# North Carolina Radon-in-Water Advisory Committee Report

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**This document represents the final product of the NC Radon-in-Water Advisory Committee. Member signatories include:**


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# Executive Summary

Radon-222 (radon) is a naturally occurring radioactive gas and human carcinogen found in groundwater drinking supplies in some parts of North Carolina (NC) at levels that may pose a public health risk. Radon is produced during the decay of uranium-238, an element common in many rocks throughout the Piedmont and mountains of NC. In some areas, dissolved radon concentrations are among the highest in the United States (Hess and others, 1985; Horton, 1983; 1985). This is problematic because about 40 percent of North Carolinians use groundwater as their principal drinking supply.

Radon is the leading cause of lung cancer among non smokers and one of the leading environmental causes of cancer mortality in the United States (Field, 2010). The primary risk associated with radon in water is from inhalation (lung cancer) of radon gas released during household water use; a minor secondary risk is from ingestion (stomach cancer). <u>Increased cancer risks associated with radon in water are greater - in some cases by an order of magnitude or more - than a large number of Environmental Protection Agency (EPA) and State (15A NCAC 02L .0200) regulated contaminants at their respective maximum contaminant levels (MCLs)</u>, including benzene, trichloroethylene, tetrachloroethylene, ethylene dibromide, vinyl chloride, combined radium, uranium, and others. Generally, the risks associated with radon in water are relatively small when compared to the risks associated with radon from soil and rock.

In 1991, the U.S. Environmental Protection Agency (EPA) proposed an MCL of 300 picocuries per liter[1] (pCi/L) for radon in community water supplies. In 1999, EPA proposed an alternate MCL of 4,000 pCi/L (Federal Register, November, 1999) for water suppliers with a multi-media radon mitigation program that included reduction of airborne radon exposure. These levels were designed to prevent additional cancer incidents resulting from exposure to radon in water. To date, these standards have not been enacted, and many states have established their own radon-in-water advisories at levels ranging from 800 to 10,000 pCi/L.

Geology is the primary influence on dissolved radon levels in NC (Loomis, 1987; Campbell, 2006, 2008). About 25 percent of the Piedmont and mountains of NC are underlain with rocks commonly associated with elevated radon in water, namely granites and granitic gneisses. Based on geology and radon-in-water data collected to date, seven areas in the state are considered to be particularly susceptible to elevated radon in water and are mapped in this report. These areas comprise part of 19 counties, including Buncombe, Caldwell, Catawba, Cleveland, Franklin, Gaston, Henderson, Jackson, Lincoln, McDowell, Mecklenburg, Mitchell, Rutherford, Transylvania, Vance, Wake, Watauga, Wilkes, and Yancey Counties. Many of these areas are also associated with elevated indoor air radon. Surface water supplies in general, and groundwater supplies in the Coastal Plain, tend to be relatively low in dissolved radon. Radon-in-water data are lacking in many counties that contain rock units commonly associated with elevated radon in water, and an ongoing sampling program (NC Division of Water Quality) is helping to fill these gaps.

Private bedrock wells sampled within seven areas of particular susceptibility to dissolved radon (n = 358; median radon = 4,680 pCi/L) show that 99% contained radon above 300 pCi/L, 57% above 4,000 pCi/L, and 19% above 10,000 pCi/L. The estimated increased lifetime cancer mortality risk associated with these radon levels is 2, 27, and 67 deaths in 10,000, respectively, for a mixed population of ever and never smokers. These risks well exceed the typical EPA risk tolerance range of 1 in 10,000 to 1 in 1,000,000. The vast majority of wells across NC contain

[1] A pCi/L is a unit of measure that represents 0.037 atomic disintegrations per second per liter of substance.

radon above the proposed EPA MCL of 300 pCi/L. For practical and economic reasons, agencies generally have been willing to tolerate a larger risk for radon in water than for other dissolved contaminants.

The North Carolina Radon-in-Water Advisory Committee was formed to evaluate radon-in-water occurrence and exposure in North Carolina, review peer-reviewed scientific literature on radon risks, and recommend a level of radon in water above which treatment should be considered. The committee was established by the NC Department of Environment and Natural Resources (DENR) (Division of Environmental Health and Division of Water Quality) and NC Department of Health and Human Services (DHHS) (Division of Public Health), and members include scientists from universities and from state and county government. The advisory level recommended by the Committee is not intended to be a regulatory standard. Rather, it is intended to be a guideline for well owners and state and local officials responsible for drinking water supplies and public health, education, and planning.

The Committee's approach to radon in water is as follows (fig. 1). The Committee recommends an indoor air radon test for all occupied dwellings in NC. The Committee also recommends a radon-in-water test for all homeowners on a potable well that meet either of two criteria: (1) the home has an indoor air radon test result, after mitigation, above 4 pCi/L, or (2) the home has an indoor air radon test result above 2 pCi/L and is located within an area of moderate to high susceptibility to elevated radon in water as identified by the DWQ's program to map naturally occurring contaminants (currently identified areas are mapped in this report). The primary purpose of the radon-in-water test is to determine whether water is a significant contributor to indoor air radon levels. While the Committee does not ignore the ingestion risk, it focuses primarily on the much larger inhalation risk. In keeping with the EPA goal of limiting indoor air radon to 4 pCi/L (the current EPA action level), the Committee seeks to address the <u>combined</u> sources of radon (radon from soil gas and radon released from water[2]) by limiting the combined exposure level to no more than 4 pCi/L. The Committee also recognizes the benefit of achieving an even lower exposure level and the associated reduced risk, and suggests that homeowners consider, as an option, a mitigation goal for combined sources of radon of between 2 and 4 pCi/L.

<u>The Committee recommends a radon-in-water advisory be set at two levels. At the moderate level, concentrations between 4,000 and 10,000 pCi/L in water, treatment is considered optional. At the elevated level, concentrations at or above 10,000 pCi/L in water, treatment should be considered in conjunction with the treatment of indoor air radon released from soil gas.</u> In most cases, mitigation of soil gas radon will have the greatest impact on reducing overall radon exposure and will usually take precedence over treatment of radon in water.

Testing well water for radon is easy and costs about $20 to $75. Bubble aeration systems effectively remove radon in water and range in price from about $2000 to $4000. Somewhat less expensive, whole house granular activated carbon filtration systems may be appropriate when radon levels do not exceed about 5,000 pCi/L[3].

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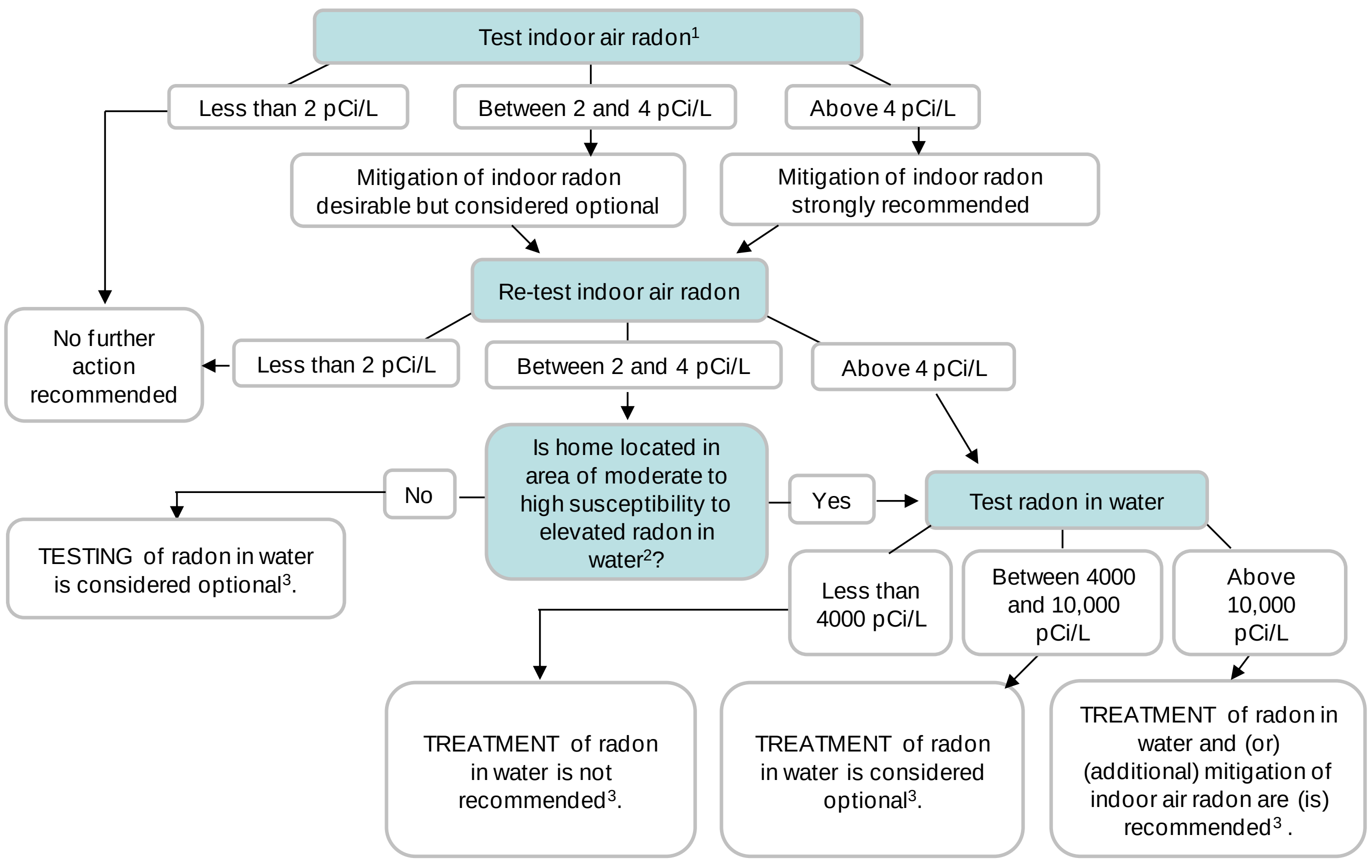
[2] On average, 10,000 pCi/L in water equates to 1 pCi/L in indoor air radon. This ratio may vary somewhat from home to home.

[3] Filter disposal issues are known to occur at radon levels above about 5,000 pCi/L due to the buildup, over time, of radioactive decay elements.

A program of additional sampling of radon in water is recommended in areas that lack adequate data, particularly in areas that contain rock units commonly associated with elevated radon in water.




1 All occupied dwellings in North Carolina should be tested for indoor radon before and after mitigation

2 Areas of moderate to high susceptibility to elevated radon in water are outlined in this report and may be updated periodically with additional findings by N.C. Division of Water Quality

3 Combined sources of indoor air radon (water and soil gas) should be as low as practicable but not greater than 4 pCi/L. As an average for all homes, 10,000 pCi/L of radon in water is comparable to 1 pCi/L of indoor air radon; this ratio may vary somewhat in any given home.

Figure 1. Recommended radon testing and mitigation for home and well owners in North Carolina.

# Committee Findings

## 1. Introduction

Radon is a human carcinogen that occurs naturally in groundwater drinking supplies in some areas of NC at levels that are among the highest in the United States (Hess and others, 1985; Horton, 1983, 1985) and that may pose a public health risk. In 1991, the EPA proposed an MCL of 300 pCi/L for radon in community water supplies, and in 1999, proposed an alternate MCL of 4,000 pCi/L (Federal Register, November, 1999) for water suppliers with a radon mitigation program. These standards were designed to prevent increases in cancer deaths that result from exposure to radon in water. The EPA has not enacted the radon-in-water standards for various reasons, including the fact that radon is naturally occurring and the majority of radon health risk tends to occur from soil gas rather than waterborne sources. Because standards have not been enacted at the Federal, State, or local level, confusion persists among well owners and community water suppliers about risk levels and the need for testing and treatment.

The lung cancer risks associated with long term exposure to radon are well studied and significant when compared to other environmental hazards. Inhalation of radon is responsible for an estimated 21,000 lung cancer deaths in the United States each year (EPA, 2003), mostly among smokers. Radon is the leading cause of lung cancer among non smokers and one of the leading environmental causes of cancer mortality in the United States (Field, 2010). Studies have shown that cancer risks are considerable even at radon concentrations below the EPA indoor air action level of 4 pCi/L, and even very small amounts of airborne radon may pose at least some risk (Field, 2010, 2000; Krewski and others, 2005; Darby and others, 2005). The greatest source of radon in indoor air typically is from soil gas, while a much smaller amount emanates from some building materials and from radon in water that off gases during showering as well as clothes and dish washing. A radon concentration of 10,000 pCi/L in water contributes, on average, an additional 1 pCi/L to the overall indoor air radon concentration (National Research Council, 1999).

Though generally small in comparison to the risks associated with breathing indoor air radon derived from soil gas, the increased lifetime cancer mortality risks associated with radon in water are greater - in some cases by an order of magnitude or more - than a large number of EPA regulated contaminants at their respective MCLs, including benzene, trichloroethylene, tetrachloroethylene, ethylene dibromide, vinyl chloride, combined radium, uranium, and others. The primary risk associated with long term exposure to radon in water is from inhalation (lung cancer). A much lower secondary risk is from ingestion (stomach cancer). Because the proposed EPA radon-in-water standards have not been enacted, several states have begun to establish their own advisories (table 1).

While a great deal of attention over the last decade has been given to educating the public about the risks of radon in indoor air from soil gas, far less attention has been paid to the exposure, cancer risks, treatment options, and policy objectives related to radon in groundwater drinking supplies. Many researchers and policy makers believe that the risks associated with radon in water, when compared to the risks associated with other regulated drinking water contaminants, warrant clear guidelines about use, sampling, and treatment. The heavy focus of researchers and policy makers on indoor air radon from soil gas sources has left a void in public information and resulted in legitimate questions about the risks and appropriate treatment strategies associated with radon in water.

Table 1. Selected state advisories and increased lifetime cancer risk levels for radon in water.

| State | Radon in water recommended guideline, pCi/L | Lifetime cancer mortality risk[1] |
|---|---|---|
| New Jersey | 800 | 5 per 10,000 |
| New Hampshire | 2,000 | 13 per 10,000 |
| Maine | 4,000 | 27 per 10,000 |
| Rhode Island | 4,000 | 27 per 10,000 |
| Connecticut | 5,000 | 33 per 10,000 |
| Vermont | 5,000 | 33 per 10,000 |
| Wisconsin | 5,000 | 33 per 10,000 |
| Massachusetts | 10,000 | 67 per 10,000 |

1 Mixed population of ever- and never-smokers

The NC Radon-in-Water Advisory Committee was formed in December 2006 to evaluate radon-in-water occurrence and exposure in NC, review the peer-reviewed scientific literature on radon risks, recommend a level of radon in water above which treatment should be considered, and discuss treatment options. The Committee was established by the NCDENR (Division of Environmental Health and Division of Water Quality) and NCDHHS (Division of Public Health), and members include experts from universities and from state and county government. The advisory level recommended by the Committee is not intended to be a regulatory standard. Rather, it is intended to be a recommended guideline that may be used by state and local officials responsible for drinking water supplies and public health, education, and planning. Criteria used to establish this advisory include cancer risks taken from epidemiology studies, measured levels of radon in groundwater in NC, and economic and technical feasibility of treatment. This document provides information and the technical basis used by the Committee to establish the radon-in-water advisory recommendation.

This report is divided into six sections:

1. Introduction
2. Radon sources and exposure in NC
3. Cancer risk from radon in water
4. Key considerations in selecting a recommended advisory level
5. Recommended advisory
6. Implications for NC well owners and recommended steps

## 2. Radon Sources and Exposure in North Carolina

Radon is a naturally occurring radioactive gas that is found everywhere – in soils, rocks, water, and indoor and outdoor air. It is part of the uranium-238 decay series and is produced during the decay of its parent element radium-226 (fig. 2). Radon is tasteless, odorless, colorless, and highly mobile. Concentrations of radon in outdoor air are usually very low, but concentrations in indoor air may build up to harmful levels in areas underlain by uranium rich rock and soil. Because it readily transfers into and out of the water phase it is found in groundwater that flows through uranium rich rock formations. Radon concentrations in surface waters are usually very low due to rapid volatilization of the gas to the atmosphere.

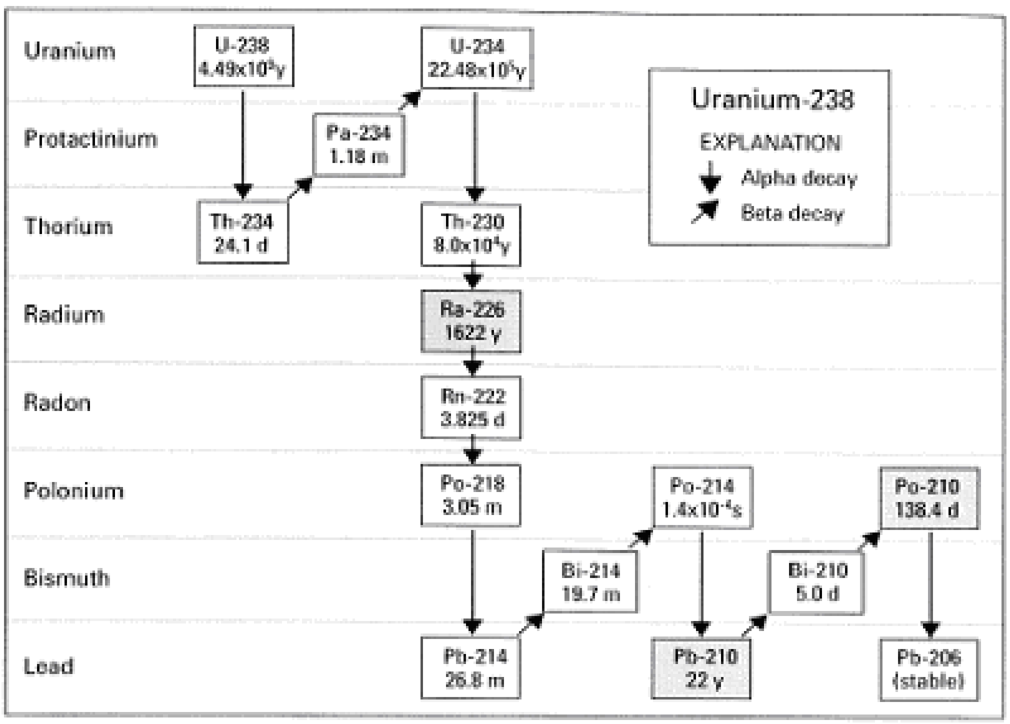



Figure 2. Schematic showing the uranium-238 radionuclide decay chain with parent and daughter elements and half-lives (in seconds (s), minutes (m), hours (h), days (d), or years (y), from Focazio and others (2000), as adapted from Hall and others (1985). Radium-226 is shown as Ra-226, and radon is shown as Rn-222.

<u>Radon in water</u>

Radon in groundwater drinking supplies occurs at elevated levels, often one or two orders of magnitude above the proposed EPA MCL, in several areas of the NC Piedmont and mountains based on a non-random[4] dataset of 890 bedrock supply wells. This is problematic because about

[4] The radon-in-water dataset for NC was obtained from radon studies with varied objectives and is not considered to be random.

40 percent of this population relies on groundwater as its principal drinking supply. Geology is the primary influence on dissolved radon levels (Loomis, 1987; Campbell, 2006 and 2008), and many areas in the Piedmont and mountains contain rock units commonly associated with elevated radon in water.

At least seven areas comprising parts of 19 counties are particularly susceptible to elevated radon in water, as inferred from existing radon-in-water data[5] and geology (table 2 and pink areas in fig. 3). These areas - referred to as "moderate to high susceptibility to elevated radon in water" – typically are underlain by uranium-rich, meta-igneous intrusive rock formations of granitic composition (granites and granitic gneisses). About a quarter of the Piedmont and mountains are underlain by similar rocks. Areas of moderate to high susceptibility are defined here as 20 percent or more of sampled wells within the area exceeding the proposed alternate EPA radon standard of 4,000 pCi/L. A median radon-in-water value was determined for each of these areas, and values ranged from 3,010 pCi/L (granodiorite and other gneisses of Watauga County) to 6,580 pCi/L (Rolesville and other granites of Vance/Franklin/central-eastern Wake Counties) (table 2). Within each area, the percentage of wells exceeding the 4,000 pCi/L threshold ranged from 30 percent (southern Mitchell/eastern Yancey Counties) to 73 percent (Vance/Franklin/central-eastern Wake Counties). Of the 358 wells sampled in these seven areas, 57 percent were above 4,000 pCi/L, and 19 percent were above 10,000 pCi/L.

In contrast, some of the sampled areas in the state are associated with relatively low levels of radon in water (blue areas in fig. 3). These areas – referred to here as "relatively low susceptibility to elevated radon in water" - generally were underlain by metamorphosed sedimentary and volcanic rocks[6], and the median radon-in-water value for all 465 wells sampled in these areas was 1,000 pCi/L. Within the low susceptibility areas, only western Wake County (n = 173, median = 1,590 pCi/L, 14% above 4,000 pCi/L) had over 10 percent of wells with radon above 4,000 pCi/L. Because rock types may vary locally, counties with low average susceptibility may still have areas that should be the focus of radon efforts. Limited data suggest that wells drilled in the unconsolidated sediments of the Coastal Plain also generally tend to be relatively low in radon in water (Watson and others, 1993; n = 43, maximum = 1,700 pCi/L).

For many areas of the state, radon-in-water data are very limited or not available (light yellow areas in fig. 3). Data from these areas were deemed insufficient to make inferences about susceptibility to elevated radon in water. Some of these areas contain meta-igneous intrusive rocks (shown as red stipple in fig. 3) that are commonly associated with elevated radon in water in other parts of the state.

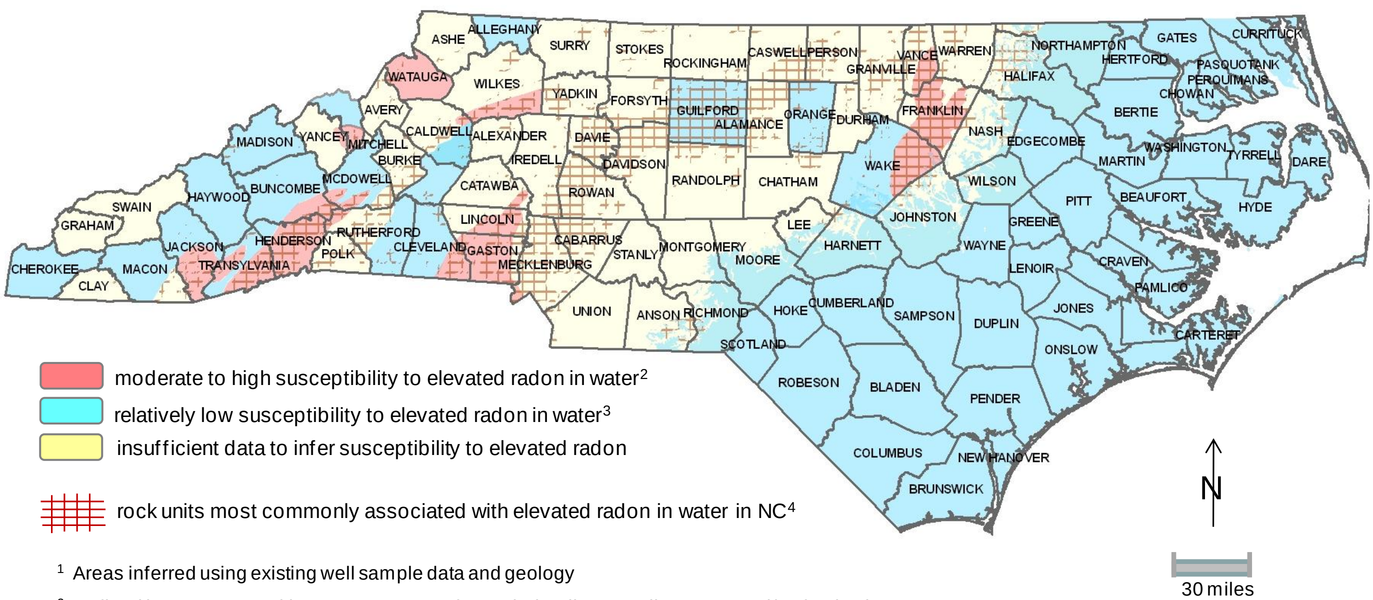
[5] Most sampling has been county by county. Where high radon rocks extend past county boundaries, the high radon may be inferred to continue with those rock types. Other data were considered in the assessment but were not reliably associated with elevated levels of radon in water. These included dissolved uranium, radium-226, and gross alpha results obtained from community water supply well samples (written communication, E. Chai, Division of Public Health, March 27, 2008), and dissolved uranium and uranium in stream sediment results obtained from the National Uranium Resource Evaluation study (Reid, 1993).

[6] Not all "relatively low susceptibility" areas are underlain with metamorphosed sedimentary and volcanic rocks. For example, Guilford and Orange Counties are underlain with meta-igneous intrusive rocks (commonly associated in other areas with elevated levels of radon in water) and yet are associated with widespread low levels of dissolved radon (n = 30, median = 340 pCi/L, maximum = 2900 pCi/L). These counties have been identified as having a "relatively low susceptibility" to elevated radon in water.

Overall, the data demonstrate that concentrations of radon in water can vary widely within a given rock formation, area, or county, and some well owners in moderate to high susceptibility zones have very low radon levels while some well owners in areas outside these zones have very high radon levels. A well sample is the only definitive means of determining the level of radon in water at a specific location. An ongoing sampling program is helping to fill data gaps, and results are being stored in a statewide radionuclides-in-groundwater geodatabase housed at the NC Division of Water Quality.

Radon-in-water data for various counties in NC are summarized in table 3. In this table, county-to-county comparisons of radon susceptibility are only approximate because (1) the data are non-uniformly distributed, (2) rock units contributing high radon occupy only parts of counties, and (3) alternate sources of radon-free potable water (municipal surface water supplies, for example) may be available in some of the areas that are otherwise susceptible to elevated radon in groundwater.

Areas of Relative Susceptibility to Elevated Radon in Water in North Carolina[1]




[1] Areas inferred using existing well sample data and geology

[2] Defined here as areas with over 20 percent of sampled wells exceeding 4,000 pCi/L of radon in water

[3] Defined here as areas with less than 20 percent of sampled wells exceeding 4,000 pCi/L of radon in water

[4] These units are characterized by meta-igneous intrusive rocks ; one exception to this association was the area of Guilford and Orange Counties where 45 wells tested relatively low in radon; excluding these wells, the remaining 253 wells sampled in these rock units had a median radon value of 3610 pCi/L, with 46 percent above 4,000 pCi/L and 18 percent above 10,000 pCi/L

Figure. 3 Map showing areas of relative susceptibility to elevated radon in water in NC, as inferred from existing well data and geology.

Table 2. Currently documented areas of moderate to high susceptibility to elevated radon in water in North Carolina, as inferred from well data and geology.

| Currently Documented Areas of Moderate to High Susceptibility to Elevated Radon in Water | Geologic Belt | Principal Geology | Median Radon in Water, pCi/L | Percent of Wells Above 4,000 pCi/L | Percent of Wells Above 10,000 pCi/L | Number of Wells Sampled |
|---|---|---|---|---|---|---|
| central and east Wake, Franklin, and Vance Counties | Raleigh | Rolesville granite; other granites | 6580 | 73 | 28 | 94 |
| south Transylvania, Henderson, and southeast Buncombe Counties | Inner Piedmont | Henderson gneiss; other granitics | 5210 | 61 | 22 | 135 |
| south Wilkes County | Inner Piedmont | granite; granite gneiss | 4360 | 63 | 13 | 8 |
| south Jackson and southwest Transylvania Counties | Blue Ridge | biotite gneiss; Whiteside granite | 3970 | 49 | 6 | 35 |
| south Mitchell and east Yancey Counties | Blue Ridge | granitic and granodiorite gneiss; pegmatites, other gneisses | 3330 | 30 | 10 | 10 |
| east Cleveland, east Lincoln, Gaston, and south Mecklenburg Counties | King's Mountain, Inner Piedmont, and Charlotte | Cherryville granite; other granites | 3090 | 41 | 18 | 51 |
| Watauga County | Blue Ridge | granodiorite gneiss; other gneisses | 3010 | 40 | 5 | 20 |

Radon in indoor air

Elevated levels of indoor air radon are common in many areas of the Piedmont and mountains of NC (NC Radiation Protection Section, http://www.ncradon.org/zone.htm accessed August 5, 2010). Concentrations vary widely within any area and county, and locations with high radon in water are not necessarily high in indoor air radon. This is due in part to the fact that indoor air radon is highly influenced by home construction, heating and air system type and usage, weather, local geologic characteristics, and other site scale factors. The primary source of the indoor radon is uranium rich rock – including granites and granitic gneisses – prevalent across much of the Piedmont and mountains. Eight counties, all in Western NC, are classified as EPA Zone 1 counties with predicted year long average indoor air radon concentrations above the EPA action level of 4 pCi/L (fig. 4). North Carolina county averages of indoor air radon are shown in Appendix 1 at the end of this report.

Table 3. Concentrations of radon in groundwater drinking supplies in North Carolina based on samples from private bedrock wells. Sample locations within a given county are not uniformly distributed.

| County | Number of wells sampled | Median radon, pCi/L | Maximum radon, pCi/L | % above 4000 pCi/L | Data source |
|---|---|---|---|---|---|
| **Mountain region** | | | | | |
| Henderson | 47 | 6640 | 37300 | 68 | NCDWQ, 2005-2010 |
| Transylvania | 85 | 4480 | 45600 | 52 | NCDWQ, 2005-2010 |
| Wilkes | 7 | 4210 | 10190 | 57 | NCDWQ, 2005-2010 |
| Watauga | 19 | 3000 | 21390 | 37 | NCDWQ, 2005-2010 |
| Yancey | 6 | 2650 | 4170 | 17 | NCDWQ, 2005-2010 |
| Jackson | 31 | 2640 | 20420 | 42 | NCDWQ, 2005-2010 |
| Cherokee | 11 | 2200 | 5040 | 9 | NCDWQ, 2005-2010 |
| Buncombe | 56 | 1990 | 10150 | 23 | NCDWQ, 2005-2010 |
| Avery | 2 | 1420 | 2370 | 0 | NCDWQ, 2005-2010 |
| Alleghany | 13 | 1330 | 8300 | 8 | NCDWQ, 2005-2010 |
| Haywood | 42 | 810 | 3880 | 0 | NCDWQ, 2005-2010 |
| Macon | 13 | 990 | 3880 | 0 | NCDWQ, 2005-2010 |
| Mitchell | 14 | 695 | 13820 | 14 | NCDWQ, 2005-2010 |
| Ashe | 4 | 635 | 4860 | 25 | NCDWQ, 2005-2010 |
| Madison | 15 | 320 | 2600 | 0 | NCDWQ, 2005-2010 |
| **Piedmont region** | | | | | |
| Mecklenburg | 4 | 16445 | 23090 | 75 | NCDWQ, 2005-2010 |
| Rockingham | 3 | 4220 | 7470 | 67 | NCDWQ, 2005-2010 |
| Vance | 13 | 3630 | 22600 | 38 | NCDWQ, 2005-2010 |
| Cleveland | 22 | 3010 | 57550 | 41 | NCDWQ, 2005-2010 |
| Franklin | 11 | 2560 | 18910 | 27 | NCDWQ, 2005-2010 |
| Gaston | 25 | 2520 | 24420 | 28 | NCDWQ, 2005-2010 |
| Wake | 242 | 2422 | 52974 | 34 | Wake County, 2005 |
| Union | 3 | 2400 | 2750 | 0 | NCDWQ, 2005-2010 |
| Lincoln | 8 | 2240 | 8800 | 38 | NCDWQ, 2005-2010 |
| Burke | 6 | 1880 | 4200 | 17 | NCDWQ, 2005-2010 |
| Polk | 12 | 1440 | 4100 | 8 | NCDWQ, 2005-2010 |
| Davidson | 3 | 1420 | 4400 | 33 | NCDWQ, 2005-2010 |
| Caldwell | 10 | 1380 | 8820 | 20 | NCDWQ, 2005-2010 |
| Iredell | 5 | 1040 | 3980 | 0 | NCDWQ, 2005-2010 |
| McDowell | 22 | 1015 | 12740 | 9 | NCDWQ, 2005-2010 |
| Rutherford | 9 | 980 | 6420 | 22 | NCDWQ, 2005-2010 |
| Randolph | 2 | 900 | 950 | 0 | NCDWQ, 2005-2010 |
| Guilford | 74 | 820 | 6300 | 7 | Spruill and others, 1997 |
| Orange | 41 | 570 | 4220 | 5 | Orange County, 1997 |
| Catawba | 5 | 470 | 3160 | 0 | NCDWQ, 2005-2010 |
| **Coastal Plain** | | | | | |
| various counties | 43 | 210 | 1700 | unknown | Watson and others, 1993 |

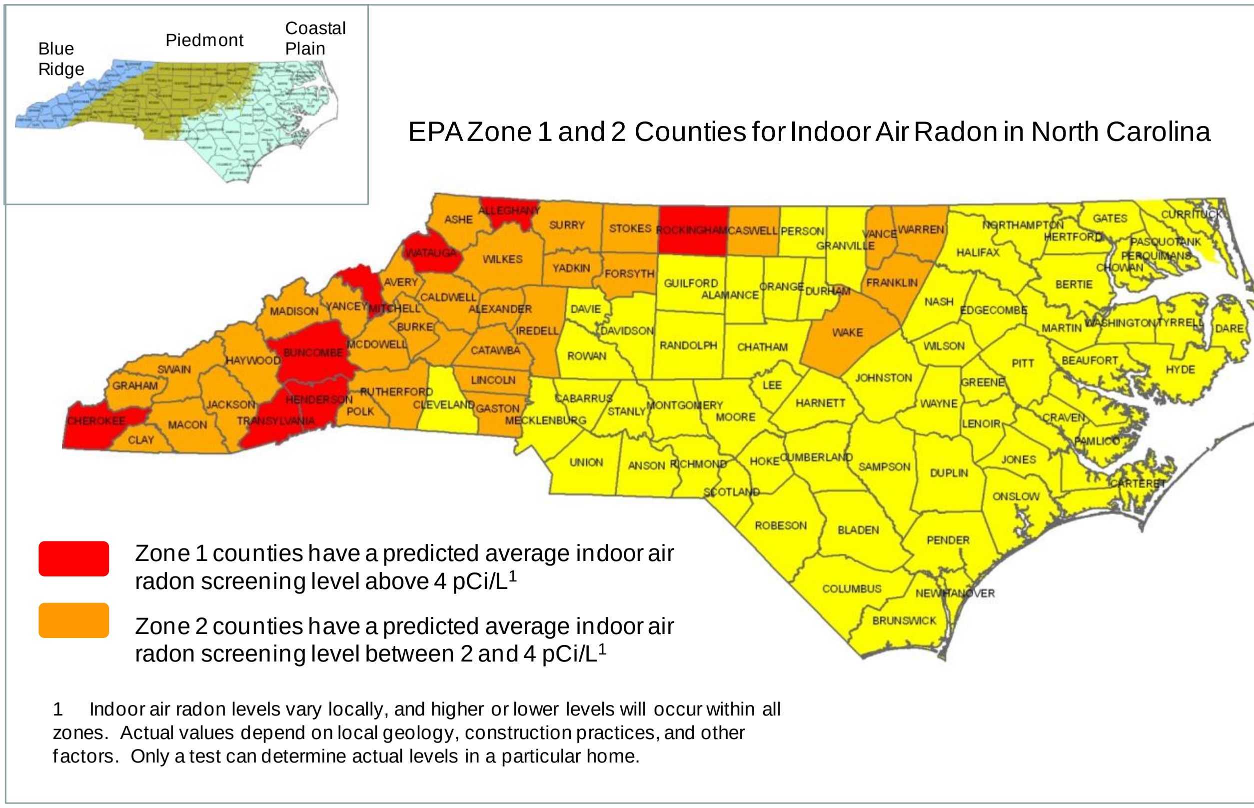



Figure 4. EPA indoor air radon map of North Carolina showing zones based on predicted countywide averages.

It is possible to estimate the amount of indoor air radon that is produced by the escape of radon from water. The degassing of radon from water into the entire volume of a home can be expressed as a transfer coefficient that is a function of home air volume, ventilation rate, water use, and the temperature dependent transfer efficiency. Several studies have assessed the transfer coefficient, either by modeling or by measurement. These are described in the 1999 National Research Council report, *Risk Assessment of Radon in Drinking Water*, which remains the most recent review of the subject. The NRC report concluded that the average transfer coefficient most likely lies within 0.8 and 1.2 units of radon in air per 10,000 units of radon in water (Gesell and Prichard, 1980; Hess and others, 1982; Hess and others, 1990; National Research Council, 1999; Nazaroff and others, 1987). In other words, on average, <u>10,000 pCi/L in water will add about 1 pCi/L to indoor air.</u> This amount *is in addition to* the amount of airborne radon entering the home from underlying soil and rock. It should be noted that many of the data used by the NRC were collected in the Northeast portion of the United States, and may not accurately represent the types of house construction common in NC.

Because of the uncertainties involved, the 10,000:1 transfer coefficient is only a general approximation of average whole-house radon exposure levels across the entire groundwater-dependent population of homes. It is not useful for predicting the transfer coefficient or actual exposure level for an individual home. Depending on the size of the home, ventilation rates, and water use, 10,000 pCi/L of water could result in higher or lower concentrations of indoor air radon.

Measuring total radon levels in household air is a simple matter (notwithstanding temporal fluctuations), but separating the contribution of radon that escapes from water from that of soil-derived radon is difficult for several reasons. Radon is typically measured in living areas, but bathrooms, laundry rooms, and kitchens have short-term spikes in localized radon levels that coincide with water use. These short-term exposures (such as during and after showering) may not always be incorporated into the 10,000:1 transfer coefficient, which assumes that radon from water is mixed evenly throughout the house. Experimental and field data have shown significantly *lower* ratios between radon in water and airborne radon in bathrooms (Fitzgerald and others, 1997; Vinson and others, 2008). That is, lower levels of radon in water were needed to produce the 1 pCi/L in indoor air in bathrooms. However, because of short exposure times, the extra exposure caused by short-term water use is believed to be a relatively small addition to the overall radon exposure expected from the 10,000:1 transfer coefficient (an additional 2 to 20 percent), depending on time spent in bathroom after showering (Vinson and others, 2008; Fitzgerald and others, 1997).

## 3. Cancer Risk from Radon in Water

The link between radon and lung cancer is well established and is based on studies of underground miners and residential and combined residential epidemiology studies (National Research Council, 1999, 1998; Field, 2000, 2010; Darby, 2005; Krewski, 2002, 2005; Lubin, 2010). Radon has been shown to be a human carcinogen that follows a linear threshold risk model in which a lower safe threshold is assumed not to exist. Even very small doses over long periods are believed to pose at least some cancer risk. The EPA automatically sets a maximum contaminant level goal (MCLG) of zero for known human carcinogens, including radon.

Cancer risks from radon in water are associated with two exposure routes: inhalation and ingestion. The inhalation component of risk - about 90 percent of the total risk (National Research Council, 1999) - is associated with airborne radon emanating from soil and rock and, to a lesser extent, emanating from construction materials and from radon that escapes from water during household use. About ten percent of the total risk is from direct ingestion of radon from drinking water.

Inhaling indoor air radon over long periods is linked to about 21,000 lung cancer deaths in the United States each year (EPA, 2003), and the total number of lung cancer deaths in the United States from all causes in 1998 was 160,100 (American Cancer Society, 1998). The number of radon-attributable lung cancer deaths each year for never-smokers is estimated to range from 4,400 to 6,100 and for smokers is estimated to range from 12,500 to 18,000 (Lubin, 2010). Although radon's link to cancer is clear, currently there is no scientific evidence of teratogenic (damage to the developing fetus) or reproductive risks associated with radon in tissues from either inhalation or ingestion (NRC, 1999).

The majority of inhalation health risks are not from the radon gas itself, but rather from the radioactive decay of radon's short-lived decay products. These decay products, specifically polonium-218 (Po-218) and polonium-214 (Po-214), are ionized and adhere to lung tissue, unlike radon gas which is inert and is readily exhaled from the body. As each polonium atom decays it releases a highly energetic alpha particle that collides with bronchial cells in close proximity. These high energy alpha particle collisions can, over time, damage DNA in the bronchial cells and result in lung cancer. Alpha dose to other organs in the body, via transport in the blood, is estimated to be substantially lower than the dose to lung tissue.

The increased cancer mortality risk posed by inhaling indoor air radon at 1 pCi/L is estimated to be 9.6E-3 (96 per 10,000) for ever smokers (defined as having smoked at least 100 cigarettes in a lifetime, MMWR Weekly, Nov. 28, 1986, 35(47);740-3, http://www.cdc.gov/mmwr/preview/mmwrhtml/00000830.htm,) and 1.9E-3 (19 per 10,000) for never smokers (EPA, 2003). The increased cancer mortality risk posed by inhaling radon released from water at 1,000 pCi/L is 9.6E-4 (10 per 10,000) for ever smokers and 1.9E-4 (2 per 10,000) for never smokers (NRC, 1999).

Risk levels at various concentrations in indoor air and water are presented in table 4. Smokers are much more susceptible to lung cancer deaths than non-smokers because of the synergistic relationship between radon and smoking.

Table 4. Estimated increased lifetime lung cancer mortality risks from inhalation of radon and decay products in indoor air and off gassed from radon in water for ever smokers and never smokers, from National Research Council, Risk Assessment of Radon in Drinking Water, National Academy Press, p. 16, Table ES-1.

| Concentration of radon in air, pCi/L | Estimated increased lifetime cancer mortality risk for ever smokers[a] | Estimated increased lifetime cancer mortality risk for never smokers[a] |
|---|---|---|
| 1 | 9.6E-3 (96 per 10,000) | 1.9E-3 (19 per 10,000) |
| 2 | 1.9E-2 (190 per 10,000) | 3.7E-3 (37 per 10,000) |
| 4 | 3.8E-2 (380 per 10,000) | 7.4E-3 (74 per 10,000) |
| 8 | 7.7E-2 (770 per 10,000) | 1.5E-2 (150 per 10,000) |
| 10 | 9.6E-2 (960 per 10,000) | 1.9E-2 (190 per 10,000) |

| Concentration of radon in water, pCi/L | Estimated increased lifetime cancer mortality risk for ever smokers[a] | Estimated increased lifetime cancer mortality risk for never smokers[a] |
|---|---|---|
| 300 | 2.9E-4 (3 per 10,000) | 5.6E-5 (less than 1 per 10,000) |
| 1,000 | 9.6E-4 (10 per 10,000) | 1.9E-4 (2 per 10,000) |
| 2,000 | 1.9E-3 (19 per 10,000) | 3.8E-4 (4 per 10,000) |
| 4,000 | 3.8E-3 (38 per 10,000) | 7.6E-4 (8 per 10,000) |
| 10,000 | 9.6E-3 (96 per 10,000) | 1.9E-3 (19 per 10,000) |
| 15,000 | 1.4E-2 (140 per 10,000) | 2.9E-3 (29 per 10,000) |
| 20,000 | 1.9E-2 (190 per 10,000) | 3.8E-3 (38 per 10,000) |
| 40,000 | 3.8E-2 (380 per 10,000) | 7.6E-3 (76 per 10,000) |

[a] From National Research Council (NRC), Risk Assessment of Radon in Drinking Water, National Academy Press, p. 16, Table ES-1, as derived from NRC's 1999 report titled Biological Effects of Ionizing Radiation VI: The Health Effects of Exposure to Indoor Radon.

Ingestion of radon rich water is associated with an estimated 20 stomach cancer deaths each year in the United States, as compared to 13,700 total stomach cancer deaths per year from all causes (NRC, 1999). A large portion of the U.S. population does not consume elevated radon in drinking water, so the 20 deaths are from among a much smaller subpopulation that represents those who actually consume radon rich water.

The fate and movement of ingested radon and its daughter products within the body has been modeled, and it has been determined that most of the radiation dose is delivered to the stomach as radon diffuses through the stomach wall. Ingested radon diffuses into the tissues of the stomach and small intestines and enters the bloodstream where it is circulated through the body before being eliminated by exhalation and urination.

Increased cancer mortality risk posed by ingesting water that contains radon at 1,000 pCi/L is estimated to be 7.4E-5 (less than 1 in 10,000) (NRC, 1999) (table 5). This risk is based on a daily water intake of 0.6 L/d over a lifetime and does not factor indirect use such as water used in juices, coffee, and food preparation; this amount is well lower than the 2-liter consumption volume assumed in a typical ATSDR and EPA risk estimate. This risk also assumes that all of the radon in the water remains dissolved in the process of transferring the water from the faucet to the stomach.

Table 5. Estimated increased lifetime cancer mortality risk for *mixed population* of ever smokers and never smokers from ingestion of radon in water.

| Concentration of radon in water, pCi/L | Estimated increased lifetime cancer mortality risk for mixed population of ever and never smokers[a] |
|---|---|
| 300 | 2.2E-5 (less than 1 per 10,000) |
| 1,000 | 7.4E-5 (less than 1 per 10,000) |
| 2,000 | 1.5E-4 (less than 2 per 10,000) |
| 4,000 | 3.0E-4 (3 per 10,000) |
| 10,000 | 7.4E-4 (7 per 10,000) |
| 15,000 | 1.1E-3 (11 per 10,000) |
| 20,000 | 1.5E-3 (15 per 10,000) |
| 40,000 | 3.0E-3 (30 per 10,000) |

[a] From National Research Council (NRC), Risk Assessment of Radon in Drinking Water, National Academy Press, p. 17, Table ES-2.

Table 6 shows the total combined increased lifetime cancer mortality risk posed from ingestion and inhalation of different levels of radon in water. This table combines the risk of ingesting radon rich water and inhaling radon and its daughter decay products released from water.

Several factors affect the reliability of radon risk estimates. Uncertainties in the risk estimate include: spatial and temporal variation of radon, quality control of radon measurements, site-dependent variability in the transfer coefficient from water to air, aerosol size distribution and particle “inhalability” during showering, variation in bathroom ventilation rates, variation in residential air exchange rates, variation in rates of water consumption, variation in rates of home and room occupancy (for example, bathroom versus living room), variation in non-residential radon exposure, variation in inhalation rates, lack of exposure data from early-life (previous) dwellings, co-exposure effects such as from smoking, and exposure from radon-220 (thoron).

Another factor regarding the reliability of radon risk estimates deserves consideration. The assessment of exposure risk in miner studies (National Research Council, 1998) is considered an indirect estimate because it was not based on actual internal dose rates but instead was based on exposure to decay products measured in mine air. However, since this time, several researchers have derived direct estimates of exposure risk using pooled residential studies from populations in China, Europe, and the U.S. (Lubin, 2010; Field, 2010; Darby, 2005). Their direct estimates from pooled residential studies corroborate the indirect model-derived risk estimates obtained from miner studies (Krewski, 2000).

Table 6. Estimated total combined increased lifetime cancer mortality risk for mixed population of ever and never smokers from inhalation of radon and decay products released from water and ingestion of radon in water.

| Concentration of radon in water, pCi/L | Estimated total combined increased lifetime cancer mortality risk for mixed population of ever and never smokers from inhalation of radon and decay products released from water and ingestion of radon in water[a] |
|---|---|
| 300 | 2.0E-4 (2 per 10,000) |
| 1,000 | 6.7E-4 (7 per 10,000) |
| 2,000 | 1.3E-3 (13 per 10,000) |
| 4,000 | 2.7E-3 (27 per 10,000) |
| 10,000 | 6.7E-3 (67 per 10,000) |
| 15,000 | 1.0E-2 (100 per 10,000) |
| 20,000 | 1.3E-2 (130 per 10,000) |
| 40,000 | 2.7E-2 (270 per 10,000) |

[a] From National Research Council (NRC), Risk Assessment of Radon in Drinking Water, National Academy Press, p. 16, Table ES-1, as derived from NRC's 1999 report titled Biological Effects of Ionizing Radiation VI: The Health Effects of Exposure to Indoor Radon.

When considering the contribution of waterborne radon to the inhalation risk, a distinction must be made. Release of radon from water contributes both to the average (whole-house) exposure throughout the home and to the short-term exposure in bathrooms, laundry rooms, and kitchens during water use. Generally, the largest source of short-term exposure is the release of radon from water during showering, and the subsequent inhalation of the ionized decay products Po-218 and Po-214 which emit potentially damaging high energy alpha particles. It is estimated that showering may add from 2 to 20 percent to the overall radon exposure otherwise expected from a direct 10,000:1 (whole-house average) transfer coefficient, depending on the time spent in the bathroom during and after showering (Vinson and others, 2008).

Assessing the actual risk from ingestion of waterborne radon is problematic. Large-scale epidemiologic studies with the power to examine the association between ingesting high concentrations of waterborne radon and the occurrence of adverse health outcomes are lacking. Risk is estimated using calculations of the dose absorbed by the tissues at risk. This presents some challenges because estimates of the tissue dose per radon intake (dose coefficient) vary widely and are not conclusive. For example, questions remain about the extent to which radon diffuses into the stomach wall (alpha particles emitted by radon and its daughter products while inside the stomach do not have the range to impact cells in the stomach wall). Questions also remain about the behavior of radon activity as it moves through the body.

## 4. Key Considerations in Selecting a Recommended Advisory Level

Radon is a known human carcinogen that occurs in indoor air and groundwater drinking supplies at elevated levels that could pose a public health risk to citizens of NC. This risk can be divided into three components: 1) inhaling radon that originates in soil gas beneath the home, 2) inhaling radon that degasses during use of household water, and 3) ingesting radon rich drinking water.

Inhaling indoor air radon that originates in soil gas beneath the home on average poses, by far, the largest component of the cancer risk related to radon exposure. **However, even though water may contribute only a small amount of the total radon found in indoor air, the amount of radon released from water - *by itself* – may pose a greater estimated health risk than the risk posed by many other drinking water contaminants that are regulated, including other radionuclides such as uranium and combined radium.** This point is significant and is a key consideration facing policy makers. That is, should the regulatory community address a *portion* of the overall risk associated with a contaminant like radon in drinking water, even if the much larger risk – that associated with soil gas radon - cannot be regulated directly? Many argue that the answer is yes. They reason that if soil gas radon did not exist, radon in water would already have been regulated at stringent levels in order to adhere to EPA's typical increased lifetime cancer risk tolerance range (1 in 10,000 to 1 in 1,000,000 increased lifetime cancer risk) for contaminants in drinking water[7].

The typical range of increased lifetime cancer incidence risk that EPA and most states will accept is 1.0E-4 to 1.0E-6, as shown in Table 7. This level of increased cancer incidence risk is exceeded by radon in water at even the very low level of 300 pCi/L (the proposed EPA MCL), which carries an estimated increased lifetime cancer mortality risk for never smokers of 2.0E-4 (table 6). Radon in water at 4,000 pCi/L (the proposed Alternate EPA MCL) carries an estimated increased lifetime cancer mortality risk for never smokers of 2.7E-3 (table 6).

Often, radon in water may add only a small increment to indoor air radon concentrations because of the relatively small volume of water used in the home in comparison to the large volume of air into which the radon is released and because of the natural exchange of indoor and outdoor air. So for most homes, even if water is treated to remove radon, the mitigation of radon in water may not substantially reduce the total radon-related cancer risks faced by the homeowner. For this reason, most residents will choose to mitigate indoor air radon before treating radon in water and by so doing will usually achieve higher risk reduction per dollar spent. However, for public water suppliers, economies of scale may help reduce the per capita cost of treating radon in water.

It is recognized that radon mitigation dollars usually should be spent first on lowering the soil gas contribution to indoor air concentrations. However, it also is recognized that there are instances where mitigation of radon in water is prudent and necessary. Examples include cases where radon rich water is used in dwellings that are less susceptible to soil gas radon such as mobile homes and upper floor apartments. Other examples include homes in which soil gas mitigation is not completely successful or in cases where radon in well water is very high. Another consideration is that homeowners with indoor air radon just below the EPA action threshold of 4

[7] While a naturally-occurring background concentration clause exists in the NC groundwater standards, the maximum allowable concentration for regulated contaminants is typically linked to an incremental lifetime cancer risk of 1.0E-6 as prescribed in NC Administrative Code 15A NCAC 02L .0202 Paragraph d (2).

pCi/L may choose to forgo mitigation, but their overall exposure risk may actually be *above* the threshold when household water use and short-term exposure risks are considered.

Table 7. Current Federal drinking water standards or enforceable standards for public water supplies and associated estimated increased lifetime cancer incidence risks.

| EPA-Regulated Compound | MCL, in ug/L | Basis for MCL | Increased Lifetime Cancer Risk Estimate |
|---|---|---|---|
| Arsenic | 10 | Cost; EPA believes, given present technology and resources, this is the lowest level to which water systems can reasonably be required to treat | 1E-2 (1 in 100) |
| Benzene | 5 | Analytical feasibility | 5E-6 (5 in 1,000,000) |
| Ethylene dibromide (EDB) | 0.05 | Analytical feasibility | 1E-4 (1 in 10,000) |
| Heptachlor epoxide | 0.2 | Analytical feasibility | 5E-5 (5 in 100,000) |
| Pentachlorophenol | 1 | Analytical feasibility | 3E-6 (3 in 1,000,000) |
| Tetrachlorodibenzodioxins | 0.00003 | Analytical feasibility | 1E-4 (1 in 10,000) |
| Tetrachloroethylene | 5 | Analytical feasibility | 1E-5 (1 in 100,000) |
| Trichloroethylene | 5 | Analytical feasibility | 5.9E-5 (6 in 100,000) |
| Vinyl chloride | 2 | Analytical feasibility | 8E-5 (8 in 100,000) |

MCL, maximum contaminant level; ug/L, micrograms per liter

In selecting a recommended advisory level, it is important to consider and balance risk, feasibility of mitigation, costs, and percentage of wells expected to exceed the chosen level. It is widely agreed that it is technically feasible to mitigate radon in water to very low levels of 100 pCi/L or less using well-known treatment techniques such as aerators and filtration. Treatment options have been thoroughly evaluated and summarized in the NRC report (1999). However, costs to treat radon in water (bubble aeration, granular activated carbon, and others) are estimated to average about $2000 to $4000 per home, an amount that may be cost prohibitive to some homeowners. Costs to treat indoor air radon from soil gas (passive or active depressurization systems) are estimated to average about $1500 to $2500 per home. These systems are usually very effective at reducing indoor air levels to below 4 pCi/L, and often to 2 pCi/L (NRC, 1999). Given the cost considerations and the fact that soil gas treatment is usually more effective in lowering one's overall exposure to radon than treating radon in water, limited mitigation dollars must be allocated with this in mind. Any recommended advisory must consider and acknowledge this fact.

Best available estimates suggest that about half of all wells in the NC Piedmont and mountains may exceed a value of about 1,900 pCi/L, a level which poses a total combined inhalation and ingestion increased lifetime cancer mortality risk of 1.3E-3 (13 in 10,000) among a mixed population of ever and never smokers, and an ingestion only increased lifetime stomach cancer mortality risk of 1.4E-4 (1 in 10,000). However, the risks increase in the radon susceptible areas where about half of the wells may exceed a value of 4,680 pCi/L, a level which poses a total combined inhalation and ingestion increased lifetime cancer mortality risk of 3.1E-3 (31 in 10,000) among a mixed population of ever and never smokers, and an ingestion only increased lifetime stomach cancer risk of 4E-4 (4 in 10,000). It should be noted that given the geology of NC, homes in the Blue Ridge Province, and EPA Zone 1 counties in particular, typically have higher indoor air radon, hence overall radon exposure in this region is expected to be higher than other parts of the state.

Risk also can be considered in another way. Overall population risk can be estimated based on a given level of radon in water. This was done using results from a non-random distribution of 890 wells across the Piedmont and mountains (written communication, T. Campbell, August 1, 2010). About 90 percent of wells in this dataset have radon levels above 300 pCi/L. As shown in table 6, an advisory level of 300 pCi/L (the proposed EPA MCL) would result in a total combined inhalation and ingestion increased lifetime cancer mortality risk of 2.0E-4 (2 in 10,000) among a mixed population of ever and never smokers, and an ingestion only increased risk of 2.2E-5 (less than 1 in 10,000). About 29 percent of wells in the dataset have radon levels above 4,000 pCi/L. An advisory level of 4,000 pCi/L (the proposed Alternate EPA MCL) would result in a total combined inhalation and ingestion increased lifetime cancer mortality risk of 2.7E-3 (27 in 10,000) among a mixed population of ever and never smokers, and an ingestion only increased risk of 3.0E-4 (3 in 10,000). About 9 percent of wells in the dataset have radon levels above 10,000 pCi/L. An advisory level of 10,000 pCi/L would result in a total combined inhalation and ingestion increased lifetime cancer mortality risk of 6.7E-3 (67 in 10,000) among a mixed population of ever and never smokers, and an ingestion only increased risk of 7.4E-4 (7 in 10,000).

Table 8 provides a comparison of the risks associated with radon in water and indoor air to the risk associated with other factors as shown in tables 4 to 7. As shown in the table, exposure to radon at even moderate levels carries a higher risk than various other compounds, and exposure to moderate levels of indoor air radon carries a much higher risk than exposure to moderate levels of radon in water.

To summarize, increased lifetime cancer mortality risks associated with radon may be considered significant when compared to other contaminants. Typically, most of the risk can be significantly reduced by avoiding smoking and by mitigating indoor air radon that emanates from soil gas. However, even if a homeowner treats the indoor radon that emanates from soil gas, the risk from radon in water (degassing during household water use and direct ingestion) may remain unacceptably high. Importantly, the risk associated with radon in water alone may be greater than the risks associated with exposure to many other EPA regulated compounds. This point often is overlooked or minimized.

Table 8. Estimated increased lifetime cancer risks associated with selected radon exposure levels and other factors.

| Risk Factors | Increased Cancer Mortality |
|---|---|
| Cigarette smoking | 7.7E-2 (770 per 10,000) |
| Air pollution | 1.0E-3 (10 per 10,000) |
| Inhaling indoor air radon at 2 pCi/L | 1.1E-2 (110 per 10,000) |
| Inhaling indoor air radon at 4 pCi/L (EPA Target Action Level) | 2.2E-2 (220 per 10,000) |
| Using water with: | |
| 300 pCi/L of radon (proposed MCL) | 2.0E-4 (2 per 10,000) |
| 2,000 pCi/L of radon | 1.3E-3 (13 per 10,000) |
| 4,000 of radon (proposed alternate MCL) | 2.7E-3 (27 per 10,000) |
| 10,000 pCi/L of radon | 6.7E-3 (67 per 10,000) |
| 20,000 pCi/L of radon | 1.3E-2 (130 per 10,000) |
| Using water with: | |
| 10 ug/L (MCL) of arsenic | 7.1E-3 (71 per 10,000) |
| 5 ug/L (MCL) of trichloroethelyene | 6.0E-5 (less than 1 per 10,000) |
| 5 ug/L (MCL) of tetrachloroethelyene | 1.0E-5 (less than 1 per 10,000) |
| 5 ug/L (MCL) of benzene | 5.0E-6 (less than 1 per 10,000) |
| 2 ug/L (MCL) of vinyl chloride | 8.0E-5 (1 per 10,000) |
| 0.05 ug/L (MCL) of ethylene dibromide | 1.0E-4 (1 per 10,000) |

pCi/L, picocuries per liter; MCL, maximum contaminant level; ug/L, micrograms per liter

## 5. Recommended Advisory

The EPA strongly recommends mitigating indoor air radon above 4 pCi/L (increased lifetime cancer mortality risk of about 7.4E-3 (74 in 10,000) for never smokers). However, the EPA also supports mitigating indoor air radon above 2 pCi/L (www.epa.gov/radon/healthrisks.html) (increased cancer mortality risk of about 3.7E-3, or 37 in 10,000, for never smokers) because research suggests that even low levels of radon carry some risk. The risk associated with 2 pCi/L is two to three orders of magnitude higher than the risk level associated with most EPA-regulated compounds in drinking water. Lubin (2010) estimated that two-thirds of radon-induced cancers occur in homes with indoor radon *below* 4 pCi/L. The World Health Organization recommends mitigating indoor air radon above 2.7 pCi/L (WHO, 2009). Given these considerations, a reasonable target for combined sources of radon to indoor air is 4 pCi/L or below, with the understanding that an indoor air level of 2 pCi/L or less is far safer and is desired. This is the view held by the Committee.

Existing data suggest that the median indoor air radon level for homes across NC is about 2 pCi/L. Fortunately, mitigation systems can, in most instances, reduce indoor air radon concentrations from soil gas to 2 pCi/L or less and can reduce radon in water to inconsequential levels (soil gas and water are the two main sources of indoor radon).

In keeping with the EPA's goal of limiting indoor air radon to the EPA action level (currently set at 4 pCi/L or less), the Committee seeks to address the *combined* sources of radon (radon from soil gas and water) and limit the combined exposure level accordingly. In most homes in NC the predominant source of indoor air radon is from soil gas. However, in some areas of the state that are particularly susceptible to elevated levels of radon in water, a significant portion of the indoor air radon may be from water. This advisory accounts for both sources of radon and thus is a comprehensive and practical approach to effective mitigation. While the Committee does not ignore the ingestion risk, the recommended advisory focuses primarily on the much larger inhalation risk.

The Committee approach to radon in water is as follows (fig. 1): Indoor air radon should be tested in all occupied dwellings in NC. A radon-in-water test is recommended for all homeowners on a potable well that meet either of two criteria: (1) the home has an indoor air radon test result, after mitigation, above 4 pCi/L, or (2) the home has an indoor air radon test result above 2 pCi/L and is located within an area of moderate to high susceptibility to elevated radon in water as identified by the DWQ's program to map naturally occurring contaminants (currently identified areas are outlined in fig. 3 and table 2). The primary purpose of the radon-in-water test is to determine whether water is a significant contributor to indoor air radon levels. The Committee recommends limiting the combined radon exposure (from soil gas and water) to 4 pCi/L or less. However, the Committee also recognizes the benefit of achieving an even lower exposure level (and the reduced risk associated with a lower level), and suggests that homeowners consider, as an option, a mitigation goal for combined sources of indoor air radon of between 2 and 4 pCi/L.

The Committee recommends a radon-in-water advisory be established at two levels. The "moderate" level is between 4000 and 10,000 pCi/L, and the "elevated" level is above 10,000 pCi/L. Each level triggers specific recommended actions for the well owner. The goal of the advisory is to encourage well owners to evaluate their *overall* radon exposure from both water and soil gas sources and to lower the combined risk to an equivalent of 4 pCi/L or preferably less. This advisory uses the widely accepted average water-to-air transfer coefficient estimate of 10,000 to 1, in which 10,000 pCi/L of radon in water contributes 1 pCi/L in indoor air[8].

## Moderate Level: Radon in water between 4,000 and 10,000 pCi/L

The "moderate level" advisory of 4,000 to 10,000 pCi/L was determined as follows. Since radon is a known human carcinogen, many believe that a prudent public health goal is no additional risk above normal ambient outdoor radon concentrations. Across the United States, the average outdoor radon concentration is 0.4 pCi/L (maximum is 1 pCi/L). However, studies show that the Appalachian Mountains are associated with higher levels of outdoor radon than the national average (NRC, 1999), and many areas of the Piedmont and mountains are underlain by uranium rich rocks. A reasonable range of outdoor radon values for NC was assumed to be 0.4 to 1 pCi/L. This range equates to water concentrations of 4,000 to 10,000 pCi/L when applying the 10,000:1 water to air transfer coefficient. Using these assumptions, a radon-in-water advisory of 4,000 to 10,000 pCi/L may be considered to be as protective as exposure to estimated NC outdoor air concentrations. The actual outdoor radon concentrations across NC will vary widely depending on geology, season, and other factors. This "moderate level" advisory is designed to alert the well owner that radon in water is present at a moderate level, and re-testing is recommended to confirm the original value. Mitigation is considered optional at this advisory level.

[8] The transfer coefficient estimate is based on an *aggregate* of all homes and may under- or over-estimate the transfer coefficient at a specific home due to the wide range of home sizes, volumes, air exchange efficiencies, and other factors specific to a given home (NRC, 1999).

Recommended actions: The well owner is advised to re-test both the radon in water and indoor air radon levels to confirm the original results. Values can fluctuate based on season, recent rainfall, window and heating and air system use, and other factors, so re-testing is important. Worst case indoor air concentrations often are obtained when the home is closed and heating or cooling systems are operating. If the original radon-in-water results are confirmed, treatment of radon in water may be considered optional. If the indoor air radon level is 4 pCi/L or more, then mitigation of soil gas radon is strongly recommended. A lower action threshold of 2 pCi/L is safer and should be considered as an optional mitigation goal. It is assumed here that building materials are not a significant source of radon to the indoor air, but further testing by a N.C.-certified radon specialist may be used to confirm this.

Professionally installed indoor air radon mitigation systems typically rely on reversing or neutralizing pressure-induced airflows into the home. These systems are usually very effective at reducing indoor air radon to acceptable levels. Prices can vary substantially but often range from about $1200 to $2500. Other simple methods also may be used to help lower indoor air radon levels (table 9), but most may be minimally effective when not used in conjunction with an installed pressure reversal system.

Table 9. Simple indoor air radon mitigation methods often used in conjunction with an installed pressure reversal system.

| Mitigation technique | Potential drawbacks |
|---|---|
| leave house windows open as often as comfortable | solution is only temporary; may significantly reduce energy efficiency of the home; may be only minimally effective |
| use a bathroom exhaust fan and keep a window and (or) door open during showering | use of bathroom fan may be only minimally effective |
| use fans, vents, and thick plastic ground cover in crawl spaces | may be only minimally effective (Brennan and others, 1990; Scott, 1993) |
| seal cracks in basement slabs | difficult to identify and seal all cracks; may be only minimally effective |
| repair seals around plumbing fixtures that protrude through basement slabs | may be only minimally effective |

## Elevated Level: Radon in water above 10,000 pCi/L

Radon in water at 10,000 pCi/L contributes on average about 1 pCi/L to the total indoor air concentration. This is a significant portion – about a third to a half - of the overall amount of indoor air radon measured in an average home in NC (the average indoor air radon level in NC homes is about 2.6 pCi/L[9]).

[9] The average indoor air radon concentration for measured NC homes is 2.6 pCi/L, based on data obtained from NC Radiation Protection Section website http://www.ncradon.org/countydata/weballcounty_1.html, accessed January 6, 2010 (median values were not reported). Median indoor air radon concentration for the

The "elevated level" advisory of above 10,000 pCi/L was determined as follows. First, in a large number of homes this amount of radon in water would represent a significant portion of the overall radon contribution to the indoor air. In many cases, radon in water at this level would contribute between a third and a half of the radon dose from all sources (including soil gas). Second, the Committee adopted a radon-in-water risk model methodology used by EPA. For EPA risk assessments, a compound found in drinking water may contribute no more than 20 percent of the overall exposure dose received from all pathways (EPA, 1990). So in the case of radon, 20 percent of the overall exposure limit recommended by EPA (4 pCi/L of radon in indoor air) would be allowed from water, and 80 percent would be allowed from soil gas. Therefore, the amount of radon allowed from the waterborne source would be 20% x 4 pCi/L = 0.8 pCi/L. Using the 10,000 to 1 transfer coefficient, this amount equates to 8,000 pCi/L in water. Finally, it is assumed that the well water will be stored for a short period inside the well bore, pressure tank, and (or) water heater prior to use inside the home. During this short storage period radon will decay somewhat (radon has a half life of 3.8 days) so a slightly higher level would be acceptable. Therefore, a target advisory level of 10,000 pCi/L represents a reasonable threshold for radon in water above which treatment may be desired. Radon in water at 10,000 pCi/L adds a total increased lifetime cancer risk of about 2.5E-3 (25 in 10,000) among never smokers.

<u>Recommended actions:</u> The well owner is advised to re-test both the radon in water and indoor air radon levels to confirm the original results. Values can fluctuate based on season, recent rainfall, window and heating and air system use, and other factors, so re-testing is important. The well owner should compare, using the 10,000:1 water to air transfer coefficient, the relative radon contributions from soil gas (as measured by the indoor air radon test) and radon in water. It is assumed that building materials are not a significant source of radon to the indoor air, but further testing by a certified radon specialist may be used to confirm this.

Cases in which radon in water may be the primary contributor to overall indoor air radon include 1) mobile homes (which generally are not in close, sealed contact with the ground and thus may have lower relative soil gas radon contributions than other dwelling types), 2) upper level apartments/room (which tend to have lower soil gas contributions than ground level apartments/rooms), and 3) homes in areas of susceptibility to high levels of radon in water (currently identified areas are shown in fig. 3 and table 2). Radon in water may be the predominant source of radon in each of these cases, and this possibility should be considered when evaluating whether to mitigate soil gas radon, radon in water, or both.

The goal is to achieve an overall combined radon exposure from water and soil gas of 4 pCi/L or preferably less. Wells with radon of 10,000 pCi/L will contribute on average about 1 pCi/L to the overall indoor air level. Therefore the total target soil gas contribution will be 3 pCi/L or less. If measured indoor air radon levels are above 4 pCi/L, it may be appropriate to mitigate at least one, but possibly both, sources of radon exposure. In most though not all cases, it is advisable to mitigate soil gas radon first as it typically is the dominant source.

Aerator systems (bubbler systems that vent off-gassed radon out of doors) are considered to be an optimal, though somewhat costly ($2000 to $4000) treatment technique to remove radon from water. Somewhat less expensive, whole house carbon filtration systems are usually very effective at removing radon but often have significant drawbacks when radon levels exceed about 5,000 pCi/L. Carbon filters may become saturated fairly quickly depending on the radon levels and

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890 well study area in the Piedmont and mountains was 1.6 pCi/L, based on data obtained from 238 homes at which indoor air radon was measured.

filter size, and disposal problems can occur due to the buildup of radioactive decay products over time.

If treatment costs are prohibitive for a well owner, a low cost, low technology approach such as temporary storage may reduce the risk of radon ingestion to acceptable levels. Because half of the radon in water will decay in 3.8 days, simply storing water for several days may be effective in significantly reducing the level of ingestion risk from radon in water. For example, radon in water of 20,000 pCi/L will be reduced to 5,000 pCi/L in about 8 days. If this water is stored outside the living space of the home, then it will also reduce the inhalation risk associated with off gassing of the radon rich water. However, one drawback to stored water is the potential degradation of water quality over time, depending on length of storage, type of container, storage temperature, exposure to sunlight, and other factors.

In some cases, some simple methods may help lower indoor air radon levels, particularly when used in conjunction with a professionally installed radon venting system. These methods and their potential drawbacks are shown in table 9.

## 6. Implications for North Carolina Well Owners and Recommended Steps

An indoor air radon test is recommended for all homes in NC. The flow chart shown in figure 1 may be used to help determine whether or not to mitigate indoor air radon and whether or not to test for and treat radon in water. Mitigation of indoor air radon is usually more effective at reducing overall radon exposure than treating radon in water. Any mitigation strategy should weigh the relative benefits of lowering indoor air radon concentrations that enter the home as soil gas versus those that enter from water.

As detailed in this report, several areas in the NC Piedmont and mountains are particularly susceptible to elevated radon in groundwater, a region heavily dependent upon groundwater for drinking supplies (USGS Water Use, 2005, http://nc.water.usgs.gov/infodata/wateruse.html). Of all *public* groundwater users in these regions, 20 percent are in areas of particular susceptibility to elevated radon in water[10]. Based on existing radon-in-water data and geology, it is inferred that perhaps 15 to 20 percent of all wells in the Piedmont and mountains may exceed 4,000 pCi/L of radon in water (increased lifetime cancer mortality risks of 27 per 10,000), and 5 percent may exceed 10,000 pCi/L (increased lifetime cancer mortality risks of 67 per 10,000). The large majority of these exceedances are expected to occur in parts of Buncombe, Caldwell, Catawba, Cleveland, Franklin, Gaston, Henderson, Jackson, Lincoln, McDowell, Mecklenburg, Mitchell, Rutherford, Transylvania, Vance, Wake, Watauga, Wilkes, and Yancey Counties (fig.3 and table 2). It is recommended that these areas receive extra focus on community awareness, education, and radon reduction. Additional areas may be added to this list as new data are collected.

Several counties lack radon-in-water data, and nearly half of public groundwater users in the Piedmont and mountains are located in areas that lack sufficient data to infer susceptibility to elevated radon in water. Moreover, many of these counties are known to contain rock units that

[10] Some studies suggest that dissolved radon tends to be higher in private wells than in public systems (Hess and others, 1985). Private wells are small, closed systems that can result in radon build up, while public systems generally have a longer residence storage time with longer distribution systems which allows for some radon decay before reaching the end user.

are commonly associated in other areas of the state with elevated radon in water (fig. 3). Few wells in the Coastal Plain are expected to contain elevated levels of radon in water.

It should be emphasized that dissolved radon levels may vary widely – from high to low – within a given area. Wells drilled in most rock types across the Piedmont and mountains have at least some probability of containing elevated dissolved radon. The conclusions drawn in the Committee report are based on existing data and the relative likelihood of a given radon level in a given rock type.

Information about indoor air radon testing and mitigation may be found at www.ncradon.org, http://www.epa.gov/radon/index.html, and http://www.epa.gov/radon/pubs/consguid.html. It is recommended that homeowners follow the protocols described by the EPA for indoor air radon using a short-term test kit (exposure period of two to seven days) followed a week later by a second short-term test. Closed house conditions should be maintained 12 hours prior to and during radon testing. Radon testing should be performed in the lowest living level of the home and the detector should be placed at least 20 inches off the floor and away from drafts or other objects. Testing should not be performed in bathrooms due to issues related to humidity. If the indoor air radon concentration is near or above 4 pCi/L, then a long-term test of three months to a year is recommended to confirm the levels measured by the short-term tests (short-term results may fluctuate hourly due to weather and other factors).

If the results of the longer-term radon testing indicate that the indoor air radon concentrations are close to or exceed 4 pCi/L on an average annual basis, then mitigation of indoor air radon from soil gas is strongly recommended. A lower action threshold of 2 pCi/L is safer and should be considered as an optional mitigation goal. The higher the radon concentration, the greater the risk and need for radon reduction in the home. A list of certified mitigation specialists who can reduce the radon concentrations in indoor air is available from the American Association of Radon Scientist and Technologists (http://www.aarst.org/measure_mitigation.shtml). It is recommended that the homeowner obtain two to three mitigation bids and use only a reputable contractor experienced in radon mitigation.

Short-term and long-term indoor air radon kits can be obtained from local hardware or building supply stores, and, in some cases, at county environmental health departments and county extension agencies. Kits also can be obtained by calling 1-800-SOS-RADO. Short-term indoor radon tests range in price from $10 to $25. Long-term tests should be placed for at least 90 days; costs vary from around $25 to $125. Radon test results are usually sent directly to the homeowner. Questions about test results may be directed to the laboratory, NCDENR Radiation Protection Section, NCDENR Division of Water Quality, NCDHHS Division of Public Health, the county environmental health department, or the EPA.

Radon-in-water test kits can be obtained from local home improvement or building supply stores, selected laboratories that specialize in radon-in-water analysis, and the N.C. Division of Water Quality Asheville Regional Laboratory. These tests range in price from $20 to $75. If radon in water is above the advisory levels in this report then re-testing is recommended to confirm the results prior to evaluating mitigation strategies.

A program of additional sampling of radon in water is recommended in areas that lack adequate data. Emphasis should be placed on areas underlain by uranium rich rocks. Elevated dissolved radon susceptibility maps should be updated as new data become available. Currently, the N.C. Division of Water Quality and others continue to sample and map additional areas as resources allow.

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Appendix 1: Average indoor air radon levels for counties in North Carolina, obtained from N.C. Radiation Protection Section website http://www.ncradon.org/countydata/weballcounty_1.html, accessed January 6, 2010.

| County | Number of readings | Average indoor air radon, pCi/L | County | Number of readings | Average indoor air radon, pCi/L |
|---|---|---|---|---|---|
| ALAMANCE | 62 | 0.92 | JOHNSTON | 15 | 0.48 |
| ALEXANDER | 22 | 2.09 | JONES | 63 | 1 |
| ALLEGHANY | 18 | 5.67 | LEE | 135 | 1.19 |
| ANSON | 96 | 1.29 | LENOIR | 22 | 0.39 |
| ASHE | 42 | 3.22 | LINCOLN | 50 | 3.26 |
| AVERY | 61 | 3.69 | MACON | 71 | 2.85 |
| BEAUFORT | 22 | 0.79 | MADISON | 15 | 1.46 |
| BERTIE | 98 | 1.01 | MARTIN | 11 | 0.74 |
| BLADEN | 7 | 0.6 | MCDOWELL | 39 | 2.98 |
| BRUNSWICK | 15 | 0.33 | MECKLENBURG | 275 | 1.06 |
| BUNCOMBE | 243 | 4.95 | MITCHELL | 23 | 7.27 |
| BURKE | 55 | 2.53 | MONTGOMERY | 15 | 1.43 |
| CABARRUS | 56 | 1.87 | MOORE | 42 | 2.08 |
| CALDWELL | 59 | 2.31 | NASH | 100 | 1.03 |
| CAMDEN | 11 | 1.54 | NEW HANOVER | 74 | 0.54 |
| CARTERET | 27 | 0.38 | NORTHAMPTON | 23 | 2.71 |
| CASWELL | 105 | 2.77 | ONSLOW | 44 | 0.87 |
| CATAWBA | 114 | 2.03 | ORANGE | 97 | 1.87 |
| CHATHAM | 26 | 1.1 | PASQUOTANK | 13 | 0.28 |
| CHEROKEE | 25 | 4.41 | PENDER | 13 | 1 |
| CHOWAN | 16 | 0.74 | PERQUIMANS | 13 | 0.58 |
| CLAY | 17 | 3.67 | PERSON | 15 | 2.43 |
| CLEVELAND | 347 | 3.47 | PITT | 42 | 0.59 |
| COLUMBUS | 19 | 0.37 | POLK | 27 | 3.48 |
| CRAVEN | 20 | 0.59 | RANDOLPH | 50 | 1.62 |
| CUMBERLAND | 98 | 1.04 | RICHMOND | 16 | 1.02 |
| CURRITUCK | 14 | 0.45 | ROBESON | 25 | 0.64 |
| DARE | 16 | 0.32 | ROCKINGHAM | 73 | 3.98 |
| DAVIDSON | 65 | 2.04 | ROWAN | 50 | 1.22 |
| DAVIE | 30 | 2.15 | RUTHERFORD | 149 | 2.57 |
| DUPLIN | 11 | 0.47 | SAMPSON | 21 | 0.66 |
| DURHAM | 230 | 1.23 | SCOTLAND | 15 | 0.98 |
| EDGECOMBE | 43 | 0.86 | STANLY | 37 | 2.56 |
| FORSYTH | 433 | 3.53 | STOKES | 119 | 2.7 |
| FRANKLIN | 23 | 3.11 | SURRY | 100 | 2.18 |
| GASTON | 325 | 3.01 | SWAIN | 26 | 3.46 |
| GATES | 74 | 0.98 | TRANSYLVANIA | 46 | 6.08 |
| GRAHAM | 12 | 3.52 | TYRRELL | 14 | 0.35 |
| GRANVILLE | 25 | 1.2 | UNION | 25 | 1.1 |
| GREENE | 13 | 0.67 | VANCE | 33 | 2.14 |
| GUILFORD | 381 | 2.16 | WAKE | 791 | 2.32 |
| HALIFAX | 18 | 1.65 | WARREN | 13 | 3.71 |
| HARNETT | 19 | 0.62 | WASHINGTON | 16 | 0.98 |
| HAYWOOD | 129 | 3.5 | WATAUGA | 144 | 8.06 |
| HENDERSON | 251 | 6.68 | WAYNE | 13 | 0.96 |
| HERTFORD | 8 | 0.34 | WILKES | 80 | 2.66 |
| HOKE | 6 | 0.53 | WILSON | 98 | 1.24 |
| HYDE | 10 | 0.36 | YADKIN | 30 | 2.42 |
| IREDELL | 84 | 2.27 | YANCEY | 10 | 2.44 |
| JACKSON | 48 | 2.51 | | | |