

RADON HAZARD MAPS OF CENTRAL APPALACHIAN STATES

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## ABSTRACT

Approximately 220,000 indoor radon measurements have been compiled for several central Appalachian states: eastern New York, New Jersey, eastern Pennsylvania, Maryland and Virginia. The measurements have been compiled according to zip codes, and strong geologic control seems evident. The Coastal Plain Province is mostly composed of zip code areas that average less than 3 pCiL<sup>-1</sup> in all the central Appalachian states. The Piedmont is mostly 3-6 pCiL<sup>-1</sup> where glaciated in eastern New York, and northern New Jersey. The eastern side of the Piedmont in Maryland and Virginia are variable (most zip codes average 3-6 pCiL<sup>-1</sup> and 6 pCiL<sup>-1</sup> and above). The western side of the Maryland and Virginia Piedmont, and its extension into eastern Pennsylvania and New Jersey are mostly 6 pCiL<sup>-1</sup> and above. The rift basins which formed in the Piedmont are less than 3 pCiL<sup>-1</sup> where glaciated in eastern New York and northern New Jersey, but are mostly 3-6 pCiL<sup>-1</sup> in western New Jersey, eastern Pennsylvania, Maryland and Virginia.

The Highlands are mostly 3-6 pCiL<sup>-1</sup> where glaciated, but reach over 6 pCiL<sup>-1</sup> where not glaciated in New Jersey and eastern Pennsylvania. Similar rocks, known as the Blue Ridge in Maryland and Virginia, have a variable indoor radon signature (less than 3, 3-6 and 6 pCiL<sup>-1</sup> and above). The Valley and Ridge is less than 3 pCiL<sup>-1</sup> where glaciated in New York, but rapidly increases to 6 pCiL<sup>-1</sup> and above in most of New Jersey through Virginia.

## INTRODUCTION

Attempts to identify areas with an unusually high number of homes that contain elevated indoor radon concentrations is a popular activity that has scientific merit (Alter and Oswald, 1987, 1988; Cohen and Gromicko, 1988; Nero and others, 1986). It is estimated that 8 to 25 percent of all current lung cancer deaths are due to exposure to airborne radon (Puskin and Yang, 1988). The concern has intensified since the discovery that inhaled radon passes through the lungs to be dissolved in body fluids and tissues (Pohl and Pohl-Ruling, 1967; Lykken and Ong, 1989; Henshaw and others, 1990), and consequently may initiate soft tissue cancers.

Previous studies have shown that most homeowners are sufficiently concerned about radon hazards to properly use indoor radon monitors obtained from commercial testing companies (Mose and Mushrush, 1988a, 1988b; Mose and others, 1988; Mushrush and Mose, 1988, 1989; Mushrush and others, 1989). Homeowner concern is so great that even if the indoor radon monitors are supplied directly by a testing company, without any involvement of a science advisor beyond that provided by written instructions, the indoor measurements are quite indicative of the actual radon situation.

Few studies have been done to compare regional indoor radon levels to regional variations in geology. Some studies have concentrated on a small part of a state (Moschandreas and Rector, 1982; Froelich and Pearson, 1988; Rose and others, 1988; Washington, 1988; Brookins, 1986, 1988; Luetzelschwab and others, 1989; Smith and Hansen, 1989). Particularly relevant are studies by Hess and others (1982, 1983, 1985), who examined indoor radon variations related to a variety of rocks in Maine that are similar to rocks found throughout the Appalachian terrane.

Other studies have examined the radon potential of an entire state. Watson and others (1988) studied variability among the Appalachian geological provinces in North Carolina, and Muessig and Bell (1988) studied these same provinces in New Jersey. It was possible to show that in North Carolina and New Jersey, the eastern part tends to have lower indoor radon levels, while the central and western parts both have higher indoor radon levels.

The following interpretations of state radon hazard maps are based on compilations of many measurements supplied by several major testing companies: Air Chek in North Carolina, Enrad in Maryland, Key Technology in Pennsylvania, Tech/Ops Landauer in Illinois, and The Radon Project in Pennsylvania. The measurements were obtained using either alpha-track radon monitors with exposure intervals of several weeks to several months, or activated charcoal monitors using exposure intervals of several days. In the states examined in this study, about 10% of the compiled measurements were from alpha-track monitors, and about 90% were from activated charcoal radon monitors.

Although a particular homeowner may be better served by obtaining measurements using exposure intervals of several months (Mose and others, 1990), compilations of many short-term monitors are considered equally useful. Consequently, measurements using both types of radon monitors were combined to create the radon hazard maps presented in this paper. To make the radon hazard maps, the average radon measurements were compiled according to the zip code of the measured homes. In this method, areas in which several adjacent zip code areas show a similar high-radon or low-radon level are

deemed significant. Isolated zip code areas with an unusually high or low indoor radon compared to adjacent areas are not considered significant, and are assumed to represent a statistical anomaly. The important observation, as will be discussed below, is that state radon hazard maps show broad areas of high or low average indoor radon which correspond to particular geological units. The identification of these units is the purpose of this paper.

The following discussions are supplemented by maps which show zip code areas over entire states. The maps show zip codes with low indoor radon (less than  $3 \text{ pCiL}^{-1}$ ), intermediate ( $3-6 \text{ pCiL}^{-1}$ ) and high ( $6 \text{ pCiL}^{-1}$  and above) indoor radon. In this study, each zip code area had to have at least 5 measurements to be characterized as low, intermediate or high indoor radon. Most zip code areas had considerably more than 5 measurements; the average is about 60 measurements per zip code area.

## EASTERN NEW YORK AND NEW JERSEY

Approximately 70,000 indoor radon measurements were sent to us for eastern New York and New Jersey. Figure 1 shows the geological provinces in eastern New York and New Jersey, and their extension into the central Appalachians. Figures 2 and 3 show the distribution of indoor radon measurements. Figures 4 and 5 show the zip code areas with less than  $3 \text{ pCiL}^{-1}$ . Figures 6 and 7 show the  $3-6 \text{ pCiL}^{-1}$  areas; Figures 8 and 9 show the zip code areas that average  $6 \text{ pCiL}^{-1}$  and above.

I. The Coastal Plain Province comprises the southeastern half of New Jersey and Long Island in New York (on Figure 1, the Coastal Plain is located along the eastern margin of most of eastern North America, south and east of the Piedmont). The Coastal Plain is composed of sediments (mostly terrestrial and marine sand and clay strata) which range in age from Cretaceous to Holocene (135 million years old to the present), and which owe their origin to the opening of the modern Atlantic Ocean. A comparison of the geology map with the radon hazard maps shows that the Coastal Plain is characterized by the lowest range of indoor radon (less than  $3 \text{ pCiL}^{-1}$ ).

II. The Piedmont Province comprises the most densely populated portion of the central Appalachians (see Figure 1: Province "A"). The Piedmont continues into the northeastern Appalachians, and constitutes most of New England (see Figure 1: Province "B"). The Piedmont is composed of Latest Precambrian through Ordovician rocks (@ 600 to 450 million years old) which were recrystallized deep in the Earth during the more recent of the two Appalachian mountain building events. In southeastern New York, part of this terrane is covered by red terrestrial sandstone and shale, plus basaltic volcanic rocks, which range in age from Late Triassic through Early Jurassic (230 to 190 million years ago). These cover rocks accumulated in a fault-bounded valley ("rift basin") which formed due to tensional forces just prior to the opening of the modern Atlantic. In New Jersey, most of the ancient Piedmont rocks are covered by the rift basin rocks.

In southeastern New York and in northeastern New Jersey, the Piedmont and its rift basin cover rocks are partly covered by glacial till, deposited during glacial advances over the past 2 million years. In both southeastern

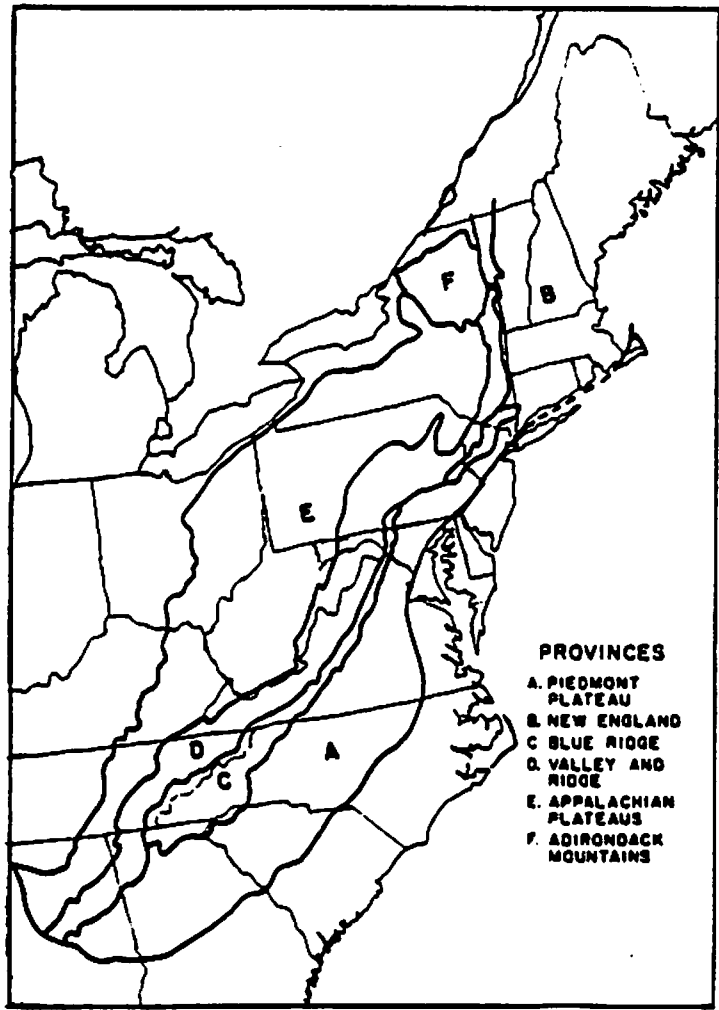
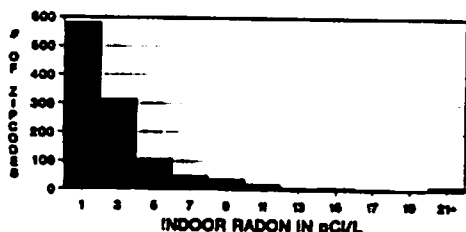


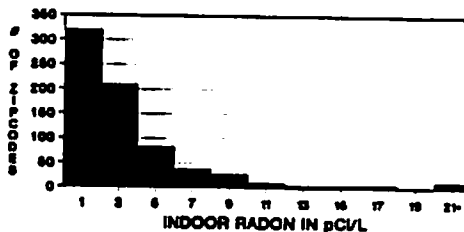
Figure 1. Geological provinces in eastern North America.

**EASTERN NEW YORK  
INDOOR RADON  
DISTRIBUTION OF ZIPCODE AVERAGES**



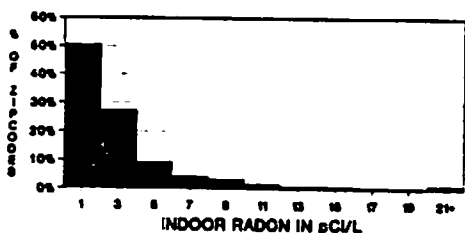
STATE AVERAGE IS 3.49 pCi/L  
STATE MEDIAN IS 1.99 pCi/L

**NEW JERSEY  
INDOOR RADON  
DISTRIBUTION OF ZIPCODE AVERAGES**



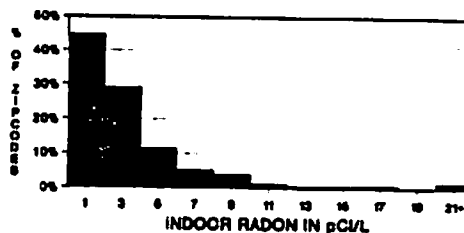
STATE AVERAGE IS 3.72 pCi/L  
STATE MEDIAN IS 2.23 pCi/L

**EASTERN NEW YORK  
INDOOR RADON  
DISTRIBUTION OF ZIPCODE AVERAGES**



STATE AVERAGE IS 3.49 pCi/L  
STATE MEDIAN IS 1.99 pCi/L

**NEW JERSEY  
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STATE AVERAGE IS 3.72 pCi/L  
STATE MEDIAN IS 2.23 pCi/L

Figure 2. Eastern New York.

Figure 3. New Jersey.

**RADON HAZARD MAP OF EASTERN NEW YORK BY ZIPCODE**



AVERAGE RADON/ZIPCODE  
MEASURED IN pCi/L

■ UP TO 3

Figure 4. Eastern New York zip code areas with average indoor radon of less than 3 pCiL<sup>-1</sup>.

### RADON HAZARD MAP OF NEW JERSEY BY ZIPCODE



AVERAGE RADON /ZIPCODE  
MEASURED IN pCi/L

■ UP TO 3

Figure 5. New Jersey zip code areas with average indoor radon of less than 3 pCiL<sup>-1</sup>.

### RADON HAZARD MAP OF EASTERN NEW YORK BY ZIPCODE



AVERAGE RADON/ZIPCODE  
MEASURED IN pCi/L

■ 3 TO 6

Figure 6. Eastern New York zip code areas with average indoor radon of 3-6 pCiL<sup>-1</sup>.

### RADON HAZARD MAP OF NEW JERSEY BY ZIPCODE



AVERAGE RADON /ZIPCODE  
MEASURED IN pCi/L

■ 3 TO 6

Figure 7. New Jersey zip code areas with average indoor radon of 3-6 pCiL<sup>-1</sup>.

### RADON HAZARD MAP OF EASTERN NEW YORK BY ZIPCODE



AVERAGE RADON /ZIPCODE  
MEASURED IN pCi/L

■ 6 AND ABOVE

Figure 8. Eastern New York zip code areas with average indoor radon of 6 pCiL<sup>-1</sup> and above.

New York and northeastern New Jersey, the zip code areas of the glaciated rift basin rocks mostly average less than 3 pCiL<sup>-1</sup>. However, south and west of the limit of glaciation in New Jersey, the rift basin zip codes mostly average 6 pCiL<sup>-1</sup> and above (some areas are above 12 pCiL<sup>-1</sup> in Hunterdon County, NJ and Mercer County, NJ).

Virtually none of the ancient Piedmont rocks are exposed in New Jersey due to the subsequent formation of the overlying rift basin strata. In southeastern New York, the Piedmont terrane is mainly characterized by indoor radon of 3-6 pCiL<sup>-1</sup>, though areas of 6 pCiL<sup>-1</sup> and above are found close to the Connecticut border (parts of Dutchess County, NY have zip codes with average indoor radon concentrations of over 12 pCiL<sup>-1</sup>).

III. The Blue Ridge Province (Figure 1: Province "C") contains the oldest rocks of the central Appalachians. Rocks of similar age and composition are found in New England: Reading Prong in eastern Pennsylvania and New Jersey; Hudson Highlands in New Jersey and southeastern New York. Rocks of the Blue Ridge and related areas in New England are mainly granites and gneisses, Late Precambrian in age (1300-800 million years old), which were formed during the older of the two Appalachian mountain building episodes. Where glaciated in southeastern New York and northeastern New Jersey, most areas average 3-6 pCiL<sup>-1</sup>. However, near and south of the glacial termination, in northwestern New Jersey, indoor radon averages quickly increase to over 6 pCiL<sup>-1</sup> (parts of Warren County, NJ and Morris County, NJ have zip codes that average above 12 pCiL<sup>-1</sup>).

IV. The Valley and Ridge Province (Figure 1: Province "D") is underlain by faulted and folded terrestrial and marine sedimentary rocks that range in age from Cambrian through Devonian (570 to 345 million years ago). These rocks were deformed during the Appalachian mountain building event that recrystallized the older rocks of the Piedmont Province, and were subsequently glaciated in all but western New Jersey. In the Valley and Ridge, indoor radon increases from north to south. Valley and Ridge zip codes are less than 3 pCiL<sup>-1</sup> in eastern New York, 3-6 pCiL<sup>-1</sup> in southeastern New York and northwestern New Jersey, and 6 pCiL<sup>-1</sup> and above in western New Jersey (part of the Valley and Ridge terrane is above 12 pCiL<sup>-1</sup> in Warren County, NJ).

V. Two additional provinces are found in New York. The Plateau Province (Figure 1: Province "E"), which consists of undeformed Cambrian through Devonian strata, and the Adirondack Province (Figure 1: Province "F"), a circular uplift area which is geologically similar to the Highlands Province. The Plateau Province shows a high variability in indoor radon (approximately equal numbers of zip code areas of less than 3, 3-6 and more than 6 pCiL<sup>-1</sup>). Approximately half of the Adirondack Province zip codes have enough measurements to be compiled, and these areas all have averages of less than 3 pCiL<sup>-1</sup>.

#### EASTERN PENNSYLVANIA

Approximately 50,000 measurements were compiled in eastern Pennsylvania.



## RADON HAZARD MAP OF NEW JERSEY BY ZIPCODE

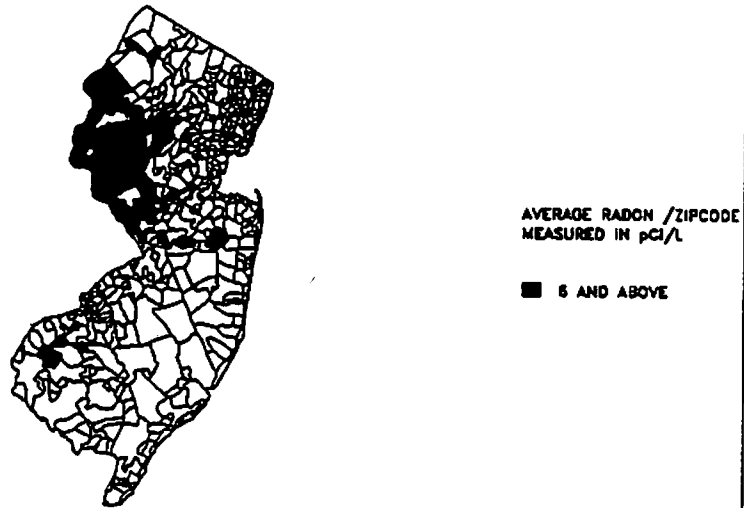
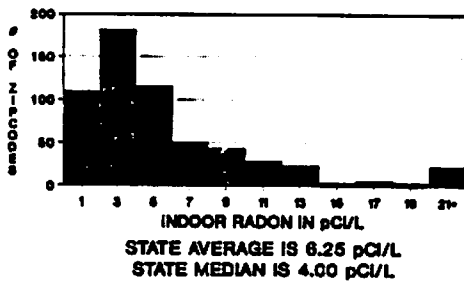
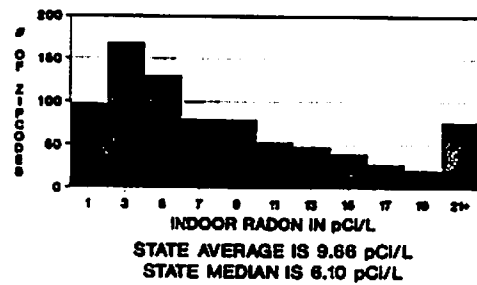


Figure 9. New Jersey zip code areas with average indoor radon of 6 pCi/L and above.

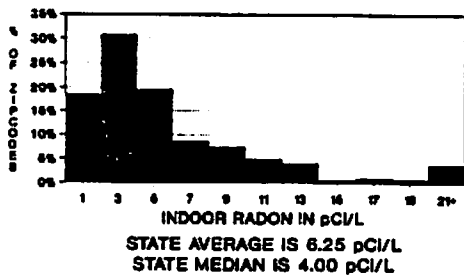
### WESTERN PENNSYLVANIA INDOOR RADON DISTRIBUTION OF ZIPCODE AVERAGES



### EASTERN PENNSYLVANIA INDOOR RADON DISTRIBUTION OF ZIPCODE AVERAGES



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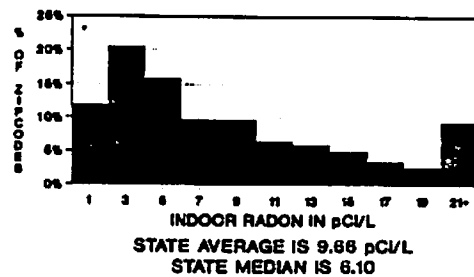


Figure 10.

Figure 10 shows the distribution of measurements. Figures 11-13 show the areas with low, intermediate and high indoor radon.

Only a small part of eastern Pennsylvania, located along the extreme southeastern margin of the state, contains sedimentary strata of the Coastal Plain Province. As is found in other states, the Pennsylvania Coastal Plain contains almost entirely zip code areas with average indoor radon concentrations of less than  $3 \text{ pCiL}^{-1}$ .

The metamorphic rocks of the Piedmont in eastern Pennsylvania are partly overlain by rift basin red sedimentary rocks and volcanic rocks. The Pennsylvania rift basin strata are similar in age and origin to rift basin rocks found in New York and New Jersey, and though the rift basin is not continuous, similar rocks persist through Maryland and Virginia. In eastern Pennsylvania, the rift basin zip code areas mostly average 3-6  $\text{pCiL}^{-1}$ . No zip code areas carry average indoor radon levels of less than  $3 \text{ pCiL}^{-1}$ ; a few areas exceed  $6 \text{ pCiL}^{-1}$ .

The metamorphic rocks of the Pennsylvania Piedmont are located south and east of the rift basin terrane. Most of the Piedmont zip code areas average  $6 \text{ pCiL}^{-1}$  and above (many areas exceed  $12 \text{ pCiL}^{-1}$  in York County, PA and in Lancaster County, PA).

Rocks of the Highlands Province are mainly exposed in the Reading Prong in Pennsylvania (in PA and NJ, "Reading Prong" is the proper name for the Highlands Province). Rocks of similar age and origin are found within oval uplifts in the Piedmont. In eastern Pennsylvania, zip codes over these metamorphic rocks are mainly in excess of  $6 \text{ pCiL}^{-1}$  (in parts of Delaware County, PA, the zip code averages exceed  $12 \text{ pCiL}^{-1}$ ).

The Valley and Ridge has a mixed characterization in terms of average zip code compilations. Some of the terrane is between 3-6  $\text{pCiL}^{-1}$ , but most of the terrane is above  $6 \text{ pCiL}^{-1}$  (zip code averages for about half of the zip code areas in Pennsylvania counties Northampton, Lehigh, Berks and Lebanon exceed  $12 \text{ pCiL}^{-1}$ ).

The Plateau Province in eastern Pennsylvania has a wide spectrum of average indoor radon estimates for zip code areas. The flat-lying Plateau Province is about equally divided between up-to-3, 3-6 and more than  $6 \text{ pCiL}^{-1}$ . Although not the subject of the paper, evidence gathered during field studies indicate that when comparing inclined riverside areas with flat-lying areas, indoor radon concentrations are often larger in riverside homes. In Pennsylvania, the distribution of radon concentrations in the Plateau Province appear to be higher in areas containing extensive river valleys. The rationale for this observation is that hillsides contain less clay in the soil, compared to flat-lying areas, so radon can more easily move greater distances before it decays to less mobile radionuclides. Present investigations are underway to investigate this observation, but at this point, the Plateau Province in Pennsylvania can best be described as having variable indoor radon.

## MARYLAND

Approximately 55,000 indoor radon measurements are available for homes in Maryland. Figure 14 shows the distribution of measurements. Figures 15-17 show the areas with low, intermediate and high indoor radon.

**RADON HAZARD MAP OF EASTERN PENNSYLVANIA BY ZIPCODE**

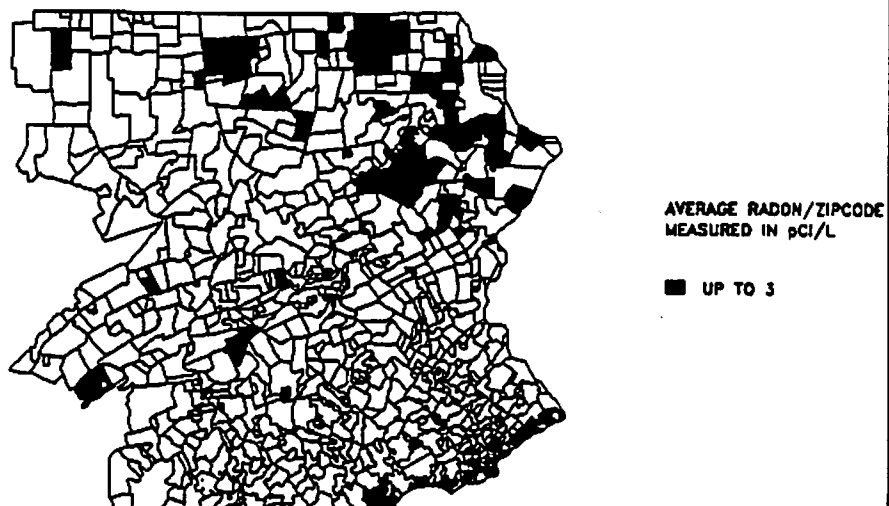


Figure 11. Eastern Pennsylvania zip code areas with average indoor radon of less than 3 pCiL<sup>-1</sup>.

**RADON HAZARD MAP OF EASTERN PENNSYLVANIA BY ZIPCODE**

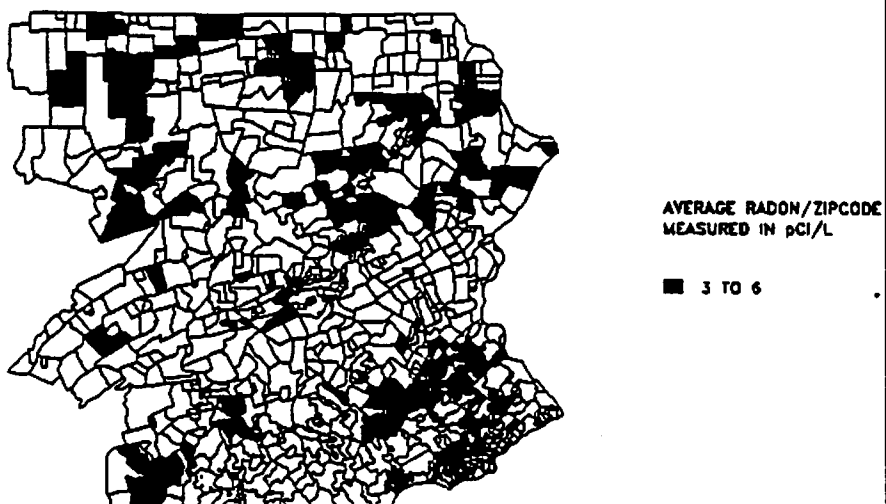


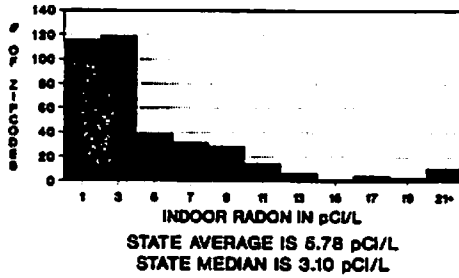
Figure 12. Eastern Pennsylvania zip code areas with average indoor radon of 3-6 pCiL<sup>-1</sup>.

**RADON HAZARD MAP OF EASTERN PENNSYLVANIA BY ZIPCODE**

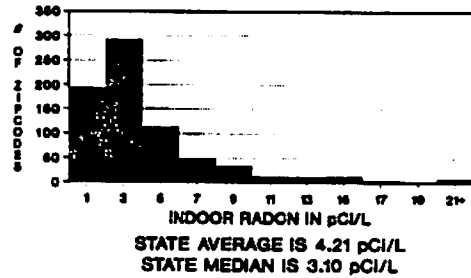


Figure 13. Eastern Pennsylvania zip code areas with average indoor radon of 6 pCiL-1 and above.

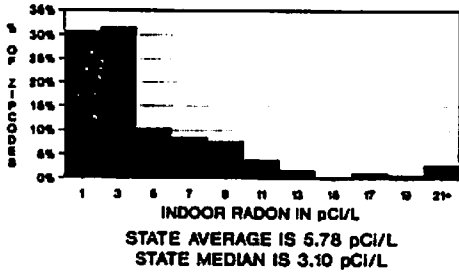
**MARYLAND**  
INDOOR RADON  
DISTRIBUTION OF ZIPCODE AVERAGES



**VIRGINIA**  
INDOOR RADON  
DISTRIBUTION OF ZIPCODE AVERAGES



**MARYLAND**  
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**VIRGINIA**  
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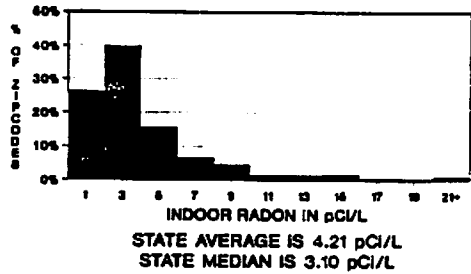


Figure 14.

Figure 18.

**RADON HAZARD MAP OF MARYLAND BY ZIPCODE**



Figure 15. Maryland zip code areas with average indoor radon of less than 3 pCiL-1.

**RADON HAZARD MAP OF MARYLAND BY ZIPCODE**

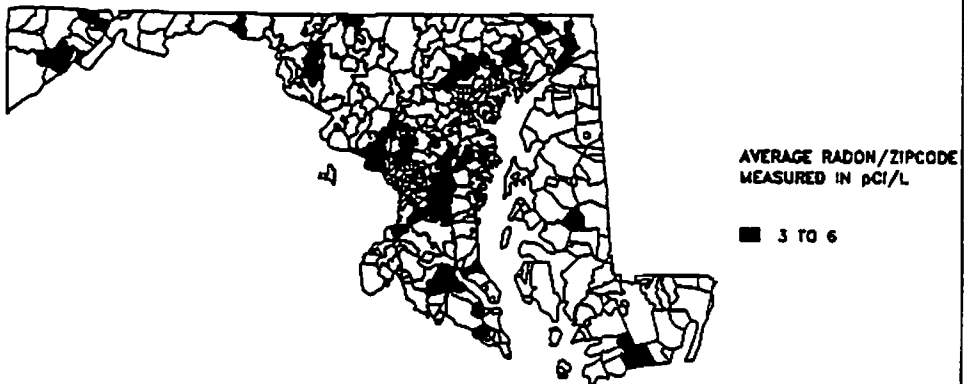


Figure 16. Maryland zip code areas with average indoor radon of 3-6 pCiL-1.

Although about half of the zip code areas in the Coastal Plain do not contain many indoor radon measurements, the measured zip code areas show that the younger and eastern part, composed primarily of marine sediments, has the lowest indoor radon. The western part of the Coastal Plain, composed of terrestrial and marine strata, mostly contains areas of low indoor radon, with fewer areas of intermediate indoor radon and a very few areas of high indoor radon.

The eastern side of the Piedmont Province, composed of highly metamorphosed strata, intrusive rocks and domal uplifts, has almost no zip code areas with less than 3 pCiL<sup>-1</sup>. The majority of the measured zip code areas average 3-6 pCiL<sup>-1</sup>. A few average 6 pCiL<sup>-1</sup> and above. The western side of the Piedmont, composed of slightly to moderately metamorphosed strata, contains the greatest concentration in Maryland of areas 6 pCiL<sup>-1</sup> and above, and almost no areas of lesser indoor radon.

The Blue Ridge Province, composed of high-grade metamorphic rocks, is relatively narrow in Maryland, with relatively few zip code areas. However, it is apparent that the zip code areas which are entirely or mostly in the Blue Ridge range from low, through intermediate, to high indoor radon.

The eastern side of the Valley and Ridge Province, which contains early Paleozoic strata dominated by limestone, contains zip code areas that average 3-6 pCiL<sup>-1</sup> or above 6 pCiL<sup>-1</sup>. The western side of the Valley and Ridge, composed of mid-Paleozoic strata dominated by clastic strata, has relatively few zip code areas. The available data suggest a range from low to high indoor radon.

The Appalachian Plateau, composed of unfolded mid- to late-Paleozoic strata, contains only a few zip code areas in Maryland. Available data suggest a range of indoor radon from low to intermediate; almost no zip code areas exceed 6 pCiL<sup>-1</sup>.

## VIRGINIA

Approximately 45,000 indoor radon measurements are available for this compilation. Figure 18 shows the distribution of measurements. Figures 19-21 show the areas with low, intermediate and high indoor radon.

The areas of lowest indoor radon are mainly in poorly consolidated clastic strata of the Coastal Plain. The metamorphic rock of the Piedmont Province shows equal numbers of zip code areas that average less than 3 pCiL<sup>-1</sup> and 3-6 pCiL<sup>-1</sup>, but the 3-6 pCiL<sup>-1</sup> areas are concentrated in the western third of the Province. The older metamorphic rock of the Blue Ridge is quite variable, with approximately equal numbers of zip code areas that average less than 3, 3-6, and more than 6 pCiL<sup>-1</sup>.

The Valley and Ridge Province with its dominantly limestone stratigraphy is the area of highest indoor radon. Almost all of the compiled zip code areas have indoor radon concentrations that exceed 6 pCiL<sup>-1</sup>. The westernmost area known as the Plateau Province has no zip code areas with enough measurements to estimate indoor radon.

## CONCLUSION

### RADON HAZARD MAP OF MARYLAND BY ZIPCODE

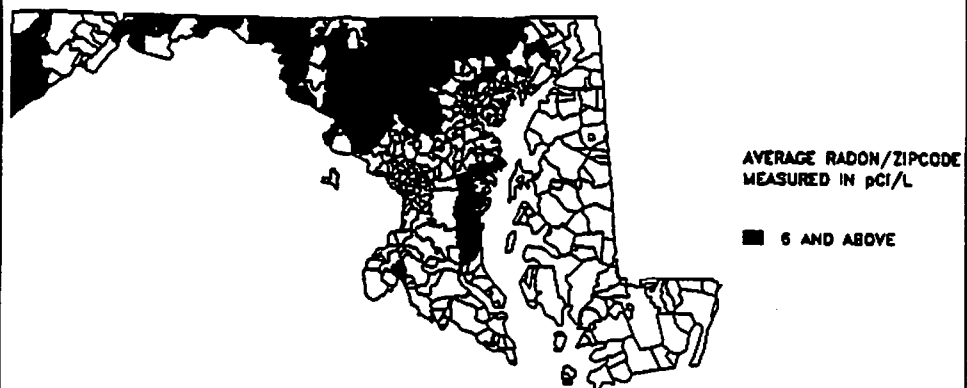


Figure 17. Maryland zip code areas with average indoor radon of 6 pCiL-1 and above.

### RADON HAZARD MAP OF VIRGINIA BY ZIPCODE



Figure 19. Virginia zip code areas with average indoor radon of less than 3 pCiL-1.

### RADON HAZARD MAP OF VIRGINIA BY ZIPCODE



Figure 20. Virginia zip code areas with average indoor radon of 3-6 pCiL-1.

### RADON HAZARD MAP OF VIRGINIA BY ZIPCODE



Figure 21. Virginia zip code areas with average indoor radon of 6 pCiL-1 and above.



Homeowner interest allowed the Center for Basic and Applied Science at George Mason University to compile over 200,000 indoor radon measurements for central Appalachians homes. Compilations of large numbers of activated charcoal indoor radon measurements and of alpha-track measurements are both useful, and can be quickly compiled to create radon potential maps. If properly constructed, these maps can be used to characterize the radon potential of large geographic areas, and to identify geological units that are of particular concern.

In eastern New York and New Jersey, zip codes with averages less than 3 pCiL<sup>-1</sup> comprise most of the Coastal Plain, the northern glaciated portion of the rift basin, and the Adirondacks. The Valley and Ridge is mostly less than 3 pCiL<sup>-1</sup> in New York, mostly 3-6 pCiL<sup>-1</sup> on both sides of the NY/NJ border, and mostly 6 pCiL<sup>-1</sup> and above in New Jersey. The glaciated portion of the Piedmont and the glaciated Highlands are mostly 3-6 pCiL<sup>-1</sup>. The unglaciated Piedmont and the unglaciated Highlands are mostly 6 pCiL<sup>-1</sup> and above.

In eastern Pennsylvania, the Coastal Plain is mostly less than 3 pCiL<sup>-1</sup>. The rift basin is mostly 3-6 pCiL<sup>-1</sup>. The Valley and Ridge contains a mixture of 3-6 and over 6 pCiL<sup>-1</sup>. The Piedmont and the Highlands are mostly 6 pCiL<sup>-1</sup> and above.

In Maryland, the Coastal Plain is mostly less than 3 pCiL<sup>-1</sup>, except along the western margin of the area, where many of the zip codes areas average 3-6 and 6 pCiL<sup>-1</sup> and above. The western Valley and Ridge is mostly less than 3 pCiL<sup>-1</sup> and 3-6 pCiL<sup>-1</sup> and the eastern side of the Valley and Ridge is mostly 3-6 and 6 pCiL<sup>-1</sup> and above. The eastern side of the Piedmont is mostly 3-6 and over 6 pCiL<sup>-1</sup>, and the western side is mostly over 6 pCiL<sup>-1</sup>.

In Virginia, the Coastal Plain is mostly less than 3 pCiL<sup>-1</sup>. The Blue Ridge and the eastern side of the Piedmont contain approximately equal numbers of zip codes that average less than 3, 3-6 and more than 6 pCiL<sup>-1</sup>. The western Piedmont is mostly 3-6 and more than 6 pCiL<sup>-1</sup>. The Valley and Ridge is mostly 6 pCiL<sup>-1</sup> and above.

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