CORRELATION BETWEEN SOIL/GEOLOGICAL CHARACTERISTICS AND INDOOR RADON IN TULSA COUNTY

By

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Introduction

Radon-222 gas is a colorless, odorless, and tasteless noble gas that is naturally occurring. The roots of radon gas formation are found in a chain of radioactive decay products of heavy unstable elements. The reaction begins with uranium-238, an unstable atom which emits an alpha particle to lower its energy potential and hence becomes more stable. This new lower energy, but also radioactive, atom is called thorium which decays to a lower energy as well. Five successive such decay events occur producing the atom of radium (Cohen, 1987). Radium, a solid, then decays to form the gaseous atom of radon-222. Since radon-222 is a gas it can percolate up through the parent radium deposits in which it was formed. Radon-222 gas may reach the surface of the earth within its 3.8 day half-life if a path with sufficiently high permeability exists. The gas can then seep into a home and become a potential health hazard to humans. The radon-222 gas atoms trapped in a closed structure, concentrate to much higher levels than the natural outdoor air radon level.

Radon-222, during its 3.8 day half-life, will decay into 4 major daughter products. These positively charged, short-lived atoms become attached to airborne particles (such as dust) and can be inhaled by a human. The inhaled

dust and its radioactive passenger are pulled deep within the bronchi of the lungs where the radon daughter products decay producing two alpha-particles which may penetrate the sensitive lung cells causing genetic damage and increasing the likelihood of lung cancer (Kerr, 1988; Cohen,1987; Sextro, 1987). An alpha particle is the nucleus of a helium atom. The most dangerous daughter products are polonium-218 and polonium-214 (Boyle, 1988). The very short half-life (3 min. for Po-218 and 1.6×10^{-4} sec. for Po-214), of the daughter products makes the dose of radiation even more dangerous since the polonium atoms will decay and emit alpha particles before the lungs' natural cleaning mechanisms can dislodge the dust particles and the damaging ionizing alpha radiation.

Other isotopes of radon are produced from the decay of radioactive elements in rocks and soils. Radon-219 and radon-220 also produce radiation as they decay but are in low concentrations in indoor air due to their very short half-life (Kunz, 1988). References to radon gas in the remainder of this paper will refer only to radon-222.

The dangers of radon gas exposure were first documented by uranium miners' elevated levels of lung cancer. Further research found radon levels could also be dangerously high in homes as well as uranium mines (Kerr, 1988). This data combined with other substantiating evidence prompted the Environmental Protection Agency (EPA) to set an advisory

action level of 4 picocuries per liter (pCi/l) of air for residential exposure in order to reduce the 5,000-20,000 lung cancer deaths a year attributed to radon gas in the United States (EPA, 1986). A curie is the rate of radioactive decay of one gram of radium per second. A picocurie is one trillionth of a curie.

Radon is not a new occurrence on the planet earth. Radon and its decay products are the major source of background radioactivity in the lower atmosphere (NEA, 1976). Radon gas atoms are constantly emerging from the earth at about 5 atoms per second for each square inch of ground (Lillie, 1986). This rate produces an average outdoor level of radon concentration of about 0.2 picocuries per liter of air. The average outdoor level of radon is normally not a public health concern due to the very low concentration.

The danger of radon's alpha radiation on public health is well accepted (Hanson, 1989). Much research has been completed across the United States to identify areas of high indoor radon potential with some success. It has also been well established that even though radon may have many means to enter a house, such as through building materials, burning of natural gas, and ground water usage, the most prominent method of radon entry is infiltration from the rocks and soil beneath a structure (Sextro, 1987; Kerr, 1988).

Very little information exits on the occurrence of indoor radon in the state of Oklahoma. Oklahoma has several

geologic deposits of elevated uranium concentration that could be radon sources (Totten and Fay, 1982; Convey, 1988). However, most of these areas are of limited geographic extent and in areas of sparse population. The deposits of elevated uranium concentration that may pose the greatest possible health risk are the black phosphatic shales of northeastern Oklahoma. The black shales are known to contain elevated levels of uranium and are also located in densely populated areas (Totten and Fay, 1982).

This paper documents a study of the radon potential of these black shales through the investigation of the geology of the black shale, soil, and indoor radon of 48 homes in Tulsa County during the summer of 1990 and the winter of 1991. The intent of this project was to produce a cost effective method that would increase the ability for homeowners and builders to predict the indoor radon potential of any construction site. The Pennsylvanian age phosphatic black shales cover wide areas of northeastern Oklahoma, Kansas, Iowa, Missouri, Illinois, and Indiana (Convey, 1988). Although only tested in Tulsa County; the procedure described within this paper should allow for easy preliminary site evaluation in any of these areas affected by radon gas produced from the black phosphatic shales.

RADON GEOLOGIC CORRELATION

Uranium-238 is found in all parts of the earth's crust at an average concentration of 2.8 parts per million (ppm). This concentration may seem very low, but in comparison, uranium is much more abundant than many other familiar minerals such as 0.1 ppm for silver and 0.005 ppm for gold (Lillie, 1986). The distribution of rocks that are high in U-238 is well documented in geologic literature. Rocks that are known to have higher levels of uranium than normal are: granites, metamorphics, black shales, and phosphate bearing rocks. As these radioactive rocks weather, the soils produced may also become more radioactive than normal (Boyle, 1988; Totten and Fay, 1982; Tanner, 1986; Durrance, 1986).

When radium in soils or rocks decay producing radon, a fraction of the radon is available for infiltration into a closed structure. Radium may be incorporated into the crystalline structure of a mineral or may be deposited on the surface of soil particles and rock fragments. Radon atoms must leave the parent radium source in order to become mobile; this can occur in the following steps: as radon atoms are produced by the disintegration of radium atoms the radon atoms recoil from the site with an initial recoil energy of 100 Kev which will produce a recoil of about 3×10^{-6} cm in a rock media (Durrance, 1986). Therefore, only radon atoms at the surface of a rock particle, near a

void or pore, may escape the rock in this manner while most of the radon remains in the soil or rock of its formation (Durrance, 1986). Radon atoms that have been produced may also diffuse from the mineral grains in which they were generated (Sextro, 1987). Since radon has such a short half life, mechanical transport in addition to diffusion is required to liberate large numbers of atoms to the surface of the earth. Mechanical transport is accomplished by moving ground water and air currents in the unsaturated zone (Durrance, 1986; Kunz, 1988). The actual percent of radon atoms that escape the parent media is known as the emanation coefficient or emanation fraction (Durrance, 1986; Kunz, 1988). Emanation coefficients tend to be higher in secondary uranium bearing minerals rather than primary uranium minerals due to the often more open molecular and physical structure of the secondary deposits (Sextro, 1987). Recoil and diffusion alone are not responsible for the emanation rate. Transport along mineral grain discontinuities also contributes to the total output (Durrance, 1986).

Moisture content of soils will increase the emanation fraction as the moisture content of soils increases from dry to 15% by volume. The increase in emanation fraction is brought about by the fact that radon atoms held in the interstitial water of the soil are more readily released to the gas phase than are atoms that have recoiled into other soil particles (Durrance, 1986).

The relationship between the radioactive decay emanation coefficient and soil parameters may be described as (Sextro, 1987) :

$$C = p*r*A / E$$

C = maximum soil gas radon concentration in undisturbed soil ($Bq\ m^{-3}$)

p = bulk density of the soil ($kg\ m^{-3}$)

r = emanation fraction

A = radium activity of the soil ($Bq\ kg^{-1}$)

E = soil porosity

Emanation coefficients also vary with time due to changes in atmospheric pressure and temperature. The release and migration of radon atoms may be most affected by faults and fractures in the rock and soil sources. Rocks with fractures and soils with desiccation cracks tend to have higher radon emanation levels than nearby areas (Osborne et al., 1989).

RADON TRANSPORT/SOIL GAS MIGRATION

Radon in soil gas may enter a home by direct movement through the foundation or openings in the floor due to cracks and services such as water, electric, natural gas, and sewage. Once radon enters a closed structure, the gas

tends to accumulate since radon is heavy, 9.73 g/l at standard temperature and pressure (STP) compared to 1.29 g/l for air at STP (Bowie and Plant, 1983). Even homes with slab foundations may provide 300 cm^2 of open area between the wall and floor slab (Eaton and Scott, 1984).

The largest percentage of infiltration of radon into homes occurs due to diffusion and pressure induced flow (Sextro, 1987; Nazaroff, 1989). Diffusion occurs because of the gradient between the low indoor concentration and the higher soil gas concentration of radon. Radon flux from the soil to the atmosphere is approximately 0.4 pCi/m^2 sec (Eaton and Scott,1984). Diffusion can account for average indoor radon levels, but pressure induced flow may be responsible for elevated concentrations of radon (Eaton and Scott, 1984).

The negative air pressure gradient between indoor air and outside air is common in all closed structures and can be accentuated by extensive weatherization of a home by decreasing the air exchange rate. Low indoor pressure is caused by the rising of warm indoor air (causing the stack effect), depressurization caused by indoor combustion sources (fireplaces, furnaces, and clothes dryers), blowing wind, and rapid atmospheric pressure changes. Absolute indoor air pressure has been measured to be 20 Pa lower than the surrounding pressure in the soil. The soil permeability and the indoor-outdoor pressure gradient may impart soil gas

transport velocities ranging from 10 cm/hr to less than 1 um/day (Eaton and Scott, 1984).

Darcy flow or pressure induced soil-gas flow can be represented as:

$$Q = K/u \quad dp/dx$$

where Q= flow in cm^3/sec, K= permeability in cm^2, u= viscosity of air= 1.8×10^{-4} poise at 18° Celsius, and dp/dx= the pressure gradient between air beneath the house and inside the house (Kunz, 1988).

Recent research in New York State conducted by the New York State Department of Health indicated that soil radon potential can be characterized by a combination of source strength and soil permeability for gas flow. Depth to bed rock, depth to water table or depth to a significantly different soil zone are also important considerations in the process (Kunz, 1988). Soil source strength may be measured by the radium concentration, emanating fraction, or the concentration of radon in the soil-gas.

Many state geologic surveys have been completed to identify problem radon areas. However, these surveys depend mainly on geological radiation data to indicate areas of high uranium/radium concentrations, hence possible high indoor radon values. This method of determination limits the usefulness of these maps to only identifying general trends. The New York study differs from most state surveys

because in it soil characteristics are of prime consideration (Kunz, 1988).

NEW YORK STATE STUDY OF SOIL AND INDOOR RADON

To examine the correlation between surficial soil radon and indoor radon in New York State, the New York State Health Department initiated a test of homes in six areas in the state (Kunz, 1988). The areas were selected by information from the National Uranium Resource Evaluation Program (NURE), mine data, surficial geology and the compiled data from a 2,400 home EPA sponsored radon survey of the state. Within each test area the surface geology did not differ greatly. The permeability of the soil to gas flow, radium-226 soil concentration and radon soil-gas concentration were measured at each home. The indoor radon concentrations were measured by carbon canister detectors during the heating season.

The results of the study brought to light the importance of source strength and permeability in characterizing the availability of the soil-gas radon for transport into homes. Areas with average soil-gas radon concentrations, but high soil permeability, produced high indoor values; while areas that had high soil-gas levels, but low soil permeability, produced low indoor radon concentrations. A combination of these factors will result in a measure of

availability of soil-gas radon for transport into homes. The New York survey employed the Radon Index Number (RIN) developed by Eaton and Scott, (1984). The calculated RIN value predicts the average indoor radon level that can be found in a home built on an evaluated site. The RIN value is dimensionless and is derived in a strictly empirical manner:

$$RIN = hE/\log k$$

E = emanation fraction of the soil

h = average ventilation period of the home (h^{-1})

k = inverse of the permeability (m^2)

The New York study suggests the RIN relationship may also be described by:

$$RIN = (\text{source term})(\text{permeability})^{1/2}$$

The source term may be soil radium concentration, soil-gas radon concentration or emanation fraction. A multiplication factor of ten was added to the RIN equation in order to make direct comparison between the RIN value and indoor radon. The multiplication factor is the number that the calculated RIN must be multiplied by in order to get the actual average indoor radon value of a tested area. The value of ten was derived by averaging all the multiplication factors calculated from different test areas in New York State. The final RIN equation employed by the New York project was:

$$RIN = 10[\text{soil-gas radon (pCi/l)}][\text{permeability (cm}^2\text{)}]^{1/2}$$

The New York study reported good success in predicting

average indoor radon values in highly permeable soils but less success in areas of low permeability (Kunz, 1988; Kunz personal communications 2/6/90, 10/12/90).

TULSA COUNTY GEOLOGY AND URANIUM

The geology of northeastern Oklahoma, including the Tulsa area, is dominated by cycles of sedimentation. During the middle Pennsylvanian age (Desmoinesian and Missourian series), the geology of Tulsa County was very active. The sea level fluctuated many times producing what is known as cyclic limestone sequences. In a typical cycle, as sea level rose due to glacial melting, deposition of dense limestones occurred. As sea level increased further, black shales and grey shales were produced as anoxic deeper water sedimentation occurred. When the glaciers returned, the sea level dropped producing coal as well as fluvial and marine deposited sandstones (Bennison et al., 1972).

The black shales in the cycles are of two varieties; phosphatic shales and carbonaceous shales. This paper will focus only on the phosphatic shales due to their high uranium content. Although radon gas is not a direct product of uranium, but of radium, almost no published information exists on the subject of radium in black shales in Oklahoma. This may be due to the lower economic value of radium in comparison to uranium. Therefore, uranium may be used as

the next best indicator of radon potential of the black shales. The geologic occurrence of uranium in the United States has been documented by many studies such as the National Uranium Resource Evaluations (NURE) flyover radiometric reconnaissance program. Oklahoma was investigated by the NURE study however the metropolitan area of Tulsa County was not surveyed (Texas Instruments, Inc., 1978). Fortunately, the tremendous economic value of oil in Oklahoma provided the impetus for much of the geologic research of the black phosphatic shales of northeastern Oklahoma.

The black phosphatic shales were known to oil well wire line loggers as marker beds due to their consistent strong "kick" on the gamma ray well log due to the uranium content. These were used for lithologic correlations between oil well bore holes. Black shales are not always black in color and can range from brown to grey to dark black. All are rich in organic matter and are characterized by (Hyden and Danilchik, 1962):

"1) common phosphatic nodules or laminae,
2) jointed and fissile occurrence,
3) high uranium content,
4) yield appreciable amounts of oil,
5) marine fossils are common,
6) commonly overlain by marine limestone caprocks."

Many phosphatic black shales outcrop in Tulsa County in the Desmoinesian and Missourian series. The shales may be

from one to two feet and up to thirteen feet in thickness north east of Oklahoma, but may have a much larger surface expression due to the low west-southwest dip and the resistance to weathering of the shales. Some of these radioactive shales are the Excello, Little Osage, Anna, Lake Neosho, and Thachet in ascending lithologic order in Tulsa County (Hyden and Danilchik, 1962).

Sextro (1987) indicated that the development of an RIN system to more systematically and efficiently locate areas of high radon potential would "depend upon the availability of relevant geological information at a sufficient geologic scale." In the case of Tulsa County, the key word again is scale. As earlier described, the black shales of interest are thin in vertical thickness and therefore surface contact is very dependent on topography. This complicates locating the shale outcrops down to the scale of individual homes in a neighborhood. One home may be constructed directly in the shale and the house next door may be above or below the shale. The Tulsa Geologic Society's geologic map of Tulsa County, as part of the Society's 1972 publication Tulsa Physical Environment, edited by Alan P. Bennison, provides unsurpassed geologic detail of the county. However, even at this scale (which is not available for much of Oklahoma) the map was inadequate to find some of the more subtle shale outcrops.

These black shales in and around Tulsa County contain

from 10 to 90 ppm uranium content with the phosphate nodules containing as high as 600 ppm (Hyden and Danilchik, 1962). The average uranium concentration of crustal material is about 2.8 ppm (Lillie, 1986). Phosphate nodules in the Excello formation were found to contain as high as 950 ppm uranium (Derby et al., 1982). Ore grade uranium contains >1000 ppm uranium (Convey, 1987). However, a great variation in uranium content can be noted in very short distances due to changes in phosphate concentration. Hyden and Danichik (1962) found a linear relationship between uranium concentration and percentage of phosphate in samples of black phosphatic shales in northeastern Oklahoma. They also found evidence of redistribution of uranium or radium by the weathering process which could greatly affect the extent of radiation contamination of other porous rocks bordering the black shales. Such migration would increase the potential of elevated radon source strength beyond the surface expression of the shale outcrop. The original source of the uranium in black shales was from precipitation from sea water during deposition and migrating formation water after deposition (Bowie and Plant, 1983). Uranium is mobile under oxidizing conditions and may be carried in solution until it encounters a reducing environment at which time the uranium will precipitate. The Pennsylvanian age black shales provided reducing conditions in the ancient ground water solutions and precipitated the uranium into the humates and

organics of the shales. When phosphate was present in the shales, uranium was deposited by uranium atoms substituting for calcium in apatite. Even in phosphate rich black shales, uranium may have originally accumulated by organic fixation, particularly if the organic matter was terrestrial (Coveney, 1988; Totten and Fay, 1982).

Soils derived from the erosion of these phosphatic shales may reflect the uranium content of the parent material depending on the oxidation-reduction characteristics and pH of circulating waters that may enrich or diminish the uranium content. However, radium is not as mobile in surface oxidizing conditions as uranium and separation from the parent material may occur (Bowie and Plant, 1983).

TULSA RADON PROJECT

The growing public concern over radon gas has prompted the initiation of many radon surveys. The EPA has tested many thousands of homes, and some states have produced radon potential maps to assist the public demand for answers.

An accurate and representative method for determining indoor radon risk from any tract of land is by actual field tests of the soils. Radon occurrence is dependent on so many factors, as outlined in this paper, that field tests may be the most cost effective method for accurate radon evaluations (Boyle, 1988).

The New York State study, described previously, provides a useful methodology for determining probable indoor radon concentrations with the RIN from geologic and soil parameters. However, the New York State study required the use of specialized tools and equipment (such as a soil gas flow probe and radiation counting electronics) that may not be available to construction companies and city planners. This project attempts to provide a method that would be available to any engineering testing company and most construction firms. Understanding the radon potential of a proposed construction site would allow city planners to design specific construction codes that would eliminate the radon soil-gas migration threat.

In order to compare soil-gas radon concentrations, indoor radon, and to attempt to develop a RIN system that is specific to Tulsa County; three areas (two control and one test) were studied in Tulsa County. In order to protect the privacy of homeowners, the exact location of the areas cannot be given, but figure 1 shows the generalized map indicating their relative distances apart. The areas were tested during the summer and winter in order to compare seasonal radon variations. The control area was divided into two sections based on soil type. Section one soil was sandy river channel deposits. Section two was more clay and organic rich over bank deposits. The test area was divided into homes that were constructed in the shale outcrop and

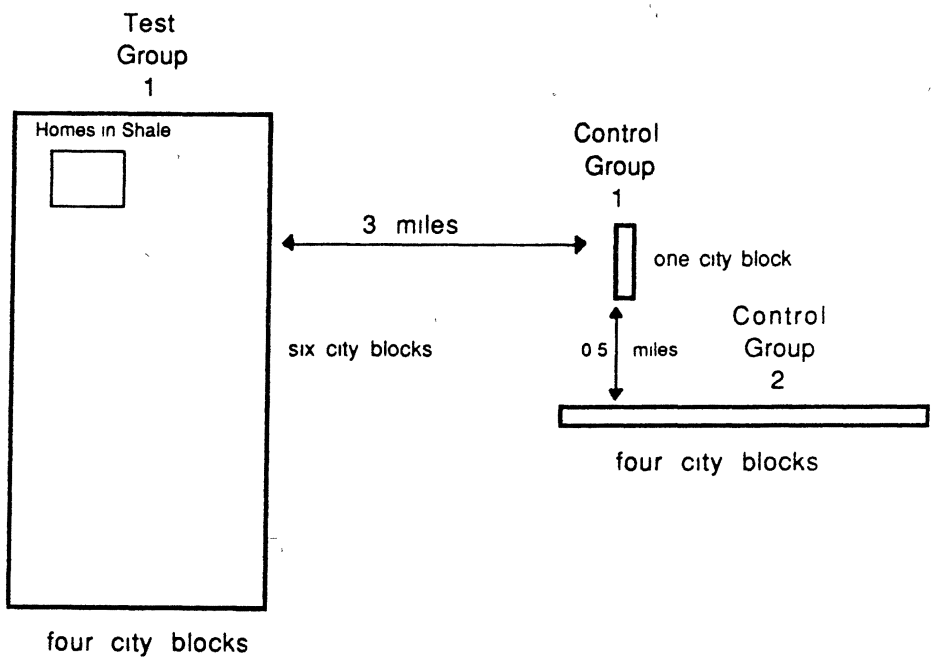

Figure 1. Generalized Map of the Investigation Area

homes that were constructed stratigraphically above and below the shale of interest.

The test area was selected by geologic occurrence of the previously mentioned phosphatic black shale outcrops within populated areas of Tulsa County. The control area was selected with homes of similar construction type (zoned single family individual structures, similar economic class, population density and with subsurface rocks/soils of normal radiation activity). The control groups contained a total of 19 homes, all of which were crawl space construction type. The test area contained 29 homes, of these 4 were slab-on-grade and the rest were crawl space type construction. Normal radiation activity of the control area was determined by geologic and radiation characteristics of the neighborhood and will be elaborated on later.

The black shale outcrops were located with the Tulsa Geological Survey map of Tulsa County and field assistance from noted Tulsa geologist Alan P. Bennison. All of the previously mentioned black shales were investigated and one formation was selected. Once the formation was selected, outcrops were studied and described. The general gamma ray activity of the formation was measured with the use of a hand held Scintrex scintillometer. The scintillometer records gamma radiation as counts per second (cps). The scintillometer detected gamma radiation only, therefore the instrument was used only to make comparative observations of

radioactivity. The assumption was made that the gamma response was produced by the elevated uranium content of the shale. The shale outcrops measured as high as 450 cps but usually registered between 120 and 300 cps depending on the weathered condition of the rock. Background radiation was measured throughout the city and was considered to be between 50 to 80 cps. No exact calculation of uranium content could be made but was assumed to be in the range (as high as 600 ppm) found by Hyden and Danilchik (1962), since the formation stratigraphy had been diligently matched to their work. Surface outcrops of the formation were uncommon and difficult to trace by visual characteristics alone because of dense home construction. The exact map location of the black phosphatic shale was determined by projecting the plane of the bed from one surface outcrop through the topographic profile of the map area, taking into account the strike and dip of the strata, and then field checking with the scintillometer. The shale registered two to three times the background activity, which allowed for identification even when no visual clues were available. However, gamma rays can only be detected through about 50 cm of soil so only near surface uranium concentrations could be located (Durrance, 1986).

The control areas were selected primarily on the basis of similar home construction type to that of the test area, single family one story bungalow of 1000 to 1500 square

feet. The radiation activity of the control area was also measured with the scintillometer and determined to have no areas of elevated gamma activity and was considered to be normal or average over the city.

Within the test area, homes were selected that came in close contact with the shale as well as stratigraphically below and above it. Homeowners were informed of the experiment by personal visits by the investigator. Homeowners did not know if they were in the test or control group. Approximately one hundred prospective homes were visited by the investigator in the test area. Of these, twenty nine homeowners agreed to participate in the project. In this group, homes were constructed in, below, and above the shale. Nineteen homes were selected in the control area where homeowner participation was more than 90% positive of those visited.

DESIGN PROCEDURE

At each house, the indoor radon concentration was measured by an activated carbon (AC) type passive flow detector (supplied by the Alpha Energy Laboratory, Inc.) placed on the first floor by the investigator in accordance with the manufacturer's instructions and EPA placement protocol for a period of three days (EPA, 1987; EPA, 1989). Concurrently, soil-gas radon of each home was tested with the use of

alpha-track (AT) etch soil monitors (supplied by Tech/Ops Landauer, Inc.) placed at a depth of 15-18 inches for a period of 30 days, per the instructions of the manufacturer, 6 feet from the foundation (in order to minimize the influence of the Darcy flow from the foundation). The vacuum effect of a depressurized home will cause increased soil-gas migration around the foundation which will dilute the true radon concentration of the soil-gas. At a distance of 6 feet from the house, this effect should be minimized (Kunz, 1988). Great care was taken, in the placement of both AC and AT detectors, to place the detectors in the same location for both winter and summer testing.

Placement and removal of all detectors was completed by the investigator only. The Alpha Energy Laboratory, Inc. and Tech/Ops Landauer, Inc. are listed as having passed the 1990 EPA radon measurement proficiency program (EPA, 1990).

Validity of the detector results were checked with the employment of ten percent blind duplicates and two to five percent blanks of both AC and AT detectors. Results of the duplicate and blank measurements are presented in Appendix A and Appendix B. The AT detectors could not be placed in the same hole but were placed in adjacent holes and therefore the detectors were not exposed to the exact same environment. The duplicate AT measurements of Home 37, which was located in the test area, were 207.4 and 52.5 pCi/l. The difference of 154.9 pCi/l is greater than the average of the

population (48.17 pCi/l). However, the inhomogeneity of the soils in the test area could easily produce large differences in soil radon due to desiccation cracks. The AC duplicate measurements averaged a difference of 0.11 (pCi/l).

Undisturbed soil samples were collected from yards where soil conditions allowed. Samples were taken with the use of a two inch diameter soil sampler which was pressed into the soil after a fifteen inch pilot hole was cut with a four inch hand auger. The collected cores were labeled and sealed to retain the in situ soil moisture conditions. Not all the collected soil samples were used in the permeability tests as some were destroyed in transit and in testing preparation.

Samples were tested for permeability with the use of a fixed walled constant head permeameter. The permeameters were located in the Geotechnical Engineering Laboratories of Oklahoma State University. Samples for permeability testing were collected in summer and winter and the results were averaged in each area. The summer and winter tests were not delineated since the hydraulic conductivity testing required that the samples be water saturated which would negate any seasonal soil characteristic differences. Permeability measurements are presented in Appendix C. Permeability, given as hydraulic conductivity, was calculated by the equation:

$$k = (Q*L) / (A*t*h)$$

k= hydraulic conductivity (cm/sec)

Q= quantity of outflow (cm^3)

L= length of sample along flow path (cm)

A= cross-sectional area of sample (cm^2)

t= interval of time over which the flow of Q occurs (sec)

h= hydraulic head (cm of water)

Currently no standard exists for fixed walled permeability measurements, however the American Society of Testing and Materials (ASTM) is currently balloting a standard for measurements entitled "Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Material Using a Flexible Wall Permeameter." The Oklahoma State Geotechnical Laboratory fixed walled permeability testing procedure was designed around the balloted system.

The summer tests were conducted during the month of August, 1990 and the winter follow up study was completed in February, 1991. During the summer experiments the average high temperature was 93.4 degrees Fahrenheit and the average low was 71.8. The total precipitation water equivalent was 1.83 inches. During the winter study the average high was 61.3 and the average low was 35.3 degrees Fahrenheit. The total precipitation water equivalent was 0.38 inches (weather data provided by the National Weather Service in Tulsa County). The hottest part of the summer was selected for the experiment because homes in Tulsa (as in many parts of the south) may be most closed to outdoor air exchange in

August when temperatures often reach day time highs of over 100 degrees Fahrenheit. The nature of the clay rich soil in Tulsa County causes tremendous shrinkage during the summer months producing desiccation cracks that may be hundreds of feet in length, three inches wide and several feet deep (as documented by the investigator during field work). These cracks can follow the same trends as deeper faults and fractures of subsurface rocks; providing an ideal radon conduit to the surface (personal communication with Alan P. Bennison 8/15/89). Desiccation cracks are controlled by the soil moisture content and therefore vary with the seasons. In the test area, desiccation cracks were most abundant in the summer and nonexistent in the winter. The cracks would supplant the bulk movement of soil-gas from the low permeability soil to the pathway of the fractures. Recent experiments on seasonal soil gas radon concentrations indicated that radon may be most abundant during the summer rather than during the winter when most radon research has been done (Rose, 1988; Sachs, 1982).

RESULTS AND DATA REDUCTION

Control Group 1

Control Group 1 consisted of 6 homes along one city block located on sandy soil which was considered to produce average indoor radon levels due to the lack of an elevated radium source. The Soil Survey of Tulsa County indicated

that the control area was in the Choska-Severn-Urban land complex (Cole et al, 1975). However, after taking many core samples of the area, the described land complex did not compare to the samples. A possible description of the soil type would be the Kiomatia soil group. The soil survey map of Tulsa County was produced from aerial maps and then field checked for accuracy but may not be accurate to the scale of this survey; this would explain the soil group inconsistency to the core samples from the area. The Kiomatia soils are described as nearly level, well drained, rapidly permeable loamy fine sand. Depth to bed rock is more than 60 inches and these soils are in locations prone to flooding. Control Group 1 soil characteristics meet the previous description and from a geologic standpoint, the location would be consistent with the dynamics of the Arkansas River. Not all homes were available for testing in the winter as well as the summer (ND appears in the tables when no data exists on that house). The test results of Control Group 1 are presented in Table 1.

The indoor radon values for summer as well as winter were, as expected from the average radiation of the soil, in the range of average indoor radon (0.8 to 1.2 pCi/l) (EPA, 1986). The winter mean indoor radon from the six homes was 30% greater than the indoor summer mean but the winter soil radon mean was 3.6% less than the summer soil mean.

Table 1

Control Group 1

House	Summer Radon Values (pCi/l) Indoor	Soil	Winter Radon Values (pCi/l) Indoor	Soil
1	0.7	162.0	0.7	138.8
2	0.4	84.0	1.2	201.4
3	0.6	339.4	1.3	51.4
4	1.2	93.6	1.1	125.3
5	0.6	110.2	0.4	153.1
6	ND	ND	1.3	242.4
ND (no data)				
Arith. Mean	0.7	157.8	1.0	152.1
Stand. Dev.	0.27	94.7	0.34	60.03

Arith. Mean Permeability 2.28×10^{-6} cm/s
Stand. Dev. 1.68×10^{-6} cm/s
(Permeability from summer and winter data)

Control Group 2

Control Group 2 consisted of 13 homes within a four city block area. The soil is listed as Choska-Severn-Urban land complex in the Soil Survey of Tulsa County, which is described as dark reddish brown, very fine sandy loam, moderately permeable, and depth to bed rock is greater than 60 inches (Cole et al, 1975). The core samples of the area coincided with the listed description but were also organic rich. The finer matrix of the soil (loamy fine sand vs. very fine sandy loam) may in part account for the lower mean permeability than that of Control Group 1. The test results are presented in Table 2.

As in Control Group 1, the winter indoor means are greater than the summer means (by almost 50%) while the winter soil radon mean values are 46% less than the summer means. The mean values of the homes tested in both winter and summer follow a similar trend.

A possible explanation for the higher indoor radon levels in the winter may be the increased negative air pressure gradient between indoor and outdoor air due to the indoor heating combustion sources.

Test Group 1

Test Group 1 covered an area four by six city blocks. Within the test area, homes located above and below the phosphatic shale were investigated. The soil in the area is classified as Coweta-Eram-Urban land complex. The soil is

Table 2

Control Group 2

House	Summer Radon Values Indoor (pCi/l)	Summer Radon Values Soil (pCi/l)	Winter Radon Values Indoor (pCi/l)	Winter Radon Values Soil (pCi/l)
7	0.6	312.3	ND	ND
8	0.5	197.9	1.4	110.5
9	1.3	238.9	ND	ND
10	0.6	186.3	ND	ND
11	0.5	192.8	1.0	124.9
12	0.8	299.3	1.4	65.4
13	1.3	202.7	2.8	180.4
14	0.1	118.2	1.8	84.6
15	1.3	349.3	ND	ND
16	1.0	267.3	ND	ND
17	0.8	ND	ND	ND
18	0.9	266.0	ND	ND
19	2.8	424.8	2.2	207.4
Arith. Mean	1.0	254.7	1.8	128.9
Stand. Dev.	0.6	80.0	0.6	50.3
Homes Tested in Both Summer and Winter				
Arith. Mean	1.0	239.3	1.8	128.9
Stand. Dev.	0.9	98.2	0.6	50.9

Arith. Mean Permeability 5.79 X 10^{-7} cm/sec
Stand. Dev. 8.01 X 10^{-7} cm/sec
(Permeability from summer and winter data)

characterized by a surface layer of very dark brown, silty clay loam, followed by a very dark grayish brown silty clay loam with the shale below. Coweta-Eram-Urban soil is listed as slowly permeable with thickness ranging from 10 to 20 inches to bedrock (Cole et al.,1975). Sampling of the soil in this area was difficult since the soil is so thin. Within the test area, 29 homes were tested. Of these homes, only 4 of the tested structures came in contact with the shale (see Table 4). The rest of the homes were constructed above and below the shale. The results of these homes are listed in Table 3.

The winter soil radon means for Test Group 1's entire population as well as the homes that were tested in both seasons are lower than the summer values, as in Control Group 2. The winter indoor radon levels are higher than the summer values in both the entire population, homes tested in both seasons and the homes below the shale. The homes above the shale had no indoor radon seasonal difference even though the soil radon was higher in the summer. The mean values for indoor and soil radon for both seasons in homes above and below the shale were very similar. This may be due to the very short distances that radon may move in low permeability soils. All the homes in this group were far enough above the shale not to be affected by the elevated source strength of the shale.

Table 3

Test Group 1

House	Summer Radon Values (pCi/l) Indoor	Soil	Winter Radon Values (pCi/l) Indoor	Soil
20 A	1.4	72.1	ND	ND
21 A	0.7	189.4	0.3	158.4
22 A	0.8	81.5	0.6	77.3
23 A	1.2	153.7	1.1	138.8
24 A	1.0(I)	301.5	ND	ND
25 A	0.5	255.8	0.6	74.4
26 A	0.4	158.0	1.3	92.0
27 A	0.2	187.6	0.6	207.4
28 A	1.9	62.4	ND	ND
29 A	1.0	95.5	ND	ND
30 B	0.5	96.9	0.8	25.0
31 A	1.0	120.7	2.1	112.1
32 B	0.3	171.1	1.5	42.9
33 B	0.8	238.7	0.3(I)	84.2
34 B	0.4	48.5	ND	ND
35 A	1.0	181.0	ND	ND
36 A	ND	ND	0.6	165.0
37 B	ND	ND	0.7	39.8
38 A	ND	ND	0.7	62.6
39 B	ND	ND	0.8	89.1
40 A	ND	ND	0.4	11.9
41 A	ND	ND	0.7	11.9
42 B	ND	ND	0.7	326.8
43 A	ND	ND	2.5	159.4
44 A	ND	ND	0.6	ND
Arith. Mean	0.8	150.9	0.9	104.3
Stand Dev.	0.4	71.5	0.6	77.0

Table 3 (Continued)

House	Summer Radon Values (pCi/l) Indoor	Soil	Winter Radon Values (pCi/l) Indoor	Soil
Homes Tested in Both Summer and Winter				
Arith. Mean	0.6	165.3	1.0	103.1
Stand. Dev.	0.3	53.5	0.5	54.4
Homes Tested Above Shale				
Arith. Mean	0.9	154.9	0.9	104.4
Stand. Dev.	0.5	70.8	0.6	76.9
Homes Tested Below Shale				
Arith. Mean	0.5	138.8	0.9	101.3
Stand. Dev.	0.2	72.3	0.3	103.5

Arith. Mean Permeability 8.80×10^{-7} cm/s
Stand. Dev. 1.38×10^{-6} cm/s
(Permeability from summer and winter data)

(I) data invalid due to tampering
(A or B following home number indicates if the home was above or below the shale)

Test Group 1 (Homes in the Shale)

Homes 45, 46, 47, and 48 in the test area came in close contact with the shale and were constructed on a slope. Twenty other homeowners of homes in the area that came in contact with the shale were contacted by the investigator, but only four homeowners agreed to participate. These four homes were less than 15 years old, slab on grade type. These homes were built later in the development of the neighborhood, after the most level home sites were taken. The slopes of the yards averaged a drop of 10 to 15 vertical ft within a horizontal distance of a 120 ft lot.

The hillside construction of these homes, combined with the thickness of the plane of the shale, complicates the prediction of indoor radon and the true soil radon value since the slab may come in contact with the shale in a small cross-sectional area as opposed to being in complete contact with the shale (see Figure 2). Homes 45 and 46 were tested twice during the summer season and at different levels within the homes to verify the test results. The test results of these four homes are presented in Table 4.

The arithmetic mean of indoor radon data from the homes constructed in the shale, in both winter and summer are above the 4 pCi/l EPA action level. An arithmetic mean of soil gas radon for each house cannot be calculated as the measurements are not comparable as in the other areas. The low winter soil radon values of Home 46, Home 47, and Home

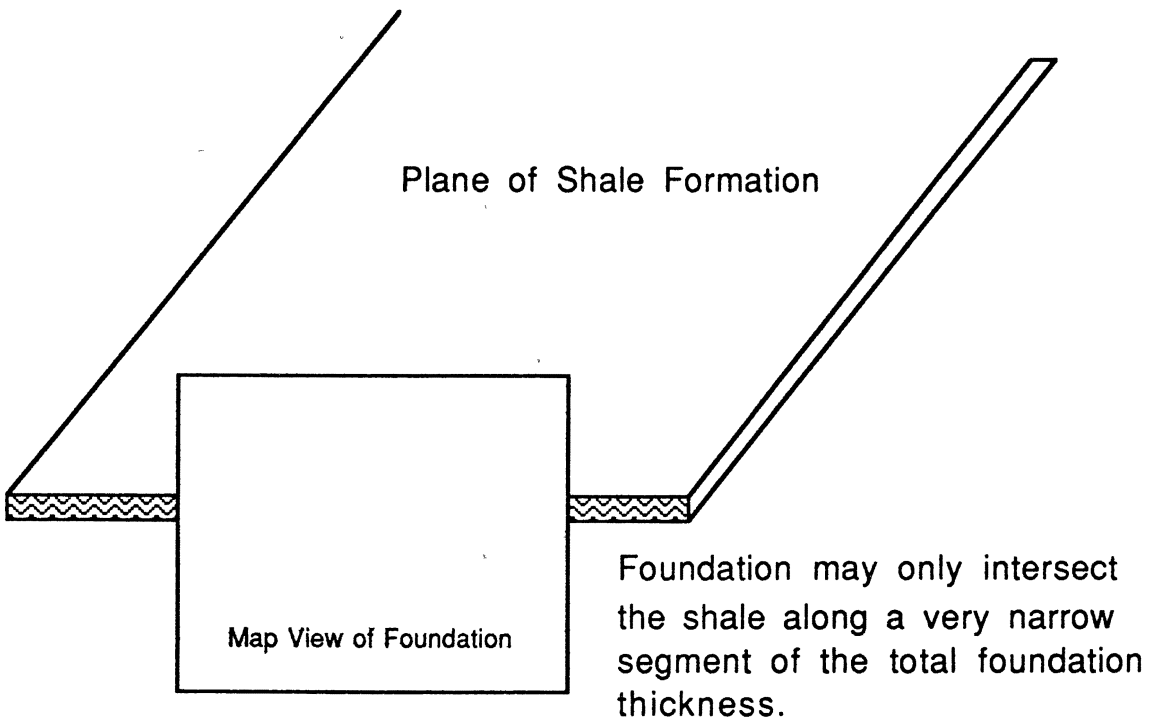

Figure 2. Map View of Foundation and Shale Intersection

Table 4

Test Group 1 (Homes in the Shale)

House	Summer Radon Values Indoor (pCi/l)	Soil	Winter Radon Values Indoor (pCi/l)	Soil
45	2.2* 3.8* 3.0* 7.6**	83.0	5.1	6883.2
46	4.9 6.6** 7.0**	866.4	3.9D 4.2D	50.6 88.1
47	ND		5.4** 4.6**	177.8 134.8
48	ND		5.1	91.0
Arith. Mean	5.0	***	4.7	***
Stand. Dev.	1.95	***	0.53	***

Arith. Mean Permeability 8.80 X 10^{-7} cm/s
Stand. Dev. 1.38 X 10^{-6} cm/s
(Permeability from summer and winter data)

*(collected at different levels (3.8 lowest, 3.0 mid, and 2.2 top) in home 45)
**(collected on different date than above data)

D Duplicate data
*** These values are not comparable (see text for details)

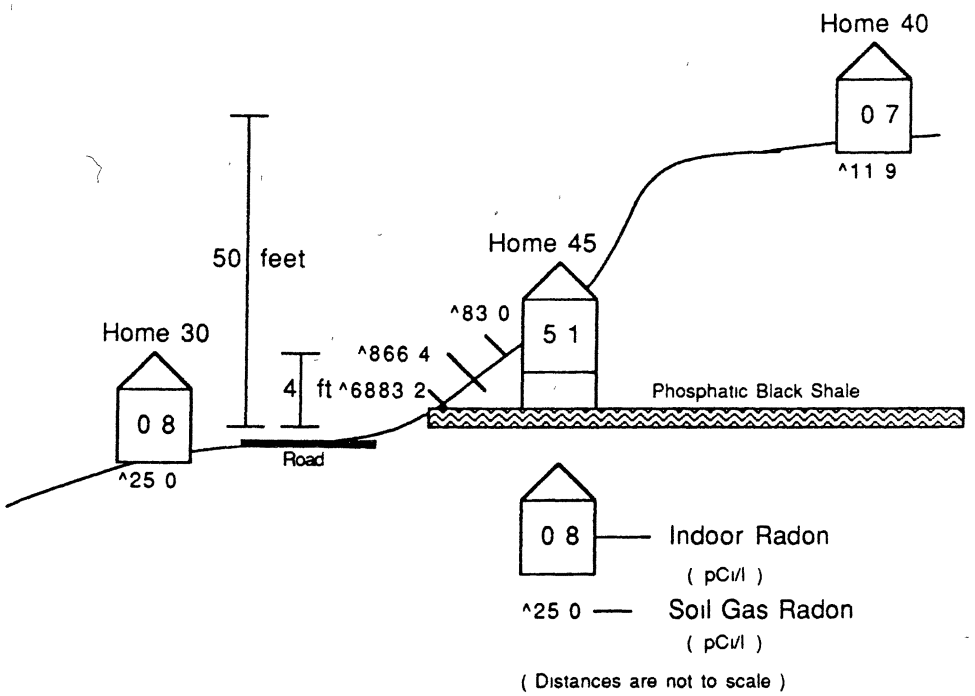

Figure 3. Cross-Sectional View of Homes 30, 45, and 40

48 obviously are not the soil radon values that produced the indoor radon of greater than 4 pCi/l. Detectors were placed above the level that the foundation came in contact with the radioactive shale and did not receive as much radon as the foundation. The exact location of the foundation-shale contact was difficult to pinpoint since the shale was underground and hidden by landscaping. Therefore, these values may not be used in calculating an average soil radon value for homes constructed in the shale. As indicated in Figure 3 (a cross-sectional view of Homes 30, 45, and 40) and Table 4, the wide variance of soil radon from a very high 6883.2 to a low 83 pCi/l is due to the deployment location of the detectors with respect to the shale outcrop. The winter soil radon value of 6883.2 pCi/l from the yard of Home 45, which was not placed in the same hole as the summer detector due to new landscaping, was taken from the soil directly above the phosphate nodule rich zone of the shale. This site registered 450 cps on the scintillometer; the highest measurement found in the test area. The low value of 83 pCi/l was taken from the same yard but four vertical feet higher and buried in fill dirt brought in after construction (unknown to the investigator at the time of placement). This very high value, only four feet below a normal soil radon value, indicates the distance that the elevated soil radon may migrate.

Home 40 (as seen in Fig. 3) which registered an indoor

radon of 0.7 pCi/l, was constructed fifty feet above the shale but was too far above the elevated radon levels to be affected by the migrating radon, as indicated by the low 11.9 pCi/l soil gas value. Home 30, which is located 150 ft from Home 45 and below the shale, also has a low winter soil gas radon value (25.0 pCi/l) which may indicate that the soil has not been affected by redistribution of the radium from the shale source.

The high summer soil gas concentration of 866.4 pCi/l from the yard of Home 46 was recorded from a detector buried 2.5 ft. above the level of the winter high of 6883.2 pCi/l from the yard of Home 45. Home 45 and 46 are next to each other. The winter duplicate values of 50.6 and 88.1 pCi/L from Home 46, which are 10 time less than the summer high of 866.4 pCi/l (deployed in the same hole), may be indicative of the general system of low permeability soil-gas radon flow due to cracks in the soil in summer and not in winter.

In low permeability soil, as found in the study areas, radon may not move by pressure induced flow as in higher permeability soils. Sextro et al. 1988, stated that convective transport of soil-gas in soils of air permeability below $10^{-12}m^2$ ($9.8x10^{-4}$ cm/sec) is negligible.

However, elevated radon levels do exist in the homes constructed in the shale. Radon is moving through the soil and is being drawn into the homes. A combination of molecular diffusion and convection may be responsible for the

elevated radon levels in the homes constructed in the shale. Radon atoms may become mobile by molecular diffusion and move into areas of higher permeability, such as desiccation cracks, where convective transport may draw the radon into a home. Control Group 2, Test Group 1, and Home 46 all exhibit seasonal variations in the mean soil radon concentration.

Control Group 1, which is in the most permeable soil of the areas studied, had a summer mean soil radon value of 157.8 pCi/l and a winter mean of 152.1 (no seasonal difference). The seasonal mean soil radon difference in Control Group 2, Test Group 1, and Home 46 in comparison to the lack of difference in Control Group 1 may indicate the role of warm temperature desiccation cracking of the soils.

Because of the close proximity of all the areas investigated in the study, they experienced similar weather conditions during the testing. However, the soils of Control Group 1 seem to have reacted differently to the seasonal weather conditions in relation to soil-gas movement and hence radon. Summer lawn watering frequency was recorded for all the test homes since watering may Affect desiccation crack formation and radon soil-gas migration. Only two homes in the entire population (in Control Group 2) watered the lawn. Therefore the effect of lawn watering on desiccation cracks and indoor radon could not be made.

The combined action of the summer desiccation cracks

and lower summer soil moisture (documented during coring attempt in winter and summer) could have caused summer mean soil radon levels to be higher in Control Group 2 and Test Group 1 while Control Group 1's sandy soil was less affected by soil cracking and produced stable mean soil-gas radon levels. The data from Control Group 1 is based on only six homes, but the assumption of the soil-gas flow may still hold true. Soil-gas may have been freer to move in Control Group 2 and Test Group 1 during the summer since the desiccation cracks provided a higher permeability path to the surface.

In all three study areas the winter indoor mean radon level was higher than the summer mean. The data is not sufficient to categorically prove or disprove the investigator's original assumption that indoor radon in Tulsa County could be higher in the summer.

Unfortunately, it is impossible to determine the net soil-gas radon concentration that occurred around the foundation of the four homes with elevated indoor radon levels (above 4 pCi/l) from this data. In order to accomplish this many AT soil detectors would have had to have been placed parallel to the foundation and perpendicular to the long axis of the hill. This would have entailed much excavation that would have been destructive to landscaping.

RIN DEVELOPMENT

In order to compare the RIN equation of the New York study to the results found in Tulsa County, several differences in the data must be addressed.

The most important difference is that of the permeability of the soil sampled. The permeability of the New York study soil samples ranged as much as six orders-of-magnitude greater than the soils tested in Tulsa County. As soil permeability decreases, flow of fluids and gases will be more affected by discontinuities such as cracks and fractures for bulk transport. This makes legitimate comparisons of radon movement in one yard difficult to superimpose on other sites at some distance.

All the homes in the New York study had basements while none did in the Tulsa study area. Which affects the amount of surface area in contact between the structure and the potential radon source soil.

As mentioned before, the very thin vertical thickness of the phosphatic black shales of northeastern Oklahoma increases the difficulty in predicting indoor radon as a foundation may come in partial contact with the shale as seen in Fig. 2. The shale formation investigated in New York State was 150 ft thick; which would change the structural dynamics of foundation contact.

The RIN equation developed by Eaton and Scott, (1984)

and utilized in the New York State study by Kunz, (1988) was used to estimate indoor radon levels to identify areas of potential radon hazard caused by high radium source strength. The elevated radioactivity of the Pennsylvanian phosphatic black shales has been demonstrated in the geologic literature reviewed in this paper. The results of the soil-gas and indoor radon data provided in this paper indicate that the shale has the potential to cause elevated indoor radon values in homes constructed in the shale.

In order to test the New York study's RIN equation of: $RIN = (\text{soil gas radon pCi/l}) * (\text{permeability})^{1/2} * (\text{multiplier})$ with the data found in Tulsa County, the mean indoor radon, mean soil radon, and mean permeability of each study area was input into the equation (just as in the development of the RIN data for the New York study). The results are set forth in Table 5.

As seen by the great variation in the multiplication factors (column 5 of Table 5), the equation does not accurately predict the mean indoor radon value of each test area equally. The multiplication factor is the number that the calculated RIN value must be multiplied by in order to get the appropriate mean indoor radon value of column 1 of Table 5. The New York study used the multiplication factor of ten to relate the RIN equation to the actual observed mean indoor radon level in the different areas in New York State. Table 6 shows the relationship of the calculated RIN value

Table 5

RIN Equation Results

Mean Indoor Radon (pCi/l)	Mean Soil Radon (pCi/l)	Mean Perm. (cm/s)	RIN	Multiplier
(Summer)		Control Group 1		
0.7	157.8	2.28×10^{-6}	0.24	2.92
(Winter)				
1.0	152.1	2.28×10^{-6}	0.23	4.35
(Summer)		Control Group 2		
1.0	254.7	5.79×10^{-7}	0.19	5.26
(Winter)				
1.8	136.5	5.79×10^{-7}	0.10	18.00
(Summer)		Test Group 1		
0.8	150.9	8.80×10^{-7}	0.14	5.71
(Winter)				
0.9	104.3	8.80×10^{-7}	0.10	9.00
		Mean Multiplier		7.54

Table 6

RIN Comparison

Mean Indoor Radon (pCi/l)	RIN (% Error)	RIN X Mean Multiplier (% Error)
(Summer)	Control Group 1	
0.7	0.24 (66)	1.81 (61)
(Winter)		
1.0	0.23 (77)	1.73 (42)
(Summer)	Control Group 2	
1.0	0.19 (81)	1.43 (30)
(Winter)		
1.8	0.10 (94)	0.75 (58)
(Summer)	Test Group 1	
0.8	0.14 (83)	1.06 (25)
(Winter)		
0.9	0.10 (89)	0.75 (175)

along with the calculated RIN value multiplied by the mean multiplier from Table 5 in comparison to the actual mean indoor radon. As seen in columns 2 and 3 (% error) of Table 6, the RIN and the RIN multiplied by the mean multiplier do not predict indoor radon equally in all areas tested. The RIN equation is only useful if it can accurately predict indoor radon over a large area and in all seasons.

The low permeability of the soils in the Tulsa study area do not seem to lend themselves to a predictive pattern. Kunz (1988), also reported lower success in utilizing the RIN equation in low permeability soils. In all areas of the study, e.g. the general home construction type, weather conditions, atmospheric pressure, and soil radon were all similar, except for the homes built in the shale. The only variable left for consideration is the soil conditions.

The soil/geologic conditions of Tulsa County, though unique are common to areas where the geology has been governed by the sea level fluctuations of an epicontinental sea. As mentioned previously, the cyclothem nature of the deposits have produced many cycles of limestone, shale, coal, and sandstone. Many of these cycles of sedimentation form the rocks below the surface in Tulsa County. As these rocks have eroded, the soils produced from the rock fragments and the action of growing plants caused the soils to have widely varying permeability. This is unique because soil characteristics may change in relatively short distanc-

es. This was encountered in the test areas. Therefore, the development of an RIN equation for Tulsa County based on permeability may be impossible.

However, the data gleaned on soil radon in Tulsa County, in particular that of the phosphatic black shale areas, may provide enough information to accurately delineate areas of high radon potential. Since soil permeability can vary within short distances it may be impractical to use for calculations in predicting radon potential of a soil.

The EPA has made an advisory action level of 4.0 pCi/l of indoor radon as a standard to which indoor radon may be compared. Since this is the level above which the EPA suggests that homeowners take action to lower indoor radon levels, the level of soil-gas radon that would produce indoor levels of radon above 4.0 pCi/l may be as valuable as an RIN equation that would predict indoor radon. Figure 4 is a graph of all summer and winter data from all test areas. The line of linear regression from the data indicate that indoor radon levels of 4.0 pCi/l and greater will be produced from soil gas radon levels of 657.9 pCi/l. The correlation coefficient of the regression line is 0.803. The soil-gas radon values of the four data points from the homes constructed in the shale which showed the highest indoor radon values, were extrapolated since the exact soil radon level at each home was not known. The soil radon values of these homes had to be between 866.4 and 6883.2

pCi/l as reflected in Table 4 and Figure 3. A conservative estimate of 1000 pCi/l of soil radon was used for these homes.

CONCLUSION

The need to cost effectively characterize areas with a potential for high indoor radon potential or any tract of land is of great significance. The phosphatic black shales of Tulsa County are known to contain elevated levels of uranium. Measurements of indoor and soil radon of homes constructed in the shale indicate that the shale may provide sufficient mobile radon gas to increase indoor radon to levels above the EPA action line of 4 pCi/l.

The RIN system, described in this paper, did not successfully project indoor radon from soil characteristic possibly due to the low soil permeability and the complexities of molecular diffusion of radon gas from the soil. A combination of molecular diffusion of radon into areas of higher permeability such as desiccation cracks and the disturbed zone under a foundation produced by home construction may have caused the elevated indoor radon values found in the homes constructed in the shale.

However, the data does indicate that soil gas radon values above approximately 650 pCi/l may produce indoor radon values above 4 pCi/l in the soil conditions in the

Tulsa test areas. Although not fully tested by this study, an apparent link to elevated indoor radon and radioactive black shales does exist. Further research into this link is necessary since the evidence points to possible public health threat from the black shales.

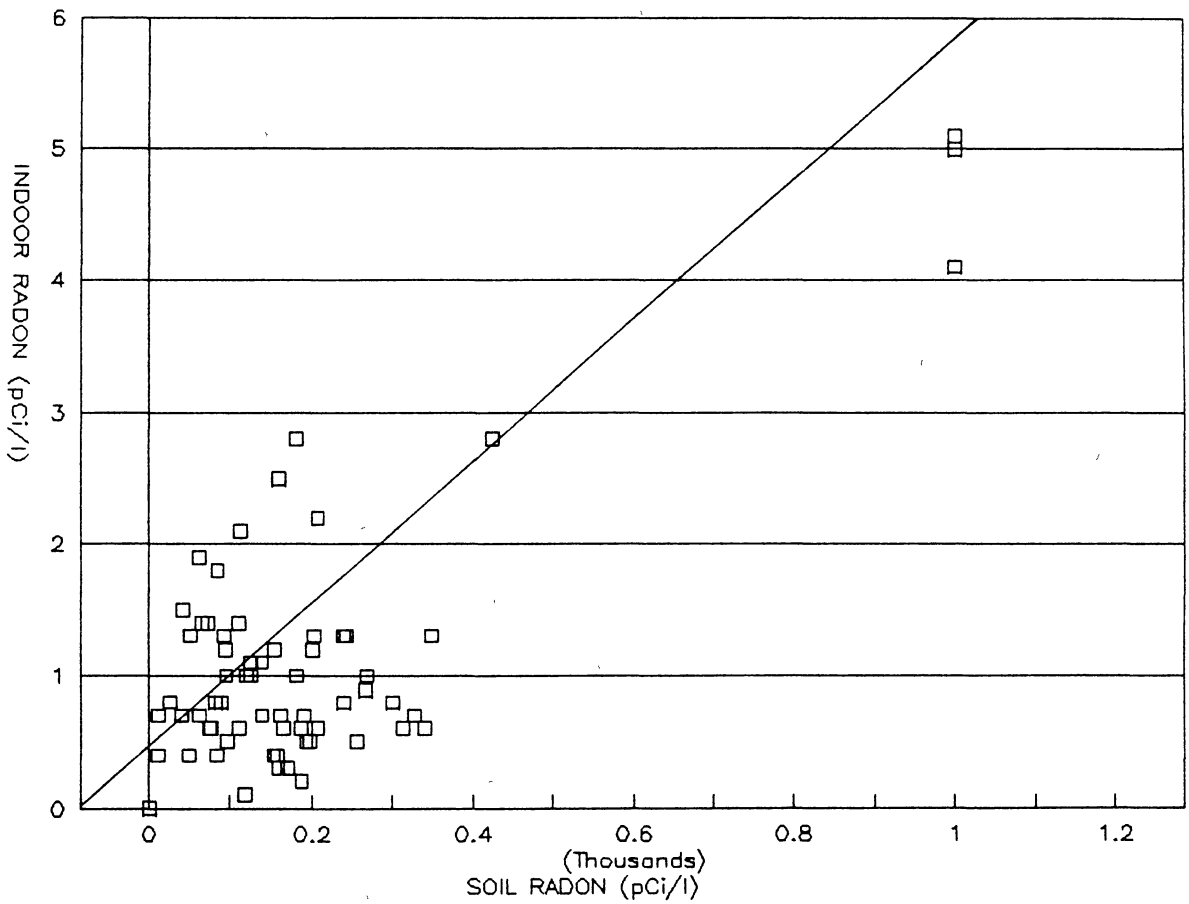

Figure 4. Plot of Winter and Summer Indoor and Soil Radon Values of all Homes Investigated

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APPENDIXES

APPENDIX A

CARBON ABSORPTION INDOOR RADON DUPLICATE AND BLANK MEASUREMENTS

CARBON ABSORPTION INDOOR RADON

DUPLICATE MEASUREMENTS

Home	Measurement (pCi/l)	Difference
16	1.0	0.1
	1.1	
46	3.9	0.3
	4.2	
37	0.6	0.0
	0.6	
36	0.6	0.0
	0.6	
42	0.7	0.0
	0.7	
1	0.7	0.0
	0.7	
19	2.4	0.4
	2.0	
	Average Difference	0.11

CARBON ABSORPTION BLANK MEASUREMENTS
(pCi/l)

0.4
0.5
0.0
0.2
0.5
0.2

APPENDIX B

ALPHA TRACK SOIL RADON DUPLICATE AND BLANK MEASUREMENTS

ALPHA TRACK SOIL RADON

DUPLICATE MEASUREMENTS

Home	Measurement (pCi/l)	Difference
47	134.8	43.8
	91.0	
46	50.6	37.5
	88.1	
37	207.4	154.9
	52.5	
36	175.7	21.4
	154.3	
1	142.8	8.1
	134.7	
19	219.0	23.3
	195.7	
	Average Difference	48.17

ALPHA TRACK BLANK MEASUREMENTS
(pCi/L)

1.4
1.9
1.4
<1.0
<1.0
<1.0

APPENDIX C

PERMEABILITY MEASUREMENTS

PERMEABILITY MEASUREMENTS
(cm/sec)

Home	Control Group 1
1	4.8317×10^{-6}
5	2.6767×10^{-6}
1	1.1692×10^{-6}
1	4.5816×10^{-7}
Arith. Mean	2.28×10^{-6}
Stand. Dev.	1.68×10^{-6}
	Control Group 2
7	7.2785×10^{-7}
8	2.4807×10^{-6}
14	2.2294×10^{-7}
17	8.9585×10^{-8}
12	2.0325×10^{-7}
18	1.8750×10^{-7}
18	1.3780×10^{-7}
Arith. Mean	5.79×10^{-7}
Stand. Dev.	8.01×10^{-7}
	Test Group 1
23	1.8174×10^{-7}
27	3.6418×10^{-6}
31	5.4646×10^{-8}
21	3.4831×10^{-7}
27	1.7170×10^{-7}
Arith. Mean	8.80×10^{-7}
Stand. Dev.	1.38×10^{-6}

VITA

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Candidate for the Degree of

Master of Science

Thesis: CORRELATION BETWEEN SOIL/GEOLOGICAL CHARACTERISTICS AND INDOOR RADON IN TULSA COUNTY

Major Field: Environmental Engineering

Biographical:

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