Radon Contamination of Residences in a City Built Upon a Karst Landscape Bowling Green, Warren County, Kentucky

James William Webster
RADON CONTAMINATION OF RESIDENCES IN
A CITY BUILT UPON A KARST LANDSCAPE
BOWLING GREEN, WARREN COUNTY, KENTUCKY

A Thesis
Presented to
The Faculty of the Department of Geography and Geology
Western Kentucky University
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In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
James William Webster
December, 1990
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RADON CONTAMINATION OF RESIDENCES IN
A CITY BUILT COMPLETELY UPON A KARST
LANDSCAPE - BOWLING GREEN, WARREN COUNTY, KENTUCKY

Recommended January 9, 1991
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Approved April 1, 1991
(Date)

Elmer Bragg
DEDICATION

This thesis is dedicated to the memory of my father:

Louis Dewey Webster
(April 18, 1919 - February 10, 1988)

A man that could not read or write but worked his whole life in order that his children might have opportunities that he never had.
ACKNOWLEDGEMENTS

The list of people to whom this author owes thanks is so great that it will not be possible to mention everyone by name. For this, the author gives his apology. The author would like to thank first the faculty and staff of the Department of Geography and Geology of Western Kentucky University for making the many years that he spent in the department both enjoyable and informative. Gratitude is expressed to Dr. Kenneth Kuehn and Dr. Wayne Hoffman for their valuable guidance. Thanks also goes to Dr. William Buckman for generously contributing his time and equipment, to Mr. Bobby Key for permitting the use of his laboratory during the later stages of the thesis research, and to Mr. Bobby Carson, the "Radon Ranger," for instructing the author on radon daughter measurement in caves. The author also would like to thank the Cave Research Foundation and the Faculty Research Committee of Western Kentucky University for providing much needed funding. The author's love and appreciation goes out to his family for their understanding and support. Above all others, the author would like to express his sincere thanks and gratitude to his thesis advisor Dr. Nicholas C. Crawford, Director of the Center for Cave and Karst Studies. Without Dr. Crawford's support this work would not have been possible.
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RADON CONTAMINATION OF RESIDENCES IN
A CITY BUILT COMPLETELY UPON A KARST
LANDSCAPE - BOWLING GREEN, WARREN COUNTY, KENTUCKY

James William Webster          December 1990          119 pages
Directed by: Dr. Nicholas C. Crawford, Dr. Kenneth Kuehn, and Dr. Wayne Hoffman
Department of Geography                  Western Kentucky University
and Geology

The United States Environmental Protection Agency (EPA) estimates that 8 to 12% of U.S. homes have radon concentrations that equal or exceed 4 picocuries per liter (pCi/l). A statewide screening of Kentucky by EPA resulted in an average residential radon concentration of 2.8 pCi/l with 17% of the homes at or above 4 pCi/l. EPA requires routine monitoring and maintenance of worker health records in mines and caves having radon daughter concentrations at or above 0.30 working levels (WL).

Bowling Green is a city located in a karst region of south central Kentucky. Residents of Bowling Green have been subjected to various environmental hazards that are closely linked with the landscape. Of particular concern has been the recurring problem of chemical fumes rising from contaminated caves and collecting in buildings.
The author has recorded radon daughter concentrations in excess of 5 WLs in caves beneath Bowling Green. A preliminary screening of residential radon concentrations in Bowling Green resulted in an average concentration of 25.8 pCi/l. Two of the test results were above 100 pCi/l and were recorded in homes that were known to have a history of fume problems. These results spurred this thesis which addresses the magnitude of residential radon contamination in Bowling Green and its association with the karst landscape.

The investigation involved radon daughter testing in Bowling Green caves and residential radon testing. A total of 84 measurements were conducted in order to establish a working average residential radon concentration for the city. Twelve other tests were performed in buildings known to have a history of chemical fume problems. The resulting average residential radon concentration was 9.06 pCi/l. First floor measurements averaged 4.73 pCi/l, and basement measurements averaged 22.92 pCi/l. The overall average for buildings with a history of fume problems was 35.15 pCi/l with first floors and basements averaging 29.75 and 57.40 pCi/l respectively. Forty-six percent of the homes comprising the sample population equalled or exceeded 4 pCi/l.
The results of the investigation indicates that:

1. Bowling Green Caves sometime have radon daughter concentrations far in excess of 0.30 WL.
2. The average residential radon concentration for Bowling Green exceeds the average for Kentucky obtained by EPA.
3. The percentage of houses that have radon concentrations at or above 4 pCi/l for the study area exceeds the estimated national average of 8 to 12% and the statewide average.

The author suggests that insufficient data was collected to determine whether radon concentrations in Bowling Green homes with a history of chemical fume problems are higher that for the city as a whole.
CHAPTER I

INTRODUCTION AND STATEMENT OF HYPOTHESES

The two purposes of this study are to determine the magnitude of the residential radon problem in Bowling Green, Kentucky, a city that is built completely upon a karst landscape and to investigate the hypothesized relation between radon concentrations in buildings and in caves beneath the city.

Radon 222 is a naturally occurring radioactive gas that is a product of the decay of radium. Radium is a daughter of uranium, an element that is widely distributed in rock and soil. It is estimated that igneous rocks contain an average concentration of 3.5 ppm of uranium. Sandstones, carbonates, and shales average 0.45, 2.2, and 3.7 ppm of uranium respectively (Andrews and Woods, 1972). Uranium may also be found in relatively high concentrations in rock and soils containing phosphate and pitchblende (U.S. Environmental Protection Agency, 1986).

The decay of radon results in the formation of several radioactive ions collectively referred to as radon daughters or progeny. When inhaled, these ions may attach to the tissue of the lungs. Subsequent decay of the radon
daughters lodged in the lungs results in release of particles which can damage, destroy, or mutate lung tissue.

Exposure to elevated levels of radon gas or radon daughters is believed by many to increase one's risk of developing lung cancer. The risk of developing cancer increases with radon concentration and length of exposure (Table 1). For example, the Environmental Protection Agency (EPA) estimates that persons exposed for 75 percent of their lifetime to one Working Level (WL) of radon daughters incur a risk of developing lung cancer that is 60 times that of people who do not smoke cigarettes. This risk is greater than that taken by persons who smoke four packs of cigarettes per day. The lung cancer risk incurred by persons exposed to between 0.5 and 0.2 WL, under the same conditions, is similar to that resulting from being subjected to 20,000 chest x-rays per year. The EPA has adopted a protection standard of 4 pCi/l (0.02 WL) as the indoor, nonoccupational radon gas concentration at which remedial action to lower concentrations of the gas is advised.

Outdoors, radon is not thought to present a significant health hazard because dilution by the atmosphere results in low radon concentrations. On the other hand, radon can accumulate to elevated concentrations in enclosed spaces such as houses. The gas is released into buildings from soil and rock through openings in floors and walls. Even the tiny pores in cinder block walls may provide routes for
### Radon Risk Evaluation Chart

<table>
<thead>
<tr>
<th>pCi/l</th>
<th>WL</th>
<th>Estimated number of lung cancer deaths due to radon exposure (out of 1000)</th>
<th>Comparable exposure levels</th>
<th>Comparable risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1</td>
<td>440—770</td>
<td>1000 times average outdoor level</td>
<td>More than 60 times non-smoker risk</td>
</tr>
<tr>
<td>100</td>
<td>0.5</td>
<td>270—630</td>
<td>100 times average indoor level</td>
<td>4 pack-a-day smoker</td>
</tr>
<tr>
<td>40</td>
<td>0.2</td>
<td>120—380</td>
<td>100 times average outdoor level</td>
<td>20,000 chest x-rays per year</td>
</tr>
<tr>
<td>20</td>
<td>0.1</td>
<td>60—210</td>
<td>100 times average outdoor level</td>
<td>2 pack-a-day smoker</td>
</tr>
<tr>
<td>10</td>
<td>0.05</td>
<td>30—120</td>
<td>10 times average indoor level</td>
<td>1 pack-a-day smoker</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
<td>13—50</td>
<td>10 times average outdoor level</td>
<td>5 times non-smoker risk</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
<td>7—30</td>
<td>10 times average outdoor level</td>
<td>200 chest x-rays per year</td>
</tr>
<tr>
<td>1</td>
<td>0.005</td>
<td>3—13</td>
<td>Average indoor level</td>
<td>Non-smoker risk of dying from lung cancer</td>
</tr>
<tr>
<td>0.2</td>
<td>0.001</td>
<td>1—3</td>
<td>Average outdoor level</td>
<td>20 chest x-rays per year</td>
</tr>
</tbody>
</table>

Table 1. Estimated risk of developing lung cancer through radon exposure. Source: U.S. Environmental Protection Agency (1986).
Radon entry. Radon contained naturally in groundwater also can be released into buildings at the faucet, shower head, or other points of water use. Moreover, some building materials may be sources of radon. Houses with basements are particularly susceptible to radon infiltration because basements are usually built below ground level; therefore, a greater surface area contacts the radon source. Some basements have exposed soil or rock thus allowing direct emanation of radon into the home.

Geographic regions underlain by materials with high uranium content such as crystalline rock, shales, or phosphate deposits are often singled out as potential radon hotspots. Although the concentrations of radon and radon progeny in caves can be many times higher than the concentrations in outdoor air this residential radon contamination in karst areas has largely not been investigated.

**Identification of Problem**

The residents of Bowling Green, Kentucky, have been subjected to various environmental hazards that are closely linked with the karst landscape upon which the city is built. Of particular concern has been the recurring problem of toxic and potentially explosive chemical fumes
rising from contaminated caves and collecting in buildings (Crawford, 1984).

Research has shown that, in many cases, buildings which have a history of chemical fume problems have some type of direct connection with the cave system beneath the city (Crawford, 1984; Crawford and Webster, 1986; and Stroud, Gilbert, Powell, Crawford, Rigatti, and Johnson, 1986). Excavation at fume sites has repeatedly revealed the source of concentrated fume emissions to be solutionally enlarged crevices in the limestone bedrock.

During January of 1987, radon screening measurements were made in fourteen separate Bowling Green homes, three of which were known to have had fume problems. Other detectors were exposed in homes in the same neighborhood. The overall average residential radon concentration for this preliminary survey was 25.8 pCi/l (Table 2). The radon concentration in two of the houses was measured at over 100 pCi/l. Ten of the fourteen houses had radon levels above 4 pCi/l. The two highest radon levels were recorded in the basements of homes which were known to have a history of fume problems. Moreover, it was known through previous excavations by Crawford (1984) that one of the two houses had a discrete air-to-air linkage with the subsurface. These alarmingly high radon levels raised specific questions regarding the magnitude and sources of residential radon contamination in Bowling Green. This thesis is an attempt to answer these questions.
<table>
<thead>
<tr>
<th>Rank</th>
<th>Radon Level (pCi/l)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130</td>
<td>Basement</td>
</tr>
<tr>
<td>2</td>
<td>101</td>
<td>Basement</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>First Floor</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>Basement</td>
</tr>
<tr>
<td>5</td>
<td>23</td>
<td>Basement</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>First Floor</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>First Floor</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>First Floor</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>First Floor</td>
</tr>
<tr>
<td>10</td>
<td>4.7</td>
<td>Basement</td>
</tr>
<tr>
<td>11</td>
<td>3.7</td>
<td>First Floor</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>First Floor</td>
</tr>
<tr>
<td>13</td>
<td>2.8</td>
<td>First Floor</td>
</tr>
<tr>
<td>14</td>
<td>2.5</td>
<td>First Floor</td>
</tr>
</tbody>
</table>

Overall Average: 25.8 pCi/l  
Basement Mean: 56.5  
First Floor Mean: 9.2
Statement of Hypotheses

Hypothesis One
The caves beneath Bowling Green, Kentucky, have radon concentrations that are in excess of the 0.30 WL, the level at which weekly monitoring and maintenance of worker health records is required.

Hypothesis Two
The average residential radon concentration for Bowling Green homes exceeds the estimated average for Kentucky of 2.8 pCi/l, estimated from the 1987 EPA screening survey.

Hypothesis Three
The percentage of Bowling Green homes that equal or exceed the EPA warning level of 4 pCi/l is greater than the estimated national average of 8 to 12% and the average for Kentucky of 17%, estimated by the EPA in 1987.

Hypothesis Four
The average radon concentration for homes and other buildings in Bowling Green with a history of chemical fume problems is significantly higher than the average for Bowling Green houses as a whole.
CHAPTER II

REVIEW OF LITERATURE

In 1886, the French scientist, Henri Becquerel, discovered that the element uranium emitted an invisible radiation capable of affecting photographic plates (Hausmann and Slack, 1948). Soon afterward, Pierre and Marie Curie were successful in isolating the element radium from pitchblende (Oldenberg, 1954). In time a number of elements were found to emit this invisible radiation. The name radioactivity was applied to the phenomenon.

Radioactive Decay and Half-Life

Elements are radioactive because of inherent nuclear instability. Consequently radioactive atoms will, given time, restructure themselves to achieve stable internal configurations. Such restructuring is accomplished by casting off a portion of each nucleus either by emission of particles and/or electromagnetic energy. Such processes are known collectively as radioactive decay.

Naturally occurring radioactive elements decay by three principal mechanisms (Table 3): alpha emission, beta emission, and gamma ray emission.

An alpha particle is composed of two protons and two
<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Symbol</th>
<th>Charge</th>
<th>Atomic Mass</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>+2</td>
<td>4</td>
<td></td>
<td>Double ionized helium atom (a helium nucleus)</td>
</tr>
<tr>
<td>Beta</td>
<td>-1</td>
<td>1/1840</td>
<td></td>
<td>Electron emitted from the nucleus</td>
</tr>
<tr>
<td>Gamma</td>
<td>0</td>
<td>0</td>
<td></td>
<td>Electromagnetic radiation emitted from the nucleus</td>
</tr>
</tbody>
</table>
neutrons. These particles are relatively large in size and travel at great speeds but have very low penetrating power. A thin sheet of paper is effective at blocking the path of these particles. Even so, a high speed alpha particle may ionize (strip electrons from) many thousands of atoms before coming to rest.

Beta particles are electrons emitted from the atomic nucleus. When a beta particle is emitted, a neutron in the nucleus is changed into a proton; thus, the decayed atom will retain its atomic mass but its atomic number will increase by one. Beta particles have greater penetrating power than alpha particles but have lower ionizing energy due to their small size.

Gamma rays are not particles but short wavelength photons of electromagnetic energy and have great penetrating power. Since gamma rays have no mass or charge, their emission does not result in transformation of the radioactive element into another element. However their emission does lower the energy level of the nucleus.

Half-Life

Radioactive decay takes place as a definable function (Bueche, 1982). The radioactive decay curve is defined by an exponential function of time (Figure 1). The time that it takes for one-half of a given amount of radioactive nuclei of an element to decay is termed the half-life
Figure 1. Radioactive Decay Curve.
Source: Bueche (1982).
(T1/2) of the element. Each radionuclide has a characteristic half-life. Half-lives vary from a fraction of a second to billions of years.

**Radon**

Radon and its decay products are part of a larger decay series which begins with uranium 238 and ends with the stable lead 206 isotope (Table 4). Uranium 238 undergoes five decay steps before reaching radium 226, radon's immediate parent.

Radon has a relatively short half-life of 3.825 days and undergoes seven decay intermediates before becoming its stable end product, lead 206. Polonium 218 is the first daughter product that is formed in the radon decay series followed by lead 214, bismuth 214, polonium 214, lead 210, bismuth 210, polonium 210, and finally lead 206.

Radon itself is chemically inert; however, its progeny are all extremely active ions. Typically the first daughter product, polonium 218, will attach to particulate matter, and subsequent decay products are so attached when they form.

**Health Effects of Radon Exposure**

Recently radon has received considerable attention because it has been determined that exposure to element may increase one’s risk of developing lung cancer. Radon itself is inert; therefore, any of the substance that is
<table>
<thead>
<tr>
<th>Parent Isotope</th>
<th>Half Life</th>
<th>Decay Type</th>
<th>Principal Daughter Isotope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium 238</td>
<td>4.5 x 10^9 years</td>
<td>Alpha, Gamma</td>
<td>Thorium 234</td>
</tr>
<tr>
<td>Thorium 234</td>
<td>24.1 days</td>
<td>Beta, Gamma</td>
<td>Protactinium 234</td>
</tr>
<tr>
<td>Protactinium 234</td>
<td>1.17 minutes</td>
<td>Beta, Gamma</td>
<td>Uranium 234</td>
</tr>
<tr>
<td>Uranium 234</td>
<td>2.44 x 10^5 years</td>
<td>Alpha, Gamma</td>
<td>Thorium 230</td>
</tr>
<tr>
<td>Thorium 230</td>
<td>7.7 x 10^4 years</td>
<td>Alpha, Gamma</td>
<td>Radium 226</td>
</tr>
<tr>
<td>Radium 226</td>
<td>1.6 x 10^3 years</td>
<td>Alpha, Gamma</td>
<td>Radon 222</td>
</tr>
<tr>
<td>Radon 222</td>
<td>3.82 days</td>
<td>Alpha, Gamma</td>
<td>Polonium 210</td>
</tr>
<tr>
<td>Polonium 210</td>
<td>3.05 minutes</td>
<td>Alpha</td>
<td>Lead 214</td>
</tr>
<tr>
<td>Lead 214</td>
<td>26.8 minutes</td>
<td>Beta, Gamma</td>
<td>Bismuth 214</td>
</tr>
<tr>
<td>Bismuth 214</td>
<td>19.8 minutes</td>
<td>Beta, Gamma</td>
<td>Polonium 214</td>
</tr>
<tr>
<td>Polonium 214</td>
<td>1.64 x 10^-4 seconds</td>
<td>Alpha, Gamma</td>
<td>Lead 210</td>
</tr>
<tr>
<td>Lead 210</td>
<td>22.3 years</td>
<td>Beta, Gamma</td>
<td>Bismuth 210</td>
</tr>
<tr>
<td>Bismuth 210</td>
<td>5.01 days</td>
<td>Beta</td>
<td>Polonium 210</td>
</tr>
<tr>
<td>Polonium 210</td>
<td>138.4 days</td>
<td>Alpha, Gamma</td>
<td>Lead 206</td>
</tr>
<tr>
<td>Lead 206</td>
<td>Stable</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Modified from U.S. Environmental Protection Agency (1985).
taken into the lungs may be breathed out without any ill effect. However, if the gas decays while in the lungs, there are two results. First, the radon atom emits an alpha particle which may damage many tissue cells. Second, a later radioactive decay product, polonium 218, is formed which may become lodged in the lung tissue and continue to decay. It has been noted that when inhaled, radon progeny tend to become lodged in the lungs whether or not they are attached to particulate matter, (Budnitz, 1974).

Detection of Radon and Radon Progeny

A number of techniques have been developed to detect and measure radon gas and radon progeny. Several of these rely upon grab samples - samples taken over a very short span of time. Others utilize passive collection methods to yield time integrated measurements for periods up to one year. Recently, continuous radon monitors capable of providing a direct reading, real time measurement of radon (or radon progeny) concentration have become available.

Units of Measure

The quantity of radioactive nuclei of an element that decay per unit of time is referred to as the activity of the element. The unit of activity is called the becquerel (Bq) and is defined as the number of radioactive disintegrations that take place during one second.
One gram of the element radium undergoes $3.6 \times 10^{10}$ disintegrations per second which defines its activity as $3.6 \times 10^{10}$ Bq. This activity value has been adopted as the unit of measure known as the curie (Ci); thus, one curie is equal to $3.6 \times 10^{10}$ Bq.

The picocurie per liter (pCi/l) and the Working Level (WL) are common ways of expressing the concentration of radon gas and radon daughters concentrations respectively. The picocurie is equal to one trillionth of a curie. One working level is defined as any combination of radon daughters in one liter of air which will result in the ultimate emission of $1.5 \times 10^{10}$ million electron volts of alpha energy. Electron volts (eV) are a measure of radiation energy.

Conversion from pCi/l to WL necessitates conversion from concentrations of radon gas to concentrations of radon daughters. Such a conversion cannot be accomplished without establishing an equilibrium ratio between radon gas and radon daughters. Under 100% equilibrium the presence of 100 pCi/l of radon gas would mean that 1 WL of radon daughters is also present also.

In reality, perfect equilibrium rarely exists between radon gas and radon progeny in the atmosphere. The EPA (1986) has adopted 50% as the conversion factor. Thus, 1 WL of radon daughters would approximate 200 pCi/l of radon gas. Unless otherwise specified, all conversions between
WL and pCi/l in this thesis will be based on 50% equilibrium.

**Scintillation**

Some materials are known to produce pulses of light when struck by small particles moving at high rates of speed such as radioactive decay particles. This phenomenon is known as scintillation. Scintillation is the principle behind the operation of luminous watch dials that were once so common. The luminescence in watch dials resulted from scintillation of zinc sulfide which was mixed with a small amount of radium and painted onto the dial.

Scintillation detection is the basis for many types of radon measurement techniques. The scintillation counter works by converting light pulses to electrical current. The weak pulses of current are subsequently magnified by a device known as a photomultiplier tube. The magnified pulse can be counted with an electronic counter. The activity of the substance is proportional to the count rate.

**Geiger Counter**

The geiger counter is usually the only device that comes to mind when the majority of people think of radioactivity detectors. Basically the geiger counter consists of a gas-filled tube containing a wire along its
central axis. An electrical potential exists between the wire and the sides of the tube. High speed particles entering the detector through a thin window in conjunction with the voltage potential result in a pulse of current. A counting device such as a loudspeaker is used to register the passage of the current. Each metallic click normally associated with the operation of a geiger counter corresponds to a particle entering the detector.

Geiger counters are not normally sensitive to radon because alpha particles do not have the power to penetrate the membrane window of the detector. Although the counter can be fitted with a window which allows the entrance of alpha particles, geiger counters are not usually employed for radon detection.

Grab Sampling Techniques

Lucas Chamber. One of the more common methods for detecting and measuring radon gas is the Lucas Chamber (Budnitz, 1974). In this technique, a sample of filtered air is collected in a metal or glass chamber that is lined with zinc sulfide which acts as a scintillator. Radon measurements are made by counting the scintillations with a photomultiplier linked to a counting device.

Two Filter Method. Another technique for measuring radon gas is the two-filter method (Thomas and LeClare, 1970). This method involves drawing an air sample through a tube
fitted with a filter at each end. The first filter serves to remove radon daughters from the sample. As the sample passes between the filters a small fraction of the radon gas decays, and these daughters are trapped on the second filter. Alpha activity on the second filter is counted and radon concentration from alpha activity.

Kusnetz Method. The standard technique recommended for radon daughter measurement in mine atmospheres is the Kusnetz Method (Butnitz, 1974) developed by Kusnetz (1956). In this method, an air sample is drawn through a filter which traps radon daughters. After a prescribed time to allow radon daughters to buildup on the filter, alpha activity on the filter is measured using a detector/photomultiplier combination. Radon progeny concentration is calculated as a function of sample volume, measured count, decay time, and an efficiency factor specific to the counting system. Breslin (Butnitz, 1974) indicates that at concentrations less than 0.3 WL the sensitivity of the Kusnetz method degenerates due to statistical fluctuations in the rate measurement.

Passive Measurement Techniques

All the techniques described thus far require active collection of a grab sample and yield radon or radon progeny concentrations over a short time period. In many studies a passive measurement technique is more desirable.
Also, it may be more useful to know the radon concentration over a few days, weeks, or months. Such detection techniques may be more useful in assessing overall residential radon hazards than grab sampling.

The two most common passive techniques used currently for longer term measurement of radon concentration in buildings are nuclear track detection and activated charcoal collection. These two methods provide integrated radon levels from a few days up to one year. A third method, photographic film detection, is less useful for measuring radon concentrations in buildings.

**Nuclear Track Detectors.** The nuclear track detector or Track Etch technique (Fleischer, Alter, Furman, Price, and Walker, 1972, and Alter 1981) is a passive method for measuring radon. This technique can be used to obtain average radon concentrations over time periods of up to one year or more.

Nuclear track detectors work off the fact that heavily charged particles such as alpha particles that strike certain plastic materials leave damage trails. The resulting damaged area can be enhanced by chemical etching to produce tracks that are visible through a microscope. The number of damage trails is proportional to radon concentration.

Etchable tracks are produced only by particles having energies that exceed a certain critical value
Alpha particles possess the required energy while beta particles do not and since gamma rays are not particles, they do not leave damage trails. It is this specificity to alpha particles that makes track detectors ideal for radon. Another factor in favor of nuclear track detectors is that the tracks are stable; therefore, they can be stored for periods of time before processing and can also be used for long exposure periods. The detectors are also unaffected by humidity and by temperature nearly to the softening point of the detector material.

Nuclear track detectors may be obtained in several configurations. The particular configuration utilized depends upon the type of measurement desired (Fleischer, 1981). The open cup design consists of an open plastic cup with a detector attached to the inside bottom. This configuration is sensitive both to activity of radon and radon daughters. Another configuration, the membrane cup, is fitted with a semi-permeable membrane that retards diffusion of gases. This configuration is used to block the inflow of thoron, another radioactive gas much less common than radon, in situations when the presence of this gas may interfere with radon measurements. The filtered cup design is fitted with a paper filter that blocks the passage of radon daughters but will allow the passage of radon gas. This design is useful for measuring the concentration of radon gas alone. The bare badge is, as the name implies, a bare detector mounted on a card or
The bare badge detector is small enough to be worn as a personal detector.

**Activated Charcoal Detectors.** Another technique used for radon measurement is collection on activated charcoal followed by radon activity by gamma scintillation. George (1984) outlines the advantages of this method:

> It is simple, maintenance-free, completely passive and requires no transfer of sample and is reusable making it a low-cost and attractive collection-detection monitoring instrument for use in broad studies of indoor radon levels.

In the charcoal method, activated carbon contained in a metal canister or permeable packet is exposed to the atmosphere in the area where a radon measurement is desired. After a specified exposure period the container is sealed. Atmospheric radon gas adsorbed onto the charcoal is counted by measuring its gamma ray emission. The counting system usually consists of a sodium iodide (NaI) crystal scintillator detector coupled with a photomultiplier and a multichannel analyzer. The radioactivity is determined from the adsorption peaks of Pb214 and Bi214.

It is extremely important to seal the charcoal container immediately upon termination of the exposure period. Radon desorption from activated charcoal occurs if
the carbon is left open to the atmosphere. George (1984) found that 50% desorption occurred within 36 hours when an open canister was moved from a 35pCi/l radon atmosphere to one in which the radon concentration was 0.2 to 0.3 pCi/l. If the container is sealed properly the natural decay rate of radon is the only limiting factor on storage time.

Although charcoal detection reveals little information regarding short term flux in radon concentration, research indicates that this technique can yield reliable data on short term average radon concentrations. George (ibid) compared the average radon concentration in a residential building determined from a charcoal collector to the radon concentration as determined by a continuous monitor and found good agreement between the two methods. George also compared the average radon levels in twelve buildings determined through charcoal collection to those determined on a previous occasion with nuclear track detectors and found differences of less than 10%. He did point out that because the sampling periods were not concurrent, interpretation of the results was difficult.

Photographic Films. A third passive technique makes use of the fact that an ionizing particle or photon will affect a photographic film upon exposure. These films can record the passage of ionizing particles or photons and may be used to detect and measure such activity (Bueche, 1982).
The major drawback of this method is that it is not specific solely to alpha particles. Films also are affected by gamma and beta radiation. Photographic films are sensitive to light and humidity and over time are prone to image fading (Rock, Lovett, and Nelson, 1969). Due to these difficulties, photographic films are not widely employed as residential radon measurement devices.

Radon and Radon Daughter Concentrations in Caves

Studies have shown that concentrations of radon gas and radon daughters in cave atmospheres can be many times higher than concentrations found in outdoor air.

Fryer (1936) reported up to 545 micro micro curies per liter of air (equivalent to pCi/l) in five Arkansas caves he investigated (Table 5). Fryer believed that influent water carried radon into the caves from overlying soils possessing high radon concentrations. He concluded that the caves he investigated exhibited uniform but low activity and attributed it to the dryness of the caves that were investigated.

Fryer also monitored radon levels in Mayes cave near Bloomington, Indiana. His study spanned a four-month period beginning in October of 1935. During the period, he collected air samples from the cave on a weekly basis. On one occasion, three days after a 2.6 inch rain event, he recorded a radon level of 447 pCi/l.
# TABLE 5
Radon Gas Concentration in Arkansas Caves
Investigated by Fryer

<table>
<thead>
<tr>
<th>Cave</th>
<th>Location</th>
<th>Activity (pCi/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bell</td>
<td>Independence Co., Arkansas</td>
<td>545</td>
</tr>
<tr>
<td>Trent</td>
<td>Independence Co., Arkansas</td>
<td>300</td>
</tr>
<tr>
<td>Cushman</td>
<td>Independence Co., Arkansas</td>
<td>307</td>
</tr>
<tr>
<td>Bone</td>
<td>Independence Co., Arkansas</td>
<td>61</td>
</tr>
<tr>
<td>Crystal</td>
<td>Independence Co., Arkansas</td>
<td>337</td>
</tr>
<tr>
<td>Onyx</td>
<td>Boone Co., Arkansas</td>
<td>428</td>
</tr>
</tbody>
</table>

Source: After Fryer (1936)

Note: Units micro, micro curies per liter have been converted to pCi/l.
Bloomington, Truett Cave, tested by Fryer on one occasion, exhibited no activity.

Spurred by his interest in caves as potential fallout shelters, Reckmeyer (1962a, 1962b) conducted a study of radioactivity in selected Alabama caves. On three visits to Hughes Cave in April and May of 1962, Reckmeyer observed that the radiation count measured with a geiger counter varied from 14 to 48 counts per minute (cpm) while outside the cave he observed the background to be 60 cpm. He attributed the radiation variation within the cave to inwashing of nuclear fallout by spring rains. In July of 1962, he observed, to his astonishment, that the radiation count 100 feet inside Tumbling Rock Cave was 148 cpm—higher than the outside air background of 99 cpm. Reckmeyer attributed the high radiation count to the ability of air movement to carry and deposit contaminated dust in the cave. Reckmeyer further associated high radiation counts with wet sections of both Tumbling Rock and Hughes Cave. Another cave surveyed by Reckmeyer, Hughes Junior Cave, a 60 foot dead-end passage with no air flow, displayed counts of only 25 and 29 cpm.

Breisch (1968) conducted a review of literature on the occurrence of radioactive minerals in carbonates. He noted that some limestones of the Colorado Plateau have uranium levels of up to 1 percent (10,000 ppm); however, he indicated that limestones generally have low radioactivity, averaging about 1.3 ppm uranium.
Briesch (ibid) also measured the radiation at Fort Stanton Cave, Lincoln County, New Mexico, using a geiger counter. He recorded the background radiation outside the cave at 0.02 millirem/hour\(^1\), while inside the levels were as high as 0.12 millirem/hour (gamma radiation) and 0.05 to 0.09 millirem/hour (beta radiation). Based upon these readings, he concluded the following (p. 88):

1) Radioactivity seemed to be concentrated only in the deepest sections of the cave;

2) For any room, no specific mineral or rock form had a detectably higher activity than any other rock;

3) Activity seemed less near the top of a room in a tight passage with no air flow, and;

4) No gammas were detected in a gamma spectrum analysis of a small rock sample removed from the cave.

Briesch further suggested that the activity he was measuring was that of a radioactive gas - radon.

Trout (1975) used radon measurements to study air movement within Cottonwood and Jurnigan caves in New

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1. The rem (roentgen equivalent man) is a unit used to measure exposure of human body tissue to radiation in terms of the dose of gamma rays which would produce the same biological effect. A millirem is equal to 1/1000th of rem. It is estimated that the average annual dose of radiation to humans from various sources is on the order of 180 millirems. In comparison, an acute exposure of 800 to 2,000 rems of radiation will result in death within a few hours or days.
Mexico. The average radon level recorded in Jurnigan cave was 25 pCi/l compared with the outdoor background of 0.15 pCi/l. Afternoon samples in Jurnigan Cave averaged about 50 pCi/l. Trout noted that from morning to evening the outside temperature generally increased but the relative humidity and barometric pressure usually dropped. He suggested that change in barometric pressure may be the reason that evening samples averaged about three times higher than morning samples.

In Cottonwood Cave, Trout observed that radon concentration increased with increasing distance into the cave. He felt that this finding strongly supported his hypothesis that the cave had only one entrance.

Beckman and Rapp (1976) presented the findings of winter and summer surveys of radon occurrence in Carlsbad Caverns, New Mexico. The survey involved measurement of radon and thoron daughters by the Kusnetz Method and a method developed by the U.S. Public Health Service. Average values for the various sections of Carlsbad varied from 0.14 WL to 0.37 WL. Two other nearby caves, New Cave and Spider Cave, yielded average radon daughter concentrations of 0.23 WL and 0.37 WL respectively.

Wilkening and Watkins (1976) found that during the summer, radon levels in Carlsbad Cavern average 49 pCi/l. They indicated that this was about three times the January/February average of 15 pCi/l, and concluded that the seasonal variation was due to temperature induced air
exchange between the cave and outside air. The two researchers developed a model that predicted radon levels in the caves during any given season of the year.

Yarbrough (1976a) summarized the events which led to a survey of radon levels in all caves managed by the National Park Service (NPS). He indicated that based upon independently gathered data, the NPS had initiated a program of routine monitoring of radon in all NPS caves and began to maintain health records of workers in Carlsbad Caverns.

Yarbrough (1976b) presented the results of a survey of radon levels in NPS administered caves. The survey data indicated that radon levels in NPS caves experience daily and seasonal fluctuation. Yarbrough attributed the fluctuation to variations in air flow patterns within the caves.

Yarbrough and Ahlstrand (1976) presented two general models to explain observed daily and seasonal fluctuations in radon levels in caves (Figure 2). They called the two models the up-side-down configuration (USD), and the right-side-up configuration (RSU). In both models radon levels are higher in the summer months than the winter.

In the USD cave, air flow tends to be out of the cave during the summer months. The cooler and therefore denser cave air tends to spill out of the cave, thereby flushing out radon and preventing influx of outside air. In winter, since the outside temperature is generally lower than the
Figure 2. Up-side-Down (USD) and Right-Side-UP (RSU) Cave Models. Source: After Yarbrough and Ahlstrand (1976).
temperature of the cave air, a reverse pattern of air flow occurs. Outside air moves into the cave and, through dilution, lowers radon levels.

In RSU caves, since all entrances are higher than the body of the cave, air flow stagnates in the summer. As a result, radon levels increase. In winter, the colder and denser outside air settles into the cave thereby diluting radon concentrations.

Yarbrough and Ahlstrand (ibid) also suggested that radon levels in caves can exhibit significant daily fluctuations during the transitional seasons of spring and fall. The reason for these short term fluctuations is that during spring and autumn, daily temperatures can vary greatly. Consequently, airflow patterns in both types of caves may change through the course of a day resulting in changes in radon concentrations within the caves.

Yarbrough and Ahlstrand (1977) gave a preliminary report on the alpha radiation monitoring program in caves administered by the NPS. The preliminary survey confirmed that radon levels were a problem in many of the caves and as a result rigorous monitoring and limitation of worker time spent in the NPS caves was necessary (Table 6). Mammoth, Crystal, and Great Onyx caves, all in Kentucky, exhibited some of the highest average radon levels of all the caves monitored by the NPS. In Mammoth Cave the maximum concentration of radon daughters was reported to be 1.24 WL. The minimum concentration was 0.39 WL, and the
### TABLE 6

Summarized Radon Daughter Concentrations in Caves Administered by the National Park Service (NPS)

<table>
<thead>
<tr>
<th>CAVE</th>
<th>MAXIMUM (WL)</th>
<th>MINIMUM (WL)</th>
<th>AVERAGE (WL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timpanogos Cave, Utah</td>
<td>0.02</td>
<td>0.003</td>
<td>0.01</td>
</tr>
<tr>
<td>Lehman Cave(s), Nevada</td>
<td>0.37</td>
<td>0.10</td>
<td>0.21</td>
</tr>
<tr>
<td>Wind Cave, South Dakota</td>
<td>0.19</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Jewel Cave, South Dakota</td>
<td>0.28</td>
<td>0.13</td>
<td>0.21</td>
</tr>
<tr>
<td>Crystal Cave, Sequoia NP</td>
<td>0.22</td>
<td>0.003</td>
<td>0.07</td>
</tr>
<tr>
<td>Marble Cave, Sequoia NP</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Oregon Cave(s), Oregon</td>
<td>0.35</td>
<td>0.02</td>
<td>0.15</td>
</tr>
<tr>
<td>Valentine Lava Tube, CA</td>
<td>0.13</td>
<td>0.003</td>
<td>0.07</td>
</tr>
<tr>
<td>Hot Springs, Arkansas</td>
<td>0.03</td>
<td>0.001</td>
<td>0.0075</td>
</tr>
<tr>
<td>Central Hot Water Reservoir</td>
<td>1.15</td>
<td>0.53</td>
<td>0.76</td>
</tr>
<tr>
<td>Closed Spring, when opened</td>
<td>13.37</td>
<td>0.001</td>
<td>---</td>
</tr>
<tr>
<td>Round Spr. Cave, MO</td>
<td>0.60</td>
<td>0.003</td>
<td>0.29</td>
</tr>
<tr>
<td>Carlsbad Caverns, NM</td>
<td>1.03</td>
<td>0.04</td>
<td>0.27</td>
</tr>
<tr>
<td>New Cave, NM</td>
<td>0.40</td>
<td>0.17</td>
<td>0.26</td>
</tr>
<tr>
<td>Mammoth Cave, Kentucky</td>
<td>1.24</td>
<td>0.39</td>
<td>0.73</td>
</tr>
<tr>
<td>Crystal Cave, Kentucky</td>
<td>1.49</td>
<td>0.83</td>
<td>1.12</td>
</tr>
<tr>
<td>Great Onyx Cave, KY</td>
<td>1.22</td>
<td>0.68</td>
<td>1.00</td>
</tr>
</tbody>
</table>

overall average was 0.73 WL. In Crystal and Great Onyx caves, the maximum, minimum, and average working levels were 1.49, 0.83, 1.12, and 1.22, 0.68, and 1.00 respectively. Yarbrough and Ahlstrand pointed out that EPA and OSHA require weekly monitoring of radon concentrations and maintenance of exposure records of all personnel working in environments possessing 0.30 WL or greater of radon daughters and that this approach is followed by the NPS. All three Kentucky caves fell within this category.

Carson (1981), who has performed over 20,000 radon daughter measurements in Mammoth Cave, indicates that radon levels in the monitored portions of the cave consistently exceed the 0.30 WL mark.

Ahlstrand (1980) found that barometric pressure influences the radon level in New Cave (New Mexico) more than does temperature. During two years of investigation, yearly average radon levels were found to be 0.23 +/- 0.05 WL and 0.22 +/- 0.04 WL respectively. Ahlstrand noted that airflow in the cave did not vary significantly throughout the year, but barometric pressure did and therefore might influence radon levels.

Swank (1977) reported that radon daughter concentrations as high as 4 WLs had been observed in Horsethief Cave, Wyoming. Kobal, Skofljanec, and Zavrtanik (1978) found average radon concentrations of 1.50 kBq/m³ (41 pCi/l) and 0.22 kBq/m³ (6 pCi/l) for Postojna and Skocjan caves in Yugoslavia. The largest and most
frequently visited commercial cave in Italy, Grotta Grande del Vento, was reported by Cigna and Clemente (1981) to have an average radon concentration of 14 - 20 pCi/l and an average radon daughter concentration of 0.08 - 0.15 WL. Radon concentrations in Castlegard Cave, in the Columbia icefields of Alberta, were found to range from 1 to 10 pCi/l (Atkinson, Smart, and Wigley, 1983). Measurements in Petronalona Cave in Greece indicated dramatic variation in the radon level within the cave, from 5 pCi/l to 2,380 pCi/l (Papastefanou, Manolopoulou, Savvides, and Charalambous, 1986).

Radon in Dwellings

Rundo, Markun, and Plondke (1978) reported high concentrations of the radioactive gas in some homes in the Chicago, Illinois, area. The investigators suggested that the high concentrations were not related to excessive radioactivity in building materials or uranium tailings in the foundations. A reading of 26 pCi/l of radon in one house spurred the investigators to sample additional houses having unpaved crawlspaces. Of 22 houses surveyed, 9 displayed radon levels of 5 pCi/l or more, while 6 of the 22 yielded concentrations of 10 pCi/l or more. The lowest value, 0.3 pCi/l, was recorded in a brick veneer house.

The effect of phosphate deposits on residential radon concentrations was reported by Guimond, Ellett, Fitzgerald,
Windham, and Cuny (1979). Radon daughter concentrations in excess of 0.03 WL (6 pCi/l) were recorded in 15% of the Florida homes tested.

Stranden, Bertig, and Ugletveit (1979) presented the results of a study of the effects of construction material on radon concentration in Norwegian homes. Wooden outer-walled structures averaged 1.3 pCi/l, concrete structures averaged 2.0 pCi/l, and clay brick buildings averaged 1.0 pCi/l. The overall average radon concentration was 1.4 pCi/l. In a continuation of the study, Stranden (1980) recorded residential radon levels up to 6 pCi/l, and concluded that residential radon concentrations may have increased in Norway because of lower ventilation resulting from more efficient insulation of buildings.

Hess, Weiffenbach, and Norton (1982) reported the findings of a study involving 100 houses located in the state of Maine. The investigative technique involved placing a nuclear track detector in a bedroom, bathroom, kitchen, livingroom, and basement of each house under investigation. The exposure period ran from October, 1980, until May of 1981. The radon concentration in each house’s water supply was also determined at the time of emplacement of the nuclear track detectors. Average radon levels of 3.0 pCi/l for bedrooms, 3.4 pCi/l for bathrooms, 3.1 pCi/l for kitchens and livingrooms, and 6.4 pCi/l in basements were recorded. Continuous radon monitors were placed in 18
of the houses in the study. The researchers indicated that intermittent periods of higher radon concentrations could be correlated with periods of water use in homes with high concentrations of radon in their water supplies.

Gesell (1983) presented the findings of six European and Canadian studies of residential radon contamination. Collectively the average radon level ranged from 0.4 to 4.9 pCi/l. For a Canadian study of 10,000 dwellings, Gesell reported the geometric mean to range from 0.14 pCi/l in Vancouver, British Columbia, to 0.88 pCi/l for St Lawrence, Newfoundland. He cautioned the acceptance of the results of the 10,000 house study however, since it involved only one grab sample in each house and was conducted in the summer months, a time during which ventilation would be expected to be at a maximum.

Cohen (1986) conducted a nation-wide survey of radon in the homes of 453 physics professors in 101 universities in 42 states and the District of Columbia. Measurements were made with nuclear track detectors with an exposure period of one year. He reported a lognormal distribution of radon levels with a geometric mean concentration of 1.03 pCi/l compared with an arithmetic mean of 1.47 pCi/l. Cohen found that correlations with various factors such as age, location of the detector, number of floors, and what was beneath the house were much weaker than expected, and suggested that geographic location might be the dominant
factor in radon concentration. The highest of 453 readings was reported to be 15.1 pCi/l. He contrasted this to an earlier study (Cohen, 1985) in which 3 of 169 Pittsburgh homes surveyed possessed radon levels above 23 pCi/l and in which the overall average was 2.3 pCi/l.

In a 1979 study conducted through the University of North Carolina, radon concentrations were measured in houses built over phosphate deposits in eastern North Carolina, in the North Carolina State Office buildings, and in various caverns across the state (Watson, 1986). In the state office buildings radon levels were reported to be 3 and 4 pCi/l, while houses built over phosphate deposits exhibited an average radon level of less than 1 pCi/l. In the spring of 1986, nuclear track detectors were placed in various homes in areas of North Carolina which were thought to have a potential for elevated radon levels. Houses were selected in areas having phosphate deposits in eastern North Carolina, and in two areas of the state underlain by granitic bedrock. The average radon concentrations for the three areas were 0.51, 3.82, and 3.21 pCi/l respectively. The overall range was 0.16 to 13.75 pCi/l of radon. Watson reported that no correlation was found between the radon level in water supplies and in houses.

The results of a study of the seasonal variations of indoor radon in Butte, Montana was presented by Hans (1986). In total, the data base consisted of 112,000 radon measurements, 11,000 of which were used in preparation of
### TABLE 7
SUMMARY OF EPA TEN STATE
RADON SCREENING CONDUCTED
DURING 1986 - 1987

<table>
<thead>
<tr>
<th>State</th>
<th>Percent of Homes in Certain Radon Level Categories</th>
<th>Mean Conc. (pCi/l)</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>&lt;4  6  &lt;1</td>
<td>1.8</td>
<td>1,200</td>
</tr>
<tr>
<td>Colorado</td>
<td>61 37 2</td>
<td>4.6</td>
<td>900</td>
</tr>
<tr>
<td>Conn</td>
<td>81 18 1</td>
<td>2.9</td>
<td>1,500</td>
</tr>
<tr>
<td>Kansas</td>
<td>79 21 1</td>
<td>2.9</td>
<td>1,000</td>
</tr>
<tr>
<td>Kentucky</td>
<td>83 16 1</td>
<td>2.8</td>
<td>900</td>
</tr>
<tr>
<td>Michigan</td>
<td>91 9 &lt;1</td>
<td>1.8</td>
<td>200</td>
</tr>
<tr>
<td>Rhode I.</td>
<td>81 16 3</td>
<td>3.5</td>
<td>190</td>
</tr>
<tr>
<td>Tennessee</td>
<td>84 15 1</td>
<td>2.7</td>
<td>1,800</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>73 26 1</td>
<td>3.4</td>
<td>1,200</td>
</tr>
<tr>
<td>Wyoming</td>
<td>74 24 2</td>
<td>3.6</td>
<td>800</td>
</tr>
</tbody>
</table>

## TABLE 8
TEN HIGHEST RADON MEASUREMENTS IN THE 1986-87 EPA TEN STATE SCREENING

<table>
<thead>
<tr>
<th>Rank</th>
<th>Radon Level (pCi/l)</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>Alabama</td>
</tr>
<tr>
<td>2</td>
<td>162</td>
<td>Michigan</td>
</tr>
<tr>
<td>3</td>
<td>142</td>
<td>Wisconsin</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>Tennessee</td>
</tr>
<tr>
<td>5</td>
<td>94</td>
<td>Alabama</td>
</tr>
<tr>
<td>6</td>
<td>84</td>
<td>Wisconsin</td>
</tr>
<tr>
<td>7</td>
<td>83</td>
<td>Wisconsin</td>
</tr>
<tr>
<td>8</td>
<td>81</td>
<td>Colorado</td>
</tr>
<tr>
<td>9</td>
<td>81</td>
<td>Connecticut</td>
</tr>
<tr>
<td>10</td>
<td>81</td>
<td>Wyoming</td>
</tr>
</tbody>
</table>

the final report. The study involved 68 houses which were divided into three groups based upon the frequency of radon measurement in each. Hans found that radon concentrations tended to be lower during the warmer months, a phenomenon he suggested was largely due to increased ventilation. He maintained that elevated radon concentrations during the colder months were due to a combination of decreased ventilation and elevated concentrations of radon in soil gas caused by ground freezing and snow cover.

Fleischer (1986) indicated in the Reading Prong region of the eastern United States has an abundance of homes with high radon concentrations, and cited as an example, one house was reported to have 16 WL of radon daughters.

The EPA has estimated that as great at 12% of U.S. homes have radon concentrations that exceed 4 pCi/l (Watson, ibid). To help states in conducting radon surveys, the EPA established a radon screening program. The results of the initial program were release in 1987 (EPA, 1987). The study involved nearly 10,000 homes in 10 states (Tables 7 and 8). Based on the results of the initial study, EPA estimated that between 8% and 12% of U.S. homes have an average annual radon concentration that equals or exceeds 4 pCi/l. Of the 10 states surveyed, Colorado had the highest average residential radon concentration at 4.6 pCi/l and the greatest percentage of homes in which the average radon concentration, at 39%, equalled or exceeded 4 pCi/l.
Kentucky was included in the EPA-sponsored state surveys. The overall average residential radon concentration in Kentucky was 2.8 pCi/l, with 17% of the homes tested equalled or exceeded 4 pCi/l. Three of the six highest test results for the state were recorded in Warren County (Figure 3). Moreover, 60% of the 25 Warren County homes tested displayed radon concentrations at or above the EPA warning level of 4 pCi/l (Table 9).

In 1988, EPA released the results of a continuation of the radon screening survey (EPA, 1988). The expanded survey involved an additional 11,000 tests in seven states (Table 10). Of the seven states surveyed, North Dakota displayed both the highest average residential radon concentration at 7.0 pCi/l and the greatest percentage of houses testing above 4 pCi/l at 63%. Five of the 11,000 screening measurements exceeded 100 pCi/l (Table 11).

**Karst**

Jennings (1971, p.1) describes karst as, "a terrain with distinctive characteristics of relief and drainage arising primarily from a higher degree of rock solubility in natural waters than found elsewhere." Although most commonly developed in limestone, White (1976) indicates that karst features may develop in dolomite, gypsum, chalk, halite, and even in clastic and igneous rock. Rock susceptible to solutioning is located at or near the
TEN HIGHEST RADON MEASUREMENTS IN KENTUCKY

THREE HOMES IN WARREN COUNTY WERE IN THE SIX HIGHEST MEASURED IN THE STATE

<table>
<thead>
<tr>
<th>RADON LEVEL pCl/l</th>
<th>COUNTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>66</td>
<td>Bullitt</td>
</tr>
<tr>
<td>32</td>
<td>Warren</td>
</tr>
<tr>
<td>31</td>
<td>Bourbon</td>
</tr>
<tr>
<td>29</td>
<td>Scott</td>
</tr>
<tr>
<td>28</td>
<td>Warren</td>
</tr>
<tr>
<td>27</td>
<td>Warren</td>
</tr>
<tr>
<td>25</td>
<td>Hart</td>
</tr>
<tr>
<td>25</td>
<td>Jefferson</td>
</tr>
<tr>
<td>24</td>
<td>Bullitt</td>
</tr>
<tr>
<td>23</td>
<td>Cumberland</td>
</tr>
</tbody>
</table>

These single measurements may not be representative of all houses in these counties.

Figure 3. The ten highest radon measurements recorded in Kentucky during the EPA sponsored screening conducted in 1986 and 1987.
# TABLE 9

Results of EPA Sponsored Residential Radon Screening of Warren County, Kentucky

<table>
<thead>
<tr>
<th>Rank</th>
<th>Radon Conc (pCi/l)</th>
<th>Rank</th>
<th>Radon Conc (pCi/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.7</td>
<td>13</td>
<td>5.4</td>
</tr>
<tr>
<td>2</td>
<td>28.3</td>
<td>14</td>
<td>5.1</td>
</tr>
<tr>
<td>3</td>
<td>16.7</td>
<td>15</td>
<td>5.0</td>
</tr>
<tr>
<td>4</td>
<td>14.6</td>
<td>16</td>
<td>4.0</td>
</tr>
<tr>
<td>5</td>
<td>11.9</td>
<td>17</td>
<td>3.9</td>
</tr>
<tr>
<td>6</td>
<td>9.5</td>
<td>18</td>
<td>3.6</td>
</tr>
<tr>
<td>7</td>
<td>9.4</td>
<td>19</td>
<td>2.8</td>
</tr>
<tr>
<td>8</td>
<td>8.4</td>
<td>20</td>
<td>2.5</td>
</tr>
<tr>
<td>9</td>
<td>7.0</td>
<td>21</td>
<td>0.9</td>
</tr>
<tr>
<td>10</td>
<td>5.8</td>
<td>22</td>
<td>0.7</td>
</tr>
<tr>
<td>11</td>
<td>5.6</td>
<td>23</td>
<td>0.7</td>
</tr>
<tr>
<td>12</td>
<td>5.5</td>
<td>24</td>
<td>0.5</td>
</tr>
<tr>
<td>25</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: (pers. comm.) Kentucky Department for Environmental Protection, Radiation Control Branch.
<table>
<thead>
<tr>
<th>State</th>
<th>Percent of Homes in Certain Radon Level Categories</th>
<th>Mean Conc. (pCi/l)</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arizona</td>
<td>&lt;4 93 7 &lt;1</td>
<td>1.6</td>
<td>1,507</td>
</tr>
<tr>
<td>Indiana</td>
<td>74 24 2</td>
<td>3.6</td>
<td>1,217</td>
</tr>
<tr>
<td>Mass.</td>
<td>76 23 1</td>
<td>3.4</td>
<td>1,659</td>
</tr>
<tr>
<td>Minnesota</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missouri</td>
<td>83 17 &lt;1</td>
<td>2.6</td>
<td>1,859</td>
</tr>
<tr>
<td>Penn.</td>
<td>63 31 6</td>
<td>6.2</td>
<td>429</td>
</tr>
<tr>
<td>N. Dakota</td>
<td>37 59 4</td>
<td>7.0</td>
<td>1,596</td>
</tr>
</tbody>
</table>

## TABLE 11
TEN HIGHEST RADON MEASUREMENTS
IN THE 1988 EPA SEVEN STATE SCREENING

<table>
<thead>
<tr>
<th>Rank</th>
<th>Radon Level (pCi/l)</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>184</td>
<td>North Dakota</td>
</tr>
<tr>
<td>2</td>
<td>134</td>
<td>North Dakota</td>
</tr>
<tr>
<td>3</td>
<td>127</td>
<td>North Dakota</td>
</tr>
<tr>
<td>4</td>
<td>114</td>
<td>Pennsylvania</td>
</tr>
<tr>
<td>5</td>
<td>106</td>
<td>Pennsylvania</td>
</tr>
<tr>
<td>6</td>
<td>86</td>
<td>North Dakota</td>
</tr>
<tr>
<td>7</td>
<td>80</td>
<td>Pennsylvania</td>
</tr>
<tr>
<td>8</td>
<td>78</td>
<td>North Dakota</td>
</tr>
<tr>
<td>9</td>
<td>72</td>
<td>Indiana</td>
</tr>
<tr>
<td>10</td>
<td>70</td>
<td>Minnesota</td>
</tr>
</tbody>
</table>

land surface over approximately 15% of the conterminous United States (Figure 4).

The Process of Solutioning of Rock in Karst Development

The process of solutioning is central to development of karst terrains, and largely responsible for development of karst features ranging from minor solution sculpture to large, complex cave systems and integrated subsurface drainage networks.

Many rocks are soluble to some degree in acidic solutions. Limestone and other carbonate rocks are particularly susceptible to solutioning. In the natural environment, the acid necessary for solutioning to occur most often begins with the addition of atmospheric carbon dioxide (CO₂) to meteoric water which results in a weak carbonic acid solution. This acidity is increased by addition of greater amounts of CO₂ in the soil due to the much greater concentrations (10 to 100 times greater) of carbon dioxide in the soil atmosphere (Atkinson and Smith, 1976).

Cave Development

A number of diverse models for the origin of caves have been proposed. Many early workers sought general models that could be applied to all types of cave development. Their models differ primarily in the proximity
Figure 4. Distribution of karst areas and areas of carbonate and other soluble rock at or near the land surface. Source: Davies and LeGrand (1972).
to the phreatic, or saturated, zone where the majority of cavern development occurs. More recent speleogenetic models stress the importance of site specific factors as influencing cavern development.

Cvijic (1893) proposed that caves form deep below the water table due to circulation of groundwater through joints, fissures, and bedding planes.

Davis (1930) likewise believed that caves are formed deep within the phreatic zone and formulated a speleogenic model which described the process. He proposed that caves develop deep below the water table during the old age stage of the geographic cycle and are later uplifted above the water table during the rejuvenation stage of landscape development.

Bretz (1942) added a third stage to the Davis model in which very slow moving water facilitates sediment deposition in solution openings prior to the rejuvenation stage.

Swinnerton (1932) set forth a sharply different model for cavern development than the Davis model. Swinnerton believed that significant solutional activity does not occur below the water table because of insufficient circulation of water in that region of the saturated zone. He maintained that the majority of groundwater movement occurs at, or just below, the water table and that consequently, this zone is where the majority of solutional activity occurs.
Martel (1921) offered a nonphreatic model for cavern development in which caves originate in the vadose zone. The Martel model also attributed corrosion a larger role in the karst development process than models proposed by others.

Ford (1965 and 1971), is representative of more recent ideas on cave development, in that he maintains that none of the classic models can be accepted as applicable in all situations. Instead, he emphasizes the hydrogeologic setting of each particular system as the central dominant factor controlling cave development.

Karst Hydrogeology

Conceptually, the nature of groundwater flow in karst aquifers ranges from totally diffuse (slow laminar flow) to totally discrete (conduit flow) (White, 1976). Smith, Atkinson, and Drew (1976) visualize karst groundwater flow as a series of transfers and storages for varying lengths of time depending on the nature of the system (Figure 5).

The primary porosities and permeabilities of limestone is generally very low rarely exceeding two percent (Smith Atkinson, and Drew, ibid). However, solutional activity concentrated along joints, faults, and bedding planes can result in exceedingly high secondary permeabilities (Smith, Atkinson, and Drew, 1976).

During karst development, as the dissolution of the bedrock increases, the ability of the subsurface to capture
Figure 5. Flowchart of the hydrologic cycle for carbonate aquifers. Source: Smith, Atkinson, and Drew (1976).
and transmit surface water is increased. The increased volume of captured water leads to greater solutional activity. Finally, the subsurface drainage system develops to the point that it is capable of capturing and transmitting virtually all surface runoff except that which occurs during times of exceedingly high runoff resulting from intense or prolonged storm events. As a result, a well developed karst landscape is often marked by numerous sinkholes, caves, and losing or sinking streams. Generally surface drainage is lacking except for major streams. Lesser surface streams are usually ephemeral or intermittent and often terminate where the stream flows to the subsurface through a swallow hole or into the mouth of a cave. Some streams may just seem to dwindle to nothing as water is gradually pirated to the subsurface by infiltration through the stream bed or through small solutional openings without sufficient capacity to capture the entire flow of the stream. Thus, it is not uncommon in karst regions to hear the story of the canoeist who ran out of stream.

Closed topographic depressions known as sinkholes or dolines are the dominant features of many karst terraines and are regarded by Sweeting (1972) as the primary feature of karst relief (Figures 6 and 7). Sinkholes function to capture surface runoff and channel it to the subsurface. In this respect the closed depression might be equated to the drainage basin of nonkarst regions (Gun, 1981).
Figure 6. Sinkhole classification as given by Jennings. Source: After Jennings (1971).
Figure 7. Sinkhole classification as given by Sweeting. Source: After Sweeting (1973).
movement of water from the sinkhole to the subsurface varies depending upon the type of sinkhole and whether the depression has a soil mantle which retards the flow of water to the subsurface.

The Subcutaneous Zone

Williams (1983) stresses that the zone of weathered rock near the soil to bedrock interface that he terms the subcutaneous zone, is an important area of water storage and movement in karst regions. In karst landscapes which have a soil mantle (covered karst), the majority of weathering occurs at the interface between the soil and bedrock. Such solutional activity is greatest along joints and bedding planes in the rock. As the aggressivity of downward moving water to calcium carbonate is diminished, the amount of solutional activity decreases. Consequently, the amount of solutional enlargement and permeability decreases with depth (Figure 8). Thus, the subcutaneous zone is characterized by high secondary permeability that decreases sharply with depth and a marked lateral component of flow that is punctuated by downward flow along master joints and fractures.

The subcutaneous zone may act as an important zone of storage in the karst aquifer and may feed the permanently saturated zone, contributing greatly to the maintenance of base-flow conditions. Communication with the permanently saturated zone occurs through joints and fractures in the
Figure 8. Schematic diagram depicting relationship between availability of carbon dioxide in the soil and the rate of limestone solution with depth. Source: After Williams, 1983.
rock ranging from hairline cracks to openings that have undergone considerable solutional enlargement. These larger openings are thought to be the primary avenues of vertical flow and are often referred to as master joints and fractures. The vertical component of flow in the subcutaneous zone becomes increasingly dominant as the permeability of the vadose zone increases.

Environmental Hazards in Karst Regions

Karst processes and the nature of karst landscapes pose unique environmental hazards to the residents of such regions. The principal hazards associated with karst regions are: 1) sinkhole collapse, 2) sinkhole flooding, and 3) karst groundwater contamination and related problems.

Sinkhole Collapse

Sinkhole collapse is an ever present hazard to residents of certain karst areas. The problems that may be associated with catastrophic collapse or subsidence of the land surface are fairly obvious. For example, Newton (1976) indicates that in Alabama, sinkhole collapse has proven costly owing to their occurrence beneath highways, streets, railroads, buildings, and even animals and people.

Unfortunately, human activities, such as alteration of surface drainage and drawdown of watertables through
overpumping, are thought to be principal factors contributing to sinkhole collapse. Newton (ibid) estimates that from 1900 to 1976, over 4,000 sinkhole collapses occurred in Alabama which can be attributed to human activities compared to approximately 50 naturally occurring collapse features.

In Bowling Green, Kentucky, Crawford and Groves (1984) have documented over forty sinkhole collapses attributable to such human activities as alteration of surface drainage patterns and improper drainage well construction.

Sinkhole Flooding

Flooding in karst areas is a natural phenomenon. During intense or prolonged storm events or due to constriction or blockage, the subsurface system sometimes cannot accept all storm water runoff. The result is an overload of the subsurface system that must be compensated for by temporary storage of water on the surface (Crawford 1981a and 1981b).

Urban development often alters the natural flow system by creating large expanses of impervious surfaces and by filling many sinkholes. The outcome is increased amounts of surface runoff and decreased avenues for the additional water to reach the subsurface. Consequently, sinkhole flooding problems are increased in urban areas.
Groundwater Contamination and Chemical Fumes

Karst aquifers are extremely vulnerable to contamination because: 1) the speed with which water enters and moves through the aquifer and 2) the lack of filtration of downward moving water by overlying soils. Atkinson (1971) suggests that while percolation input to the karst aquifer may comprise 60 to 100% of the total input, much in the form of vadose trickles. Such trickles and streams flowing through the vadose zone undergo little filtration by the soil.

Crawford (1984) has shown that chemicals entering cave streams may present hazards other than groundwater contamination to residents of sinkhole plains. He indicates that Bowling Green, Kentucky, a city underlain by an extensive karst groundwater flow system has recurring problems with chemical fumes entering homes and other buildings. Crawford hypothesizes that chemicals from sources such as spills and leaking underground storage tanks, entering cave streams may volatilize and rise through solutionally enlarged openings in the overlying bedrock and enter buildings on the surface.

A technique developed by Crawford which has proved to be very effective in mitigating chemical fume problems in buildings is subsurface venting (Stround, Gilbert, Powell, Crawford, Rigatti, and Johnson, 1986). This technique involves excavating near the affected building and finding a crevice in the bedrock from which fumes are thought to be
rising (Figure 9). Installation of a vent and explosion proof fan over such crevices has alleviated fume problems in every case in Bowling Green where it has been tried.
Figure 9. Chemical Fume Ventilation System installed at a Bowling Green elementary school.
CHAPTER III

STUDY AREA

Bowling Green is the principal city of south-central Kentucky (Figure 10). The city currently occupies an area of more than 28.8 square miles and supports a growing population in excess of 40,000 (U.S. Census, 1980; and General Statistics, 1982).

Regional Physiography and Geology

Bowling Green lies completely within the physiographic region classified by Sauer (1927) as the Pennyroyal Plain (Figure 11). This region is a classic example of karst development. The Pennyroyal Plain is a gently rolling landscape of low relief with a few residual hills near its northern boundary, the Dripping Springs Escarpment. The most prominent feature of much of the Pennyroyal Plain is the countless, topographic depressions known as sinkholes. Due to predominance of sinkholes, the region is often referred to simply as the Sinkhole Plain.

Geologically, the Pennyroyal Plain is part of a larger region composed of low plateaus underlain by Mississippian age bedrock, predominantly limestones (Figure 12).
LOCATION OF BOWLING GREEN AND THE LOST RIVER KARST GROUNDWATER BASIN, WARREN COUNTY, KENTUCKY

Figure 10. Location of Bowling Green, Warren County, Kentucky and the Lost River Karst Groundwater Basin.
Figure 11. The Pennyroyal Region of Kentucky.
Figure 12. Physiographic Diagram of Kentucky.
Source: After Lobeck (1932).
structural and lithologic pattern of the strata underlying the region has resulted in a roughly concentric pattern of cuestas (Dilamarter, 1982).

The Pennyroyal Plain lies at the southeastern margin of the Illinois Basin. Regional dip is to the northwest and generally averages 1/2 to 1 degree. However, there can be considerable local variation in degree and direction of dip.

Local Geology

The study area is underlain by a thick sequence of Mississippian carbonates. In stratigraphic order the formations which outcrop in the area are the St. Louis, Ste. Genevieve, and Girkin Formations (Shawe, 1963a, and 1963b) (Figure 13).

The St. Louis Limestone is a light to dark grey, fine to coarsely crystalline limestone which may be thin to medium bedded.

The Ste. Genevieve Formation is a dark grey to white limestone that is predominantly oolitic in nature. This thin to thick bedded limestone may contain beds and stringers of chert which are particularly plentiful near the base.

Two major chert zones occur near the boundary between the Ste. Genevieve and St. Louis, and they have dominant roles in influencing the hydrology and cave development within the study area.
Figure 13. Stratigraphic Column for the study area and the Mammoth Cave area of Kentucky. Source: Palmer (1981).
The Lost River Chert (Elrod, 1899) appears as lenses and stringers of chert in a white micrite host rock that is thickly bedded and averages 10 to 20 feet (3 to 6 meters) in thickness. Although the rock may be pure white, it weathers to a reddish brown and it may have a black coating in caves. The chert is easily recognizable because of its blocky appearance and the abundance of fossils, especially bryozoans.

About 15 to 20 feet (4.6 to 6 meters) below the Lost River Chert lies the Corydon Member of the St. Louis Limestone (Woodson, 1981), informally known as the "Ball Chert." The Corydon is a nodular chert that occurs in a 20 to 40 foot (6 to 12 meter) thick layer.

The contact between the St. Louis and Ste. Genevieve Formations has long been a subject of considerable debate. The break between the two formations has been drawn based on at least six varying criteria (Pohl, ibid). The Kentucky Geological Survey (KGS) places the contact at the bottom of the Lost River Chert bed. During geologic mapping of the study area, the Lost River Chert was misidentified, resulting in misplacement of the contact at the land surface by as much as one-half mile (Schindel, 1984).

The Girkin Formation is the uppermost stratigraphic unit that outcrops in Bowling Green. It is typically a medium to thickly bedded limestone that differs little from the Ste. Genevieve although it may be argillaceous in
places. Weller (1927) indicates that the Girkin may unconformably overlie the Ste. Genevieve in places. Within the study area, the Girkin is preserved only on the tops of two residual hills near the center of the city locally known as College Hill and Reservoir Hill.

**Hydrogeology**

In a well-developed karst terrain the subsurface drainage system is so efficient at transmitting runoff that surface streams are uncommon. This lack of surface drainage common to many karst regions is readily apparent in Bowling Green where, except for a few major streams such as the Barren River and Drakes Creek, perennially flowing surface streams are virtually absent.

Bowling Green lies within portions of three known karst groundwater basins: Lost River, Harris Spring, and Double Springs. The Lost River Karst Groundwater Basin is by far the largest and most intensively studied (Figure 14).

**Lost River Karst Groundwater Basin**

The Lost River Groundwater Basin delineated by Lambert (1976) and Crawford (1985a), encompasses an area of approximately 55 square miles (142 square kilometers). Twelve percent of the basin lies within the city limits of Bowling Green. Dye tracing by Crawford (ibid) has demonstrated that the Lost River begins about twelve miles (19 kilometers) south of Bowling Green.
Figure 14. Groundwater flow routes and monitoring stations in the Lost River Karst Groundwater Basin.
The Lost River is, for the most part, a subsurface stream. However, it can be viewed from the surface at several points along its course at places where karst windows have developed. The most extensive exposure of the Lost River occurs at the southern edge of the study area in a large type of sinkhole, termed a uvala, formed by the collapse of the Lost River Cave. In this uvala, the Lost River boils to the surface as a large spring and flows northwest for approximately 400 feet (120 meters) before flowing into the entrance to Lost River Cave (Figure 15). From this point the Lost River is a totally subsurface stream until it finally resurges for the last time at the Lost River Rise in the northwest part of the city. From the Rise, the Lost River flows on the surface for approximately 600 feet (180 meters) to join Jennings Creek which is a tributary of Barren River, a major waterway of the area.

Cave Mapping

From 1985 to 1988, the Center for Cave and Karst Studies of Western Kentucky University, in a joint project with the Green River Grotto of the National Speleological Society (NSS) was involved in an intensive cave mapping program in Bowling Green. As of December, 1986, the Lost River Cave System totals over 6.5 miles (10.5 kilometers) of mapped passage. In addition, a total of more than 12 miles (19 kilometers) of cave passage has been charted.
Figure 15. Main entrance to Lost River Cave, Warren County, Bowling Green, Kentucky. For scale, note person in center of photograph.
Figure 16. The Lost River Cave System.
Figure 16. The Lost River Cave Group.
beneath the city much of which is shown in Figure 16.

Unfortunately, as of the date of this report, a data gap of several miles (kilometers) exists between the farthest downstream known portion of the Lost River Cave, the Alexander section, and the resurgence at the Lost River Rise. Although the downstream section of Lost River Cave may never be entered by humans, a combination of dye tracing, water table measurements, topographic analysis, and microgravimetric techniques have allowed the delineation of the hypothesized route of the present and paleo Lost River (Figure 17) (Stroud, Gilbert, Powell, Crawford, Rigatti, and Johnson, 1986).

State Trooper Cave and Lampkin Park Cave are two other Bowling Green caves of interest to this investigation. State Trooper Cave is located in the southwestern portion of the study area (Figure 16). As of 1986, a total of 4,963 feet (1,513 meters) of State Trooper Cave have been explored and mapped (Bogle, 1988). Dye tracing has demonstrated that State Trooper Cave is hydrologically connected to the Lost River. Mapping has shown that the cave terminates at the Lost River uvala very close to the entrance to Lost River Cave. Lampkin Park Cave is believed to be a paleo-section of the Lost River Cave (Figure 18). It has a surveyed length of approximately 500 feet (150 meters) and lies about 30 feet (9 meters) above present base level (Shafstall, 1984). The cave has two entrances which lie about 200 feet (60 meters) apart.
Large collapses of the cave roof have caused the Lost River to repeatedly change its course. Exploratory drilling into gravity anomalies has revealed abandoned upper level passages and extensive areas of broken rock where massive collapses have occurred.

Figure 17. Location of Known and Hypothesized Route of the Present and Paleo Lost River. Source: Stroud, Gilbert, Powell, Crawford, Rigatti, and Johnson (1986).
LAMPKIN PARK CAVE
WARREN COUNTY, KENTUCKY

SURVEYED BY
THE GREEN RIVER GROTTO
OF THE
NATIONAL SPELEOLOGICAL SOCIETY

PERSONNEL:
BOB TAYLOR
KATHY TAYLOR

CARTOGRAPHY:
TIM SCHAFSTALL
BOB TAYLOR

Figure 18. Lampkin Park Cave. Source: Schafstall (1984).
Chemical Fume Problems

Bowling Green has been plagued by recurring episodes of chemical fume problems. Crawford (1984) reported that in 1969, several Bowling Green residents had to be evacuated from their homes due to explosive levels of chemical fumes. Since that time, several episodes of fume problems have occurred in various areas of the city.

Forest Park

The most recent serious episode of fume problems in the study area occurred in the Forest Park neighborhood located in the northwestern part of the city. Crawford (1984) reported that as of August, 1984, five houses in this area had fumes either in basements or crawl spaces. He noted that in addition, several residents had reported fumes entering their homes through open windows or had smelled a heavy chemical odor outside their houses. Crawford also noted that fumes were known to issue from several drainage wells, improved sinkhole drains, and sinkholes in the area.

In response to the Forest Park problem, the Centers for Disease Control issued a health advisory for Bowling Green in March of 1985. This action cleared the way for the United States Environmental Protection Agency (EPA) to respond to the problem in April of 1985 (Stroud, Gilbert, Powell, Crawford, Rigatti, and Johnson, ibid).

The emergency action resulted in an intense effort to find the source of the fumes. It was hypothesized that
contaminants trapped in caves beneath the city may contribute to the problem. Thus, a major effort of the investigation was to find a route into the downstream portion of the Lost River Cave System which was thought to pass beneath the Forest Park area.

An innovative technique, smoke tracing, was employed during the investigation in an attempt to determine direct air-to-air connections between the surface and subsurface (Stroud, Gilbert, Powell, Crawford, Rigatti, and Johnson, ibid). In this smoke trace, a nontoxic smoke was generated and forced by high pressure fans into the entrance of a shallow cave that was known to be the source of heavy fume emissions. After a prolonged period of smoke injection, reconnaissance of the area revealed smoke coming to the surface around the foundation of a house. Streams of smoke were also observed issuing from the ground at several locations in the vicinity of the injection point. More remarkable was the discovery of smoke issuing from a drainage well over 300 yards (275 meters) distance from the point of smoke injection.
CHAPTER IV

RESEARCH DESIGN

Testing the Hypotheses

The stated hypotheses were tested by monitoring radon gas and radon daughter concentrations in caves, homes, and other buildings within the study area. A comparison of radon levels was made between the various categories of buildings. The results were also compared to the findings of other radon studies as reported in the literature.

Testing Hypothesis One

Hypothesis one was tested by conducting measurements of radon daughters in the Lost River Cave System and other caves within the study area. If the average radon daughter concentrations were determined to be in excess of 0.30 WL, hypothesis one was to be accepted.

Testing Hypothesis Two

Hypothesis two was tested by conducting a systematic screening of residences in the study area. If average residential radon concentrations were found to be significantly higher than the estimated national average of 2.8 pCi/l estimated by the EPA (1987), hypothesis two was to be accepted.
Testing Hypothesis Three

Hypothesis three was tested by comparing the percentage of homes in the screening survey that equalled or exceeded 4 pCi/l with the national average of 8 to 12% estimated by the EPA (1987). If the percentage of homes in the study area that equal or exceed 4 pCi/l was found to be significantly higher than the estimated national average, hypothesis three was to be accepted.

Testing Hypothesis Four

Hypothesis four was tested by conducting radon measurements in buildings which are known to have had recurring chemical fume problems. If the average radon concentration for this group was found to be significantly higher than the overall average for the study area, then hypothesis four was to be accepted.

Sampling Design

Several approaches may be taken in designing a sampling plan. Each sampling design has advantages and disadvantages which are largely dependent on the population being sampled. Sample designs usually are roughly divided into two principal categories, random designs and systematic designs.

In a random design, each sample point is designated by a random selection process. Each member of the available
population has an equal chance of being selected each time a sample point is selected. A drawback with random sampling however, is that this technique tends to generate clusters of sample points. This clustering results in uneven areal coverage, thus making spatial trends more difficult to detect (Berry and Baker, 1969).

In a systematic sample design, the initial sample point is chosen randomly with all subsequent points determined by some fixed interval. The systematic design insures even and complete areal coverage; however, should hidden periodicities exist in the population, the systematic design can lead to serious bias in the data.

In this investigation, it was desired to have full coverage of the study area but still maintain a degree of randomness in the sample. Therefore, a sample plan that draws elements from both the random and systematic designs was necessary. To satisfy this criteria, the Stratified, Systematic, Unaligned Sample Design (SSU) described by Berry and Baker (ibid) was chosen.

An SSU sample is generated by dividing the area to be sampled into a grid of rows and columns of a selected size. A random point is then established in the first quadrant of the grid, designated point A1. The X coordinate of A1 is used to fix the X coordinate of every other point in the first row of quadrants; however, each point in the first row is assigned a random Y coordinate.
The result is a row of points all having constant X coordinates and random Y coordinates. In the first column, the Y coordinate of Al is used to fix the Y coordinate for each quadrant of the column. Each point in the first column is assigned a random X coordinate however. All remaining points of the sample are fixed by the random X and Y coordinates in their respective rows and columns.

The sampling plan for Bowling Green, Kentucky, was generated by first superimposing a grid upon a map of the city. An arbitrary quadrant size of 2,000 by 2,000 feet was chosen based upon the maximum number of samples possible given available resources. Once constructed, approximately 200 quadrants fell partially or fully within the boundaries of the city, yielding a potential sample size of 200 points. Specific sample points in each quadrant were determined using the prescribed SSU method (Figure 19).

Upon inspection it was determined that not every quadrant had a house within its boundaries. Also, in many cases, the nearest building that could potentially be sampled was separated from the established sample point by several hundred feet. To overcome these problems, it was decided that in the absence of a suitable sample location at the specified point, the nearest house within a radius of 1,000 feet from the predetermined sample point would be accepted regardless of whether the building was within the quadrant being sampled.
Figure 19. Systematic, Stratified, Unaligned Sample Design overlain on an outline map of Bowling Green, Kentucky.
Once the approximate locations of all sample points was established, Bowling Green residents were contacted and asked to participate in the study. If a resident was willing to have his or her home sampled, he or she was given a charcoal canister, instruction sheet, and a short questionnaire requesting general physical information about the building and the conditions that existed during the testing period. In many instances, a resident was willing to have his or her home tested but preferred to have the investigator handle the detector. In these cases, the author or a representative thereof exposed the canister and came back 48 hours later to seal and retrieve it.
CHAPTER V

RESULTS AND DISCUSSION

Results of Radon Testing in Caves

Sampling in caves was greatly curtailed due to unexpected events which made it necessary to utilize electronic components, originally intended for use in testing caves, to analyze charcoal canisters. Although weekly sampling of caves was not carried out as planned, a total of 21 radon daughter measurements were conducted in the Lost River and Bertha section of the Lost River System, in Lampkin Park Cave, and in State Trooper Cave.

The results of working level measurements in caves reveals that radon daughter concentrations in Bowling Green caves are sometimes extremely elevated and undergo considerable fluctuation (Table 12).

First Sample Event - May 21, 1987

The first radon daughter measurements were conducted on May 21, 1987. This event consisted of a total of eight samples taken from three caves. Two samples taken less than 100 feet (30 meters) inside the main entrance to Lost River Cave yielded 5.36 and 5.41 WL (Figure 16). Three samples were taken in Bertha Cave (Figure 16). The first measurement was made about 300 hundred feet (90 meters)
# TABLE 12

**WORKING LEVEL MEASUREMENTS**

**FOR BOWLING GREEN CAVES TESTED DURING INVESTIGATION**

<table>
<thead>
<tr>
<th>Date</th>
<th>Cave</th>
<th>Location</th>
<th>WL</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/21/87</td>
<td>Lost River</td>
<td>50 Feet Inside the Main Entrance</td>
<td>5.36</td>
</tr>
<tr>
<td>05/21/87</td>
<td>Lost River</td>
<td>Side Passage 30 Feet Inside Main Entrance</td>
<td>5.41</td>
</tr>
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<td>10/06/87</td>
<td>Lost River</td>
<td>50 Feet Inside the Main Entrance</td>
<td>0.01</td>
</tr>
<tr>
<td>10/08/87</td>
<td>Lost River</td>
<td>50 Feet Inside the Main Entrance</td>
<td>0.02</td>
</tr>
<tr>
<td>03/02/88</td>
<td>Lost River</td>
<td>Small Hole Entrance at River Level</td>
<td>0.65</td>
</tr>
<tr>
<td>05/21/87</td>
<td>Bertha Cave</td>
<td>Ultimate Scrunge Room</td>
<td>2.58</td>
</tr>
<tr>
<td>05/21/87</td>
<td>Bertha Cave</td>
<td>At the Base of the Entrance Slope</td>
<td>2.06</td>
</tr>
<tr>
<td>05/21/87</td>
<td>Bertha Cave</td>
<td>Just Inside the Bertha Entrance</td>
<td>1.24</td>
</tr>
<tr>
<td>10/08/87</td>
<td>Bertha Cave</td>
<td>Just Inside the Bertha Entrance</td>
<td>0.35</td>
</tr>
<tr>
<td>10/08/87</td>
<td>Bertha Cave</td>
<td>At the Junction with the Potter Passage</td>
<td>0.35</td>
</tr>
<tr>
<td>10/08/87</td>
<td>Bertha Cave</td>
<td>Room at Junction With Ultimate Scrune</td>
<td>0.03</td>
</tr>
<tr>
<td>03/02/88</td>
<td>Bertha Cave</td>
<td>Just Inside Bertha Entrance</td>
<td>0.42</td>
</tr>
<tr>
<td>05/21/87</td>
<td>Lampkin Park</td>
<td>Just Outside West Entrance</td>
<td>0.43</td>
</tr>
<tr>
<td>05/21/87</td>
<td>Lampkin Park</td>
<td>Point &quot;A&quot; Beginning of Back Section*</td>
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</tr>
<tr>
<td>05/21/87</td>
<td>Lampkin Park</td>
<td>Point &quot;B&quot; at Back of Cave*</td>
<td>4.68</td>
</tr>
</tbody>
</table>
TABLE 12 CONTINUED
WORKING LEVEL MEASUREMENTS
FOR BOWLING GREEN CAVES TESTED DURING INVESTIGATION

<table>
<thead>
<tr>
<th>Date</th>
<th>Cave</th>
<th>Location</th>
<th>WL</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/17/87</td>
<td>Lampkin Park</td>
<td>Point &quot;C&quot; at Back of Cave*</td>
<td>5.15</td>
</tr>
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<td>08/17/87</td>
<td>Lampkin Park</td>
<td>Point &quot;B&quot; at Back of Cave*</td>
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<td>08/18/87</td>
<td>Lampkin Park</td>
<td>Just Inside East Entrance</td>
<td>0.39</td>
</tr>
<tr>
<td>10/08/87</td>
<td>Lampkin Park</td>
<td>Point &quot;B&quot; Back Room*</td>
<td>0.04</td>
</tr>
<tr>
<td>10/08/87</td>
<td>Lampkin Park</td>
<td>Point &quot;B&quot; Back Room*</td>
<td>0.03</td>
</tr>
<tr>
<td>10/06/87</td>
<td>State Trooper</td>
<td>Just Inside Main Entrance</td>
<td>0.01</td>
</tr>
</tbody>
</table>

* Refer to Figure 20.
inside the cave in a large room where a small side passage known as the Ultimate Scunge joins the main cave. This sample measured 2.58 WL. The second Bertha sample was taken approximately 100 feet (30 meters) into the cave at the base of a breakdown slope leading to the entrance of the cave. Here the radon daughter concentration was recorded to be 2.06 WL. The third measurement, just inside the entrance of the cave was 1.24 WL.

Initially it was thought that the radon daughter concentration in Lampkin Park Cave would be relatively low due to ventilation resulting from the cave’s relatively shallow depth and because it is small in size and has two large entrances located in close proximity to one another. However, a grab sample taken just outside the west entrance registered a surprising 0.43 WL (Figure 20). Two samples taken in the back section of the cave at points A and B resulted in radon daughter concentrations of 3.36 WL, and 4.68 WL, respectively.

Second Sampling Event - August 17-18, 1987

A second sampling event, limited to Lampkin Park Cave, occurred on August 17, 1987. Two samples were taken during this event (Figure 20). The first sample was taken near the terminus of the cave at point C. The second sample was taken at point B. Analysis of the samples resulted in radon daughter concentrations of 5.15 and 4.80 WL.
Figure 20. Location of radon daughter measurement points within Lampkin Park Cave.  
respectively. On August 18th, 0.39 WL was recorded just inside the east entrance.

Third Sampling Event - October 8, 1987

Working Level measurements made on October 8, 1987, yielded sharply different results from former sampling events. On this event, one sample was taken from Lost River, Bertha, and two samples were taken from Lampkin Park Cave. Just inside the entrance of Bertha Cave the radon daughter concentration was 0.68 WL. The samples taken in Lampkin Park Cave, at points A and B, resulted in 0.04 and 0.03 WL where previously radon daughter measurements of 4.68 and 4.80 WL had been recorded (Figure 20).

Fourth Sampling Event - March 2, 1988

On March 2, 1988, 0.42 WL was recorded inside the entrance of Bertha Cave. A sample was also taken at the Small Hole Entrance to Lost River Cave, located near the entrance to Bertha Cave, (Figure 16). At the Small Hole Entrance, the cave is accessed via a steep climb through breakdown to the Lost River. A sample taken at river-level resulted in 0.65 WL.

A sample also was taken in State Trooper Cave. This cave had previously been closed to caving because of fumes encountered there by Center for Cave and Karst Studies personnel in 1987 (Smith, 1987 pers comm). This sample was
taken a few feet inside the entrance and was recorded to be 0.002 WL (Figure 16).

Results of Radon Testing in Buildings

During 1987, a total of 132 charcoal canisters were exposed in 113 homes and other buildings within the study area. Eighty-four measurements were conducted in homes that were tested in order to establish a working average residential radon level for the city. This group will be referred to as Category I. Twelve screening measurements were performed in structures having a history of chemical fume problems. This group will be referred to as Category II. A total of 17 of the tests had to be discarded as unusable for various reasons including, canisters being closed at the wrong time or at an unknown time or being dropped and spilled. The results of the remaining tests do not appear in this thesis. They were performed as a courtesy to various people, or to study the effects of ventilation techniques and radon rebound rates.

Participants in the study were assured that their identity would remain confidential; therefore their names and addresses will not appear in this thesis. Instead, test results will be referred to by their overall numerical rank within their respective categories.

Overall, the radon concentration for Category I ranged from 0.1 pCi/l to 123.38 pCi/l (Table 13). The summary statistics for Categories I and II appear in Table 14. The
### TABLE 13
**DATA SUMMARY FOR BOWLING GREEN CATEGORY I SAMPLE**

<table>
<thead>
<tr>
<th>Rank</th>
<th>Date</th>
<th>pCl/1</th>
<th>Placement</th>
<th>Room</th>
<th>Constr.</th>
<th>Under Bld.</th>
<th>No. Fls.</th>
<th>Age Cat.</th>
<th>Insulation Cat.</th>
<th>Vents or Windows Open</th>
<th>Vent Fan On</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bat/Clasp</td>
<td>Attic</td>
</tr>
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<td>05/13/87</td>
<td>123.30</td>
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<td>Bat</td>
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<td>4</td>
<td>2,3</td>
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</tr>
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<td>05/13/87</td>
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<td>Bat/Clasp</td>
<td></td>
</tr>
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<td>Al/Sd</td>
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**Misc:**
- (-) - Not Answered or Not Applicable
- UK - Unknown
- Lv. Sp. - Living Space of Building

**Construction:**
- Al Sd - Aluminum Siding
- **Under Bld:**
  - Bt - Basement
  - Clap - Crawlspace
  - Slab - Concrete Slab

**No. Floors:**
- * - Excluding Basement

**Age Category:**
- 1 - < 10 Years
- 2 - 10 to 25 Years
- 3 - 26 to 50 Years
- 4 - > 50 Years

**Insulation Cat.:**
- 1 - Exterior Walls
- 2 - Attic or Ceiling
- 3 - Beneath Floor
TABLE 14
Summary Statistics for Categories I and II

<table>
<thead>
<tr>
<th>Category</th>
<th>Mean (pCi/l)</th>
<th>Median (pCi/l)</th>
<th>Number</th>
<th>Percent &gt;4 pCi/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>9.06</td>
<td>3.20</td>
<td>84</td>
<td>47.6</td>
</tr>
<tr>
<td>IA</td>
<td>4.73</td>
<td>2.63</td>
<td>64</td>
<td>35.9</td>
</tr>
<tr>
<td>IB</td>
<td>22.92</td>
<td>12.52</td>
<td>20</td>
<td>85.0</td>
</tr>
<tr>
<td>II</td>
<td>35.15</td>
<td>16.64</td>
<td>12</td>
<td>69.0</td>
</tr>
<tr>
<td>IIA</td>
<td>29.75</td>
<td>12.42</td>
<td>7</td>
<td>57.0</td>
</tr>
<tr>
<td>IIB</td>
<td>57.40</td>
<td>27.75</td>
<td>5</td>
<td>100.0</td>
</tr>
</tbody>
</table>

I - Mean Sample for Study Area
IA - Category I First Floors
IB - Category I Basements
II - Buildings With History of Chemical Fume Problems
IIA - Category II First Floors
IIB - Category II Basements
average for Category I was 9.06 pCi/l and the median was 3.20 pCi/l. Sixty-four of the Category I measurements were carried out on the first floors of houses without basements. The sample mean and median for this group, designated Category IA, was 4.73 and 2.63 pCi/l respectively, and ranged from 0.14 to 25.63 pCi/l (Table 14). The remaining twenty Category I tests were conducted in basements. This group, Category IB, averaged 22.92 pCi/l with a median of 12.52 pCi/l. Category IB values ranged from 2.47 to 123.38 pCi/l.

The average for Category II homes, those with a history of chemical fume problems, was 35.15 pCi/l (Tables 14 and 15). The median for Category II was 16.64 pCi/l of radon gas. Category IIA samples averaged 29.75 pCi/l while Category IIB averaged 57.40 pCi/l.

Discussion of Results

Caves

It is readily apparent from inspection of the available data that the radon daughter concentrations within Lost River, Bertha, and Lampkin Park Caves, can be extremely high (Table 12). It is also apparent that the radon daughter concentrations in the caves are subject to considerable fluctuation.

In the literature it is suggested that radon/radon progeny concentrations in caves display a marked seasonality. Levels tend to be elevated during summer and
### Data Summary for Bowling Green Category II Sample

<table>
<thead>
<tr>
<th>Rank</th>
<th>Date</th>
<th>pCi/l</th>
<th>Placement</th>
<th>Room</th>
<th>Constr. Under Bld.</th>
<th>No. Fls.</th>
<th>Age Cat.</th>
<th>Insulation Cat.</th>
<th>Vents or Windows Open</th>
<th>Vent Fan On</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>02/07/87</td>
<td>137.97</td>
<td>Basement</td>
<td>-</td>
<td>Stone</td>
<td>2</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>no</td>
</tr>
<tr>
<td>02</td>
<td>08/10/87</td>
<td>136.17</td>
<td>First Fl</td>
<td>Lv Rm</td>
<td>Wood</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>03</td>
<td>06/08/87</td>
<td>105.97</td>
<td>Basement</td>
<td>-</td>
<td>Wood</td>
<td>1</td>
<td>3</td>
<td>1,2</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>04</td>
<td>08/08/87</td>
<td>33.18</td>
<td>First Fl</td>
<td>Rm #4</td>
<td>Brick</td>
<td>1</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>yes</td>
</tr>
<tr>
<td>05</td>
<td>05/19/87</td>
<td>27.75</td>
<td>Basement</td>
<td>-</td>
<td>Brick</td>
<td>2</td>
<td>3</td>
<td>1,2</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>06</td>
<td>08/10/87</td>
<td>20.87</td>
<td>First Fl</td>
<td>Office</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>07</td>
<td>01/25/87</td>
<td>12.42</td>
<td>First Fl</td>
<td>Lv Rm</td>
<td>Wood</td>
<td>1</td>
<td>3</td>
<td>1,2</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>08</td>
<td>08/10/87</td>
<td>7.69</td>
<td>Basement</td>
<td>-</td>
<td>Other</td>
<td>1</td>
<td>4</td>
<td>-</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>09</td>
<td>06/08/87</td>
<td>7.62</td>
<td>Basement</td>
<td>-</td>
<td>Stone</td>
<td>2</td>
<td>4</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>10</td>
<td>08/10/87</td>
<td>2.57</td>
<td>First Fl</td>
<td>Bdrm</td>
<td>Wood</td>
<td>1</td>
<td>4</td>
<td>1,2</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>11</td>
<td>08/10/87</td>
<td>1.83</td>
<td>First Fl</td>
<td>Office</td>
<td>Wood</td>
<td>1</td>
<td>3</td>
<td>1,2</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>12</td>
<td>08/10/87</td>
<td>1.19</td>
<td>First Fl</td>
<td>Brick</td>
<td>Clap</td>
<td>1</td>
<td>3</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

#### Rooms:
- Bd Rm - Bedroom
- Dn Rm - Dining Room
- Lv Rm - Living Room

#### Construction:
- Al Sd - Aluminum Siding

#### Under Bld:
- Bt - Basement
- Clap - Crawlspace
- Slab - Concrete Slab

#### No. Floors:
- * - Excluding Basement

#### Age Category:
1 - < 10 Years
2 - 10 to 25 Years
3 - 26 to 50 Years
4 - > 50 Years

#### Insulation Cat:
1 - Exterior Walls
2 - Attic or Ceiling
3 - Beneath Floor

#### Misc:
- (-) - Not Answered or Not Applicable
- UK - Unknown
- Lv. Sp. - Living Space of Building
relatively lower during the winter months. Radon gas and radon daughter concentrations fluctuate greatly during the transition seasons of spring and fall because of greater fluctuation of outside temperature.

Insufficient data was collected during this study to determine whether radon daughter concentrations in Bowling Green caves exhibit seasonal fluctuation. However, it can be noted that the highest radon daughter concentrations were recorded during the May and August sample events while October and March were much lower.

Residential Radon Levels

Overall, the average radon gas concentration for Category II was over four times higher than the average for Category I (Figure 21). Moreover, the average radon concentration for Category IIA (first floors) exceeds the average for Category IB (basements).

These test results suggest that some factor is influencing radon levels in Category II houses that is not present in Category I or which has a smaller effect on Category I buildings. As noted previously, studies of chemical fume problems in the Bowling Green area by Crawford (Crawford, 1984) have repeatedly demonstrated that buildings plagued with intermittent fume problems often have a direct air-to-air connection to the subsurface via solutionally enlarged openings in the bedrock. Since the subsurface atmosphere is known to have elevated
COMPARISON OF AVERAGE RADON CONCENTRATIONS CATEGORIES I AND II

Figure 21. Comparison of the Average Radon Concentration for Category I and Category II.
concentrations of radon gas, these solutional openings may act as a source of radon laden air to buildings (Figure 22). The data from this investigation supports this scenario in that, as previously noted, the average radon concentrations for houses within the study area with a history of fume problems is three times higher than those without a history of such problems.

Comparison With EPA Results for Kentucky

In 1987, the EPA sponsored a statewide radon screening surveys of seven states including Kentucky. These data became available to the author in 1987 (Nodler, 1987, pers comm)

The statewide survey involved 879 homes and 117 counties. Heavily populated areas of the state were sampled more intensively than sparsely settled regions. For example, Jefferson County, a highly populated area, received 125 samples while some counties, such as Adair and Harlan, had only one home tested. Furthermore, three Kentucky counties were not sampled. Comparison of data obtained during the Bowling Green investigation with the state survey data indicates a striking difference in both average radon concentration and percentage of homes at or above 4 pCi/l.

Comparison of the data for Kentucky obtained during the EPA sponsored screening with data for Bowling Green Category I suggests that the study area has higher average
Figure 22. Generalized diagram depicting possible source of radon entry into buildings. Radon rises through solutionally enlarged joints, bedding planes, and soil.
residential levels and a greater percentage of residences testing above 4 pCi/l than that the State as a whole (Figure 23). Statewide, 83% of the homes tested were below 4 pCi/l compared to 54% for the study area. Sixteen percent of the houses tested statewide and 33% of the Bowling Green test results fall into the 4 to 20 pCi/l range. For Kentucky, less than 1 percent of the houses tested were above 20 pCi/l while in Bowling Green 13% of the houses tested were above the 20 pCi/l mark.

The State survey included 25 Warren County homes. Fifteen of these (60%) tested above 4 pCi/l (Table 9). Three of the six highest values recorded for the entire state were obtained in Warren County (Figure 3).

**Comparison with Other EPA State Surveys**

Bowling Green also displays higher average radon levels and a greater percentage of measurements above 4 pCi/l than other states screened during the 1987 EPA survey (EPA 1987). In the 1987 EPA survey, Colorado displayed both had the highest average residential radon level and the greatest percentage of homes testing at or above 4 pCi/l. In Colorado, 39% of the homes tested at or above 4 pCi/l compared to 46% for the study area (Figure 24).

The 1988 EPA survey focused on midwest states (EPA, 1988). Overall, this survey yielded higher average radon levels and greater percentages of homes testing above 4
Figure 23. Comparison of Bowling Green to EPA Statewide Screening Survey.
COMPARISON OF BOWLING GREEN TO EPA TEN STATE SCREENING

Figure 24. Comparison of Bowling Green Cat. I to EPA Ten State Screening. 
pCi/l than the previous EPA survey (Figure 25). However, of the seven states, only North Dakota had a higher percentage of homes at or above 4 pCi/l, at 63%, than did the study area. The average residential radon concentration for Bowling Green, 9 pCi/l, was higher than the average determined for North Dakota of 7 pCi/l (Table 9). Five houses of the 11,000 tested during the EPA survey, had measured radon levels in excess of 100 pCi/l (Table 10). Overall, the Bowling Green sample yielded 5 houses with radon levels in excess of the 100 pCi/l mark.
COMPARISON OF BOWLING GREEN
TO EPA 1988 STATE SCREENING

Figure 25. Comparison of Bowling Green Cat. 1
to EPA 1988 State Screening.
CHAPTER VI

CONSIDERATION OF HYPOTHESES AND CONCLUSIONS

Consideration of Hypotheses

Hypothesis One Considered

Hypothesis one stated that the average radon daughter concentrations in Bowling Green caves are in excess of 0.30 WL. The results of radon daughter measurements in the caves of the study area, though limited, do confirm that the caves at times have exceedingly high radon daughter concentrations. Several of the measurements were as much as 15 times greater than the 0.30 WL concentration at which the EPA and OSHA requires routine monitoring of occupational environments and maintenance of worker health records. Given these results, hypothesis one is accepted.

Hypothesis Two Considered

Comparison of the results from the Bowling Green study with the results of a statewide screening conducted by EPA indicates that the average residential radon level for the study area exceeds the statewide average of 2.8 pCi/l. The state survey results for Warren County support this hypothesis also. Therefore hypothesis two is accepted. The average residential radon level for Bowling Green, Kentucky is higher than the overall state average of 2.8 pCi/l obtained by the EPA (1987).
Hypothesis Three Considered

Hypothesis three stated that the percentage of houses in the study area that equal or exceed 4 pCi/l is significantly higher than the estimated state average of 17 percent and the national average of 8 to 12 percent estimated by the EPA (1987). Overall, 46% of the Bowling Green homes tested equalled or exceeded 4 pCi/l; therefore, hypothesis three is accepted.

Hypothesis Four Considered

Hypothesis four stated that the average radon level for Bowling Green buildings with a history of chemical fume contamination problems is significantly higher than the overall average for the city. The author suggests that the data base for fume houses, Category II, is not sufficient to make a definitive comparison although the average radon concentration for this category was three times greater than that of houses in Category I - 35.5 pCi/l compared to 9.06 pCi/l. Therefore, hypothesis four cannot be accepted or rejected without further study.

CONCLUSIONS

The purpose of this thesis was to investigate radon contamination in Bowling Green, Kentucky and its
association with the karst landscape. The results have demonstrate that radon daughter concentrations in Bowling Green caves are sometime exceedingly high. The results of this study also shows that residential radon concentrations in Bowling Green are higher than in many other areas that have been investigated.

Although this study was limited in geographic scope, it was conducted in an area that is part of a much larger karst region. To date, karst areas have largely been ranked low as potential residential radon problem areas. The author suggests that residential radon contamination in karst regions should receive more attention than it has been previously afforded. Residents of these areas are faced with hazards specific to these regions. The results of this investigation indicates that residential radon contamination should be added to the list of environmental hazards in karst regions.
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