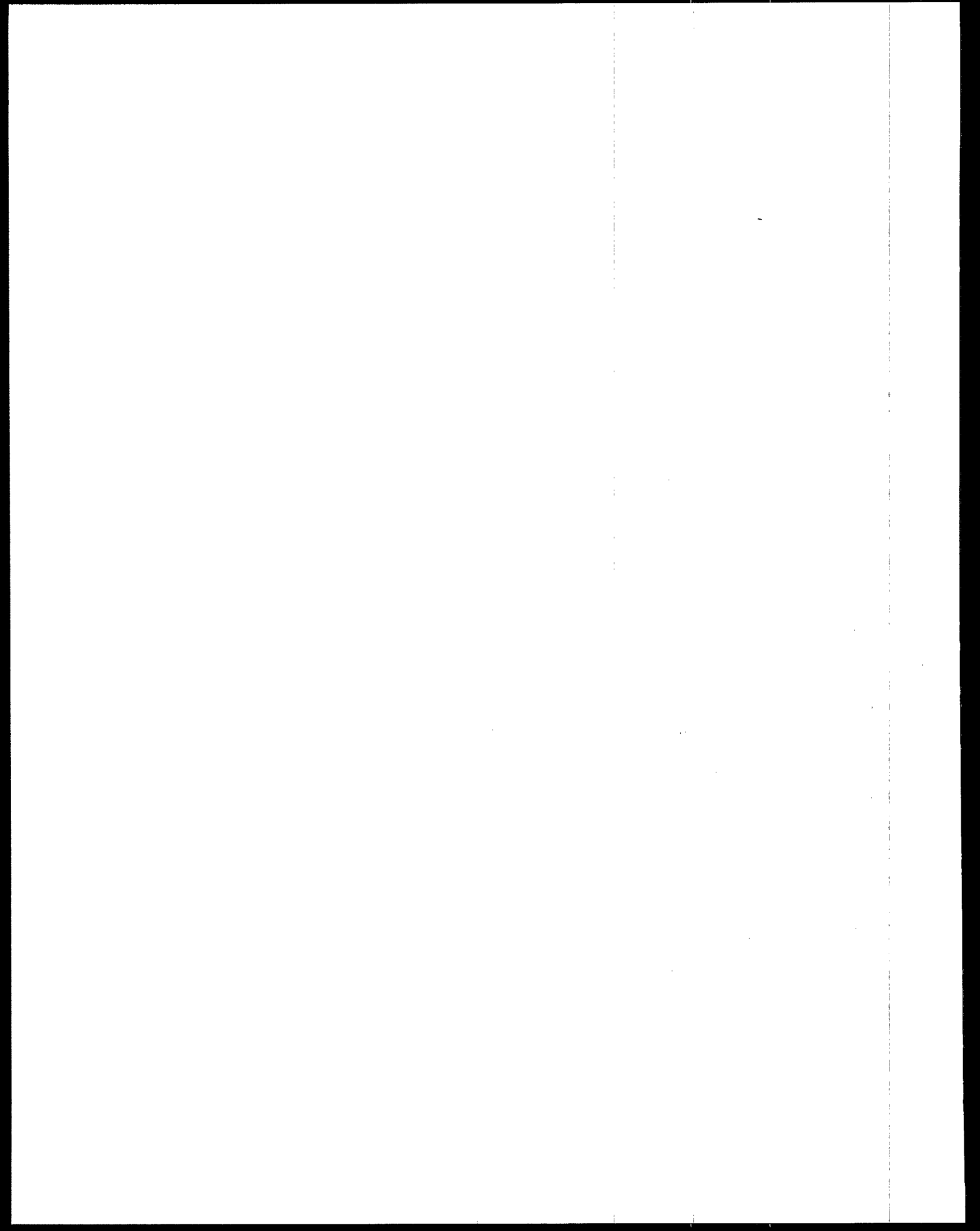
6. POTENTIAL EXPOSED POPULATIONS

This chapter presents estimates of the populations exposed to radon at various levels, and discusses exposures to specially sensitive populations. Estimates of the populations exposed were derived by multiplying the numbers of systems above various radon levels by the average numbers of individuals served by each size system.

6.1 Data Sources

The data sources used to estimate the numbers of systems of different sizes in the U.S. and the average populations served per systems was EPA's *Baseline Handbook* (EPA 1999a). These data were derived from analyses of the SDWIS database based on information gathered in mid-1998. Regional and state estimates of the proportions of systems of different sizes above potential regulatory levels were derived as explained in Section 5.8

6.2 Populations Above Regulatory Levels

Exhibit 6-1 presents estimates of the numbers of populations served by systems with influent radon above various potential regulatory limits.

Exhibit 6-1. Populations Potentially Exposed Above Potential Regulatory Levels By System Size (Thousands)

Radon level (pCi/l)	Very Very Small	Very Very Small	Very Small	Small	Medium	Large	Total
	25-100	101-500	501-3,300	3,301-10K	10K-100K	> 100K	
4,000	9.4	46	20	0.2	0.9	0.4	77
2,000	41	183	119	5.7	21.7	11.0	381
1,000	128	541	513	85.5	289	147	1,695
700	202	848	962	267	859	436	3,558
500	290	1,210	1,620	672	2,070	1,050	6,893
300	445	1,880	3,140	2,080	6,060	3,070	16,641
100	733	3,290	8,080	8,760	23,400	11,900	56,054

Based on SDWIS data, a total approximately 89.7 million people are served by community water systems. Of these, just over 56 million (62.6 percent) are served by community groundwater systems with radon levels above 100 pCi/l. Approximately 16.6 million (18.6 percent) are served by systems with long-term radon levels above 300 pCi/l. The proportions

potentially exposed decrease as the regulatory levels increase; only about 77 thousand people (0.09 percent) are estimated to be exposed above the NAS estimated AMCL level of 4,000 pCi/l.

The proportions of the population exposed above the potential regulatory levels do not match the proportions of systems above these levels shown in Section 5.8. This is because the larger systems, while comprising only a small proportion of the total systems, account for large fractions of the total populations served.

6.3   Special Populations

The numbers of individuals potentially exposed to radon in Exhibit 6-1 includes all members of the general residential population. EPA has identified only one population that may be especially sensitive to radon exposures (actually exposure to radon progeny), namely, smokers. In their risk assessment for radon exposures from drinking water (see EPA 1999b), the Agency has assumed a historical "ever-smoking" prevalence of 58 percent for males, and 42 percent for females. The agency recognizes that smoking prevalence is currently decreasing, and thus the numbers of sensitive individuals exposed to radon could decrease in the future.

A further 5.2 million individuals are estimated to be exposed to radon from non-community non-transient systems (EPA 1999a). In addition, an undetermined number of individuals are exposed to radon from community water systems in non-residential settings. There is no data that allows the extent of overlap among these populations to be evaluated. The levels of exposure associated with a given radon level in water are expected to be lower for non-residential exposures and exposures to non-community systems than for residential exposures from community systems.

6.4   References

EPA (1999a), *Drinking Water Baseline Handbook, First Edition*, Prepared by International Consultants, Inc, for the Office of Ground Water and Drinking Water, March 2, Draft.

EPA (1999b), *Regulatory Impact Analysis and Revised Health Risk Reduction and Cost Analysis for Radon in Drinking Water*, Office of Groundwater and Drinking Water, August.

7.   CO-OCCURRENCE ASSESSMENT

7.1   Data Sources

In its analysis of the patterns of co-occurrence of radon with other contaminants, EPA has relied on two primary data sources. The first is the US Geological Survey (USGS) National Water Information System (NWIS). NWIS contains data on water quality parameters in surface and groundwater sources in all fifty states (SAIC 1999). The data are available on-line through the USGS Water Resources Division, and have been the subject of extensive analysis by the agency to determine co-occurrence patterns for a wide range of contaminants

In addition to NWIS, the NIRS measured the levels of analytes other than radon, and thus provides information concerning radon co-occurrence with other analytes in distribution systems. While the number of systems sampled is limited, EPA has also analyzed the NIRS data to investigate the co-occurrence patterns of radon, other radionuclides, and inorganic analytes.

7.2   Co-Occurrence of Radon With Other Contaminants

Screening analysis of the NWIS database (SAIC 1999) have identified statistically significant correlations between the occurrence of radon and several other contaminants in certain regions of the U.S. The correlations are summarized in Exhibit 7-1.

Exhibit 7-1. Correlations of Radon With Other Analytes in INWIS DATA

EPA Region	Significant Correlation of Radon Levels With:
4	Iron
	Manganese
	Sulfate
7	Nitrate
	Sulfate
9	Beryllium
	Selenium
	Sulfate
10	Barium
	Chromium
	Manganese

Levels of radon in the INWIS data were found to be significantly correlated with the levels of one or more inorganics in each of four EPA regions. At the national level, radon is not

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significantly correlated with any other analytes in groundwater systems. It is not clear that the number of correlations seen exceeds the number that would be expected to occur by chance, given the number of comparisons that were made. No analyses have been conducted of the correlations between radon and other analytes in systems of different sizes.

Based on only this preliminary analysis, it is not possible to determine whether their might be any geological factors contributing to the observed patterns of co-occurrence. Given the greatly differing geochemical properties of the analytes with which radon co-occurs, it is hard to develop any hypothesis that would explain the co-occurrence. In the NIRS data, radon levels are significantly correlated with only one analyte (chloride) at the national level, and with none at the regional level. Taken together, the available data therefore do not suggest that, at the national level, radon occurrence is correlated with the occurrence of any inorganic contaminants. Additional analyses are needed to determine if there are any patterns of co-occurrence on smaller distance scales.

Few data are available regarding the co-occurrence of radon and organic compounds. Because radon is primarily naturally occurring, and not often associated with human activities, there is little reason to believe there is a correlation between man-made groundwater pollution with organic contaminants and radon levels. Generally, groundwater sources tend to have lower levels of organic compounds than surface water sources. As reported in the proposed Disinfection and Disinfection Byproducts Rule (EPA 1994), a survey of surface waters showed TOC levels with 25th, 50th, and 75th percentiles of 2.6, 4.0, and 6.0 mg/l, respectively. Ground-waters showed TOC levels at the same percentiles of "non-detect", 0.8, and 1.9 mg/l, respectively. Nationally, typical ground waters have low TOC levels. However, some areas of the U.S., e.g., the Southeastern U.S. (EPA Region 4) have some aquifers with high TOC levels.

7.2   Implications of Co-Occurrence

Despite the fact that radon occurrence is not significantly correlated with any other contaminants at the national level none the less, the existing patterns of its co-occurrence with some common analytes have important implications for the selection of radon mitigation technologies and for radon mitigation costs. The most important of these is iron and manganese. EPA has estimated (EPA 1999) that a substantial fraction of groundwater systems with radon levels exceeding potential regulatory limits would also have levels of iron (Exhibit 7-2) and manganese (Exhibit 7-3) exceeding levels that would require sequestration or some other to protect aeration systems from fowling. This pattern has the potential for increasing the radon mitigation costs for those systems not already treating for iron and manganese.

One other important instance where co-occurrence is potentially important are those situations where radon and arsenic co-occur. In these cases, there is the potential that aeration treatment to reduce radon levels could also aid in the reduction of arsenic exposures because aeration would oxidize arsenic from soluble trivalent for to the comparatively insoluble pentavalent form. This would make it easier to remove arsenic from the water (EPA 1999).

Table 7-2. Co-Occurrence of Radon with Dissolved Iron in Raw Ground Water[1] (4188 samples)

Radon (pCi/L)	Dissolved Fe (mg/L)					
	ND	< 0.3	0.3–1.5	1.5–2.5	>2.5	Totals
ND	0.67%	0.36%	0.21%	0.02%	0.31%	1.57%
<100	2.17%	1.72%	0.53%	0.12%	0.48%	5.02%
100–300	7.55%	10.20%	2.67%	1.34%	1.74%	23.50%
300–1,000	18.89%	22.61%	3.08%[3]	0.57%	1.31%	46.46%
1,000–3,000	6.42%	9.05%	0.74%	0.10%	0.62%	16.93%
>3,000	2.10%	3.82%	0.31%	0.02%	0.26%	6.51%
Totals	37.80%	47.76%	7.54%	2.17%	4.72%	100.00%

Notes:
1. Source: EPA analyses of NWIS data (EPA 1999)

Exhibit 7-3. Co-Occurrence of Radon with Dissolved Manganese in Raw Ground Water (4189 samples) [1]

Radon (pCi/L)	Dissolved Mn (mg/L)				
	ND	< 0.02	0.02–0.05	> .050	Totals
ND	0.69%	0.26%	0.05%	0.57%	1.57%
<100	2.67%	0.84%	0.36%	1.15%	5.02%
100–300	8.00%	5.97%	2.20%	7.33%	23.50%
300–1,000	21.99%	11.84%	3.17%	9.48%[3]	46.48%
1,000–3,000	6.45%	5.90%	1.24%	3.34%	16.93%
> 3,000	1.43%	3.39%	0.53%	1.17%	6.52%
Totals	41.23%	28.20%	7.55%	23.04%	100.00%

Notes:
1. Source: EPA analyses of NWIS data (EPA 1999)

7.3 References

EPA (1999), *Regulatory Impact Analysis and Revised Health Risk Reduction and Cost Analysis for Radon in Drinking Water*, Office of Groundwater and Drinking Water, August.

EPA (1994), *Proposed Disinfection and Disinfection Byproducts Rule*, 59 Federal Register 38668, July 29.

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8. MONITORING APPROACHES

8.1 Background

The monitoring regulation for radon proposed in 1991 by EPA required that groundwater systems monitor for radon at each entry point to the distribution system quarterly for one year initially. Monitoring could be reduced to one sample annually per entry point to the distribution system if the average of all first quarterly samples was below the MCL. States could allow systems to reduce monitoring to once every three years if the system demonstrated that results of all previous samples collected were below the MCL. The proposal also allowed States to grant waivers to groundwater systems to reduce the frequency of monitoring, up to once every 9 years, if States determined that radon levels in drinking water were consistently and reliably below the MCL. Comments made in response to the proposed monitoring requirements for radon were mainly concerned that the proposed monitoring requirements did not adequately take into account the effect of seasonal variations in radon levels on determining compliance. Other commenters felt that sampling at the entry point of the distribution system was not representative of exposure to radon, and they suggested that sampling for radon should be done at the point of use.

Since the 1991 proposal EPA has obtained additional information from states, the water utilities, and academia on the occurrence of radon, including data on its temporal variability (See Section 5.7). Utilizing this additional data, the Agency performed extensive statistical analyses to predict how temporal, analytical variations and variations between individual wells may affect exposure to radon. The results of these analyses are described in detail in the previous sections of this document. As a result of the new information, EPA was able to refine the requirements for monitoring and address the concerns expressed by the commenters on the 1991 proposal.

8.2 Objectives of Monitoring Program

The objectives of the monitoring program are to provide for rapid, cost-effective identification of groundwater sources that are above and below proposed regulatory limits. The proposed monitoring requirements for radon are consistent with the monitoring requirements for regulated drinking water contaminants, as described in the Standardized Monitoring Framework (SMF) promulgated by EPA under the Phase II Rule of the National Primary Drinking Water Regulations (NPDWR) and revised under Phases IIB and V. The goal of the SMF is to streamline the drinking water monitoring requirements by standardizing them within contaminant groups and by synchronizing monitoring schedules across contaminant groups.

In developing the proposed compliance monitoring requirements for radon, EPA considered:

- The likely source of contamination in drinking water;

- The differences between ground water and surface water systems;

- The need to collect samples which are representative of consumer exposure;

- Sample collection and analytical methods;

- The use of appropriate historical data to identify vulnerable systems and to specify monitoring requirements for individual systems;

- The analytical, temporal and intra-system variance of radon levels;

- The use of appropriate historical data and statistical analysis to establish reduced monitoring requirements for individual systems; and

- The need to provide flexibility to the States to tailor monitoring requirements to site-specific conditions by allowing them to:

  --grant waivers to systems to reduce monitoring frequency, provided certain conditions are met,
  --require confirmation samples for any sample exceeding the MCL/AMCL
  --allow the use of previous sampling data to satisfy initial sampling requirements.
  --increase or decrease monitoring frequency.

8.3   Description of Proposed Monitoring Requirements

Exhibit 8.1 provides a description of the monitoring requirements proposed for radon, and compares them to the requirements in the 1991 Proposal and in the Standardized Monitoring Framework. The major provisions include

Monitoring for Surface Water Systems

Systems relying exclusively on surface water as their water source will not be required to sample for radon. Systems that rely in part on ground water would be considered groundwater systems for purposes of radon monitoring. Systems that use ground water to supplement surface water during low-flow periods will be required to monitor for radon. Ground water under the influence of surface water would be considered ground water for this regulation.

Sampling, Monitoring Schedule and Initial Compliance for Groundwater Systems

EPA is retaining the quarterly monitoring requirement for radon as proposed initially in the 1991 proposal to account for variations such as sampling, analytical and temporal variability

Exhibit 8.1   Comparison of Monitoring Requirements

MONITORING REQUIREMENTS FOR RADON		
1991 Proposal	1999 Proposal - MCL/AMCL	SMF for IOCs in Groundwater
INITIAL MONITORING REQUIREMENTS		
Four consecutive quarters of monitoring at each entry point for one year. Initial monitoring must be completed by January 1, 1999.	Four consecutive quarters of monitoring at each entry point for one year. Initial monitoring must begin by 3 years from after publication of the final rule in Federal Register or 4.5 years from date of publication of the final rule in Federal Register (depending on effective date applicable to the State).	Four consecutive quarters of monitoring at each entry point for sampling points initially exceeding MCL .
ROUTINE MONITORING REQUIREMENTS		
One sample annually if average from four consecutive quarterly samples taken initially is less than MCL.	One sample annually if average from four consecutive quarterly samples is less than MCL/AMCL, and at the discretion of State.	One sample at each sample point during the initial 3 year compliance period for groundwater systems for sampling points below MCL.
1991 Proposal	1999 Proposal - MCL	SMF for IOCs in Groundwater
REDUCED MONITORING REQUIREMENTS		
State may allow groundwater systems to reduce the frequency of monitoring to once every three years provided that they have monitored quarterly in the initial year and completed annual testing in the second and third year of the first compliance period. Groundwater systems must demonstrate that all previous analytical samples were less than the MCL.	State may allow groundwater systems to reduce monitoring frequency to: Once every 3 years if average from four consecutive quarterly samples is less than ½ the MCL/AMCL, provided no samples exceed the MCL/AMCL or if the system is determined by State to be "reliably and consistently below MCL/AMCL".	State may allow groundwater systems to reduce monitoring frequency to: Once every 3 years if sample subsequently detects less than MCL and determined by State to br "reliably and consistently below MCL".

Exhibit 8-1. Comparison of Monitoring Requirements (Continued)

INCREASED MONITORING REQUIREMENTS		
Systems monitoring annually or once per three year compliance period that exceed the radon MCL in a single sample would be required to revert to quarterly monitoring until the average of 4 consecutive samples is less than the MCL. Ground water systems with unconnected wells would be required to conduct increased monitoring only at those wells exceeding the MCL. The State may require more frequent monitoring than specified. Systems may apply to the State to conduct more frequent monitoring than the minimum monitoring frequencies specified.	Systems monitoring annually would be required to increase monitoring if the MCL/AMCL for radon is exceeded in a single sample, the system would be required to revert to quarterly monitoring until the average of 4 consecutive samples is less than the MCL/AMCL. Systems monitoring once every three years would be required to monitor annually if the radon level is less than MCL/AMCL but above ½ MCL/AMCL in a single sample. Systems may revert to monitoring once per three years if the average of the initial and three consecutive annual samples is less than ½ MCL/AMCL Ground water systems with un-connected wells would be required to conduct increased monitoring only at those wells which are affected.	If the MCL is exceeded in a single sample, the system required to begin sampling quarterly until State determines that it is "reliably and consistently "below MCL. .
MONITORING REQUIREMENTS FOR RADON		
1991 Proposal	1999 Proposal - MCL	SMF for IOCs in Groundwater

Exhibit 8.1   Comparison of Monitoring Requirements (Continued)

CONFIRMATION SAMPLES		
Where the results of sampling indicate an exceedence of the maximum contaminant level, the State may require that one additional sample be collected as soon as possible after the initial sample was taken [but not to exceed two weeks] at the same sampling point. The results of the initial sample and the confirmation sample shall be averaged and the resulting average shall be used to determine compliance.	Systems may collect confirmation samples as specified by the State. The average of the initial sample and any confirmation samples will be used to determine compliance.	Where the results of sampling indicate an exceedence of the maximum contaminant level, the State may require that one additional sample be collected as soon as possible after the initial sample was taken [but not to exceed two weeks] at the same sampling point. The results of the initial sample and the confirmation sample shall be averaged and the resulting average shall be used to determine compliance.
GRANDFATHERING OF DATA		
If monitoring data collected after January 1, 1985 are generally consistent with the requirements specified in the regulation, than the State may allow the systems to use those data to satisfy the monitoring requirements for the initial compliance period.	If monitoring data collected after proposal of the rule are consistent with the requirements specified in the regulation, then the State may allow the systems to use those data to satisfy the monitoring requirements for the initial compliance period.	States may allow previous sampling data to satisfy the initial sampling requirements provided the data were collected after January 1, 1990
WAIVERS		
State may grant waiver to groundwater systems to reduce the frequency of monitoring, up to 9 years, if State determines that radon levels in drinking water are "reliably and consistently" below the MCL.	The State may grant a monitoring waiver to systems to reduce the frequency of monitoring to up to one sample every 9 years based on previous analytical results, geological characteristics of source water aquifer and if a State determines that radon levels in drinking water are reliably and consistently below the MCL/AMCL. Analytical results of all previous samples taken must be below ½ the MCL/AMCL.	State may grant waiver to groundwater systems after conducting vulnerability assessment to reduce the frequency of monitoring, up to 9 years, if State determines that radon levels in drinking water are "reliably and consistently" below the MCL. System must have 3 previous samples. Analytical results of all previous samples taken must be below MCL.

in radon levels. Results of analysis of data obtained since 1991, estimating contributions of individual sources of variability to overall variance in the radon data sets evaluated, indicated that sampling and analytical variance contributes less than 1% to the overall variance. Temporal variability within single wells accounts for between 13 and 18% of the variance in the data sets evaluated, and a similar proportion (12-17%) accounts for variation in radon levels among wells within systems (Section 5.7).

The Agency performed additional analyses to determine whether the requirement of initial quarterly monitoring for radon was adequate to account for seasonal variations in radon levels and to identify non-compliance with the MCL/AMCL. Results of analysis based on radon levels modeled for radon distribution for groundwater sources and systems in the US (ICF Consulting 1999) show that the average of the first four quarterly samples provides a good indication of the probability that the long-term average radon level in a given source would exceed the preferred regulatory levels.

Reduced Sampling Frequency

Initial compliance with regulatory levels will be determined based on an average of four quarterly samples taken at individual sampling points in the initial year of monitoring. Systems with averages exceeding the regulatory levels at any well or sampling point will be deemed to be out of compliance. Systems exceeding the regulatory levels will be required to monitor quarterly until the average of four consecutive samples are less than the regulatory levels. Systems will then be allowed to collect one sample annually if the average from four consecutive quarterly samples is less than the regulatory levels and if the State determines that the system is reliably and consistently below regulatory levels.

States will be allowed to reduce monitoring frequency to once every three years (one sample per compliance period) per well or sampling point, if the average from four consecutive quarterly samples is less than one-half the regulatory levels and the State determines that the system is reliably and consistently below one-half the regulatory levels. As shown in Exhibits 8-2 and 8-3, EPA believes that there is sufficient margin of safety to allow for this since there is a small probability that long term average radon levels will exceed the regulatory levels.

Systems monitoring annually that exceed the radon regulatory levels in a single sample will be required to revert to quarterly monitoring until the average of four consecutive samples is less than the regulatory levels. Ground water systems with unconnected wells will be required to conduct increased monitoring only at those wells exceeding the regulatory levels. Compliance will be based on the average of the initial sample and 3 consecutive quarterly samples.

Systems monitoring once per compliance period or less frequently which exceed one-half the regulatory level (but do not exceed the regulatory level) in a single sample would be required to revert to monitoring annually. Systems may revert to monitoring once every three years if the

Exhibit 8-2. The Relationship Between the First-Year Average Radon Level and the Probability of the Long-Term Radon Average Radon Levels Exceeding a Regulatory Level of 300 pCi/l

If the average of the first four quarterly samples from a source is:	Then the probability that the long-term average radon level in that source exceeds 300 pCi/l is:
Less than 50 pCi/l	<0.1 percent
Between 50 and 100 pCi/l	<1 percent
Between 100 and 150 pCi/l	<1 percent
Between 150 and 200 pCi/l	7.2 percent
Between 200 and 300 pCi/l	26.8 percent

Exhibit 8-3. The Relationship Between the First-Year Average Radon Level and the Probability of the Long-Term Radon Average Radon Levels Exceeding the AMCL

If the average of the first four quarterly samples from a source is:	Then the probability that the long-term average radon level in that source exceeds 4000 pCi/l is:
Less than 2,000 pCi/l	< 0.1 percent
Between 2,000 and 2,500 pCi/l	9.9 percent
Between 2,500 and 3,000 pCi/l	15.1 percent
Between 3,000 and 4,000 pCi/l	32.9 percent

average of the initial and three consecutive annual samples is less than one-half the regulatory level. Ground water systems with unconnected wells will be required to conduct increased monitoring only at those wells exceeding the regulatory level.

States may grant a monitoring waiver reducing monitoring frequency to once every nine years (once per compliance cycle) provided the system demonstrates that it is unlikely that radon levels in drinking water will occur above the regulatory levels. In granting the waiver, the State must take into consideration factors such as the geological area where the water source is located, and previous analytical results which demonstrate that radon levels do not occur above the regulatory levels. The waiver may be granted for up to a nine year period. (Given that all previous samples are less than one-half the regulatory levels, then it is highly unlikely that the long-term average radon levels would exceed these levels.)

Confirmatory Samples

If the analytical results from any sampling point are found to exceed the regulatory level (in the case of routine monitoring) or one-half the regulatory level (in the case of reduced monitoring), the State may allow the system to collect a confirmation sample(s). The results of the initial sample and the confirmation sample(s) can then be averaged and the resulting average used to determine compliance.

Grandfathering of Data

At a State's discretion, sampling data collected since the proposal could be used to satisfy the initial sampling requirements for radon, provided that the system has conducted a monitoring program not less stringent than that specified in the regulation and used analytical methods specified in the regulation.

8.4   Costs and Effectiveness of the Proposed Monitoring Requirements

8.4.1   Incremental Skills/Equipment Requirements and Cost of Radon Monitoring

The skill requirements required to implement this monitoring scheme are discussed in detail in Section 2-5. Generally, the skills required to collect water samples for radon analysis are comparable to those required to sample for gas chromatographic or atomic absorption analysis.

EPA has conducted two surveys of the potential costs of radon analysis, as discussed in Section 2.6. The agencies best estimate of radon costs ranges from $60 to $120 per sample. In the Regulatory Impact Analysis (EPA 1999), the Agency has estimated that the annual costs of monitoring for radon by community water systems would be 14.1 million. However, these costs were estimated assuming all sources would need to be monitored quarterly for the indefinite future. Subsequent analysis of the impacts of reduced monitoring requirements (ICF Consulting 1999) suggests that, after the first-year quarterly monitoring, the numbers of samples required, and monitoring costs, would be reduced by approximately 89 percent compared to a requirement for continuous quarterly monitoring.

8.5   References

EPA (1999), *Regulatory Impact Analysis and Revised Health Risk Assessment for Radon in Drinking Water*, Office of Ground Water and Drinking Water, August.

ICF Consulting (1999) *Methods, Occurrence and Monitoring Document for Radon: Addendum: Statistical Analysis of Radon Monitoring Requirements*, Submitted to the U.S. Environmental Protection Agency Office of Ground Water and Drinking Water, July 20.

APPENDIX A. DATA MANAGEMENT METHODS AND

SUPPLEMENTAL DATA SETS
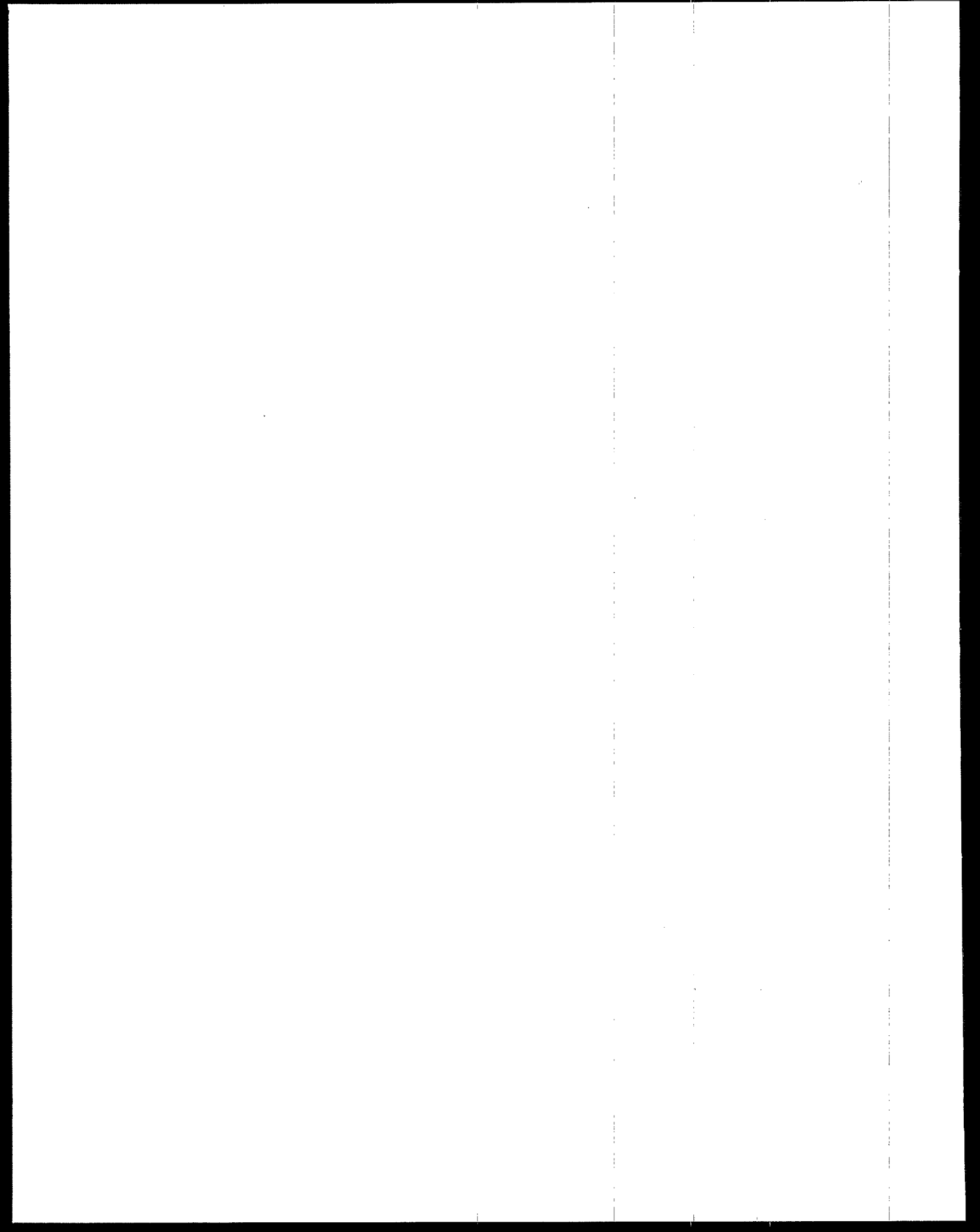
This appendix provides a description of the methods that were used to manage data related to radon occurrence and in the estimation of the numbers of groundwater systems that would exceed regulatory levels. Appendix A.1 addresses data management and the development of data sets for statistical analysis, and Appendix A.2 provides summary descriptions of the supplemental state data sets.

A.1   Data Management and Manipulation

Data concerning the levels of radon in groundwater and in drinking water supplies were received from EPA and from over 20 states. Data from the NIRS survey and from 17 states[1] were evaluated in detail as part of this occurrence analysis. This section describes how these data were managed and prepared for analysis.

A.1.1   NIRS Data

The NIRS data were received from EPA-OPPE in spreadsheet format. The data set was the same one that EPA had used in its 1993 and 1995 *Uncertainty Analyses (EPA 1993, 1995)* for radon exposures and risks. The numbers of samples and systems of various sizes represented in the NIRS data are summarized in the first two columns of Exhibit A-1. The NIRS file

Exhibit A-1. NIRS Data File Characteristics

System Size[1]	NIRS Data File		Numbers of Systems Included in Occurrence Analysis	Number of Systems Included in EPA 1993 Uncertainty Analyses
	Number of Systems/ Analyses	Number of Censored Analyses		
VVS	338	71	335	335
VS	335	74	333	334
S	232	95	232	232
M	53	18	53	53
L	28	11	28	28
Total	986	269	981	982

1. VVS= very very small (25-100 served), VS = very small (101-500 served), S = Small (501-3,300), M = Medium (3,301-10,000), and L = Large (>10,000 served)

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[1] Summary statistics were developed for the radon data from Missouri (see Appendix A.2), but were received too late to include in the national model for radon occurrence.

contains a total of 986 radon analyses, one from each system. Of these, 269 observations were censored, reporting values less that the Minimum Reporting Level (MRL) of 100 pCi/l. System size data (population served) came from the Federal Reporting Date System for 1993.

During the initial data evaluation, three systems that reported radon values as "0" were excluded from the analysis, along with one observation from a system in Puerto Rico. In addition, a single large system with an anomalously high radon value (greater than 20 times the next highest value) was removed from the analysis. These procedures, which were essentially the same as those employed in EPA's previous analyses, resulted in a database of 981 valid results, compared to the 982 that were used in the previous analysis. The current analysis includes one less very small system than the previous evaluations, and the impact of the difference on the summary statistics for this size stratum is minimal.

A.1.2 Supplementary Radon Data Sets

Additional data related to radon occurrence in groundwater systems were received from states, water utilities, and academic researchers. Because there was no uniformity in the types, amount, or form of the data submitted, a great deal of effort was spent in evaluating the data and putting it into a consistent format for detailed evaluation.

Data Entry, Editing, Formatting and Quality Assurance

The data sets included the results of one-time state-wide surveys intended to evaluate the extent of the radon problem, results of ongoing monitoring programs implemented to meet state of federal drinking water standards, or smaller data sets intended to address specific issues related to radon distribution. Of the 17 state-wide data sets (Exhibit A-2), 12 consisted of single samples from single sources in each system. The remaining five data sets (California, Michigan, New Hampshire, Washington, and Wisconsin) provided results from multiple samples from the same source and/or samples from multiple sources within systems. Three other supplementary data sets from wells in Missoula, MT, central North Carolina, and residential wells in Connecticut also included multiple samples from the same and different sources within systems.

Approximately two-thirds of the data sets were provided in electronic format. Five states provided only hard copy data. In these cases, the data were manually entered into spreadsheets. When data were entered manually, senior staff first reviewed the data and identified the specific fields and data items to be entered. Data were then entered and checked by junior staff, and spot-checked by senior staff. The data were also sorted to identify unusual and outlier values that could significantly affect the results of statistical analyses, and these entries were verified against the raw data. Given the expected broad distribution of radon activity levels, however, unusually high values ("outliers") were not removed from the data unless there was clear evidence that the reported analytical result was defective (See the "Comments" column of Exhibit A-2).

EXHIBIT A-1. SUMMARY OF CENSORED OBSERVATIONS AND CENSORING LEVELS FOR STATE RADON DATA

STATE DATA BASE	NUMBER OF SAMPLES VALID CWS SAMPLES	CENSORING LEVEL, pCi/l	NUMBER OF CENSORED RESULTS	TOTAL SYSTEMS	SYSTEMS WITH NON-DETECT RESULTS	SYSTEMS WITH ONLY NON-DETECT RESULTS	COMMENTS
CALIFORNIA	1,592	~10	13	75	7	0	Eight results < 10 pCi/l adjusted to 5 pCi/l, five values <100 adjusted to 50, one value > 200,000 pci/l excluded
CONNECTICUT	32	NA	0	32	0	0	All results > 1,000 pCi/l
IDAHO	74	NA	0	64	0	0	All reported results > 100 pCi/l
IOWA	150	NA	0	150	0	0	All reported results > 40 pCi/l
KANSAS	245	~25	10	169	9	6	Abilene has three of six results below censoring limit
MAINE	64	NA	0	64	0	0	Lowest result = 22pCi/l, next lowest ~ 200 pCi/l
MARYLAND	259	~20	3	107	2	1	--
MICHIGAN	186	~50	7	120	7	5	--
MISSOURI	1,184	~ 10	12	691	12	10	Two results < 0 pCi/l excluded, 10 results < 10 pCi/l adjusted to 5 pCi/l
NEW HAMPSHIRE	2,896	~100	70	725	53	2	Three medium systems with all results < 100 excluded
NEW YORK	425	NA	0	425	0	0	Lowest result = 14 pCi/l
OHIO	228	~25	18	228	17	17	--
PENNSYLVANIA	981	~100	64	488	31	7	--
SOUTH CAROLINA	121	~20	1	89	1	1	One censored sampled deleted because another sample from the same system was > 10,000 pCi/l
TEXAS	169	100	3	120	3	2	--
WASHINGTON	331	~20	25	68	14	9	--
WISCONSIN	1,252	~50	23	610	21	7	--
Total	10,189	--	249	4,225	177	67	
Proportion	100.0%	--	2.4%	100.0%	4.2%	1.6%	

Development of Files for Statistical Analyses

The amounts and types of information provided with the radon analytical results varied greatly from state to state, ranging from just sample numbers and radon measurements to detailed information regarding sampling dates and locations, system and source names, PWSIDs, system and source type, well depths, geological units, numbers of entry points, populations served, total production, counting errors, GIS coordinates, and QA/QC information. Thus, some data sets included all the information needed for all the statistical analyses. However, ancillary data had to be added to many of the files to allow their use in analyses of radon levels across system size, intra-system and temporal variability, etc.

In formatting the data files for the occurrence analysis, we preserved the following data elements if they were present:

- PWSID or related state ID number
- Sampling date(s)
- City and State

- System name
- Source name or designation
- System type (community, noncommunity, etc.)
- Source type (groundwater, surface water, mixed)
- Population served
- GIS coordinates
- Radon analytical results (separate entries for multiple analyses)
- Detection/Quantification limits for non-detect samples

In most cases, it was necessary to supplement the data with information from other sources to complete the data files. Only two states provided information related to the populations served by the systems sampled (an important stratification variable), so it was almost always necessary to estimate population served for the sampled systems. This was done using data from searches of EPA's Safe Drinking Water Information System (SDWIS) database for the states concerned[2]. Data from SDWIS were matched to systems in each state using either PWSID number (the preferred method) or by matching utility names. In a small proportion of cases, system size was assigned solely on the basis of municipality names. In almost all cases, this procedure resulted in systems being assigned to the very small or very very small categories.

For some states, SDWIS data also provided information on system and source type. Where PWSIDs were not available and the system names did not precisely match between SDWIS and the supplied radon data, judgement was used to match systems to population served data[3]. Where matches appeared doubtful, systems were not assigned a population served value and were not included in calculations related to system size. Two state files (from Connecticut and Idaho) did not provide sufficient information to assign any systems to size categories. Data from these states were thus used only to calculate state-wide distributions and representative radon values.

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[2] The SDWIS data search that was used to identify systems through their PWSID or system names was conducted in March, 1998.

[3] In many cases, the choice was between two or more community groundwater systems falling into the same size category (e.g., systems serving 150 and 350 people are both "very small".) This meant that mis-identification would have no affect on the size-related statistical analyses.

Water Sources and Types of Systems Evaluated

Some states provided data only from groundwater supplies, and most provided data only related to community water systems. Where states did not identify the water source or system types, SDWIS data were again used to provide this information. As in the case of population served, judgement was occasionally needed to assign system or source types. Radon data from significant numbers of non-community non-transient systems were identified in six states (Idaho, Maine, Maryland, New Hampshire, Texas, and Wisconsin). The radon distributions in the non-community systems were evaluated separately from the data from community systems, as discussed in Section 5.8 of the MOM document.

When no informed choice was possible as to source type or system type, no assignment was made. Any system with a reported radon level of 100 pCi/l or greater was assumed to be a groundwater system. This assumption is justified because, as noted in Section 4 of the MOM document, radon rapidly escapes from surface water, and radon levels in surface water supplies are very low, significantly lower than 100 pCi/l. Detailed descriptions of the data contained in the individual data sets, the methods used to prepare the data for analysis, and the resultant data files themselves, are provided in Appendix A-2.

It can be seen from Exhibit A-2 that the state-wide databases include approximately 10,200 valid analytical results, from 4,225 community water systems, approximately 10 times the number of results and 4.2 times the number of systems addressed by the NIRS. The presence of duplicate analyses, multiple samples from single wells and from multiple wells within systems also provides important information that is used to estimate the proportions of variability attributed to various sources, as discussed in Section 5.7 and Appendix B-1.

References Cited in Appendix A.1

U.S. Environmental Protection Agency (EPA 1993, 1995), *Uncertainty Analysis of Risks Associated With Radon in Drinking Water*, Office of Science and Technology, April 1993 and March 1995.

A.2   Supplemental Data Sets

This appendix contains summary descriptions of the data contained in the various supplemental data sets. A one-page data summary is supplied for each major data set. The data elements provided in each summary include:

Data Element	Explanation
Area Covered	state or other region
Provider	name and affiliation
Citation	publication reference, if any
Purpose/Objective of Data	compliance, develop cross-sectional profile, etc.
Types of Data Provided:	
Approx. Dates of Sampling	time span of sample collection
Number of Samples	total
Number of Systems	total
Sampling Locations	W = well, POE = point of entry
Sampling Procedures	IF = Inverted Funnel, O = other
Analytical Methods	LSC = liquid scintillation
PWSID	water system identification number
Lab ID	identity of laboratory performing analysis
Sample Date	date individual samples were collected, analyzed
System Name	utility or company name
Source Type	groundwater or surface water
Source Name	well number, etc.
City/County	--
GIS Coordinates	--
Radon Analytical Result	corrected for background, pCi/l
Counting Error	counts per minute
Population Served	(by systems)
Points of Entry	number in system
Well Depth	(ft)
Geological Formation	name
Types of Analysis	Single or multiple analysis per source, system; samples over time from same/different sources, analytical duplicates
Data Entry, Formatting Requirements	Manual data entry, SDWIS matching of PWSID, supply names, addition of population served data, system/source type
Comments	Other concerns, features of data

In the categories "Types of Data Provided", responses in the forms may included "Y" (yes), "S" (sometimes), indicating that the indicated data elements were always of sometimes present. Where cells are left blank, this indicates that the data are not provided.

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Alabama

Provider	David Grey
	USEPA
	National Air and Environmental Radiation Laboratory
	Montgomery, AL

Citation	--

Purpose/Objective of Data Collection	Characterize radon activity levels in Alabama rural water supplies, investigate precision of analytical results

			Types of Analysis	
Approx. Dates of Sampling		1991-92		
Number of Samples		1600	Single Sample, Analysis per System	
Number of Systems		800	Multiple Analyses of Single Samples	
Types of Systems		C	Multiple Analyses of Consecutive Samples	Y
Sampling Location(s)		W.POE	Multiple Samples Over Time	
Sampling Procedure(s)		IF	Multiple Analyses of Samples From Different Days	
Analytical Method(s)		· LS	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID		Manual Data Entry	Y
Lab. ID		SDWIS Matching of PWSID Numbers	
Sample Date	Y	SDWIS Matching of Supply Names	
System Name		Addition of Pop. Served Data	
System Type		Addition of System/Source Type Data	
Source Type		Other (Specify) Data were provided from 800 systems. Due to	
Source Name		resource limitations, only 300 pairs of samples were entered. Because	
City/County	Y	system names and PWSIDs were not provided, system size could not	
GIS Coordinates		be evaluated and these data were used only to evaluate S+A variance.	
Radon Analytical Result	Y	Comments·	
Counting Error			
Population Served			
Total Production			
Points of Entry			
Well Depth			
Geologic Formation			

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	California
Provider	Dr. David Storm California Department of Health Services
Citation	
Purpose/Objective of Data Collection	Collect, compile, evaluate, and report drinking water quality data.

Approx. Dates of Sampling	1987-1997	Types of Analysis	
Number of Samples	1101	Single Sample, Analysis per System	Y
Number of Systems	64	Multiple Analyses of Single Samples	S
Types of Systems	C, NTNC	Multiple Analyses of Consecutive Samples	S
Sampling Location(s)	NS	Multiple Samples Over Time	S
Sampling Procedure(s)		Multiple Analyses of Samples From Different Days	S
Analytical Method(s)		Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID	Y	Manual Data Entry	
Lab. ID		SDWIS Matching of PWSID Numbers	Y
Sample Date	Y	SDWIS Matching of Supply Names	
System Name	Y	Addition of Pop. Served Data	Y
System Type		Addition of System/Source Type Data	
Source Type	Y	Other (Specify)	
Source Name	Y		
City/County			
GIS Coordinates	Y		
Radon Analytical Result	Y	Comments: More samples were included in the state data but not used;
Counting Error		this summary does not reflect the state data not used. Point of entry
Population Served		data only indicates whether sampled before or after treatment; some data
Total Production		are samples within the distribution system.
Points of Entry	S	
Well Depth		
Geologic Formation		

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Southern California (QA Data)	
Provider	USEPA Files	
Citation	*Southern California Radon Survey* Black&Veatch, Prepared for the Metropolitan Water District of Southern California, January 1990	
Purpose/Objective of Data Collection	Evaluate radon levels in southern California water systems	

Approx. Dates of Sampling	1989	Types of Analysis		
Number of Samples	200(100 QA duplicates)	Single Sample, Analysis per System		
Number of Systems	many	Multiple Analyses of Single Samples		Y
Types of Systems	C	Multiple Analyses of Consecutive Samples		
Sampling Location(s)		Multiple Samples Over Time		
Sampling Procedure(s)		Multiple Analyses of Samples From Different Days		
Analytical Method(s)		Raw Versus Finished Water Comparisons		
Types of Data Provided		Data Entry, Formatting Requirements		
PWSID		Manual Data Entry		Y
Lab. ID		SDWIS Matching of PWSID Numbers		
Sample Date		SDWIS Matching of Supply Names		
System Name		Addition of Pop. Served Data		
System Type		Addition of System/Source Type Data		
Source Type		Other (Specify):		
Source Name				
City/County				
GIS Coordinates				
Radon Analytical Result	Y	Comments:		
Counting Error	Y	These data were used solely in the evaluation of analytical variability.		
Population Served				
Total Production				
Points of Entry				
Well Depth				
Geologic Formation				

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Connecticut
Provider	Nancy McHone Connecticut Department of Environmental Protection Natural Resources Center Hartford, CT
Citation.	--
Purpose/Objective of Data Collection	Characterize bedrock aquifer radon levels statewide, correlate groundwater and indoor air radon levels

Approx. Dates of Sampling	?	Types of Analysis	
Number of Samples	1000	Single Sample, Analysis per System	Y
Number of Systems	32C, 968 UNK	Multiple Analyses of Single Samples	
Types of Systems	C,UNK	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	W	Multiple Samples Over Time	
Sampling Procedure(s)	IF	Multiple Analyses of Samples From Different Days	
Analytical Method(s)	LS	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID		Manual Data Entry	
Lab. ID		SDWIS Matching of PWSID Numbers	
Sample Date		SDWIS Matching of Supply Names	
System Name		Addition of Pop. Served Data	
System Type	Y(CWS only)	Addition of System/Source Type Data	
Source Type	Y(all W)	Other (Specify):	
Source Name			
City/County	Y		
GIS Coordinates			
Radon Analytical Result	Y	Comments: Only 32 samples from 15 CWS, data were not matched to population served categories. Entire data base was used to evaluate radon occurrence in CT	
Counting Error			
Population Served			
Total Production			
Points of Entry			
Well Depth			
Geologic Formation	Y		

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Idaho
Provider	Janet K. Crockett. Sr. Groundwater Quality Analyst Groundwater Quality Monitoring Division Idaho Department of Water Resources Boise. ID
Citation.	Idaho Department of Water Resources. *Idaho Statewide Ground Water Quality Monitoring Program - Summary of Results. 1991 Through 1993.* Water Information Bulletin No. 50. Part 2. April 1995
Purpose/Objective of Data Collection	Characterization of statewide groundwater quality

Approx. Dates of Sampling	1991-1993	Types of Analysis	
Number of Samples	1040	Single Sample. Analysis per System	Y
Number of Systems	64 CWS. 27 NCNTWS	Multiple Analyses of Single Samples	
Types of Systems	C.N	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	W	Multiple Samples Over Time	
Sampling Procedure(s)	IV?	Multiple Analyses of Samples From Different Days	
Analytical Method(s)	LS	Raw Versus Finished Water Comparisons	
Types of Data Provided		Data Entry. Formatting Requirements	
PWSID		Manual Data Entry	
Lab. ID		SDWIS Matching of PWSID Numbers	
Sample Date	Y	SDWIS Matching of Supply Names	Y
System Name	Y	Addition of Pop. Served Data	Y
System Type	Y	Addition of System/Source Type Data	Y
Source Type		Other (Specify). Translated use type ID ("Industrial". "cooling". etc.) into	
Source Name		system types	
City/County	Y		
GIS Coordinates	Y		
Radon Analytical Result	Y	Comments:	
Counting Error			
Population Served			
Total Production			
Points of Entry			
Well Depth	Y		
Geologic Formation			

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Iowa

Provider	Mr. Roy Ney Iowa Department of Natural Resources
Citation	Radon-222 in the Source and Finished Water of Selected Public Water Supplies in Iowa A Research Report. January 13, 1993. No. 93-1 R. Kelley & M. Mehrhoff. University of Iowa Hygienic Laboratory
Purpose. Objective of Data Collection	To assess the probable extent of elevated radon levels in both the source and finished water of public water supplies in Iowa.

Approx. Dates of Sampling	1992	Types of Analysis	
Number of Samples	150	Single Sample. Analysis per System	Y
Number of Systems	9	Multiple Analyses of Single Samples	
Types of Systems		Multiple Analyses of Consecutive Samples	
Sampling Location(s)	S	Multiple Samples Over Time	
Sampling Procedure(s)	S	Multiple Analyses of Samples From Different Days	
Analytical Method(s)	Y	Raw Versus Finished Water Comparisons	Y

Types of Data Provided		Data Entry. Formatting Requirements	
PWSID		Manual Data Entry	Y
Lab. ID		SDWIS Matching of PWSID Numbers	
Sample Date		SDWIS Matching of Supply Names	
System Name		Addition of Pop. Served Data	Y
System Type		Addition of System/Source Type Data	
Source Type		Other (Specify) Best judgement was used when adding population	
Source Name	Y	served data.	
City/County	Y		
GIS Coordinates			
Radon Analytical Result	Y	Comments: The 9 systems are geologic units (or formations). The name	
Counting Error		of the lab and an Iowa map with sampling locations were included in the	
Population Served		report.	
Total Production			
Points of Entry			
Well Depth	Y		
Geologic Formation	Y		

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Kansas
Provider	Darrel R. Plummer Public Water Supply Section. Bureau of Water Kansas Department of Health and Environment Topeka. KS
Citation	--
Purpose/Objective of Data Collection	Ongoing characterization of radon levels in water supply wells throughout the state

Approx. Dates of Sampling	3/91-11/97	Types of Analysis	
Number of Samples	250	Single Sample. Analysis per System	Y
Number of Systems	163	Multiple Analyses of Single Samples	
Types of Systems	C	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	W.POE	Multiple Samples Over Time	S
Sampling Procedure(s)	IF	Multiple Analyses of Samples From Different Days	
Analytical Method(s)	LS	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry. Formatting Requirements	
PWSID		Manual Data Entry	Y
Lab. ID		SDWIS Matching of PWSID Numbers	
Sample Date	Y	SDWIS Matching of Supply Names	Y
System Name	S	Addition of Pop. Served Data	Y
System Type		Addition of System/Source Type Data	Y
Source Type	Y	Other (Specify): Matching supply names to SDWIS information was
Source Name	Y	sometimes difficult. Approximately 35 systems with questionable IDs
City/County	Y	were omitted data base used from the occurrence analysis.
GIS Coordinates		
Radon Analytical Result	Y	Comments:
Counting Error		
Population Served		
Total Production		
Points of Entry		
Well Depth		
Geologic Formation		

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Maine

Provider	Charles T. Hess Department of Engineering University of Maine at Orono
Citation	*Radon 222 in Potable Water Supplies in Maine: The Geology, Hydrology, Physics and Health Effects*, Land and Water Resources Center, University of Maine at Orono, September 1979
Purpose/Objective of Data Collection	To evaluate the relationships among radon levels in various geological formations in Maine, estimate potential risks associated with groundwater radon exposures

Approx. Dates of Sampling	1979	Types of Analysis	
Number of Samples	550	Single Sample, Analysis per System	Y
Number of Systems	450	Multiple Analyses of Single Samples	S
Types of Systems	C,NC,P	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	Wellhead, POE	Multiple Samples Over Time	
Sampling Procedure(s)	IF	Multiple Analyses of Samples From Different Days	
Analytical Method(s)	LS	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID		Manual Data Entry	Y
Lab. ID		SDWIS Matching of PWSID Numbers	
Sample Date		SDWIS Matching of Supply Names	Y
System Name	S	Addition of Pop. Served Data	Y
System Type	Y	Addition of System/Source Type Data	
Source Type		Other (Specify)	
Source Name			
City/County	Y		
GIS Coordinates			
Radon Analytical Result	Y	Comments: Only a small minority of the noncommunity systems could be matched through SDWIS with population served estimates.	
Counting Error	Y		
Population Served			
Total Production			
Points of Entry			
Well Depth			
Geologic Formation	Y		

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Maryland
Provider	Mr. Stephen Poreda Maryland Department of Environment
Citation	
Purpose/Objective of Data Collection	Sampling program of survey to collect radon data in anticipation of proposed regulations.

Approx. Dates of Sampling	1993-1997	Types of Analysis	
Number of Samples	413	Single Sample. Analysis per System	Y
Number of Systems	244	Multiple Analyses of Single Samples	S
Types of Systems	C. NC	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	NS	Multiple Samples Over Time	S
Sampling Procedure(s)		Multiple Analyses of Samples From Different Days	
Analytical Method(s)		Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry. Formatting Requirements	
PWSID		Manual Data Entry	
Lab. ID		SDWIS Matching of PWSID Numbers	Y
Sample Date	Y	SDWIS Matching of Supply Names	
System Name	Y	Addition of Pop. Served Data	
System Type		Addition of System/Source Type Data	Y
Source Type		Other (Specify)	
Source Name	Y		
City/County	Y		
GIS Coordinates			
Radon Analytical Result	Y	Comments:	
Counting Error			
Population Served	Y		
Total Production			
Points of Entry			
Well Depth			
Geologic Formation			

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Michigan

Provider	Mr. Elgar Brown
	Michigan Department of Public Health

Citation	--

Purpose/Objective of Data Collection	To gather information on radon levels throughout the state.

Approx. Dates of Sampling	1991-1992	Types of Analysis	
Number of Samples	185	Single Sample. Analysis per System	Y
Number of Systems	120	Multiple Analyses of Single Samples	S
Types of Systems	C	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	Y	Multiple Samples Over Time	S
Sampling Procedure(s)		Multiple Analyses of Samples From Different Days	
Analytical Method(s)		Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry. Formatting Requirements	
PWSID	Y	Manual Data Entry	
Lab. ID		SDWIS Matching of PWSID Numbers	
Sample Date	Y	SDWIS Matching of Supply Names	
System Name	Y	Addition of Pop. Served Data	
System Type	Y	Addition of System/Source Type Data	
Source Type	Y	Other (Specify)	
Source Name	Y		
City/County	Y		
GIS Coordinates			
Radon Analytical Result	Y	Comments:	
Counting Error	Y		
Population Served	Y		
Total Production			
Points of Entry	S		
Well Depth			
Geologic Formation			

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Missoula, Montana
Provider	Robert Ward Mountain Water Company Missoula, MT
Citation	Ward, Robert B., *Distribution and Occurrence of Radon in the Missoula Valley Aquifer*, University of Montana, Master's Thesis, 1997
Purpose/Objective of Data Collection	Characterize radon levels, temporal and spatial variability in public water supply wells drawing from the Missoula Valley aquifer, characterize rate of aquifer recharge from adjacent surface water bodies

		Types of Analysis	
Approx. Dates of Sampling	1993-1994		
Number of Samples	>1,500	Single Sample, Analysis per System	
Number of Systems	1	Multiple Analyses of Single Samples	Y
Types of Systems	C	Multiple Analyses of Consecutive Samples	Y
Sampling Location(s)	W	Multiple Samples Over Time	
Sampling Procedure(s)	IF	Multiple Analyses of Samples From Different Days	Y
Analytical Method(s)	LS	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID		Manual Data Entry	
Lab. ID	Y	SDWIS Matching of PWSID Numbers	
Sample Date		SDWIS Matching of Supply Names	
System Name	Y	Addition of Pop. Served Data	
System Type	Y	Addition of System/Source Type Data	
Source Type	Y	Other (Specify) Data were provided in spreadsheet form requiring minimal	
Source Name	Y	formatting and editing	
City/County	Y		
GIS Coordinates			
Radon Analytical Result	Y	Comments: Almost all samples were from a single large community system	
Counting Error		(Mountain Water System). QA/QC of the data were unusually rigorous, all	
Population Served	Y	analyses were conducted in a single university laboratory using standard	
Total Production	S	methods. Data were used to evaluate temporal, sampling, and analytical	
Points of Entry		variability.	
Well Depth			
Geologic Formation	Y		

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	New Hampshire

Provider	Bernie Lucy
	New Hampshire Department of Environmental Services
	Concord, NH

Citation	--

Purpose/Objective	Results of ongoing state groundwater monitoring program; objective is to periodically sample every groundwater system
of Data Collection	in the state to determine radon levels

		Types of Analysis	
Approx. Dates of Sampling	1988-1977		
Number of Samples	>5,000	Single Sample. Analysis per System	Y
Number of Systems	699C, 602NCNT	Multiple Analyses of Single Samples	
Types of Systems	C.NCNT	Multiple Analyses of Consecutive Samples	Y
Sampling Location(s)	W.POE	Multiple Samples Over Time	
Sampling Procedure(s)	IF	Multiple Analyses of Samples From Different Days	
Analytical Method(s)	LS	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID	Y	Manual Data Entry	
Lab. ID	Y	SDWIS Matching of PWSID Numbers	Y
Sample Date	Y	SDWIS Matching of Supply Names	
System Name	Y	Addition of Pop. Served Data	Y
System Type	Y	Addition of System/Source Type Data	
Source Type	Y	Other (Specify): Data were supplied as very large files containing both CWS.
Source Name	Y	NCNTWS data. Files were sorted by system type, using state type codes.
City/County	Y	inactive sources. sytems were removed from data base: consultation with
GIS Coordinates	Y	provide identified system reporting results for treated water.
Radon Analytical Result	Y	Comments: There was some ambiguity about source identities within
Counting Error	N	some systems. This introduces uncertainty into the evaluation of temporal
Population Served	N	variability.
Total Production	N	
Points of Entry	N	
Well Depth	N	
Geologic Formation	N	

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	New York
Provider	New York State Department of Health, Bureau of Public Water Supply Protection
Citation.	Axelrod, David and Kenneth E. Slade. Report of Statewide Surveillance for Radon in Selected Community Water Systems: New York State, 1989-1990. New York State Department of Health, Bureau of Public Water Supply Protection. September 1990.
Purpose/Objective of Data Collection	To determine the distribution of radon concentrations in drinking water at community water systems in New York in anticipation of EPA setting an MCL for radon.

		Types of Analysis	
Approx. Dates of Sampling	4/3/89 - 4/26/90		
Number of Samples	429	Single Sample, Analysis per System	
Number of Systems	429	Multiple Analyses of Single Samples	Y
Types of Systems	CWS	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	Tap	Multiple Samples Over Time	
Sampling Procedure(s)		Multiple Analyses of Samples From Different Days	
Analytical Method(s)		Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID		Manual Data Entry	Y
Lab. ID		SDWIS Matching of PWSID Numbers	
Sample Date	Y	SDWIS Matching of Supply Names	
System Name	Y	Addition of Pop. Served Data	
System Type	Y	Addition of System/Source Type Data	
Source Type	Y	Other (Specify)	
Source Name			
City/County	Y		
GIS Coordinates			
Radon Analytical Result	Y	Comments:	
Counting Error			
Population Served	Y		
Total Production			
Points of Entry			
Well Depth			
Geologic Formation			

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Chapel Hill, North Carolina Vicinity
Provider	William K. Drane Department of Environmental Sciences and Engineering University of North Carolina
Citation	Drane, W.K., J.H. Hightower, J.E. Watson, Jr. "Variations of 222Rn in Public Drinking Water Supplies. *Health Physic*, 73(6), pp. 906-911. (1997)
Purpose/Objective of Data Collection	

Approx. Dates of Sampling	1993-1995	Types of Analysis	
Number of Samples	>2,000	Single Sample, Analysis per System	
Number of Systems	13	Multiple Analyses of Single Samples	Y
Types of Systems	C,N	Multiple Analyses of Consecutive Samples	Y
Sampling Location(s)	W	Multiple Samples Over Time	Y
Sampling Procedure(s)	O	Multiple Analyses of Samples From Different Days	Y
Analytical Method(s)	LS	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID		Manual Data Entry	
Lab. ID		SDWIS Matching of PWSID Numbers	
Sample Date	Y	SDWIS Matching of Supply Names	
System Name		Addition of Pop. Served Data	
System Type	Y	Addition of System/Source Type Data	
Source Type	Y	Other (Specify):	
Source Name			
City/County			
GIS Coordinates			
Radon Analytical Result	Y	Comments:	
Counting Error		The investigator used a sampling techniques different from the inverted	
Population Served		funnel technique recommended by EPA. The technique appears to be at	
Total Production		least comparable to EPA's in terms of repeatability.	
Points of Entry			
Well Depth	Y		
Geologic Formation			

SUPPLEMENTARY RADON DATA FORM

AREA COVERED	Ohio
Provider	Kathleen Pinto, Environmental Specialist at Ohio EPA, Division of Drinking and Ground Water (614) 644-2752
Citation	Radon Sampling Program -- *Radon - 222 Groundwater Study Report.*
Purpose/Objective of Data Collection	To analyze the impact of an MCL at 200 pCi/L on Ohio's public water supplies.

Approx. Dates of Sampling	12/86 - 12/88	Types of Analysis	
Number of Samples	229	Single Sample, Analysis per System	Y
Number of Systems	219	Multiple Analyses of Single Samples	
Types of Systems	RESIDENTIAL	Multiple Analyses of Consecutive Samples	
Sampling Location(s)		Multiple Samples Over Time	
Sampling Procedure(s)		Multiple Analyses of Samples From Different Days	
Analytical Method(s)	.	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID	Y	Manual Data Entry	
Lab. ID		SDWIS Matching of PWSID Numbers	Y
Sample Date	Y	SDWIS Matching of Supply Names	
System Name	Y	Addition of Pop. Served Data	Y
System Type		Addition of System/Source Type Data	Y
Source Type		Other (Specify)	
Source Name			
City/County			
GIS Coordinates			
Radon Analytical Result	Y	Comments:	
Counting Error			
Population Served			
Total Production			
Points of Entry			
Well Depth			
Geologic Formation	.		

SUPPLEMENTARY RADON DATA FORM

AREA COVERED	Pennsylvania
Provider	Jerry Rupert, Pennsylvania Department of Environmental Protection. (717) 772-2847
Citation	Internal Report: *The Occurrence of Radon in Pennsylvania Community Groundwater Systems.* Division of Drinking Water Management. Pennsylvania Department of Environmental Resources, 5/27/93
Purpose/Objective of Data Collection	Impact of EPA's proposed MCL on Pennsylvania Systems

Approx. Dates of Sampling	9/92 - 4/93	Types of Analysis	
Number of Samples	986	Single Sample, Analysis per System	
Number of Systems	493	Multiple Analyses of Single Samples	Y
Types of Systems	CWS	Multiple Analyses of Consecutive Samples	
Sampling Location(s)		Multiple Samples Over Time	
Sampling Procedure(s)		Multiple Analyses of Samples From Different Days	
Analytical Method(s)		Raw Versus Finished Water Comparisons	
Types of Data Provided		Data Entry, Formatting Requirements	
PWSID		Manual Data Entry	
Lab. ID	Y	SDWIS Matching of PWSID Numbers	
Sample Date	Y	SDWIS Matching of Supply Names	
System Name		Addition of Pop. Served Data	
System Type		Addition of System/Source Type Data	
Source Type	Y	Other (Specify)	
Source Name			
City/County	Y		
GIS Coordinates	Y		
Radon Analytical Result	Y	Comments:	
Counting Error	Y		
Population Served	Y		
Total Production			
Points of Entry			
Well Depth			
Geologic Formation			

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	South Carolina
Provider	South Carolina Department of Health and Environmental Control Columbia, South Carolina (through Max Kukoy), American Water Works Association, Washington, DC)
Citation	Results of Special Radon Study of Public Water Supply Wells in South Carolina David Price, P.E., Bureau of Drinking Water Protection, SCDHEC, September 30, 1991
Purpose/Objective of Data Collection	Characterize distribution of radon in groundwater systems of various sizes throughout the state.

Approx. Dates of Sampling	2/91-8/91	Types of Analysis	
Number of Samples	242	Single Sample, Analysis per System	Y
Number of Systems	122(C)	Multiple Analyses of Single Samples	
Types of Systems	C,NCNT	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	W,POE	Multiple Samples Over Time	
Sampling Procedure(s)	IF	Multiple Analyses of Samples From Different Days	
Analytical Method(s)	LS	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID	Y	Manual Data Entry	Y
Lab. ID		SDWIS Matching of PWSID Numbers	Y
Sample Date		SDWIS Matching of Supply Names	Y
System Name		Addition of Pop. Served Data	Y
System Type	Y	Addition of System/Source Type Data	
Source Type	Y	Other (Specify): Removed sample results from tanks, water towers	
Source Name			
City/County	Y		
GIS Coordinates			
Radon Analytical Result	Y	Comments: Data were well-stratified across system size categories.	
Counting Error		Additional data from Clemson University could not be included in the	
Population Served		occurrence analysis because systems could not be identified.	
Total Production			
Points of Entry			
Well Depth			
Geologic Formation			

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Texas
Provider	Mr. Ron Beardon Texas Natural Resource Conservation Commission
Citation	
Purpose/Objective of Data Collection	To gather information on radon distribution throughout the state.

Approx. Dates of Sampling	1995	Types of Analysis	
Number of Samples	195	Single Sample. Analysis per System	Y
Number of Systems	138	Multiple Analyses of Single Samples	S
Types of Systems	C. P	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	NS	Multiple Samples Over Time	
Sampling Procedure(s)		Multiple Analyses of Samples From Different Days	
Analytical Method(s)		Raw Versus Finished Water Comparisons	
Types of Data Provided		Data Entry, Formatting Requirements	
PWSID	Y	Manual Data Entry	
Lab. ID	Y	SDWIS Matching of PWSID Numbers	Y
Sample Date	Y	SDWIS Matching of Supply Names	
System Name	Y	Addition of Pop. Served Data	Y
System Type	Y	Addition of System/Source Type Data	
Source Type		Other (Specify)	
Source Name			
City/County	S		
GIS Coordinates			
Radon Analytical Result	Y	Comments:	
Counting Error			
Population Served			
Total Production			
Points of Entry	NS		
Well Depth			
Geologic Formation			

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Washington (State)
Provider	Jim Hudson Division of Drinking Water Washington Department of Health Olympia, WA
Citation	--
Purpose/Objective of Data Collection	Statewide characterization of radon on drinking water supplies

Approx. Dates of Sampling	1992-1995	Types of Analysis	
Number of Samples	365 (GW)	Single Sample, Analysis per System	Y
Number of Systems	63	Multiple Analyses of Single Samples	
Types of Systems	C,N	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	W,POE	Multiple Samples Over Time	S
Sampling Procedure(s)	IF	Multiple Analyses of Samples From Different Days	
Analytical Method(s)	LS	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry, Formatting Requirements	
PWSID	Y	Manual Data Entry	
Lab. ID		SDWIS Matching of PWSID Numbers	Y
Sample Date	Y	SDWIS Matching of Supply Names	Y
System Name	Y	Addition of Pop. Served Data	Y
System Type		Addition of System/Source Type Data	Y
Source Type	Y	Other (Specify):	
Source Name	S		
City/County	Y		
GIS Coordinates			
Radon Analytical Result	Y	Comments:	
Counting Error			
Population Served			
Total Production			
Points of Entry			
Well Depth			
Geologic Formation			

SUPPLEMENTARY RADON DATA FORM

AREA COVERED:	Wisconsin
Provider	Mark Wilson Wisconsin Department of Natural Resources
Citation	--
Purpose/Objective of Data Collection	Evaluation of radon levels in water supplies throughout the state

		Types of Analysis	
Approx. Dates of Sampling	1990-1996		
Number of Samples	1256 (CWS)	Single Sample. Analysis per System	Y
Number of Systems	535	Multiple Analyses of Single Samples	
Types of Systems	C	Multiple Analyses of Consecutive Samples	
Sampling Location(s)	W.POE	Multiple Samples Over Time	S
Sampling Procedure(s)	IF	Multiple Analyses of Samples From Different Days	
Analytical Method(s)	LS	Raw Versus Finished Water Comparisons	

Types of Data Provided		Data Entry. Formatting Requirements	
PWSID	Y	Manual Data Entry	
Lab. ID		SDWIS Matching of PWSID Numbers	Y
Sample Date	Y	SDWIS Matching of Supply Names	
System Name	Y	Addition of Pop. Served Data	Y
System Type	Y	Addition of System/Source Type Data	
Source Type	Y	Other (Specify): Data had to be extensively reformatted prior to analysis	
Source Name	Y		
City/County	Y		
GIS Coordinates			
Radon Analytical Result	Y	Comments:	
Counting Error		Approximately 350 samples were not included in the final data base	
Population Served		because sytems could not be identified.	
Total Production			
Points of Entry			
Well Depth			
Geologic Formation			

APPENDIX B

STATISTICAL METHODS
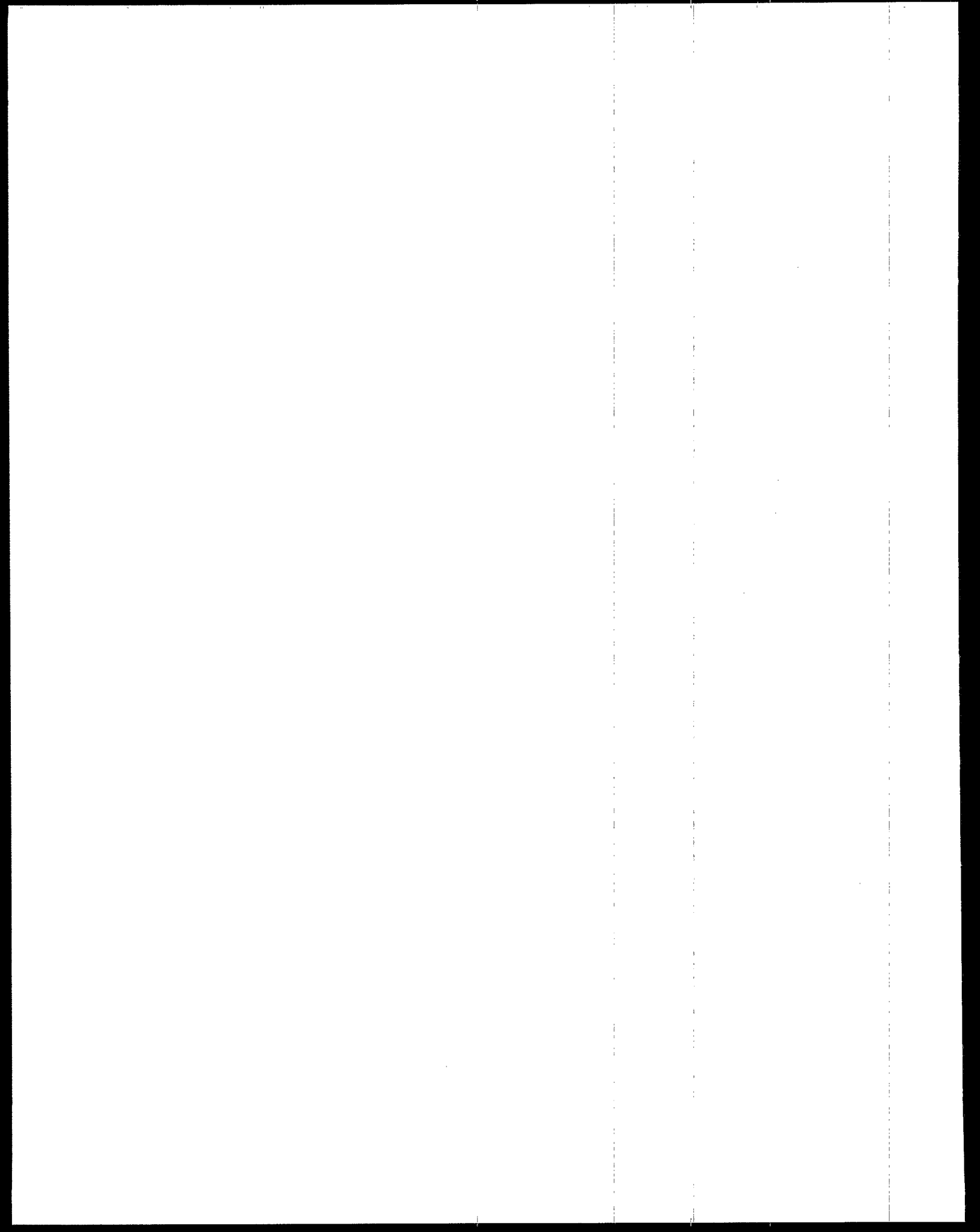
Appendix B. Statistical Methods

This appendix describes three specific statistical approaches that were used to evaluate radon occurrence data. Appendix B.1 addresses the "EM" maximum likelihood method for estimating summary statistics for radon data sets that have "censored" values. Appendix B.2 and B.3, respectively address distributional (parametric) and non-distributional (non-parametric) methods used to derive confidence intervals for the estimated proportions of water systems above potential regulatory levels.

B.1   MLE Approach to Estimating Summary Statistics for Radon Data Sets

The NIRS data in particular, and a few of supplemental data sets, contained substantial proportions of censored observations. In order to make the data generalizable to the U.S. population of groundwater systems, it was assumed that the distribution of the data was log-normal, and a separate mean and variance of the logarithm of radon levels was calculated for each facility size group in each data set. The mean and variance parameters of the log radon levels were estimated by a maximum likelihood estimation (MLE) method, a procedure proven to provide estimators with good statistical properties for reasonably large samples. The specific approach that was used was the "EM algorithm"(Dempster et al. 19__) . This algorithm provides a convenient and robust approach to developing MLE estimates of distributional parameters. The following discussion describes the calculation of distributional parameters for the radon data, estimation of the proportions of systems that would exceed regulatory limits, and development of confidence intervals for those proportions.

Let x be the natural logarithm of the radon activity and let D be the natural logarithm of the minimum detection or reporting limit (MDL of MRL). The exact value of x will be unknown for a "non-detect", i.e. if x is less than equal to D.   Let $I(x) = 1$ if x is a detect and $I(x) = 0$ if x is a non-detect. Based on the available data, the log-likelihood for the single observation x is:

$$l(x; \mu,\sigma^2) = I(x) \log [\phi((x-\mu)/\sigma)/\sigma] + [1-I(x)] \log \Phi((D-\mu)/\sigma), \qquad \text{(B-1)}$$

where $\phi(z)$ is the standard normal probability density function, and $\Phi(z)$ is the standard normal cumulative probability distribution function:

$$\phi(z) = \frac{1}{\sqrt{2\pi}}e^{-1/2z^2}, \quad \Phi(z) = \int_{-\infty}^{z} \phi(u) \ du. \qquad \text{(B-2)}$$

The log-likelihood for a single observation is the logarithm of the probability density for detected values, and is the logarithm of the probability of being at most D for non-detects (since for a non-detect, the only available information is that the log concentration is at most D). The log-likelihood for the entire data set is the sum of the individual log-likelihoods:

$$\text{Log-likelihood} = S(\mu, \sigma^2) = \sum l(x_i;\ \mu, \sigma^2). \tag{B-3}$$

The maximum likelihood method estimates the true parameter values μ and σ^2 by finding the values of μ and σ^2 that maximize the total log-likelihood, S (keeping the observed data fixed).

Instead of a direct maximization, we used the efficient "EM algorithm" which is an iterative two-step procedure (Dempster et al.). Suppose that our initial estimates of μ and σ^2 are μ^{old} and $(\sigma^2)^{old}$. If we knew all the concentration values, including values for the non-detects, then all the I(x) values would be 1 and the complete data log-likelihood (ignoring constant terms) would be:

$$\text{Complete data log-likelihood} = \sum_{i=1}^{N} -\log(\sigma) - \frac{(x_i - \mu)^2}{2\sigma^2}. \tag{B-4}$$

The E (expectation) step of the algorithm calculates the expected value of the complete data log-likelihood given the available data, where the expectation is over the log-normal distribution with the initial estimates μ^{old} and $(\sigma^2)^{old}$. Let E_i be the expected value of x_i and let S_i be the expected value of x_i squared (given below). Then the expected complete data log-likelihood equals:

$$\text{Expected log-likelihood} = -N \log \sigma - \frac{\sum_{i=1}^{N} S_i - 2\mu \sum_{i=1}^{N} E_i + N\mu^2}{2\sigma^2}. \tag{B-5}$$

The M (maximization) step maximizes this expression for all μ and σ^2, to give the updated estimates

$$(\sigma^2)^{new} = \frac{\sum_{i=1}^{N} S_i - 2(\mu^{new}) \sum_{i=1}^{N} E_i + N(\mu^{new})^2}{N}. \tag{B-6}$$

where:

$$\mu^{new} = \frac{\sum_{i=1}^{N} E_i}{N}, \tag{B-7}$$

The iterative scheme starts with any reasonable initial estimated parameter values, such as the mean and variance of the logged detected concentrations. The E and M steps are used to iteratively

---

update these estimates until the changes in the parameter values are sufficiently small. The calculation of E_i and S_i is as follows. If the i'th (logged) observation, x_i, is a detect, then the expected value is also x_i. If the i'th observation is a non-detect, then the expected value is the conditional mean given that X is at most D:

$$E(X \mid non-detect) = E(X \mid X \leq D) = \int_{-\infty}^{D} \frac{xe^{-0.5(x-\mu^{old})^2/(\sigma^2)^{old}}}{\sigma^{old}\sqrt{2\pi}} \, dx. \qquad (B-8)$$

Integrating by parts gives the expression:

$$E_i = x_i, \text{ if } x_i \text{ is a detect,} \qquad (B-9)$$
$$E_i = \mu^{old} - \sigma^{old} \times F, \text{ if } x_i \text{ is not a detect, where} \qquad (B-10)$$
$$F = \phi((D-\mu^{old})/\sigma^{old})/\Phi((D-\mu^{old})/\sigma^{old}). \qquad (B-11)$$

A similar calculation for the expected squares gives

$$S_i = (x_i)^2, \text{ if } x_i \text{ is a detect,} \qquad (B-12)$$
$$S_i = (\mu^{old})^2 + (\sigma^2)^{old} - \sigma^{old} \times F \times (\mu^{old}+D), \text{ if } x_i \text{ is not a detect.} \qquad (B-13)$$

The EM algorithm was implemented on Excel© spreadsheets for each data set and system size stratum. The estimated censoring limits were used to estimate D for each data set. The spreadsheets were designed to perform 20 iterations of the calculation algorithm starting from user-specified initial estimates of the sample mean and variance. For all of the data sets and size strata, the EM estimates of the log mean and log variance converged very rapidly. Usually, estimates of the log mean and log standard deviation were stable to the fourth decimal place (one part per 10,000) between the fifth and tenth iteration. The final estimates of log mean and log variance were quite insensitive to the initial estimates used as inputs to the first iteration of the algorithm.

B.2   Calculation of Proportions of Systems Above Radon Levels and Confidence Limits on Proportions (Distributional Approach)

The NIRS and states data were used to estimate the proportions of facilities, p, that would exceed specified levels assuming that a single measurement was taken from a single

sources from each system.[1]   The classical approach to estimating confidence intervals in this case is to estimate the standard deviation of the estimated proportion, $\hat{p}$, using the formula

$$SD(\hat{p}) = \frac{\hat{p}(1-\hat{p})}{n}. \tag{B-14}$$

The 95 percent confidence interval is then given by the large sample approximation

$$\hat{p} \pm 1.96 \times SD(\hat{p}). \tag{B-15}$$

This formula for SD($\hat{p}$) is strictly correct only when the observed fraction of facilities exceeding the level (u) is used to estimate the population fraction (of all facilities of the given size).   Since the proportions of systems exceeding potential regulatory levels were estimated using a fitted log-normal distribution, the standard deviation of the estimated proportion will not be given by the above formula. The above formula for SD($\hat{p}$) will tend to overestimate the standard deviation because the maximum likelihood estimates have smaller variances than the empirical estimates if sample sizes are relatively large. A more exact calculation uses the asymptotic distribution of the maximum likelihood estimators, since the EM algorithm was used to derive maximum likelihood estimates of the mean and variance of the logged concentrations, which in turn were used to estimate the proportions. We therefore used a more exact calculation method for determining SD($\hat{p}$) and its associated confidence interval.

As in above, let x be the natural logarithm (denoted by log) of the concentration and let D be the natural logarithm of the minimum detection limit (MDL). The exact value of x will be unknown for a non-detect, i.e. if x is less than equal to D.   Let I(x) = 1 if x is a detect and I(x) = 0 if x is a non-detect. Then the log-likelihood for the single observation x is

$$l(x;\ \mu,\sigma^2) = I(x)\ \log\ [\phi((x-\mu)/\sigma)/\sigma]\ +[1-I(x)]\ \log\ \Phi((D-\mu)/\sigma), \tag{B-16}$$

is where $\phi(z)$ is the standard normal probability density function, and $\Phi(z)$ is the standard normal cumulative probability distribution function:

$$\phi(z) = \frac{1}{\sqrt{2\pi}}e^{-1/2z^2}, \quad \Phi(z) = \int_{-\infty}^{z} \phi(u)\ du. \tag{B-17}$$

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[1] The proportions of systems exceeding regulatory levels are estimated using the cumulative normal distribution as described in Section 5.2 and shown in Equation B-26.

Standard maximum likelihood theory shows that for a large number, N, of facilities, the asymptotic variance-covariance matrix of $\hat{\mu}$ and $\hat{\sigma}^2$ is the inverse of the expected information matrix:

$$\begin{pmatrix} Var(\hat{\mu}) & Cov(\hat{\mu},\hat{\sigma}^2) \\ Cov(\hat{\mu},\hat{\sigma}^2) & Var(\hat{\sigma}^2) \end{pmatrix} = \frac{1}{N}\begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}^{-1}. \tag{B-18}$$

The matrix T is the expected products of the partial derivatives of the log-likelihood with respect to the parameters:

$$T_{ij} = E\left(\frac{\partial l(X;\ \mu,\sigma^2)}{\partial \theta_i} \frac{\partial l(X;\ \mu,\sigma^2)}{\partial \theta_j} \right),\ \theta_1 = \mu,\ \theta_2 = \sigma^2, \tag{B-19}$$

where X is the log concentration (observed if $X > D$, otherwise a non-detect). X is assumed to have a normal distribution. Standard analytical calculations, using integration by parts, show that the components of T are given by

$$T_{11} = \frac{1}{\sigma^2}[1 - P + d\ \phi(d) + \frac{\phi(d)^2}{P}], \tag{B-20}$$

$$T_{12} = \frac{\phi(d)}{2\sigma^3}[1 + d^2 + \frac{d\ \phi(d)}{P}], \tag{B-21}$$

$$T_{22} = \frac{1}{4\sigma^4}[2(1 - P) + d\ \phi(d) + d^3\ \phi(d) + \frac{d^2\phi(d)^2}{P}], \tag{B-22}$$

where $d = (D-\mu)/\sigma$ and $P = \Phi(d)$. P is the probability that an observation is not detected, i.e. below the MDL. Inverting the 2×2 matrix T gives the variances and covariances:

$$Var(\hat{\mu}) = \frac{T_{22}}{N[T_{11}\ T_{22} - T_{12}{}^2]}, \tag{B-23}$$

$$Var(\hat{\sigma}^2) = \frac{T_{11}}{N[T_{11}\ T_{22} - T_{12}{}^2]}, \tag{B-24}$$

$$Cov(\hat{\mu},\ \hat{\sigma}^2) = \frac{-T_{12}}{N[T_{11}\ T_{22} - T_{12}{}^2]}. \tag{B-25}$$

The exceedance probability, p(u), that a facility will exceed level u is estimated by

$$\hat{p}(u) = 1 - \Phi((u - \hat{\mu})/\hat{\sigma}). \tag{B-26}$$

For large samples, this estimated exceedance probability is given by the first order terms of the Taylor expansion around the true parameter values μ and σ^2:

$$\hat{p}(u) = 1 - \Phi((u - \mu)/\sigma) + (\hat{\mu} - \mu)(\frac{H}{\sigma}) + (\hat{\sigma}^2 - \sigma^2)(\frac{Hy}{2\hat{\sigma}^2}) \qquad \text{(B-27)}$$

where y and H are given by:

$$y = \frac{u - \mu}{\sigma}, \quad H = \phi(y). \qquad \text{(B-28)}$$

Thus, the variance of the exceedance probability is given (asymptotically) by

$$Var(\hat{p}(u)) = \frac{H^2}{\sigma^2}Var(\hat{\mu}) + \frac{H^2y^2}{4\sigma^4}Var(\hat{\sigma}^2) + \frac{H^2y}{\sigma^3}Cov(\hat{\mu}, \hat{\sigma}^2). \qquad \text{(B-29)}$$

The estimated variance of p(u) is calculated by substituting the estimated values of μ and σ^2 for the unknown true values.

Finally, we obtain the 95 percent confidence interval for p(u) as:

$$\hat{p}(u) \pm 1.96\sqrt{Var(\hat{p}(u))}. \qquad \text{(B-30)}$$

The above formulae were derived for the exceedance probability estimates based on a single value for each facility of a given size. It assumes that each system has only one source of water (well) and that the decision concerning compliance is made on the basis of a single sample. In Appendix C and Section 5.8, we discuss the impacts of different sources of variance on these estimates and how the presence of multiple sources and the use of multiple samples would effect our estimates of systems exceeding potential radon regulatory levels.

B.3   Estimation of Confidence Intervals (Distribution-Free Method)

For comparative purposes, estimates of confidence intervals on the proportions of systems exceeding specified radon levels were also estimated using a distribution-free approach (Johnson and Katz 1969). This method calculates the upper and lower confidence limits, P_u and P_l, respectively on p*, the estimated proportion of systems above a certain level. (These estimates are often referred to as Clopper-Pearson confidence limits).

Again, assume a sample of N systems, and define $p* = \text{Prob}[x_i \leq x*] = n/N$, where n is the number of systems exceeding $x*$. Then P_u, the upper confidence limit, is given by

$$P_u = \frac{n}{n + (N - n + 1)P - 1(w* \mid v1, v2)} \tag{B-31}$$

where:

vl   = 2(N+1)
v2   = 2(N-n)
P(w*|v1,v2) = The F-distribution with vl, v2 degrees of freedom = p = the desired confidence level

P_l, the lower confidence limit, is:

$$P_l = \frac{(n + 1)P^{-1}(w* \mid v1, v2)}{N - n + (n + 1)P^{-1}(w* \mid v1, v2)} \tag{B-32}$$

where:

vl   = 2(N-n+1)
v2   = 2n

These confidence limits were calculated for the various system size strata in the NIRS data to help confirm the reasonableness of the parametric calculations described above. As discussed in Section 5.8, there is generally good agreement between the parametric and empirical confidence limits on the proportions of systems exceeding specified radon levels.

B.4 Comparison of distributional and Non-Distributional Confidence Limits

Exhibit B-1 presents a tabular comparison of calculations of distributional and non-distributional upper and lower confidence limits on the proportions of systems exceeding potential regulatory limits for two data sets. The first data set is the comprised of all of the NIRS data for very very small systems. As noted in Section 5.4, the lognormal distribution provides the best fit to these data, but the A-D statistic suggests a significant deviation for lognormality. The other data set is the combined data from the New York radon survey. These data also are best fit by a lognormal distribution, but the goodness-of-fit test results again suggest that lognormality may be discarded with a high degree of confidence.

Exhibit B-1. Radon Distributional Data Compared to Parameteric and Non-Parametric Confidence Limits on Proportions of Systems Exceeding Potential Regulatory Levels

Radon Level, pCi/l	1. NIRS Data (Very Very Small Systems)				
	Maximum Likelihood Lower Confidence Limit	Non-Distributional Lower Confidence Limit	NIRS Data	Non-Distributional Upper Confidence Limit	Maximum Likelihood Upper Confidence Limit
300	47.2%	50.0%	54.3%	58.6%	56.0%
500	61.3%	63.9%	68.1%	72.0%	69.5%
700	69.8%	71.3%	75.2%	78.8%	77.4%
1000	77.6%	78.0%	81.5%	84.7%	84.5%
2000	88.9%	87.4%	90.1%	92.5%	93.8%
4000	95.4%	93.9%	95.8%	97.3%	98.1%

Radon Level, pCi/l	2. New York State Data (All Systems)				
	Maximum Likelihood Lower Confidence Limit	Non-Distributional Lower Confidence Limit	New York Data	Non-Distributional Upper Confidence Limit	Maximum Likelihood Upper Confidence Limit
300	43.7%	38.7%	42.5%	46.3%	52.5%
500	60.5%	58.0%	61.8%	65.5%	68.8%
700	70.6%	73.0%	76.4%	79.6%	78.2%
1,000	79.6%	85.1%	87.7%	90.1%	86.3%
2,000	91.6%	93.8%	95.5%	96.9%	95.7%
4,000	97.3%	96.9%	98.1%	99.0%	99.1%

It can be seen from the Exhibit that both sets of confidence limits include the observed numbers of systems measured as exceeding most of the potential radon regulatory levels. The single exception is maximum likelihood lower confidence limit (5 percent) on the proportion of systems exceeding 300 pCi/l in the New York data set. The confidence limit is 43.7 percent, while the observed value is 42.5 percent. Since the table includes a total of 28 comparisons of confidence limits to measured values, on the order of one "miss" is not unexpected.

In all cases, the non-parametric confidence limits include the measured values. This is because these confidence limits take the measured values as their starting points. There do not appear to be any systematic differences between the distributional and non-distributional confidence limits.

References Cited in Appendix B

Dempster, A.P., Laird, N.M., and Rubin, D.B, (1977) "Maximum Likelihood Estimation from Incomplete Data Via the EM Algorithm", *Journal of the Royal Statistical Society*, Series B, 39, 1-38.

Johnson, N.L., and Katz, M., *Discrete Distributions,* 1969.
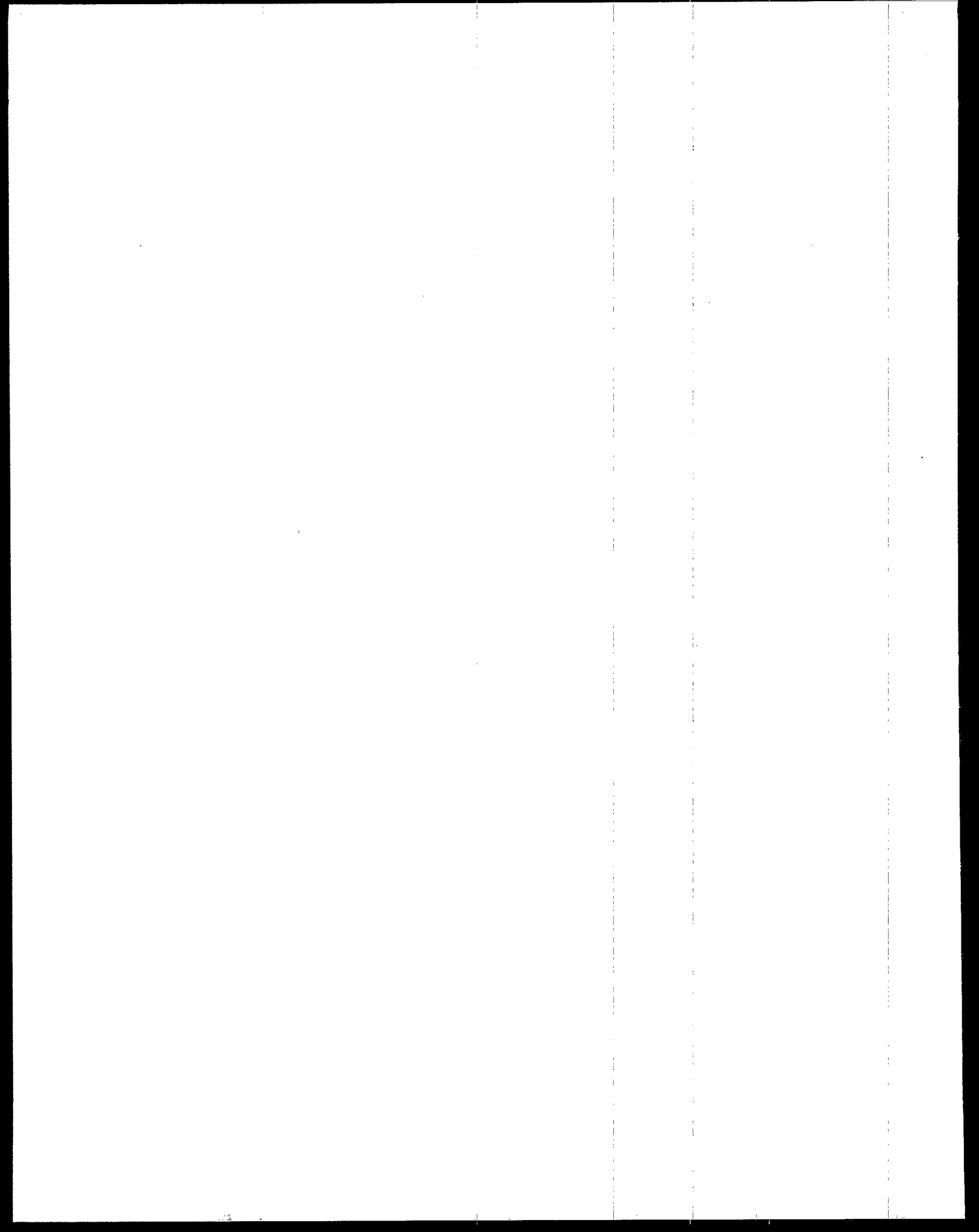
APPENDIX C. SOURCES OF VARIABILITY IN RADON MONITORING STUDIES OF GROUNDWATER SYSTEMS
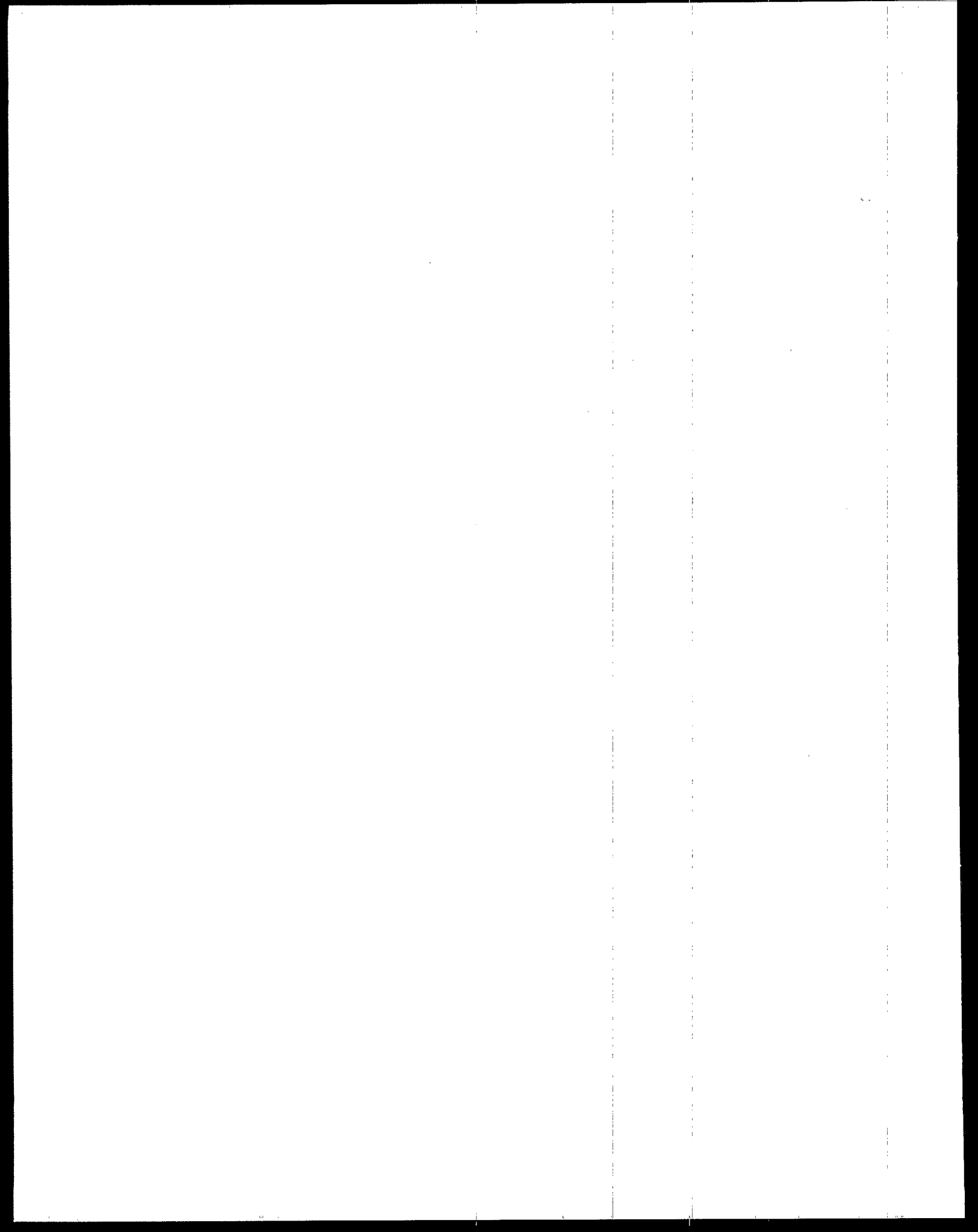
C. SOURCES OF VARIABILITY IN RADON MONITORING STUDIES OF GROUNDWATER SYSTEMS

Radon activity measurements are known to vary within regions, among sources in individuals water systems, among groups of systems, and over time. In order to accurately predict the proportions of systems and sources that might be out of compliance with radon regulatory levels, the sources and magnitude of this variability needs to be understood. In this Appendix, we provide a summary and analysis of the available data related to the major sources of variability in measured radon levels from groundwater supplies. We begin by identifying sources of variability in radon data sets and establishing a basis for estimating contributions of the individual sources to the total variability of the data. This model of variability (actually variance) is used in Section 5.8 of the MOM document to develop estimates of the proportions of systems that would exceed potential regulatory levels. We also analyze data from the NIRS and the supplemental data sets that provide information regarding the relative contribution of the individual sources to total radon variance.

C.1 A Variance Apportionment (ANOVA) Model For Evaluating Radon Data Sets

Assume a data set consisting of individual measurements of radon levels (X_i) from (N) different groundwater systems (the NIRS is a good example.) Assume that some of the systems are small, and obtain their water from only one source (well), while others obtain water from multiple sources. Samples are taken at different times by different personnel (although using standardized methods) and subject to analysis in different laboratories (again using the standard liquid scintillation procedure).

When the data from this set are evaluated, they are found to be (roughly) lognormally distributed, as are most of the data sets we identified. The calculated log mean value of all the observations is:

$$\text{Log Mean} = \sum \frac{\ln(X)_i}{N}$$

(C-1)

A commonly used measure of the variation seen within the data set is the variance of the data, or in this case the log variance:

$$\text{Log Variance} = \frac{\sum (\ln X_i - \ln \overline{X})^2}{N}$$

(C-2)

The log variance simply is simply the sum of the squared differences between the logs of the individual observations and the mean log radon value. If more than one factor contributes to the differences between the individual observations and average value, then all of these factors show contribute to the magnitude of the variance.

A useful property of variance is that variances of more than one variable are additive. That is:

$$Var(A) + Var(B) = Var(A + B) \qquad (C-3)$$

This equation indicates that if A and B are two independent variables, then the variances of the sum of the variables is equal to the sum of their variances. This relationship holds for the sum of any number of variables whose distributions are statistically independent (do not depend on one another). In the following sections, we use this relationship, and the assumption of independence, to help separate and quantify the contributions of individual sources to the overall variance in sets of radon observations.

C.1.1 Identification of Sources of Radon Variance

Five types of variance contribute to the overall variance in radon data sets. For the purpose of the following analysis, we refer to them as:

- **Var(SYS)** -- This represents the "true" inter-system variability in radon levels, that is, the variability due to differences in location, geologic setting, size, etc.

- **Var(W)** -- This is the variability among different sources (wells) within a given system.

- **Var(T)** -- This factor is the time-variability of radon levels in a given source or system. For purposes of this analysis, we use this symbol to refer to long-term differences in radon levels rather than short-term variability that may result from daily water use patterns, etc..

- **Var(S)** -- Refers to all sampling variability, or the variations in radon levels associated with the process of taking water samples, transferring them to the laboratory, and any other manipulations up to the point at which the sample enters the scintillation counter.

- **Var(A)** -- The last factor we address is variability associated with the analysis of radon samples themselves. This includes statistical counting error, as well as any other factors affecting the precision of the radon analysis. As will be discussed further below, the magnitude of this variability is measured by examining the differences in the results of duplicate analyses of the same sample.

In the language used above, we define each of these contributors factors as "variables", the combined variance of which is equal to the sum of their individual variances. For purposes of this analysis, we assume that the expected value (average) of each of these variables is zero, that is, they do not introduce any systematic bias into the estimates of radon levels. Using the additivity property discussed above, we can define the overall variance of the observations in our radon data set as:

$$Var(Total) = Var(SYS) + Var(W) + Var(T) + Var(S) + Var(A) \qquad (C-4)$$

This equation defines the relationships among the variances of the data set composed of individual radon measurements to the total variance in the data set. Based on this relationship, we can estimate the total variance of a data set if we have other data sets that allow us to estimate the contributions to variance of the individual sources. More importantly, if we have data sets that allow us to estimate the magnitude of the some of the contributions, we can use them estimate the magnitudes of the others.

Developing estimates of these contributions (for example, temporal variability) is important in and of itself. We can use such information, for example, example, to determine whether each specific source is an important contributor to overall variance in radon levels. In addition, separating the contributions to variance will enable us to develop estimates of the numbers of systems above potential regulatory levels, given specific assumptions about monitoring requirements.

C.1.2   Estimating Contributions to Variance

As noted above, estimating the magnitudes of individual contributions to variance is possible if data sets are available that allow the contributions of one or more sources to be separated from those of the others. This is possible, to some extent, with the various data sources that are available related to radon occurrence in drinking water systems. The types of data that are available and the sources that can be characterized by their analysis are summarized in Exhibit   C-1. More complete descriptions of the data sets can be found in the following sections or in Appendix A.

Each type of data set provides information on one or more contribution to variance. More importantly, each type of data (with the exception of that listed in the bottom row of the table) is obtained under conditions that cancels out or excludes the impact of one or more sources of variance. For example, when duplicate analyses are performed of a single sample, this provides direct information on the magnitude of Var(A), the analytical variance, and excludes contributions from any other source (e.g., the scintillation counter does not know where the sample came from). Interpreting most of the other types of data is not so simple, however. Analyses of multiple samples taken from the same well at the same time provide information concerning the magnitude of combined sampling and analytical variability, Var(S) +Var(A). The independent impacts of S and A on the total variance, however, cannot be determined unless

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duplicate analyses are also performed. In this case, the effects of these two variables can be separated by subtraction. This type of data set (same-time samples from the same source) does not provide any information about contributions from inter-system, inter-well, and temporal variability (Var(SYS), Var(W), and Var(T)), however.

Exhibit C-1. Variance Information Provided by Different Types of Radon Studies

Type of Data	Sources of Variance Held Constant [1]	Type of Variance Information Included	Available Studies [2]
Duplicate analyses of single samples	SYS, W, T, S	A	Hess, Glick, Black& Veatch, Pennsylvania, Texas
Multiple samples from the same wells taken at the same time	SYS, W, T	S, A	Grey, Ward, Drane, New York
Multiple samples from the same wells taken over time	SYS, W	S, A, T	McHone, Ward, Drane, California, Maryland, New Hampshire
Samples taken from different wells in the same system at the same time	SYS, T	S, W, A	Ward, California, New Hampshire, Maryland, Michigan, Wisconsin
Samples taken from different wells in the same systems over time	SYS	S, W, A, T	California, Ward, New Hampshire
Single samples from different systems	None	SYS, S, W, A, T	NIRS, States

Notes:
1. A = analytical, S = sampling, SYS = system, T = temporal, W = variance among wells
2. Sources identified in text, reference list.

The rest of the rows in Exhibit C-1 show the types of variance information included in, and excluded from, specific types of data sets, and examples of these types of data sets identified

during the occurrence analysis. In the following sections, these data will be described in detail and used to characterize the approximate contributions to variance from each of the individual sources at a national level.

C.2. Analytical Variance

Exhibit C-2 identifies six data sets that provide data from duplicate analyses of the same samples, and thus directly measure analytical variance, or Var(A). The studies are presented in roughly chronological order, with the earliest example being the data from Maine gathered by Hess (1979). In this study, a total of 139 duplicate results were reported, the average radon activity in individual sources ranged from less than 100 pCi/l to greater than 20,000 pCi/l. The log variance for individual duplicate samples[1] was found to increase with decreasing radon levels, and was more ten times higher for samples with average radon less than 1,000 pCi/l than for samples with average radon levels above 5,000 pCi/l. This would be consistent with reduced analytical reproducibility and accuracy at low radon levels. For the data set as a whole, the average relative standard deviation (RSD)[2] of the paired samples was 8.7 percent, but the average RSDs for the analyses below 1,000 pCi/l were all above 10 percent, which is the suggested reproducibility criterion in EPA's Standard Method (MOM document, Section 2). Altogether, approximately 29 percent of the paired analyses had RSDs above 10 percent.

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[1] The log variance for duplicate analyses was calculated as $(\ln(X_1)-\ln(X_2))^2/2$.

[2] The Relative Standard Deviation, which is equivalent to the coefficient of variation, is the standard deviation of the measurements divided by the average of the measurements.

The distribution of log variance from the paired analyses in the Hess (1979) data is summarized in the top row of Exhibit C-2. The average log variance between paired analyses was 0.023, and the median was 0.0033. The mean log variance in this data set exceeds the 75th percentile value, reflecting the fact that a large proportion of the total variance was contributed by a relative small number of high-variance sample.

The next row of Exhibit C-2 summarizes the estimates of analytical variance from the *Southern California Radon Survey* (Black & Veatch 1990) . The QA report for this study includes the results of 100 duplicate analyses. The average RSD for the paired samples is 5.7 percent, corresponding to a log variance of 0.017. Because the study covered a much narrower range of radon levels than the data from Maine, the trend of increasing variance with decreasing radon levels was not as apparent in this study. In general, the log variance was much lower than in the Hess study, and the distribution was much less skewed. The mean and median log variance were almost the same, 0.0017 and 0.0016, respectively.

Exhibit C-2. Distribution of Analytical Variance from Six Data Sets						
Data Set[1]	Percentile Log Variance					
	5th	25th	50th	Mean	75th	95th
Hess, et al. (Maine)	1.57E-05	0.00044	0.0033	0.023	0.011	0.058
Black&Veatch (Southern California)	3.00E-06	0.00020	0.0016	0.0017	0.0045	0.016
Glick (NIRS)	--	--	--	0.0043	--	--
Pennsylvania	0.00002	0.00048	0.0023	0.032	0.010	0.079
Texas	0.00000	0.014	0.052	0.087	0.063	0.248
Ward (Missoula, MT)	0.00057	0.0022	0.0045	0.0057	0.0081	0.0137
Average	0.00012	0.0035	0.013	0.026	0.019	0.083

Notes:
1. Sources defined in text, reference list

The next source of data related to analytical variance is the *Mid-Term Quality Assurance Report* for the NIRS (Glick, 1985). This report is of interest primarily because it gives direct information into the analytical precision achieved by the laboratories conducting analyses for the survey that has become the major national source of data on radon in groundwater systems. The analysis reports an RSD of 5.3 percent, corresponding to a log variance of 0.0043, for 25 duplicate samples analyzed by liquid scintillation. The average radon activity in the samples ranged from less than 100 pCi/l to 4,270 pCi/l, but no information was presented as to the

variability as a function of radon level. No data on the distribution of analytical precision (e.g., the proportion of analyses with RSDs above 10 percent) was provided.

Two of the other supplemental data sets also provide information on analytical variability, for Pennsylvania (PADER 1993), and Texas (TNRCC 1998), respectively. The former study provided results from duplicate analyses from a cross-section of 488 water systems throughout the state, while the latter data set provided multiple analyses of samples from 120 systems. The distribution of log variance for duplicate results in the Pennsylvania data set is very similar to that seen in the Hess data from Maine. The variance seen in the Texas data has a broader distribution, and both the mean and median are substantially higher than those seen in either the Maine or Pennsylvania data.

The final source of analytical variance data is a study by Ward (1997) of radon levels in supply wells for a single water utility in Missoula, Montana. The data the used to evaluate analytical variability consist of the results of quadruplicate analyses of 32 samples taken from the same well on the same day. As shown in Exhibit C-2, the average and median log variance of the quadruplicate analyses are low relative to those for the two cross-sectional state studies, but comparable to that seen in the NIRS and Southern California QA reports.

The bottom row of Exhibit C-2 averages the results of the various studies. The average median log variance from these studies 0.013 and the average log mean variance is 0.026. Based solely on the mean and median results, it appears that the Hess and Pennsylvania data are the most "typical" of the data sets, with the California and Ward data having the lowest variances, and the Texas data set having the highest variance.

C.3   Combined Sampling and Analytical Variance

After reviewing the studies of analytical variance, it would be highly desirable to have data sources that provided information solely on sampling variance. This is, however, not possible because once separate samples are taken, separate analyses must be performed. The best that can be done, therefore, is to review studies that evaluate the results of duplicate samples (analyses of samples taken from the same source at the same time using the same methods.) This provides estimates of the combined magnitude of sampling and analytical variability. Sampling variability can then be estimated indirectly using Equation C-4 or its variants.

Exhibit C-3 summarizes the results of several studies of duplicate samples. The first of these involved the analyses of paired samples from rural water systems in Alabama collected in 1991 and 1992 under the supervision of personnel from EPA's Eastern Environmental Radiation Facility (Gray 1998). Approximately 800 pairs of samples were collected, but due to resource limitations, only 300 (100 consecutive samples each from the beginning, middle, and end of the sampling period) were analyzed for variability. Samples were collected using EPA's standard methods, and mailed to EERF for analysis by liquid scintillation counting. The results of this study summarized in the top row of Exhibit C-3. The median and mean log variance (which

include contributions from both sampling and analytical variability) were 0.011 and 0.058. This again reflects a skewed distribution of log variances, with a relatively few samples contributing a large proportion of the total variability.

The average log variance was found to increases by about 200-fold from the highest to lowest radon levels, with a corresponding increase in RSD of about 15-fold. The variance of this data set is reduced by about 50 percent if the ten worst pairs of samples are removed, and the proportions of samples with RSD above 10 percent is 25.8, approximately the same as seen in the data set from Maine.

The next source of data on sampling and analytical variability is another set of data gathered by Ward (1997). In this case, the data that were used were 320 pairs of duplicate (same-day) samples taken from 32 wells in the same Missoula, MT system previously mentioned. As can be seen from the exhibit, the log variance seen in this study was considerably lower than that seen in the Alabama data set. The median and mean log variance were 0.0054 and 0.0067, respectively.

Another recent study also provides information on combined sampling and analytical variance, this time from a group of repeatedly-sampled wells in central North Carolina (Drane, et al. 1997). Five samples were taken from each well per sampling event by allowing water to run directly from the source down the side of a scintillation vile, and analyzed using standard liquid scintillation methods. This sampling method is different from that recommended by EPA and is

Exhibit C-3. Sampling Plus Analytical Variability Estimates from Four Data Sets						
Data Set[1]	Percentile Log Variance					
	5th	25th	50th	Mean	75th	95th
Grey (Alabama)	0.0001	0.0017	0.011	0.0058	0.038	0.17
Ward (Missoula, MT)	2.8E-05	0.0013	0.0054	0.0067	0.015	0.049
Drane (North Carolina)	0.0008	0.0014	0.0022	0.0039	0.0042	0.011
New York	0 [2]	0.00032	0.0024	0.019	0.011	0.074
Average	0.0003	0.0012	0.0052	0.0088	0.017	0.075

Notes:

1. Sources defined in text, reference list
2. Not detectible within analytical precision

claimed by the author to be superior in terms of consistency and precision of analytical results. Wells were sampled as many as 39 times, giving a total of 304 sampling events. Most of the sampled wells serve small subdivisions or mobile home parks, and all were within convenient driving distance of Chapel Hill. Although the wells were all located in the Piedmont province, average radon levels varied from 136 pCi/l to over 36,000 pCi/l.

The sampling results from the individual wells are summarized in the third row of Exhibit C-3. The average variability seen in this study (log variance = 0.0039) is smaller than that seen in any of the others. The median and various percentile values are also low compared to most of the other studies. The data showed a general, but not entirely consistent, increase in sampling and analytical variability with decreasing radon levels across wells. The pooled analyses from the various wells all have RSDs less than 10 percent and only 11.8 percent of the individual sampling events have RSDs at this level or above. Part of the explanation for the low variance may be the improved sampling method employed, but, as was the case in the Montana study, this effort also involved sampling from a relatively small geographic area under well-controlled conditions, and analyses in a single university laboratory.

The final data set used to evaluate sampling and analytical variance was the results of a survey of radon levels in community water systems undertaken by the New York State Department of Health in 1989-1990 (NYDOH 1990). Duplicate samples were analyzed from 411 of 424 of the community water systems that were surveyed. The distribution of log variance of the duplicate sample results, as shown in the exhibit, is comparable to that from the other studies at the low end, but the mean variance (0.019) is somewhat higher than that of the other studies.

The bottom row of Exhibit C-3 averages the results of the various studies.

C.4   Combined Sampling, Analytical and Temporal Variance

The next set of studies to be discussed are those that provide information about the variability in radon levels from multiple samples from the same sources, taken over time. Thus, the studies in Exhibit C-4 provide information about the combined magnitude of analytical, sampling, and temporal variability.

The first three data sets are derived from state-wide surveys in New Hampshire, California, and Maryland. The data from New Hampshire (NHDES 1998) provide information

Data Set [1]	Percentile Log Variance					
	5th	25th	50th	Mean	75th	95th
New Hampshire	0.0006	0.018	0.074	0.35	0.26	1.60
California	0.0003	0.0034	0.012	0.19	0.045	0.56
Maryland	0.0003	0.0026	0.037	0.24	0.15	0.52
McHone (Connecticut)	0.009	0.010	0.019	0.20	0.16	0.76
Ward (Missoula, MT)	0.0021	0.0068	0.0098	0.024	0.015	0.078
Drane	0.0010	0.0032	0.0080	0.012	0.013	0.032
Mean of All Studies	0.0022	0.0073	0.027	0.17	0.11	0.59
Mean of Statewide Studies	0.0004	0.0079	0.041	0.26	0.15	0.89

Exhibit C-4. Estimates of Sampling Plus Analytical Plus Temporal Variance From Six Data Sets (Samples From The Same Sources Over Time)

Notes:

1. Sources defined in text and reference list

on over 5,000 radon measurements from over 1,300 community and non-community groundwater systems in the state, gathered between 1988 and 1997. A total of 849 wells serving community water systems were sampled more than once on different dates. The data from California (CADHS, 1998) include approximately 1,500 sampling results from 524 sources in 75 community systems. Of these, 316 sources are sampled more than once on different dates. The data from Maryland (MDOE 1998) come from 107 community systems, with multiple samples (usually two) taken from 43 sources.

The mean and median log variance from individual sources in New Hampshire were 0.35 and 0.074, respectively. These comparatively large values reflect the large combined sampling, analytical, and temporal variability associated with the high proportion of small systems and bedrock wells in this data set. The distributions of log variance from the two other states are lower than that seen in the New Hampshire data. The average log variance in same-source, different-day samples from the California data was 0.19, the mean value from the Maryland data was 0.24.

The other three data sets that provide data on multiple samples from the same sources, in contrast, concentrate on much smaller geographic areas. The first of these is a study of five private residential wells in Connecticut (McHone 1993). This study is included in our analysis, even though it reports data from residential wells, because it is one of the best sources of long-

term variability data for individual wells in the New England region. The study addresses both very short-term variations (hours to days) as well as longer-term (weekly) fluctuations in radon level. The five residential wells that were sampled were located in two different geologic provinces in Connecticut. Radon activities in the various wells fell into three ranges. Radon levels in the first well ranged from approximately 3,300 pCi/l to 6,000 pCi/l. Three wells had intermediate radon levels, from about 12,000 pCi/l to 31,000 pCi/l. Finally, analyses from one well, in a different geologic unit, indicated radon levels from approximately 33,000 pCi/l to 600,000 pCi/l. All of these values are greater than those typically seen in water supply wells outside New England or other high-radon areas. Long-term variability in radon levels in the five wells was evaluated by taking weekly samples from August 1991 through August 1992.

Ward (1997) also studied the long-term variability of radon levels in water supply wells in Missoula, MT. His study (in addition to the other data previously discussed) monitored radon levels in 32 wells over the period of approximately two years. An average of 39 samples (maximum 57) was taken from each well, which with one exception, drew from the same alluvial aquifer. The radon levels in all the wells averaged between 250 and 1,000 pCi/l. The final data set with multiple samples from the same sources is the study by Drane (also previously discussed). This study evaluated the changes in radon activity over approximately two years in 14 water supply wells serving very small systems, with an average of 20 sampling events per well.

The distributions of log variance for these studies are shown in the various rows of Exhibit C-4. While the study by McHone shows an average log variance similar to that seen in the three state-wide data sets, the variances seen in the more recent studies of limited areas by Ward and Drane are much lower. These lower variances may results in part from more carefully controlled sampling and analyses in the latter two studies, but the smaller spatial areas covered may also have something to do with it as well. The relatively high variances seen in the McHone study may be associated with the fact that all of the wells studied were low-capacity wells drawing from bedrock aquifers, with higher inherent variability in radon levels. While substantial short-term (hours to days), as well as long-term variability was seen in this study, there were no consistent indications of seasonal variations in radon levels.

One useful feature of the data set developed by Drane is that the availability of multiple samples per sampling event (generally five each), as well as the results of multiple analyses per sample, allows the estimation of the variance contributions of sampling and analytical error and true temporal variability. This process is illustrated in Exhibit C-5. The second column of the table shows the log variance among the daily sampling events for the 14 wells. The values for individual wells range from 0.0018 for Well 13 to 0.047 for Well 2, with a combined average log variance of 0.0142. The second column of the table shows the average sampling and analytical variance for each well. The log temporal variance (the log variance in daily radon levels minus the weighted sampling and analytical variance) is shown in the next-to-last column of the table. The estimated temporal variances for the individual wells range from 0.0002 to 0.0462, with a weighted average log variance of 0.0135.

This pattern indicates that, in this study, the contribution of sampling and analytical variability to overall variance in radon levels is relatively small compared to that from temporal

Well Number	Log Variance in Daily Geometric Means, Var(S+A) + Var(T)	Average Log Variance of Daily Analyses, Var(S+A)	Analyses Per Sampling Events	Number of Sampling Events	Log Temporal Variance Var(T)	Geometric Mean Radon Level, pCi/l
Exhibit C-5. Calculation of Temporal Variance from Drane, et al. (1997) North Carolina Community Water Systems Data						
1	0.017	0.0019	5	36	0.017	36,089
2	0.047	0.0032	5	36	0.046	24,382
3	0.014	0.00090	5	39	0.014	13,194
5	0.0078	0.013	5	22	0.0053	1,845
6	0.0069	0.010	5	20	0.0049	182
7	0.0026	0.0025	5	23	0.0021	514
8a	0.012	0.0011	5	23	0.012	3,252
8b	0.024	0.0018	5	5	0.023	1,072
9	0.012	0.0013	5	16	0.012	2,232
10	0.0021	0.00069	5	23	0.0020	2,662
11a	0.0047	0.0050	5	14	0.0037	352
11b	0.0023	0.010	5	4	0.0002	136
12	0.0072	0.0015	5	14	0.0069	1,061
13	0.0018	0.0022	5	10	0.0014	406
Weighted Average	0.0142	0.0035	--	285	0.0135	10,348

variability. In addition, the estimated temporal variance is quite low compared to those implied by the results of the other studies. (This issue will be discussed in more detail below.)

The last two rows of Exhibit C-4 show the average and median log variances across all the studies. Averages are calculated for all of the data sets, as well as just for the state-wide data sets, to show differences between the two types of studies. If the McHone study of residential wells is excluded, the average log variance for the state-wide studies would be approximately 10 times higher than that for the more localized (and more recent) studies.

C.5 Combined Sampling, Analytical, and Between-Well Variance

The next type of data set reports radon levels from different sources in the same systems, taken at the same time. These data sets contain information on the combined variability associated with analytical and sampling error and provide "snap shots" of the variability in radon levels in multiple wells in the same system ("intra-system variability") at the same point in time.

We identified only two data sets than contain such information. Data received from Wisconsin (WIDNR, 1998) reported radon analytical results from over 530 community groundwater systems. Of these, in 121 cases multiple sources (wells) from the same systems

were sampled on the same date. Between two and 20 sources (average = 3.1) were sampled per system. Data from Michigan (MIDPH, 1998) provided information on same-day samples from multiple sources at 43 groundwater systems. Usually, no more than two sources were sampled in each system.

The variances distributions for these data sets are reported in Exhibit C-6. The variance distributions are not dissimilar to those seen in the previous section. The median and mean log variance for systems in Wisconsin were 0.13 and 0.30, respectively, and the median and mean log variances for Michigan were 0.051, and 0.18. These data sets did not provide information from duplicate samples, so the contribution of sampling and analytical variability to the total variance could not be estimated.

C.6   Combined Sampling, Analytical, Temporal, and Intra-System Variance

	Exhibit C-6. Estimates of Combined Sampling Analytical, and Between-Well Variance (Samples Taken from Different Sources in the Same Systems on the Same Date)					
Data Set[1]	Percentile Log Variance					
	5th	25th	Median	Mean	75th	95th
Wisconsin	0.0046	0.044	0.13	0.30	0.30	1.14
Michigan	0.0010	0.0057	0.051	0.18	0.25	0.78
Average	0.0028	0.025	0.091	0.24	0.27	0.96

Notes:

1. Sources defined in text and in reference list

Exhibit C-7 provides summaries of the variance distributions for those data sets that carry information related to combined analytical, sampling, temporal, and intra-system (between-well) variability. These studies report the results of radon analyses from different sources in the same systems taken at different times. All of the data sets in this group except one are subsets of data sources that have been previously described. First, the supplemental data sets for California, New Hampshire, and Maryland to identify and evaluate the variability among the sources in the same systems over time. In addition to the state data sets, the other study that provided information on combined analytical, sampling, temporal, and intra-system variability that was Ward's extensive study of a single system in Missoula, MT.

All three of the state-wide data sets have very similar log variance distributions, the mean log variance among sources being 0.30, 0.50, and 0.53, for California, New Hampshire, and Maryland, respectively. In contrast, the log variance estimate from the single Missoula system is only 0.066. Again, average percentile and mean log variance values are presented both for all data sets, and for just the statewide data.

C.7   Variance from All Sources

Exhibit C-7. Estimates of Sampling Plus Analytical Plus Temporal Plus Intra-System Variability from Four Data Sets (Samples from Different Sources at Different Times in the Same Systems)						
	Percentile Log Variance					
Data Set[1]	5th	25th	50th	Mean	75th	95th
California	0.0050	0.041	0.13	0.30	0.34	1.32
New Hampshire	0.0016	0.030	0.11	0.50	0.38	2.24
Ward (Missoula, MT)	--	--	--	0.066	--	--
Maryland	0.0019	0.016	0.075	0.53	0.36	2.29
Average of All Data Sets	0.0029	0.029	0.11	0.35	0.36	1.95
Average of State-Wide Studies	0.0029	0.029	0.11	0.42	0.36	1.95

Notes:

1. Sources defined in text and in the reference list

The last piece of data needed to estimate the contribution of the individual sources of variance (using Equation C-4) is an estimate of the total combined variance from all sources. As discussed in Section C.1, estimates of total variance may be developed by analyzing the variance of individual samples taken from different systems over time. Exhibit C-8 summarizes the log variance estimates for all of the 16 state-wide supplemental data sets and for the NIRS.

This table includes log variance estimates from the seven studies discussed in detail in Section 5.5 that have substantial data related to systems if all sizes, as well as from studies that do not provide information on all system size strata. The studies are ranked in order of the total log variance for all systems combined, and the distributions of the variances are summarized in the six rows at the bottom of the exhibit. Variance values from six of the studies are entered in bold face. This designation is applied to all data sets where the system-wide radon levels reported in Section 5.5 of the MOM used to calculated variance were derived by averaging the results from multiple sources, or samples, or by averaging radon measurements over time. These values have been adjusted to offset the reduction in total variance that results from the averaging process. As discussed in more detail in Section 5.8, taking multiple samples cancels out a large portions of variance arising from the specific sources. For example, taking the average of duplicate analyses greatly reduces the analytical component of variance; averaging multiple samples from different sources greatly reduces the variance contribution from inter-well variability. (This procedure is
equivalent to going back to the original data set and calculating variance across all radon measurements, without averaging the measurements at individual sources, etc.)

In some cases (such as New Hampshire), adding this variance back into the data set greatly increases the overall variance compared to that reported in Exhibit 5-14, because much variance is lost through calculating averaged system radon values. In other cases, such as New

Exhibit C-8. Estimates of Variance From All Sources (Single Samples From Different Systems)						
	System Size					
Data Set[1]	ALL	VVS	VS	S	M	L
IDAHO	0.57	--	--	--	--	--
MICHIGAN	**0.78**	**0.88**	**1.10**	**0.70**	**0.58**	**0.57**
KANSAS	0.84	1.07	1.17	0.75	0.19	0.49
IOWA	0.86	3.24	0.61	0.72	0.80	0.00
MAINE	0.94	0.32	1.01	0.95	0.72	1.23
WISCONSIN	**0.98**	**1.06**	**1.05**	**0.98**	**0.74**	**0.48**
OHIO	0.98	--	--	0.91	0.91	1.21
TEXAS	**0.98**	**0.85**	**1.00**	**1.20**	**0.75**	**0.52**
CONNECTICUT	1.02	--	--	--	--	--
CALIFORNIA	1.02	--	3.16	0.32	1.75	0.62
WASHINGTON	1.36	2.38	1.30	0.85	1.27	1.10
NEW YORK	**1.47**	**1.49**	**2.16**	**1.03**	**0.79**	**0.72**
NIRS	<u>2.01</u>	<u>0.76</u>	<u>0.72</u>	<u>1.52</u>	<u>1.95</u>	<u>2.06</u>
PENNSYLVANIA	**2.10**	**2.10**	**2.70**	**1.68**	**1.84**	**1.20**
NEW HAMPSHIRE	**2.28**	**1.90**	**2.01**	**3.07**	**1.20**	**3.19**
SOUTH CAROLINA	2.36	0.92	2.44	1.78	2.13	1.09
MARYLAND	2.44	2.82	2.60	1.42	1.92	4.40
5th Percentile	0.74	0.59	0.68	0.59	0.46	0.33
25th Percentile	0.94	0.88	1.02	0.80	0.75	0.54
Median	1.02	1.07	1.24	0.98	0.91	1.09
Mean	*1.35*	*1.52*	*1.64*	*1.19*	*1.17*	*1.26*
75th Percentile	2.01	2.10	2.37	1.47	1.79	1.22
95th Percentile	2.38	2.99	2.86	2.17	2.00	3.56

Notes:

1. Sources defined in text and in reference list

York and Pennsylvania, only a small change (log variance increases of about 0.09) occurred.

The corrected total variances summarized in Exhibit C-8 provide the basis for estimating the contributions of individual variances sources, as discussed in the following section.

C.8   Estimates of Variance Contributions

As discussed in Section C.1, Equation C.4 and variations thereon can be used to estimate the contributions of individual sources to the overall variance seen in radon data sets. This section describes the procedure was used to estimate the relative contributions from the various sources to the total variance in a "typical" data set that captures the contributions from all of the sources. This approach makes use of the estimates of the contributions to log variance discussed in Sections C.2. through C.7.

Exhibit C-9 tabulates information related to variance contributions discussed in previous sections. The left-hand column of the exhibit indicates the type(s) of variance that were estimated through analysis of the various types of data sets, and indicates the table where the data are summarized. The four right-hand columns of the exhibit summarize the central portions (25th-75th percentile) of the distributions of log variance for the various types of data sets.

Each row in Exhibit C-9 identifies data sets that provide information about specific sources of variance in the radon data. Note that, despite the fact that the reported variances are averages of results from multiple studies, estimates do not all come from the same studies. Thus, in using these date to estimate variance contributions, we are implicitly assuming that the

Exhibit C- 9. Estimates of Log Variance Contributions From Different Studies				
	Percentile Estimate			
Type of Variance	25th	MEDIAN	MEAN	75th
A (Exhibit C-2)	0.003	0.013	0.023	0.011
A (Ward)	--	--	0.0057	--
S (Ward)	--	--	0.0029	--
S, A (Exhibit C-3)	0.0012	0.0052	0.0088	0.017
S, A, T (Exhibit C-4, State-Wide Studies)	0.008	0.041	0.26	0.15
S,A,W (Exhibit C-6)	0.025	0.091	0.24	0.27
S,A,W,T (Exhibit C-7, Statewide Studies)	0.029	0.11	0.42	0.36
SYS, S,A,W,T (Exhibit C-8)	0.94	1.02	1.35	2.01

behavior of radon variance in the different studies are consistent.

Our approach to estimating typical variance contributions from each source is summarized in Exhibit C-10. At the top, we put our best (average) estimate of total log variance (1.35) in a data set that reflects contributions from all sources of variance. Below it, we provide the equations used to develop estimates of the individual variance contributions. A good estimate of sampling and analytical variance Var(S+A) is the value 0.009, derived both from Var(S) Var(A) in the Ward study, as well as from the other six studies of sampling and analytical variance discussed in Section C.3. The studies of analytical variance themselves (Section C.2) give a higher value (about 0.02), but some of these studies are rather old, and it the more recent well-controlled studies seem to do better than this.

Exhibit C-10.Estimation of Contributions to Variance from Different Sources

Source of Variance	Typical Magnitude of Contribution to Log Variance (Method of Estimation)	Typical Proportion of Total Variance, percent
Total (All Sources)	~ 1.35 (Measured)	100
Sampling and Analytical	~ 0.009 (Measured)	~ 0.6
Temporal	(S+A+T) - (S+SA) ~ 0.19	13-18
	(S+A+T+W) - (S+A+T) ~ 0.14	
Among Wells	(S+A+W+T) - (S+A+T) ~ 0.16	12-17
	(S+A+W) - (S+A) ~ 0.23	
Among Systems	(SYS+S+A+W+T) - (S+A+W+T) ~ 0.93	~ 69
	(SYS+S+A+W+T) - (S+A) - (W) - (T) ~ 0.93	

A typical contribution of temporal variance, Var(T), is calculated in two ways. First we subtracting log Var(S+A) from the log variances of the data sets expressing sampling, analytical, and temporal variability. Second, we subtract log Var(S+A+W) from Var(S+A+W+T). Since this exercise was conducted using average values of quantities that can vary over orders of magnitude, the relatively close agreement of the estimates of temporal variance derived by these two approaches (0.19 versus 0.14) using different data sets is quite encouraging, and suggests that the additive model for variance calculations is appropriate for this data. Similarly, Var(W), the variance contribution from variations between wells, and Var(SYS), the variance across

systems, are also calculated using two sets of relationships. In each case, the estimates of the total variance contributions are quite consistent.

The last column of Exhibit C-10 summarizes the approximate proportional contribution of each variance source to the overall variance seen in radon data sets we evaluated. As expected, sampling and analytical variance contribute only a small proportion (less than one percent) of the total variance. We estimate that temporal variability within single wells typically accounts for between 13 and 18 percent of the variance in the data sets evaluated, and a similar proportion (12-17 percent) is accounted for by variation in radon levels among wells within systems. Variations among systems related to geographic and hydrogeologic setting account for the bulk (about 69 percent) of the variance seen in the data sets we evaluated.

Within their limitations, these results are generally consistent with the previous knowledge about patterns of radon occurrence in the U.S. We see a large-scale geographic affect, with levels in New England, the Appalachian Region, and isolated areas of the west having average radon levels far greater than those in the other areas. In addition, short-range spatial variability can also be significant. Between-well variability accounts for an average of about 15 percent of total variability in a typical data set. Similarly, temporal variability is also important, accounting for about the same average proportions of variance as variability between wells. For any given data set, the relative contributions of these sources of variance could differ. The values derived here are intended to be typical of data sets that are representative of large, geologically diverse regions, such as states, which have a significant proportion of multi-well systems.

These results have important implications for the development of monitoring plans for establishing radon compliance. As discussed Section 5.8, the relatively large contributions of well-to-well and temporal variability argue strongly for taking multiple samples from more than one well per system spread over time, if representative levels of radon in groundwater systems are to be established accurately. On the other hand, given the small variance contribution of analytical and sampling variability, it would appear that beyond normal QA/QC considerations, performing duplicate analyses or taking duplicate samples from the same source at the same time may not improve the accuracy of estimates of long-term radon levels very much.

C.9   References

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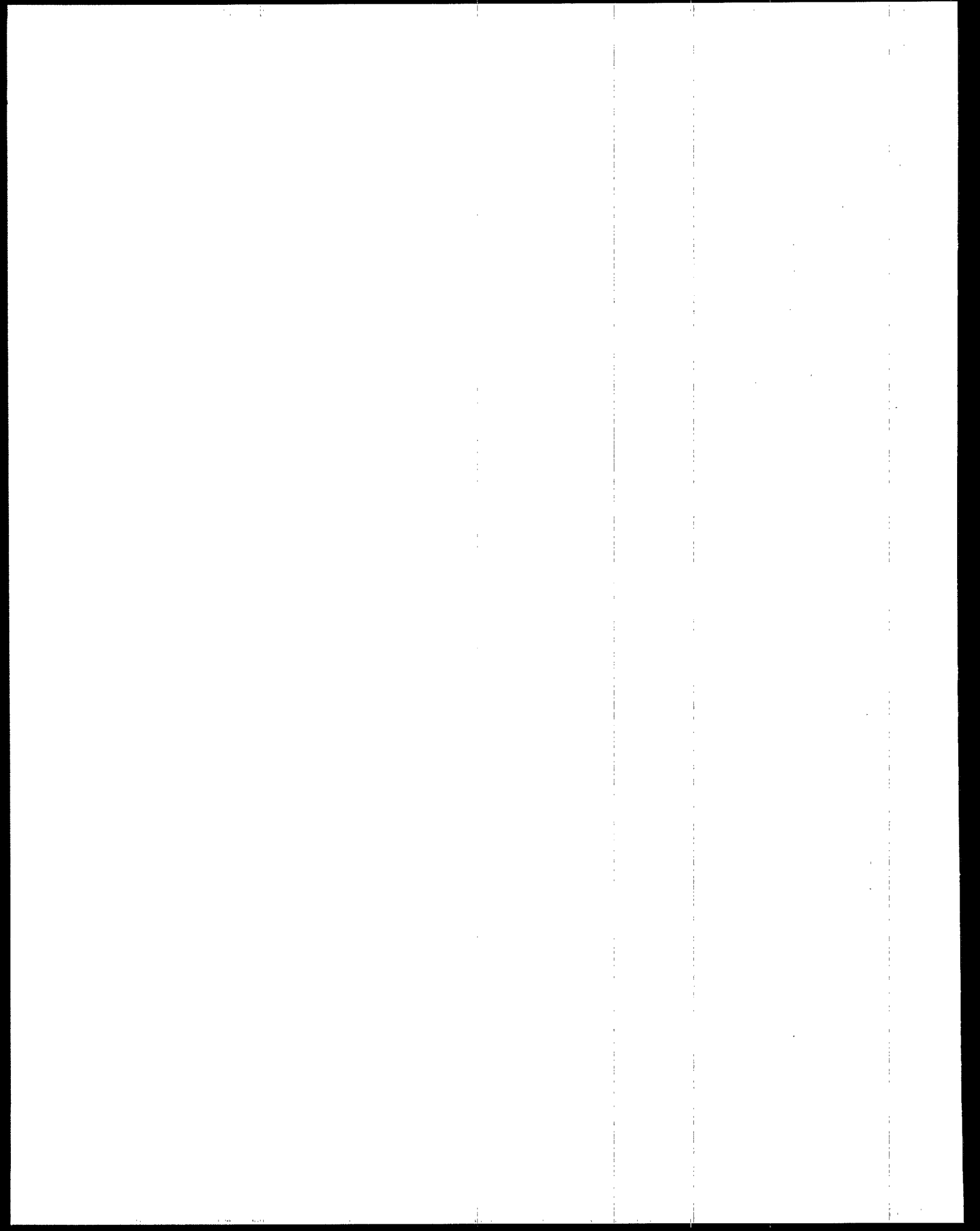
Appendix D: Estimated Numbers of Community Groundwater Systems Exceeding Potential Regulatory Levels by Region, State, and Size

Appendix D.1. Proportions of Systems Exceeding Potential Radon Regulatory Levels in the Eight NIRS regions

Exhibit D.1-1. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Total, Eight NIRS Regions, Minus Seven States

Scenario:

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Above 1,000 pCi/l	Above 2,000 pCi/l	Above 4,000 pCi/l
Very Very Small (25-100)	9,998	8,351	4,700	3,102	2,237	1,501	589	188
Very Small (101-500)	10,331	8,080	4,879	3,475	2,715	2,055	1,146	611
Small:								
501-1,000	3,149	1,978	985	573	360	201	56	15
1,001-3,300	3,901	2,349	1,143	661	415	231	65	18
10,000)	1,763	1,285	579	283	163	88	25	5
Large:								
10,001-100,000	1,154	849	328	149	77	34	5	0
>100,000	58	43	16	7	4	2	0	0
Total	30,354	22,934	12,630	8,251	5,971	4,112	1,885	838
Proportion of Total Systems	100.0%	75.6%	41.6%	27.2%	19.7%	13.5%	6.2%	2.8%

Exhibit D.1-2. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Appalachian

Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	2,477	2,040	1,311	923	690	480	198	64
Very Small (101-500)	2,169	1,755	1,359	1,141	995	843	572	355
Small:								
501-1,000	443	305	178	122	91	64	28	10
1,001-3,300	464	319	186	128	95	67	29	11
Medium (3,301-10,000)	212	198	76	23	8	2	0	0
Large/Very Large:								
10,001-100,000	153	113	43	20	10	5	1	0
>100,000	1	1	0	0	0	0	0	0
Total	5,919	4,730	3,153	2,358	1,890	1,460	829	440
Proportion of Total Systems	100.0%	79.9%	53.3%	39.8%	31.9%	24.7%	14.0%	7.4%

Exhibit D.1-3. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: California
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	1098	976	618	404	279	172	51	10
Very Small (101-500)	851	824	661	509	395	279	108	28
Small:								
501-1,000	193	191	121	55	24	7	0	0
1,001-3,300	213	210	133	61	26	8	0	0
Medium (3,301-10,000)	164	138	53	21	9	3	0	0
Large/Very Large:								
10,001-100,000	225	166	64	29	15	7	1	0
>100,000	21	15	6	3	1	1	0	0
Total	2,765	2,521	1,656	1,082	750	477	161	39
Proportion of Total Systems	1	1	1	0	0	0	0	0

Exhibit D.1-4. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Gulf Coast
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems pCi/l	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	819	674	328	174	101	50	9	1
Very Small (101-500)	1,346	914	507	336	243	163	65	21
Small:	0							
501-1,000	615	219	93	56	38	25	9	3
1,001-3,300	975	347	148	89	61	39	15	5
Medium (3,301-10,000)	435	132	39	18	10	5	1	0
Large/Very Large:	0							
10,001-100,000	259	191	74	33	17	8	1	0
>100,000	23	17	7	3	2	1	0	0
Total	4,472	2,494	1,196	709	472	291	101	30
Proportion of Total Systems	1	1	0	0	0	0	0	0

Exhibit D.1-5. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Great Lakes
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	1017	731	181	53	19	5	0	0
Very Small (101-500)	1,542	1,063	599	401	291	198	81	27
Small:	0							
501-1,000	748	477	135	50	22	8	1	0
1,001-3,300	888	566	161	59	26	10	1	0
Medium (3,301-10,000)	389	299	134	68	39	19	4	0
Large/Very Large:	0							
10,001-100,000	216	159	61	28	14	6	1	0
>100,000	7	5	2	1	0	0	0	0
Total	4,807	3,301	1,273	660	413	247	87	27
Proportion of Total Systems	1	1	0	0	0	0	0	0

Exhibit D.1-6. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: New England
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	683	680	642	582	519	435	250	103
Very Small (101-500)	554	516	448	400	363	320	235	155
Small:	0							
501-1,000	92	92	87	67	43	19	1	0
1,001-3,300	115	115	109	83	53	24	1	0
Medium (3,301-10,000)	87	87	82	72	61	46	19	4
Large/Very Large:	0							
10,001-100,000	61	45	17	8	4	2	0	0
>100,000	0	0	0	0	0	0	0	0
Total	1,592	1,535	1,385	1,210	1,042	846	507	263
Proportion of Total Systems	1	1	1	1	1	1	0	0

Exhibit D.1-7. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Northwest
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	1490	1130	237	55	16	3	0	0
Very Small (101-500)	1,143	914	344	142	66	25	2	0
Small:								
501-1,000	196	121	54	31	20	11	3	1
1,001-3,300	216	133	60	34	22	13	4	1
Medium (3,301-10,000)	80	58	18	7	3	1	0	0
Large/Very Large:								
10,001-100,000	59	43	17	8	4	2	0	0
>100,000	2	1	1	0	0	0	0	0
Total	3,186	2,400	730	276	130	55	10	2
Proportion of Total Systems	1	1	0	0	0	0	0	0

Exhibit D.1-8. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Plains
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	899	628	206	83	39	15	2	0
Very Small (101-500)	1,360	1,030	324	117	49	16	1	0
Small:	0							
501-1,000	535	256	82	38	21	10	2	0
1,001-3,300	696	333	107	50	27	13	3	0
Medium (3,301-10,000)	239	219	77	23	7	2	0	0
Large/Very Large:	0							
10,001-100,000	101	74	29	13	7	3	0	0
>100,000	3	2	1	0	0	0	0	0
Total	3,833	2,542	827	323	150	60	8	1
Proportion of Total Systems	1	1	0	0	0	0	0	0

Exhibit D.1-9. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Rocky Mountains
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	1515	1491	1177	828	574	340	78	9
Very Small (101-500)	1,366	1,063	636	430	312	210	81	25
Small:	0							
501-1,000	327	319	234	154	102	57	12	1
1,001-3,300	334	325	239	158	104	58	12	1
Medium (3,301-10,000)	157	154	101	52	26	10	1	0
Large/Very Large:	0							
10,001-100,000	80	59	23	10	5	2	0	0
>100,000	1	1	0	0	0	0	0	0
Total	3,780	3,412	2,410	1,633	1,124	677	183	36
Proportion of Total Systems	1	1	1	1	0	0	0	0

Appendix D.2. Proportions of Systems Exceeding Potential Radon Regulatory Levels in Seven States With Supplemental Data
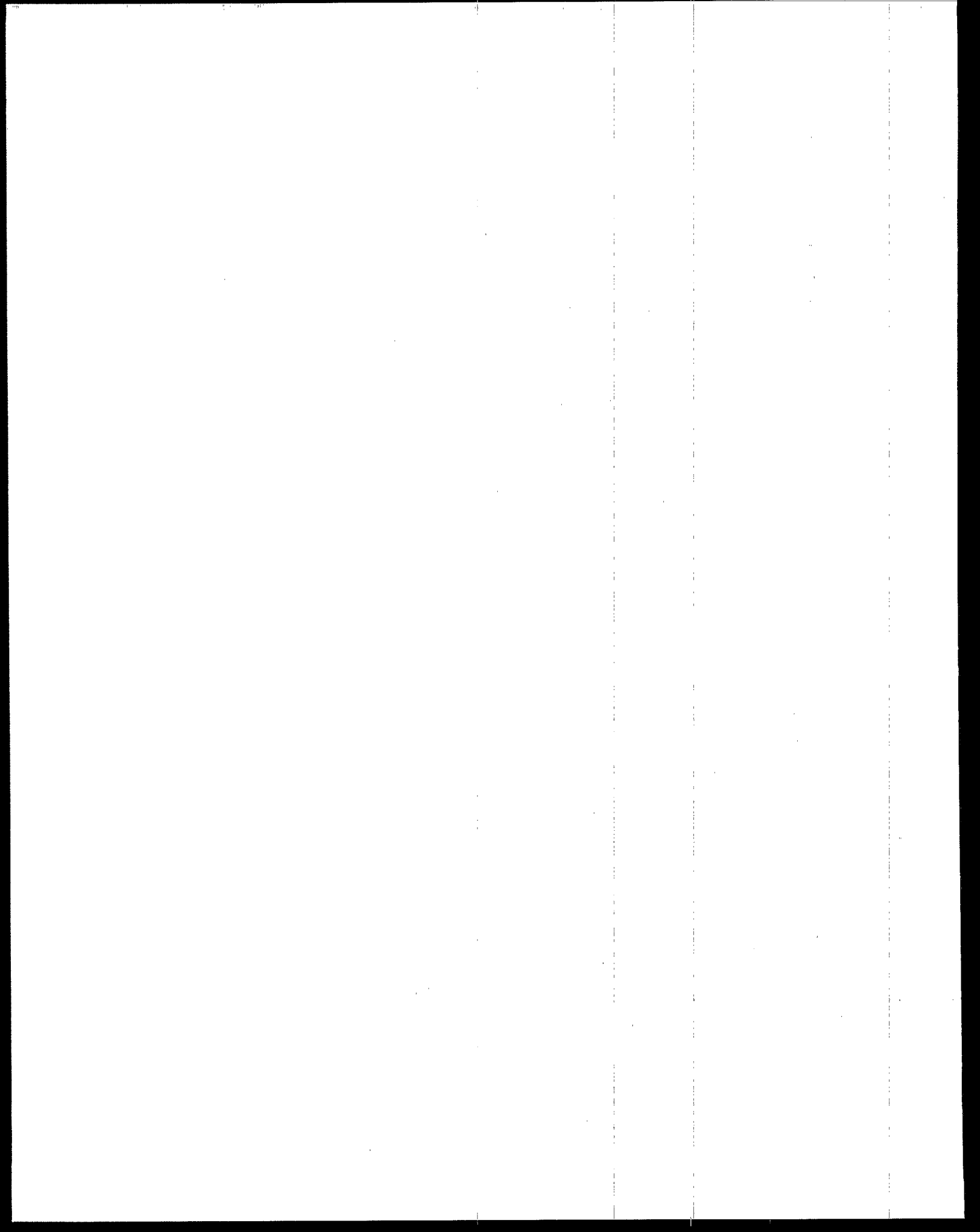
D.2-1. Estimated Proportions of Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Total (Seven States)

Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	3,689	3,114	1,848	1,278	1,011	789	458	227
Very Small (101-500)	3,529	2,728	1,599	1,133	887	679	391	206
Small:								
501-1,000	1,098	871	467	286	194	123	47	16
1,001-3,300	1,359	1,060	551	330	221	139	52	18
Medium (3,301-10,000)	572	443	190	101	64	40	16	6
Large/Very Large:								
10,001-100,000	203	150	61	29	18	11	4	1
>100,000	8	6	2	1	0	0	0	0
Total	10,458	8,372	4,718	3,157	2,395	1,780	967	475
Proportion of Total Systems	100.0%	80.1%	45.1%	30.2%	22.9%	17.0%	9.2%	4.5%

D.2-2. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels
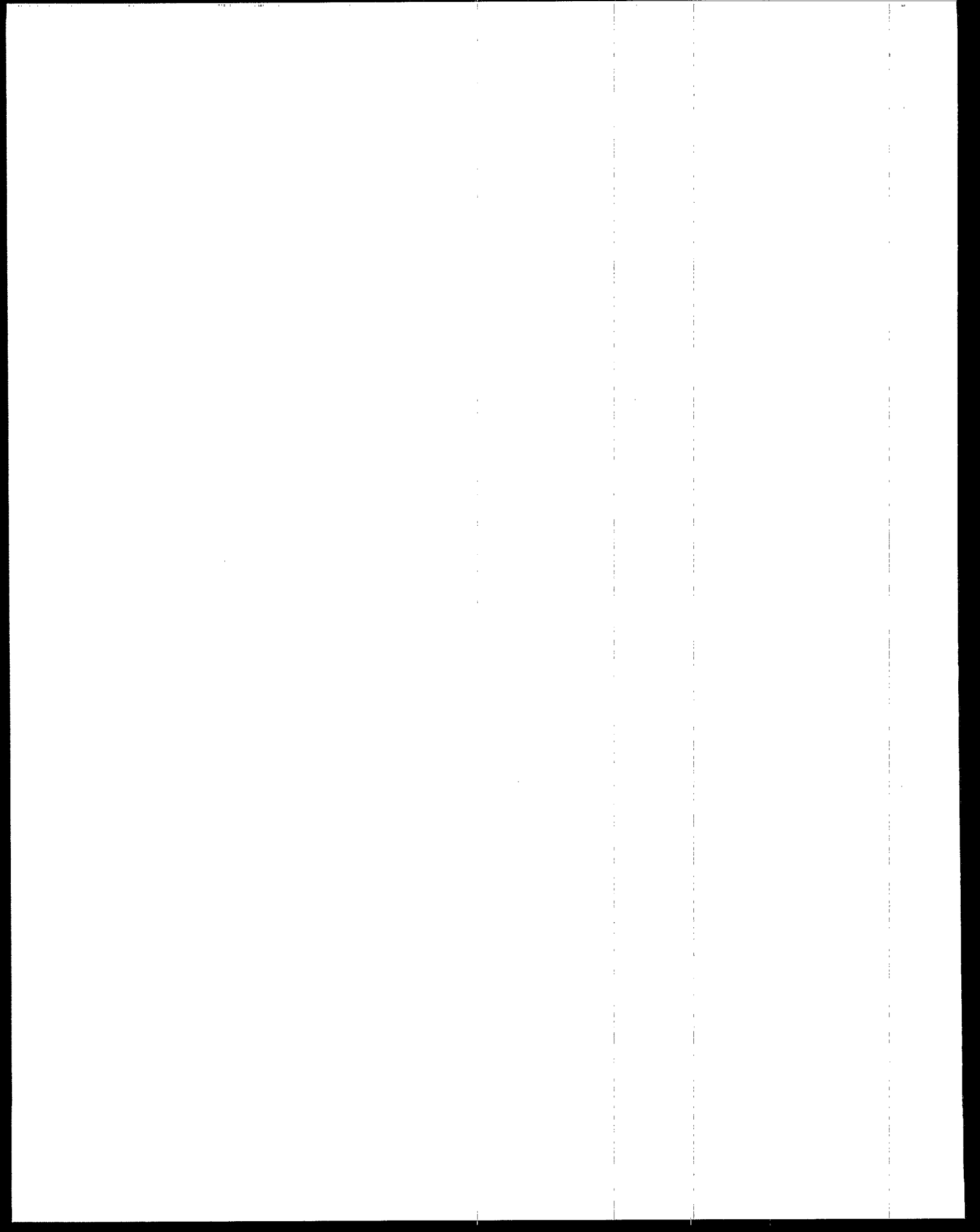
State/Region: Michigan
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	345	229	65	23	10	4	0	0
Very Small (101-500)	428	314	130	63	35	16	3	0
Small:								
501-1,000	127	108	40	15	6	2	0	0
1,001-3,300	168	142	53	20	8	3	0	0
Medium (3,301-10,000)	59	47	11	3	1	0	0	0
Large/Very Large:								
10,001-100,000	18	16	5	1	0	0	0	0
>100,000	1	1	0	0	0	0	0	0
Total	1,146	857	302	125	60	25	3	0
Proportion of Total Systems	100.0%	74.8%	26.4%	10.9%	5.2%	2.2%	0.3%	0.0%

D.2-3. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: New Hampshire
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	325	324	312	295	278	252	187	114
Very Small (101-500)	219	218	209	197	185	167	124	77
Small:	0							
501-1,000	29	26	20	17	14	12	7	4
1,001-3,300	31	27	22	18	15	13	8	4
Medium (3,301-10,000)	9	9	7	5	4	2	1	0
Large/Very Large:	0							
10,001-100,000	4	3	2	2	1	1	1	0
>100,000	0	0	0	0	0	0	0	0
Total	617	606	572	534	497	448	327	199
Proportion of Total Systems	100.0%	98.3%	92.7%	86.5%	80.5%	72.5%	53.0%	32.2%

Exhibit D.2-4. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: New York
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	815	660	398	266	191	125	45	12
Very Small (101-500)	646	519	349	260	205	152	75	31
Small:	0							
501-1,000	164	144	86	54	36	21	6	1
1,001-3,300	159	139	84	52	35	21	5	1
Medium (3,301-10,000)	54	49	28	16	10	5	1	0
Large/Very Large:	0							
10,001-100,000	47	38	16	7	4	1	0	0
>100,000	5	4	2	1	0	0	0	0
Total	1,890	1,553	963	656	479	326	133	45
Proportion of Total Systems	100.0%	82.2%	50.9%	34.7%	25.4%	17.2%	7.0%	2.4%

Exhibit D.2-5. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Pennsylvania
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	683	586	423	328	265	203	106	46
Very Small (101-500)	616	514	381	305	254	204	120	61
Small:	0							
501-1,000	162	147	110	85	69	52	25	10
1,001-3,300	177	161	120	93	75	56	28	11
Medium (3,301-10,000)	70	62	45	35	28	21	10	4
Large/Very Large:	0							
10,001-100,000	25	24	18	14	11	8	3	1
>100,000	0	0	0	0	0	0	0	0
Total	1,733	1,493	1,098	860	702	543	292	132
Proportion of Total Systems	100.0%	86.1%	63.3%	49.6%	40.5%	31.4%	16.9%	7.6%

D.2-6. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: South Carolina
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	230	230	225	213	199	177	116	55
Very Small (101-500)	160	152	131	115	103	89	61	37
Small:	0							
501-1,000	46	36	22	15	11	8	3	1
1,001-3,300	55	43	26	18	13	9	4	1
Medium (3,301-10,000)	31	25	16	12	9	7	3	1
Large/Very Large:	0							
10,001-100,000	11	8	3	2	1	1	0	0
>100,000	0	0	0	0	0	0	0	0
Total	533	492	424	376	337	290	188	95
Proportion of Total Systems	100.0%	92.3%	79.5%	70.5%	63.3%	54.5%	35.2%	17.8%

D.2-7. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Texas
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	889	690	274	124	63	27	3	0
Very Small (101-500)	1,185	762	257	111	56	24	3	0
Small:	0							
501-1,000	429	281	111	55	32	16	3	0
1,001-3,300	607	397	157	78	45	22	4	1
Medium (3,301-10,000)	262	171	45	15	6	2	0	0
Large/Very Large:	0							
10,001-100,000	65	29	2	0	0	0	0	0
>100,000	1	0	0	0	0	0	0	0
Total	3,438	2,331	846	383	201	91	14	2
Proportion of Total Systems	100.0%	67.8%	24.6%	11.2%	5.9%	2.6%	0.4%	0.0%

D.2-8. Estimated Proportions of Community Groundwater Systems With Long-Term Average Radon Levels Above Potential MCL/AMCL Levels

State/Region: Wisconsin
Scenario: Central Tendency Distribution, Quarterly Duplicate Samples

System Size (Population Served)	Total Systems	Systems Above 100 pCi/l	Systems Above 300 pCi/l	Systems Above 500 pCi/l	Systems Above 700 pCi/l	Systems Above 1,000 pCi/l	Systems Above 2,000 pCi/l	Systems Above 4,000 pCi/l
Very Very Small (25-100)	402	396	151	29	5	0	0	0
Very Small (101-500)	275	248	143	82	50	26	5	1
Small:	0							
501-1,000	141	131	78	44	26	13	2	0
1,001-3,300	162	150	89	51	30	15	2	0
Medium (3,301-10,000)	87	81	39	16	7	2	0	0
Large/Very Large:	0							
10,001-100,000	33	33	14	3	1	0	0	0
>100,000	1	1	0	0	0	0	0	0
Total	1,101	1,040	514	224	118	57	10	1
Proportion of Total Systems	100.0%	94.4%	46.7%	20.3%	10.8%	5.1%	0.9%	0.1%

Appendix E: Estimated Numbers of Non-Transient Non-Community

Groundwater Systems Exceeding Potential Regulatory Levels
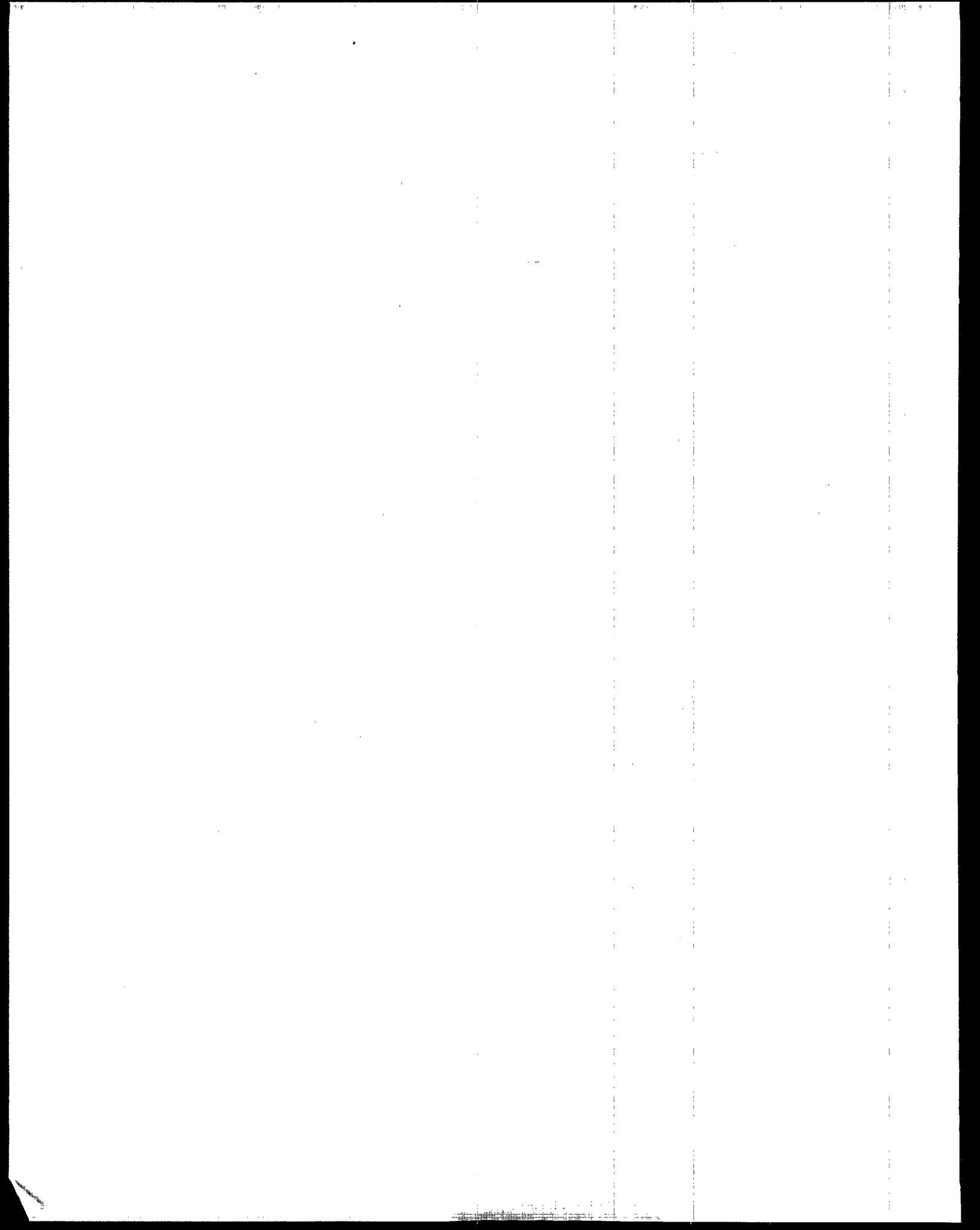
Appendix E: Estimated Numbers of Non-Transient Non-Community Groundwater Systems Exceeding Potential Regulatory Levels

In this appendix, the numbers of non-transient non-community groundwater systems (NCNTWS) exceeding potential regulatory levels are estimated. Estimates of the national total of NTNCWS are developed, the radon distributions in NTNCWS of different sizes are characterized, and the numbers and proportions of NTNCWS exceeding the various radon levels are estimated. The data supporting the estimation of radon occurrence in NTNCWS are quite limited, and thus the estimates of NTNCWS exceeding potential regulatory levels are less detailed than those developed for community systems, and are subject to much more uncertainty.

E.1   Number of Non-Transient Non-Community Systems in the U.S.

EPA's *Drinking Water Baseline Handbook* (EPA 1999) provides estimates of the numbers of NTNCWS by state and system size, as summarized in Exhibit E-1. Using data from the SDWIS database, EPA estimates that there were a total of 19,062 active NTNCWS in the U.S. in 1998. Consistent with previous analysis, the great majority of NTNCWS are very small; just over 50 percent serve fewer than 100 customers, 86 percent serve fewer than 500 customers, and 99.6 percent serve fewer than 3,300 customers. Based on the SDWIS data, there are no NTNCWS systems serving more than 50,000 customers in the U.S.

E.2.   Distribution of Radon Levels in Non-Community Non-Transient Systems

The NIRS data come solely from CWS, and do not provide any information regrading radon levels occurring in NTNCWS. Among the data sets received from the states, only six (from Idaho, Maine, Maryland, New Hampshire, Texas, and Wisconsin) contained information on radon levels in NTNCWS. The data from Idaho do not identify NTNCWS by system size and therefore were not used in the analysis.

These geometric mean and log mean radon levels in NTNCWS in the five states are summarized in Exhibit E-2, along with summary statistics relating to radon levels from the same size CWS in the same states[1]. Generally, the radon levels in the NTNCWS systems are considerably higher than those in the same size CWS in the same states, although the differences are not always statistically significant[2] due to the small numbers of systems involved. In the supplemental data from New Hampshire, the CWS and NTNCWS radon levels seem to be comparable, although the relatively small differences in log means for some strata are significant

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[1] The numbers in the "All" column for NTNCWS may be greater than the sums of the entries for some sizes because they may include systems for which size data were not available.

[2] Student's t-test for independent samples applied to the log means, two-tailed. "NO" denotes differences that were not significant at the p = 0.10 level.

Exhibit E-1. Estimated Numbers of Active Non-Transient Non-Community Groundwater Systems by State [1]						
Size (Customers Served)						
25-100	101-500	501-1000	1001-3300	3301-10000	10001-50000	50001-100000
Total in Size Category						
9,606	6,840	1,891	665	53	7	0
National Total						
19,062						
By State:						
Alabama 11	19	13	3	0	0	0
Alaska 0	0	0	0	0	0	0
Arizona 96	66	26	21	2	1	0
Arkansas 20	19	3	3	0	0	0
California 491	381	92	30	8	3	0
Colorado 68	52	7	2	0	1	0
Connecticut 426	150	50	15	0	0	0
Delaware 45	25	9	7	0	0	0
Florida 725	269	80	31	2	0	0
Georgia 143	99	32	16	1	0	0
Idaho 140	92	23	8	2	0	0
Illinois 167	210	44	21	2	0	0
Indiana 349	250	83	11	0	0	0
Iowa 55	57	14	7	0	0	0
Kansas 36	16	9	6	0	0	0
Kentucky 27	44	8	1	0	0	0
Louisiana 104	76	28	24	0	0	0
Maine 138	184	19	3	0	0	0
Maryland 235	163	76	20	1	0	0
Massachusetts 104	75	37	7	1	0	0
Michigan 961	607	125	23	2	0	0
Minnesota 601	67	11	2	1	0	0
Mississippi 28	40	37	16	4	0	0
Missouri 95	92	25	13	1	0	0
Montana 96	101	12	2	0	0	0
Nebraska 143	33	8	3	1	0	0
Nevada 56	24	5	5	1	0	0
New Hampshire 256	124	35	6	0	0	0
New Jersey 543	305	105	41	5	0	0
New Mexico 78	44	21	4	0	0	0
New York 299	237	111	41	2	0	0
North Carolina 259	281	88	23	1	0	0
North Dakota 15	7	0	0	0	0	0
Ohio 503	460	123	24	2	0	0
Oklahoma 75	40	6	0	1	0	0
Oregon 162	149	14	7	0	0	0
Pennsylvania 406	572	191	73	4	0	0
Rhode Island 31	25	11	3	1	0	0
South Carolina 126	94	19	7	0	1	0
South Dakota 15	9	1	0	0	0	0
Tennessee 29	25	3	1	0	0	0
Texas 329	281	69	45	5	0	0
Utah 22	22	3	2	1	0	0
Vermont 1	0	0	0	0	0	0
Virginia 278	328	115	45	2	0	0
Washington 134	110	25	12	0	0	0
West Virginia 82	83	11	5	0	0	0
Wisconsin 556	406	61	25	0	1	0
Wyoming 47	27	3	1	0	0	0

Notes:
1. Source: USEPA, *Drinking Water Baseline Handbook* First Edition, 1999

Exhibit E-2 . Comparison of Radon Levels in Non-Community Non-Transient Systems With Levels in Community Water Systems in the Same States

STATE	STATISTIC	ALL SYSTEMS		V.V. SMALL		V. SMALL		SMALL SYSTEMS		MEDIUM SYSTEMS		LARGE SYSTEMS	
		CWS	NCNTWS	CWS	NCNTWS	CWS	NCNTWS	CWS	NCNTWS	CWS	NCNTWS	CWS	NCNTWS
MARYLAND	NUMBER OF SYSTEMS	107	126	28	56	33	36	35	34	7	0	4	0
	ARITHMETIC MEAN	1490	3414	2759	3763	1902	4306	573	2955	1746		1926	
	GEOMETRIC MEAN	440	999	675	1,063	517	1,088	281	1,063	667		214	--
	LOG MEAN	6.087	6.907	6.514	6.969	6.248	6.992	5.639	6.969	6.503		5.364	
	LOG STD. DEV	1.562	1.568	1.678	1.590	1.614	1.659	1.193	1.430	1.387		2.097	
	DIFF. OF LOG MEANS SIGNIFICANT?	P < 0.05*		NO		NO		P < 0.05*		--		--	
MAINE	NUMBER OF SYSTEMS	64	122	4	4	13	17	24	5	7	0	3	0
	GEOMETRIC MEAN	1294	2728	870	1619	2515	5311	948	2119	1178	--	630	--
	LOG MEAN	7.166	7.911	6.768	7.389	7.830	8.578	6.855	7.659	7.071	--	6.447	--
	LOG STD. DEV	0.970	1.335	0.568	0.638	1.003	1.647	0.975	0.758	0.847	--	1.106	--
	DIFF. OF LOG MEANS SIGNIFICANT?	P < 0.05*		NO		NO		NO		--		--	
NEW HAMPSHIRE	NUMBER OF SYSTEMS	699	602	329	310	257	209	80	82	17	--	16	1
	GEOMETRIC MEAN	1789	2071	2309	2235	2237	2286	700	1210	294	--	192	1700
	LOG MEAN	7.489	7.636	7.745	7.712	7.713	7.735	6.552	7.098	5.685	--	5.258	7.438
	LOG STD. DEV	1.338	1.441	1.173	1.365	1.184	1.545	1.295	1.350	1.220	--	1.715	--
	DIFF. OF LOG MEANS SIGNIFICANT?	P = 0.057		NO		NO		P < 0.05		--		--	
TEXAS	NUMBER OF SYSTEMS	165	23	20	8	43	5	50	--	27	--	25	--
	GEOMETRIC MEAN	133	153	164	87	133	180	151	--	151	--	78	--
	LOG MEAN	4.894	5.029	5.103	4.470	4.888	5.194	5.014	--	5.020	--	4.360	--
	LOG STD. DEV	0.988	1.156	0.909	0.490	0.898	0.825	1.067	--	0.890	--	1.023	--
	DIFF. OF LOG MEANS SIGNIFICANT?	NO		P = 0.075		NO		--		--		--	
WISCONSIN	NUMBER OF SYSTEMS	535	26	126	7	128	12	187	7	64	--	30	--
	GEOMETRIC MEAN	274	410	242	406	296	679	311	173	226	--	223	--
	LOG MEAN	5.612	6.015	5.488	6.006	5.691	6.521	5.741	5.156	5.422	--	5.409	--
	LOG STD. DEV	0.954	1.004	1.058	0.722	0.987	1.014	0.921	0.645	0.750	--	0.820	--
	DIFF. OF LOG MEANS SIGNIFICANT?	P < 0.05		NO		NO		P = 0.093		--		--	

Notes
* Student's t-test for independent samples, two-tailed

because of the large numbers of systems. Breaking the general pattern, in the supplemental data from Texas, the log mean radon level for the very small NTNCWS is significantly lower than the log mean for very small CWS.

E.3 Estimation of Radon Distributions in Non-Transient Non-Community Systems of Different Sizes

As was the case with the community systems, it is necessary to extrapolate these data to develop nationwide estimates of the proportions of NTNCWS above potential regulatory levels. Because the data are so sparse, a much simpler approach has been used for the NTNCWS than for the community systems. Single values of the log mean and log standard deviation for long-term radon levels have been developed for each system size category across the U.S., based on the data from the five states identified above. The assumption is made that radon levels in the NTNCWS in the rest of the states will bear the same relationship the radon levels in community systems as they do in the five states for which radon data are available for NTNCWS.

To estimate the log mean radon levels for each size category of NTNCWS, the average ratios of the geometric mean radon levels[3] in the NTNCWS to the geometric mean radon in CWS from the same states were calculated, as shown in Exhibit E-3.

Exhibit E-3. Ratios of Geometric Mean Radon Levels in Non-Community Non-Transient Systems to Radon Levels in Community Systems in the Same States						
NCNTWS/CWS GEOMETRIC MEAN RATIOS						
State	ALL	VVS	VS	S	M	L
MARYLAND	2.271	1.575	2.104	3.780	--	--
MAINE	2.108	1.862	2.112	2.234	--	--
NEW HAMPSHIRE	1.158	0.968	1.022	1.728	--	--
TEXAS	1.144	0.531	1.359	--	--	--
WISCONSIN	1.496	1.679	2.294	0.557	--	--
Average	**1.635**	**1.323**	**1.778**	**2.075**	--	--

It can be seen that the ratios of the geometric means are highly variable across system sizes and among the states. In some cases, this is due to the small numbers of states where comparisons are possible, and the small numbers of NTNCWS systems in some size categories. In fact, average ratios were not calculated for medium or large systems because data are available for only one state each (and one system each) in these size categories.

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[3] This model assumes a constant multiplicative relationship between the radon levels in CWS and in NTNCWS. It is equivalent to assuming that the log mean radon levels in NTNCWS can be described by the log means radon levels from CWS plus a constant.

Because of the small number of data points, it was decided to use the overall average NTNCWS:CWS ratio of log means (1.635) to characterize national radon distributions for the various size NTNCWS systems. For each NTNCWS system size category, the estimated geometric mean radon level was estimated as the national average geometric mean radon level in the same size community system, multiplied by 1.635, as shown in Exhibit E-4. The resulting geometric mean (log mean) radon levels range from 520 pCi/l (6.25) for the very small systems to 260 pCi/l (5.56) for the small system category.

Exhibit E-4. Estimates of Log Mean Radon Levels for Non-Transient Non-Community Groundwater Systems Using CWS/NTNCWS Ratio				
	CWS/NTNCWS Geometric Mean Ratio:		1.635	
	Community Systems		Estimates for Non-Community Non-Transient Systems	
System Size	Log Mean	Geom. Mean	Log Mean	Geom. Mean
VVS	5.71	300	6.20	491
VS	5.76	318	6.25	520
S	5.07	159	5.56	260
M	5.19	180	5.68	294
L	5.25	190	5.74	311

Single, national estimates of log standard deviation values were also estimated for each size category of NTNCWS. As was the case with the log mean estimates, the data were limited, owing to the small number of states where comparisons could be made between NTNCWS systems and CWS of the same size. The average log standard deviation values seen in the five states and the average across all the states are shown in Exhibit E-5

Exhibit E-5. Log Standard Deviation Radon Levels in Non-Transient Non-Community Systems						
	System Size					
State	ALL	VVS	VS	S	M	L
MARYLAND	1.568	1.590	1.659	1.430		
MAINE	1.335	0.638	1.647	0.758	--	--
NEW HAMPSHIRE	1.441	1.365	1.545	1.350	--	--
TEXAS	1.156	0.490	0.825	--	--	--
WISCONSIN	1.004	0.722	1.014	0.645	--	--
Average	1.301	0.961	1.338	1.046	--	--

In the estimation of the proportions of NTNCWS exceeding potential regulatory levels, the average log standard deviation for each of the respective size classes was used. The average value for small systems (1.046) was also used as the estimate of log standard deviations for the medium and large NTNCWS systems as well. This decision has relatively little impact on the total numbers and proportions of systems exceeding regulatory levels because the medium and large systems make up such a small proportion of the total NTNCWS. The log standard deviations used in this analysis were not adjusted for multiple sampling compliance schemes, as was done for the community systems. Thus, the system log standard deviations and the proportions of systems exceeding the various radon levels may be slightly overestimated.

E.4. Estimated Numbers and Proportions of Non-Transient Non-Community Systems Exceeding Potential Regulatory Levels

The numbers and proportions of NTNCWS exceeding potential regulatory limits were calculated in the same way as described in Section 5.8 for the community systems. For each size category, the lognormal model was used to estimate the proportions of systems exceeding the various regulatory levels. These proportions were then multiplied by the total numbers of NTNCWS in each size category to give estimates of the numbers of systems exceeding regulatory levels. The results of this process are summarized in Exhibit E-6.

Exhibit E-6. Estimated Proportions of Non-Community Non-Transient Groundwater Systems With Long-Term Average Radon Above Potential Regulatory Levels								
State/Region:	**National**							
System Size (Population Served)	**Total Systems**	**Systems Above 100 pCi/l**	**Systems Above 300 pCi/l**	**Systems Above 500 pCi/l**	**Systems Above 700 pCi/l**	**Systems Above 1,000 pCi/l**	**Systems Above 2,000 pCi/l**	**Systems Above 4,000 pCi/l**
Very Very Small (25-100)	9,606	9,137	6,687	4,734	3,423	2,208	693	140
Very Small (101-500)	6,840	6,095	4,511	3,500	2,819	2,138	1,074	436
Small:								
501-1,000	1,891	1,550	842	503	325	187	48	8
1,001-3,300	665	545	296	177	114	66	17	3
Medium (3,301-10,000)	53	45	26	16	11	6	2	0
Large:								
10,001-100,000	7	6	4	2	2	1	0	0
>100,000	0	0	0	0	0	0	0	0
Total	19,062	17,377	12,367	8,932	6,694	4,606	1,834	587
Proportion of Total Systems	100.0%	91.2%	64.9%	46.9%	35.1%	24.2%	9.6%	3.1%

The general pattern of results is similar to that seen for the community water systems, except that the proportions of NTNCWS exceeding the regulatory limits are greater, owing to the generally higher radon levels in the latter systems. The great majority of NTNCWS (over 91 percent) exceed 100 pCi/l, and 64.9 percent exceed EPA's proposed regulatory level of 300

pCi/l. The proportions of systems exceeding the potential regulatory levels then decline rapidly, until only approximately 3.1 percent of the NTNCWS are predicted to exceed the NAS AMCL value of 4,000 pCi/l.

As noted above, the estimates of the numbers of NTNCWS systems exceeding regulatory limits are very uncertain, and depend heavily on the consistency of the relationship between radon levels in NTNCWS and community systems being the same throughout the country as they are in the five states for which data are available. The extent to which this is true is not known.