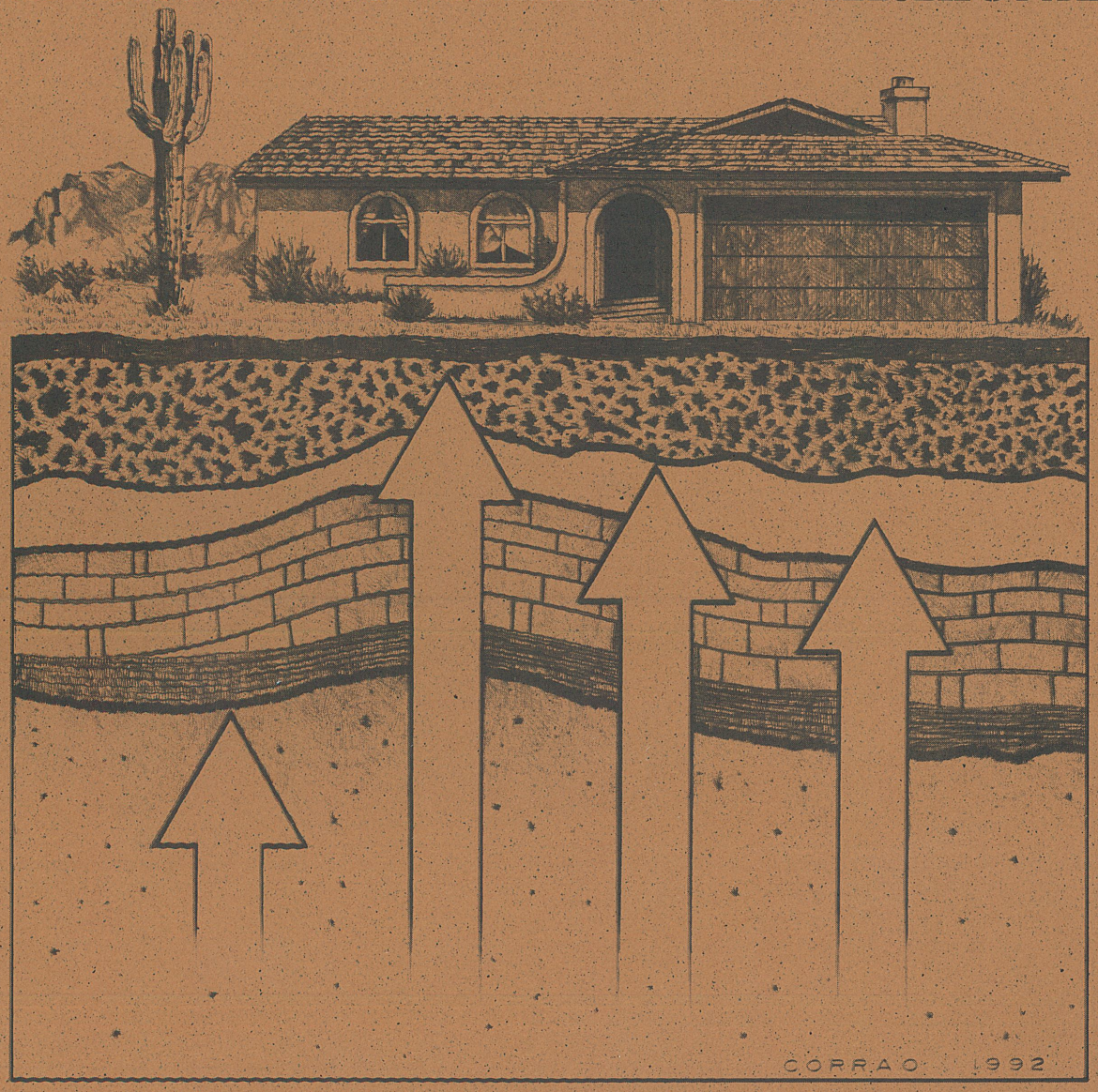
RADON GAS

A GEOLOGIC HAZARD IN ARIZONA



by
Jon E. Spencer

ARIZONA GEOLOGICAL SURVEY
Down-to-Earth Series 2

ARIZONA GEOLOGICAL SURVEY

The Arizona Geological Survey (AZGS) became an independent State agency on July 1, 1988, in accordance with Senate Bill 1102, which was enacted in 1987. The purpose of the AZGS is to assist the wise use of lands and mineral resources in Arizona by conducting scientific and investigative research and providing geologic information. Responsibility for regulating the drilling and production of oil, gas, geothermal resources, and helium was assigned to the AZGS on July 1, 1991.

The ancestral AZGS was established by the Territorial Legislature in 1881 as the Office of the Territorial Geologist. Its primary duties were to collect and provide information about mineral resources. From 1893 until statehood in 1912, Territorial Geologists were affiliated with the University of Arizona and its mineral-testing laboratory, known informally as the "Bureau of Mines." A 1915 statute created the Arizona Bureau of Mines as a State agency administered by the University of Arizona, continuing, essentially unchanged, the functions of the Territorial Geologist and "Bureau of Mines." Data collection and research activities continued to be concentrated on mineral resources. In 1977, the agency's enabling legislation was modernized and its name was changed to the Arizona Bureau of Geology and Mineral Technology. It continued to be administered by the University of Arizona. The agency was charged with investigating geologic hazards and limitations, as well as the geologic framework and mineral resources of Arizona, in anticipation of population growth and increased competition for and conflict over land, water, mineral, and energy resources.

The AZGS publishes maps, books, and reports, which are available for inspection at the AZGS office in Tucson and at libraries throughout the State. These items may also be purchased through the mail. A list of available publications may be obtained from the AZGS at the address listed below.

The AZGS office includes a library that is open to the public during normal working hours. *Arizona Geology*, published quarterly, contains summaries of AZGS research, announcements of new publications, and short general-interest articles on the geology of Arizona.

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Radon Gas: A Geologic Hazard in Arizona

Jon E. Spencer

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Preface

A high level of radon was discovered, to the surprise of almost everyone, in a home in eastern Pennsylvania in 1984. This indicated that indoor-radon concentrations throughout the country could be elevated and should be investigated.

In 1987, the Arizona Legislature appropriated $50,000 to the Arizona Radiation Regulatory Agency (ARRA) to measure indoor-radon levels in Arizona, and $8,000 to the Arizona Geological Survey (AZGS) to identify areas with elevated radioactivity caused by above-average uranium concentrations in rock and soil. (Radon is derived from uranium.) Since then, AZGS geologists have characterized those areas in more detail, with emphasis on population centers.

The results of these investigations indicate that indoor-radon levels in Arizona are among the lowest in the Nation. In several areas, however, uranium concentrations in rock and soil are elevated, as is the potential for elevated levels of indoor radon. Those areas are described in this report.

The purpose of this report is to outline the origin and migration of radon, how it accumulates indoors, its health consequences, and its geology and significance in Arizona. This report should answer questions about radon that are commonly asked by Arizona residents. It should also be useful to science teachers, as well as realtors and others who are considering the purchase or sale of a home, a building, or land.

Larry D. Fellows
Director and State Geologist

Acknowledgments

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Jon E. Spencer

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Summary

Low-level radiation is present everywhere in the natural world and is a fact of life that no one can completely avoid. Much of this natural background radiation comes from rock, soil, and their derivatives, such as concrete, brick, and cinder block. Another source of background radiation is cosmic rays, which strike the Earth from outer space. Naturally occurring radioactive substances are absorbed by plants and passed on to animals and humans through the food chain to become internal sources of radiation. Background radiation has generally been considered an insignificant health hazard because the level of exposure from natural sources is typically very low.

Radon is a colorless, odorless, radioactive gas produced by the decay of uranium, which is present in virtually all rocks and soils, typically at concentrations of 1 to 4 parts per million (**ppm**). The Earth's atmosphere contains small amounts of radon derived from radioactive decay of uranium in the ground. During the 1980's, scientists discovered that radon gas can accumulate inside homes and other buildings at concentrations that are commonly tens of times greater than in outdoor air and, in some cases, may be hundreds or even thousands of times greater. Most indoor radon is derived from uranium in underlying soil and rock and gradually seeps into buildings through cracks or other openings in the ground floor. Houses with anomalous concentrations of indoor radon are typically built on rock and soil that contain anomalous uranium concentrations.

Radon, which forms no natural chemical compounds, can travel through soil and fractured rock without adhering to it. Radon decays to radioactive elements that readily form chemical bonds and become attached to dust particles in the air, which in turn may be inhaled by humans and animals. For the average person, radon inhalation causes the lungs to receive more radiation than any other body organ (National Council on Radiation Protection and Measurements [NCRP], 1984b). High radon levels in underground mines are a known cause of lung cancer in miners (NCRP, 1984a). Based on surveys of indoor-radon levels in homes and estimates of the cancer-causing ability of radon from studies of underground miners, the U.S. Environmental Protection Agency (EPA) estimated in 1986 that 5,000 to 20,000 persons in the United States die of lung cancer each year from inhaling radioactive radon-decay products in homes and buildings (EPA, 1986a). Radon has no other perceptible effects on the human body; it does not cause symptoms of radiation exposure, nor does it cause asthma, headaches, dizziness, or nausea.

What is a geologic hazard?

*A **geologic hazard** is a geologic condition or phenomenon that presents a risk or is a potential danger to life or property (Bates and Jackson, 1980). Earthquakes, volcanic eruptions, floods, landslides, and land subsidence are geologic hazards. Because radon is a potential health hazard that results from a geologic phenomenon (emanation of radon-bearing soil gas from geologic materials), it is also a geologic hazard according to the above definition.*

Radon is a potential health hazard that originates from geologic materials and is therefore called a **geologic hazard**. (See box on this page.) The amount of uranium in underlying rock and soil is a major factor influencing indoor-radon concentrations. Knowledge of the distribution and nature of uranium-rich rocks is therefore helpful in locating areas where radon is more likely to be a health hazard than in normal geologic environments. The terms **uranium-rich** and **anomalous**, as

used in this publication, refer to soil or rocks that contain more than 6 ppm uranium, or about two to three times the average concentration in the Earth's upper crust. Uranium ore, in contrast, usually contains more than 1,000 ppm uranium.

Uranium-rich rocks are present at numerous localities in Arizona, five of which are in populated areas: (1) limestone in southwestern Tucson that contains up to 20 ppm uranium; (2) volcanic rocks in a small area of the Phoenix Mountains that contain up to 8 ppm uranium; (3) sedimentary rocks in the Cave Creek area that contain up to 33 ppm uranium; (4) sedimentary rocks in Verde Valley that contain up to 43 ppm uranium; and (5) the Dells Granite near Prescott, which contains up to 40 ppm uranium. Average indoor-radon levels in some homes in these areas are higher than in other parts of Arizona. Many other areas of the State that contain uranium-rich rock are either largely uninhabited or are small and only weakly anomalous, i.e., they contain only slightly more than 6 ppm uranium.

What is radiation?

Each of the 103 known chemical elements consists of several isotopes. Each **isotope** of a particular element has the same number of protons in the nucleus but different numbers of neutrons and, thus, different atomic weights. Some of these isotopes are **radioactive**: the number of protons in their nuclei can change spontaneously, thus creating different chemical elements. Carbon-14, for example, is a radioactive isotope of carbon that has a **half-life** of approximately 5,700 years. This means that in 5,700 years, half of the atoms of any given quantity of carbon-14 will undergo radioactive decay and will be transformed into another isotope (in this case, nitrogen-14). It is the process of radioactive decay that produces most of the radiation at the Earth's surface.

Three different types of radiation associated with radioactive decay are termed gamma, beta, and alpha. **Gamma rays**, a very high-energy and extremely short-wavelength form of electromagnetic radiation, have the greatest penetrating ability. (Light and radio waves are lower-energy, longer-wavelength forms.) Gamma rays from space can penetrate the atmosphere and reach the Earth's surface. **Beta particles** produced by beta decay are high-energy electrons that have moderate penetrating ability. **Alpha particles** produced by alpha decay are each composed of two protons and two neutrons and, because of their large size and positive charge (+2), have the least penetrating ability. Alpha particles produced by typical alpha decay will travel only a few inches through air before being stopped by collisions with air molecules and will travel only a few thousandths of an inch in rock. When alpha decay occurs externally, the amount of radiation is generally insignificant; when it occurs within the human body, however, alpha decay can be a major cause of radiation exposure.

Table 1. *Half-lives, alpha-decay energies, and maximum beta-decay energies of uranium-238 decay series. Gamma-ray energies are generally less than the maximum beta-decay energies and are significant only for the decay of lead-214 and bismuth-214. MeV = million electron volts.*

Radio-nuclide	Half-Life	Alpha Energy (MeV)	Maximum Beta Energy (MeV)
^{238}U	4.5 billion years	4.1 - 4.2	--
^{234}Th	24 days	--	0.06 - 0.2
^{234m}Pa	1.2 minutes	--	2.3
^{234}U	250,000 years	4.7 - 4.8	--
^{230}Th	80,000 years	4.6 - 4.7	--
^{226}Ra	1,600 years	4.6 - 4.8	--
^{222}Rn	3.82 days	5.5	--
^{218}Po	3.05 minutes	6.0	--
^{214}Pb	26.8 minutes	--	0.7 - 1.0
^{214}Bi	19.7 minutes	--	0.4 - 3.3
^{214}Po	16 milliseconds	7.7	--
^{210}Pb	22 years	--	< 0.1
^{210}Bi	5 days	--	1.2
^{210}Po	138 days	5.3	--
^{206}Pb	stable	--	--

86 (222)
211
202
9.91* **Rn**
(Xe)4f¹⁴5d¹⁰6s² p⁶
Radon

How does radon form?

Most of the rock in the Earth's crust, as well as soil and alluvium derived from it, contains uranium. About 99.3 percent of this uranium is the isotope uranium-238, which has a half-life of about 4.5 billion years (approximately the age of the Earth). Decay of a uranium-238 atom marks the beginning of a series of 14 decays that ends at the stable isotope lead-206 (Table 1; Figure 1). The decay product of an individual parent isotope is called its **daughter product**. Unstable daughter isotopes are referred to as **intermediate daughter products**. Radium-226 and radon-222 are intermediate daughter products in the decay of uranium-238 to lead-206. The first-generation daughter product of an individual parent isotope is called the **immediate daughter product**, and the first-generation ancestor of a daughter product is called the **immediate parent**. Radium-226, with a half-life of 1,600 years, is the immediate parent of radon-222, and radon-222 is the immediate daughter product of radium-226.

When radium-226 decays to radon-222, it releases a high-energy alpha particle that is like a bullet shot from a gun. Obeying the laws of physics, the newly formed radon-222 atom undergoes **recoil** in the same manner that a gun is propelled backward when a bullet is fired. If the radon atom is near the surface of a mineral grain, it may be knocked out of the grain by recoil. In some materials, such as clay, radon that is not dislodged by recoil is loosely trapped in the mineral's molecular structure and may escape without the assistance of recoil. This more gradual process of migration is known as **diffusion**. Radon atoms are liberated from geologic materials by both recoil and diffusion.

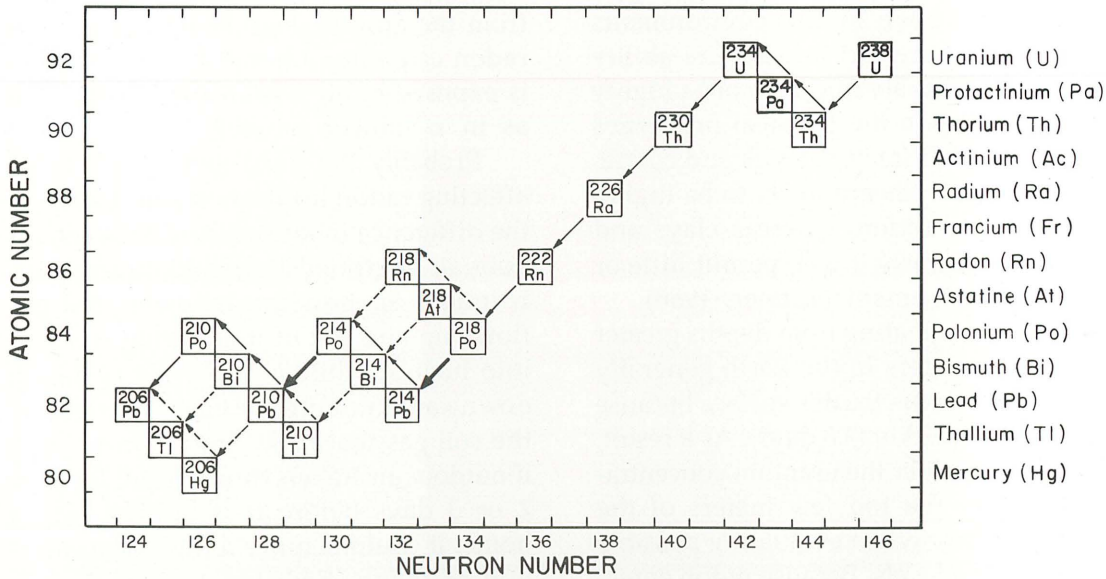


Figure 1. Decay path of uranium-238 to stable lead-206. Each box represents an isotope produced in the uranium-238 decay series. The atomic number plotted on the vertical axis corresponds to the number of protons in the nucleus; the neutron number plotted on the horizontal axis corresponds to the number of neutrons in the nucleus. The isotope number in each box is the sum of the atomic number (proton number) and the neutron number. Arrows that point down to the left represent alpha decays; arrows that point up to the left indicate beta decays. The heavy solid arrows are the two alpha decays that, by far, cause the greatest damage to lung tissue due to inhalation of airborne radon-decay products. The dashed arrows are the decay paths that are followed by a small fraction of atoms (less than 1 percent). Modified from Faure (1977).

How does radon enter homes?

Radon gas is present in the pore spaces in soil and rock after it is liberated from geologic materials. Radon is an **inert gas** and, unlike all other uranium-series decay products, does not form chemical bonds. As a result, a radon atom can move freely through the pore spaces of a porous and permeable geologic material without bonding to other mineral grains or substances. (**Porosity** is the percentage of a material's volume that consists of openings or spaces. **Permeability** is the capacity of a material to transmit gas or fluid.) The mixture of air, radon, and other gases in underground pore spaces is known as **soil gas**.

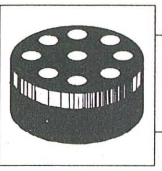
Soil gas moves through soil or fractured rock by two mechanisms: (1) diffusion in all directions due to the random movements of gas atoms and molecules, and (2) flow in one direction due to **pressure gradients** (gas flow from areas of high pressure to areas of low pressure). Diffusion and flow result in the transport of radon to above-surface environments or into underground mines. The ability of radon to migrate through soil is highly dependent upon the physical properties of the soil. Well-fractured rock and coarse, well-drained soils are likely to be highly permeable to radon, whereas clays and muds, particularly if wet, permit little or no radon movement (Tanner, 1986).

Radon originating from depths greater than a few meters in the Earth generally does not reach the Earth's surface because it decays so quickly (3.8 days). As a result, scientists consider the uranium concentration of only the top few meters of the Earth's surface when evaluating possible indoor-radon levels. Because radon enters the atmosphere at the ground surface and has a short half-life and a high density, it does not mix well with the Earth's atmosphere and tends to be concentrated at low altitudes near the land surface. Radon levels may be significantly elevated in valleys or other topographic depressions during periods of atmospheric inversion (Texas Instruments, 1975).

High indoor-radon levels are almost always the result of upward transport of soil gas from underlying soil and rock. Radon typically diffuses and flows out of underlying soil and into basements, crawl spaces, and lower levels of homes or buildings, eventually reaching upper levels. Cracks in concrete floors, open spaces around pipes that enter homes from below ground, joints where floor meets wall, and drainage outlets or sumps can all provide conduits for entry of radon-bearing soil gas into houses. Even microscopic cracks in concrete can significantly increase permeability to soil gas, although concrete-slab floors that are not cracked are generally good barriers against soil gas. In a few areas where local water supplies are derived from wells in uranium-rich rock and the water is used within a week or two from the time it is pumped from the ground, significant amounts of radon can enter a home when the water is exposed to air within the house, such as in a shower or sink.

Probably the most significant factor affecting radon infiltration into homes is the difference in air pressure between indoor air at ground level and outdoor air. If indoor air pressure is lower, soil gas flows up and out of underlying soil and into homes, while outdoor air is drawn downward into surrounding soil to replace the soil gas that flows into homes. Even if outdoor air travels through soil for only 2 or 3 days before it is sucked into a home, it could acquire a high concentration of radon. Reduced air pressure in basements and the lowest levels of homes results from heating indoor air. Warm indoor air rises to the upper levels of a house, where it builds up elevated air pressure that, in turn, pushes the heated indoor air through cracks and other openings to the outside. At lower levels in

the same house, air is drawn in through cracks and other openings as a result of lower indoor air pressures. Some homes are remarkably efficient at sucking up soil gas because of air-pressure differences. In contrast, use of evaporative coolers increases air pressure in a home, forcing indoor air downward through cracks and openings and reducing or preventing the influx of soil gas. (Other methods of reducing radon levels in the home are discussed on page 15.)



How is radon measured?

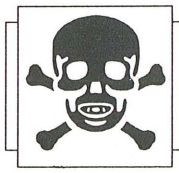
Radon concentration in air is commonly measured in picocuries per liter (**pCi/l**), the number of nuclear decays in a liter of air within a specific time period. One picocurie corresponds to about two decays per minute. The EPA has established 4 pCi/l as a general guideline for maximum acceptable, long-term, indoor-radon concentration. For the purposes of this report, **high radon levels** are defined as those above the 4 pCi/l EPA guideline.

Two types of radon monitors are commercially available and commonly used in homes and other buildings. One type is the **charcoal canister**, a small charcoal-filled can that is opened in the home, closed after several days, and sent to a laboratory for analysis. Though excellent for a quick "spot check," this type of detector does not determine average radon levels over longer periods. Seasonal radon-level variations, for example, may be substantial, and thus a quick spot check will not necessarily determine a radon level that represents the long-term average concentration. It is the best method, however, for quickly determining the approximate radon concentration in a home or building.

The other type, an **alpha-track detector**, consists of a plastic film that records the tracks of alpha particles emitted by atmospheric radon and its daughter products. The detector may be placed in the home for months or even a year, thus recording the long-term, average radon concentration that more accurately reflects the potential health hazard. Both types of detectors may be purchased at select hardware stores. The Arizona Radiation Regulatory Agency (ARRA) in Phoenix will advise citizens about detectors and detector vendors. (See box on this page.) Please note that fraudulent radon-measurement devices have been sold in some States.

For more information on radon . . .

The EPA has designated an organization in each State to receive updated information on radon gas, such as guidelines for maximum acceptable indoor-radon concentration, information on commercial vendors of radon monitors, and methods for lowering radon concentrations in homes. In Arizona, this information may be obtained from the Arizona Radiation Regulatory Agency, 4814 S. 40th St., Phoenix, AZ 85040; tel: 1-602-255-4845. Information on radon may also be obtained by calling the EPA radon hotline at 1-800-SOS-RADON.



How hazardous are radon and its decay products?

Approximately 7,000 to 12,000 liters (1,750 to 3,000 gallons) of air are inhaled and exhaled by the average adult every 24 hours. The spontaneous decay of radon in the lungs is not a major source of radiation because almost all radon is expelled after each inhalation. Polonium-218, the immediate daughter product of radon-222, begins a sequence of four decays with a total half-life of about 50 minutes before reaching lead-210, which has a half-life of 22 years (Table 1; Figure 1). Polonium and its short-lived daughter products are chemically reactive and typically highly charged immediately after decay. Newly formed polonium-218 and its daughter products tend to adhere to the first solid with which they come in contact, including lung tissue and airborne dust particles that may be temporarily trapped by the lungs. The residence time of individual radon-daughter atoms and dust particles in the lungs is usually longer than the half-lives of the short-lived daughter products of radon. Two of the four decay steps between polonium-218 and lead-210 are alpha decays that can cause significant molecular disruption in adjacent lung cells because of the large mass and high energy of ejected alpha particles (Table 1; Figure 1).

Knowledge of the hazards of radon comes largely from studies of uranium miners who were exposed to high levels of the gas in underground mines. A lung disease affecting miners who worked in the Joachimstal and Schneeburg mining areas of central Europe was described as early as A.D. 1500 and was recognized as cancer in 1879. The role of radon in causing lung cancer was not suspected until 1932 and not generally accepted until the 1960's. A greater-than-expected rate of lung-cancer deaths among underground miners working in U.S., Canadian, and Czechoslovakian uranium mines, Swedish and British iron mines, Swedish lead-zinc mines, and Newfoundland fluorspar mines has been attributed to radon-daughter exposure (NCRP, 1984a; see also Committee on the Biological Effects of Ionizing Radiations [BEIR IV], 1988). Both small-cell undifferentiated and epidermoid bronchogenic carcinomas have developed at increased frequencies in these miners. Elevated rates of lung cancer due to radon-daughter exposure have led to ventilation standards for underground mines and greatly reduced radiation exposure for underground miners (NCRP, 1984a,b).

The health consequences of radon exposure to underground miners are the primary basis for determining the health risk to people exposed to lower, more common radon levels in houses and other buildings (BEIR IV, 1988). Unfortunately, there are many problems in determining excess cancer incidence as a function of total radon exposure for underground miners. Inaccuracy is partly due to inconsistent or nonexistent monitoring of radon levels in mines, especially before the mid-20th century when ventilation was poor and radon levels in mines were high. In addition, underground miners are commonly exposed to other, possibly carcinogenic air pollutants, such as dust and combustion products from explosives and internal-combustion engines. Most estimates of lung-cancer risk due to radon-daughter exposure at typical levels in homes use a linear extrapolation from high exposure rates experienced by some groups of underground miners. In a linear extrapolation, exposure and risk are proportionally related; for example, half the exposure would constitute half the risk. It is not clear, however, that a linear extrapolation accurately represents radon-related cancer risk at low exposure rates.

The NCRP reviewed all available data on lung cancer and radon-daughter exposure from studies of underground miners and laboratory animals. Using a linear

extrapolation from high exposure rates, the NCRP produced a graph that allows estimation of risk based on the duration of exposure to a particular level of radon daughters and the age at first exposure (NCRP, 1984a; Figure 2). These studies indicate that radon-related lung cancer rarely occurs before 5 to 7 years after exposure and that the period between exposure and cancer appearance decreases with increasing age. Radon-related lung cancer rarely appears before age 40; the median age of appearance in miners is about 60 in nonsmokers and a few years younger in smokers. Some studies suggest that exposure to both radon and tobacco smoke increases lung-cancer susceptibility by an amount greater than the sum of the risks due to each type of exposure alone (BEIR IV, 1988).

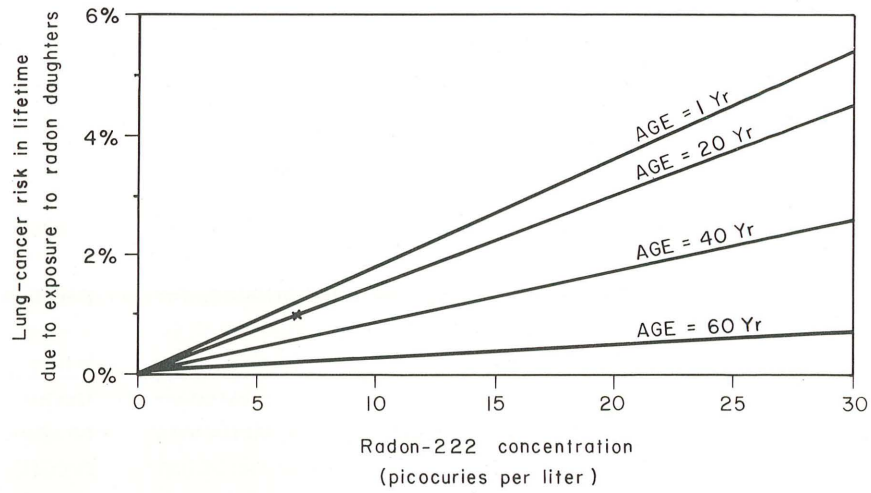


Figure 2. Increase in lifetime lung-cancer risk associated with a range of indoor-radon concentrations if half of one's lifetime is spent indoors. The age corresponds to the age of first exposure. Lung-cancer risk is based on the assumption that residents will be continuously exposed to radon daughters after their first exposure. For example, if a 20-year-old man moved into a house with a 7 pCi/l radon level ("x" in figure) and spent half of his time at home for the rest of his life, he would have a 1-percent chance of contracting lung cancer from exposure to radon daughters. A 60-year-old woman who moved into the same house would increase her risk by only about one-tenth as much because a person exposed to radon daughters late in life is more likely to die of other causes before radon-related cancer can develop. Based on Table 10.3 in NCRP (1984a).

The EPA has produced charts that compare the risk of contracting lung cancer from radon exposure to that from cigarette smoking and chest X rays (Figure 3). The agency estimates that the risk of contracting lung cancer from living in a home with an indoor-radon level of 4 pCi/l is equivalent to smoking a fourth to a half pack of cigarettes per day or receiving more than 200 chest X rays per year (EPA, 1986a, undated).

Radon Risk Evaluation Chart

pCi/l	WL	Estimated number of lung cancer deaths due to radon exposure (out of 1,000)	Comparable exposure levels	Comparable risk
200	1	440 - 770	1,000 times average outdoor level	20,000 chest X rays per year
100	0.5	270 - 630	100 times average indoor level	60 times nonsmoker risk
				4 pack-a-day smoker
40	0.2	120 - 380		
				2 pack-a-day smoker
20	0.1	60 - 210	100 times average outdoor level	
				1 pack-a-day smoker
10	0.05	30 - 120	10 times average indoor level	
				5 times nonsmoker risk
4	0.02	13 - 50		
				200 chest X rays per year
2	0.01	7 - 30	10 times average outdoor level	
				Nonsmoker risk of dying from lung cancer
1	0.005	3 - 13	Average indoor level	
				20 chest X rays per year
0.2	0.001	1 - 3	Average outdoor level	

Figure 3. Comparison of lung-cancer risk associated with radon exposure to risks associated with cigarette smoking and chest X rays. The working-level month is a commonly used unit of human radiation exposure due to radon-daughter products in air in underground mines. ***Working level (WL)*** *is defined as any combination of short-lived radon daughters in one liter of air that results in the emission of a specific quantity of potential alpha-particle energy (1.3 x 10^5 million electron volts). A* ***working-level month (WLM)*** *corresponds to exposure to one working level for a working month (170 hours). The U.S. occupational standard set in 1971 is four WLM's per year, with maximum airborne concentration not to exceed one WL (NCRP, 1984a,b). This is approximately equivalent to the amount of exposure that results from being in a home 75 percent of the time with an indoor-radon level of 15 pCi/l.*

Do homes in Arizona contain high levels (> 4 pCi/l) of radon?

The EPA provided funds to the ARRA to conduct statewide surveys of radon in homes in Arizona. The first survey, referred to as Phase 1, was conducted in 1987 and 1988. More than 2,000 homes were surveyed, mostly with charcoal-canister detectors. Alpha-track detectors were used in 170 randomly distributed homes for 1-year periods. The alpha-track data indicated that the median of the yearly average radon concentration was 0.8 pCi/l and that about 1.6 percent of homes had yearly average levels above 4 pCi/l (Figure 4; Table 2). The highest yearly average level measured by the alpha-track detectors was 8.4 pCi/l.

Phase 1 charcoal-canister testing was primarily done during the cooler months, when indoor-radon levels are typically higher. (Windows and doors are more likely to be closed during the winter, which promotes radon accumulation.) Homeowners were instructed to place the canisters in areas that inhabitants occupied frequently and to close windows and doors to the outside. Higher radon levels were recorded by the canisters than by the alpha-track detectors. The median level was 1 pCi/l, and 5.4 percent of homes had levels above 4 pCi/l (Figure 5; Table 2).

Phase 2 charcoal-canister testing in 1988 and 1989 was also primarily done during the cooler months. Canisters were distributed by county health departments using various criteria. Combined Phase 1 and Phase 2 data from homes on the Colorado Plateau (mainly the Flagstaff area) indicated that indoor-radon levels were slightly

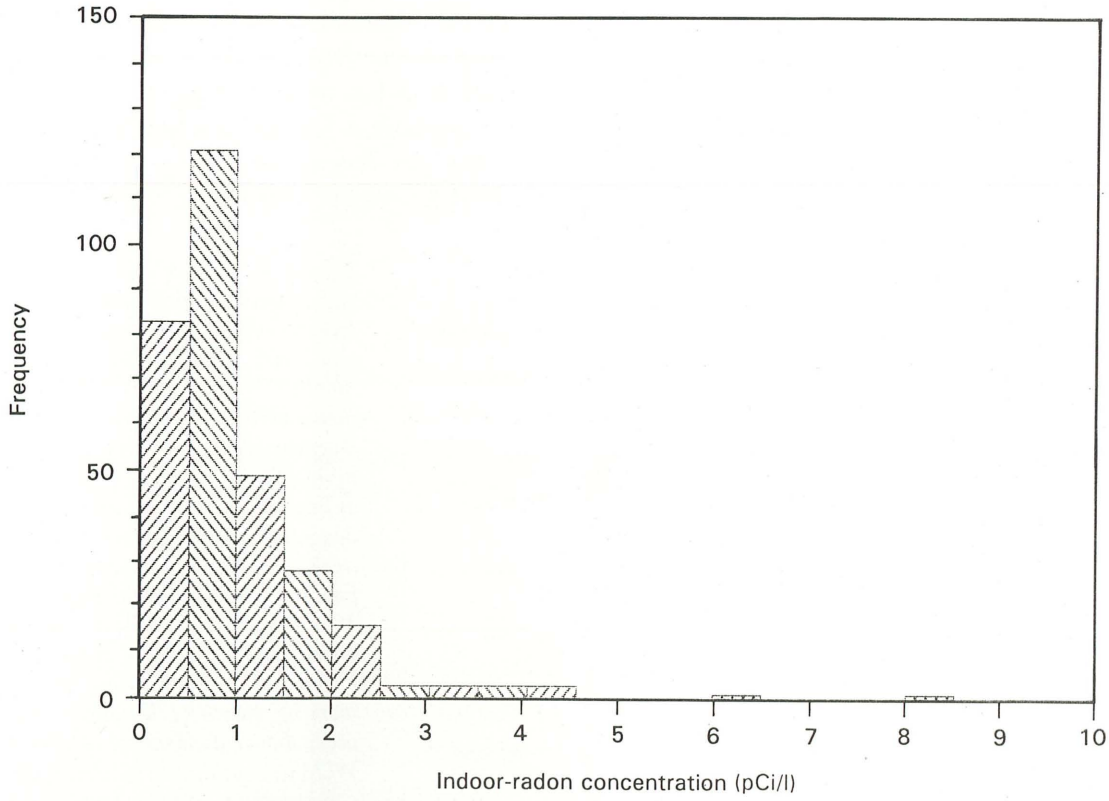


Figure 4. Histogram of randomly sampled, residential radon levels in Arizona determined using alpha-track detectors for 1-year exposure periods. The data are from the Phase 1 survey conducted by the ARRA during 1987 and 1988.

METHOD	AREA	NO. OF MEASURE-MENTS	MEDIAN VALUE (pCi/l)	PERCENT > 4 pCi/l	PERCENT > 10 pCi/l
Alpha-Track Phase 1	statewide	311	0.8	1.6	0
Charcoal Canister Phase 1	statewide	2,037	1.0	5.4	0.3
	Maricopa County	986	1.1	7.0	0.4
	Pima County	437	1.0	4.1	0.2
Charcoal Canister Phase 1 and 2	Plateau counties (Coconino, Navajo, Apache)	368	1.2	9.5	1.6
	Crystalline rock (mostly Prescott and Payson)	125	1.3	14.0	0.8
	Camp Verde area	40	1.4	10.0	7.5

Table 2. *Indoor-radon measurements from the ARRA Phase 1 and Phase 2 surveys (1987-89). The 311 alpha-track detector measurements recorded radon levels from 170 homes that typically had two detectors each, placed in different areas in each house.*

higher than statewide levels, with a median of 1.2 pCi/l and 9.5 percent of homes above 4 pCi/l. Combined Phase 1 and Phase 2 data from areas where a significant number of homes are on granite or related (crystalline) rocks, primarily in the Prescott and Payson areas, indicated that the median indoor-radon level for these homes was 1.3 pCi/l, with 14 percent of homes above 4 pCi/l (Table 2). Higher radon levels in these areas are attributed to slightly higher uranium concentrations in underlying rocks and to the greater permeability of weathered granitic rocks, which allows more rapid radon movement (see also Kearfott, 1989).

Similar studies of indoor-radon levels in other states revealed that Arizona radon levels were generally lower than most. Northern states tended to have higher radon levels because of heating and ventilation practices in colder climates and because glacial deposits and derivative soils are commonly permeable.

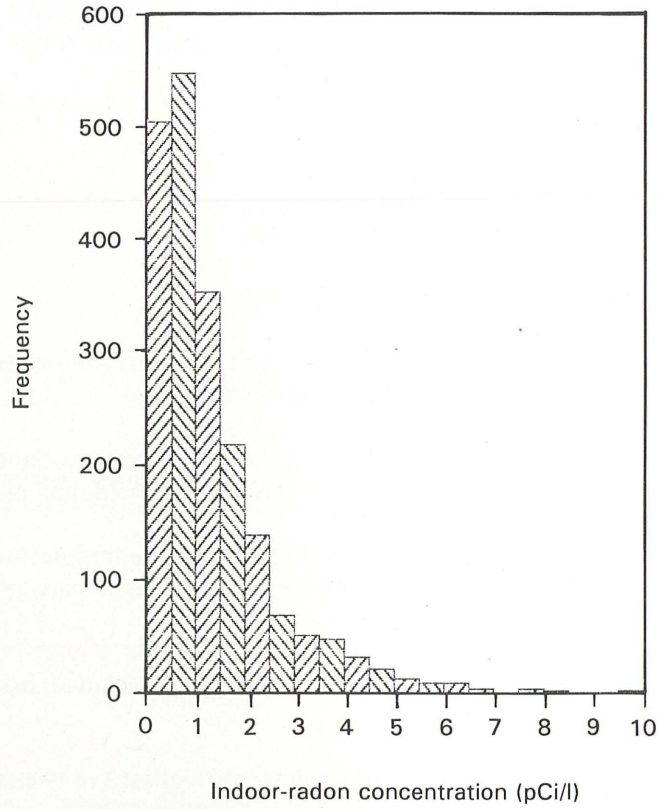
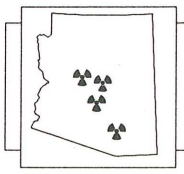


Figure 5. *Histogram of randomly sampled, residential radon levels in Arizona determined using charcoal-canister detectors. The data are from the Phase 1 survey conducted by the ARRA during 1987 and 1988 and were primarily acquired during the winter months under low-ventilation conditions.*



Which areas in Arizona contain anomalous concentrations of uranium?

High indoor-radon levels are commonly present in buildings constructed on uranium-rich bedrock and derivative soil, such as in an area of eastern Pennsylvania, northwestern New Jersey, and southeastern New York known as the Reading Prong. One home in eastern Pennsylvania had such high levels of radon that radon-decay products on the clothing and hair of one of its occupants repeatedly set off radiation alarms at the nuclear power plant where he worked. Occupants of this home were receiving more than 100 times the maximum radon-related radiation exposure considered acceptable for underground uranium miners!

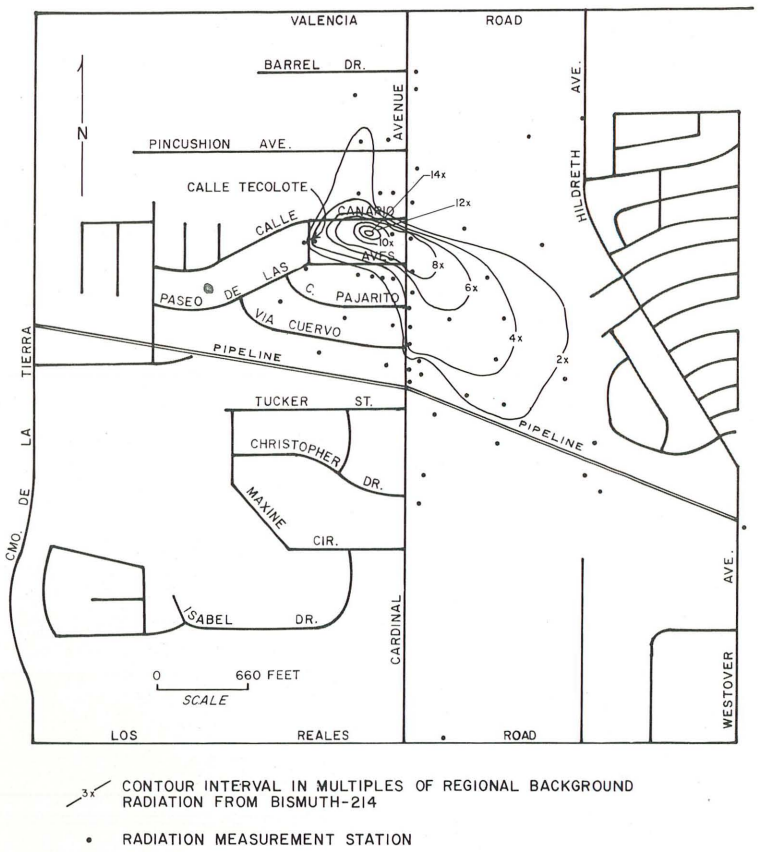
Knowledge of uranium concentrations in geologic materials is probably the most accurate basis for identifying areas that are at greatest risk of having unacceptably high indoor-radon concentrations. Most crustal rocks have uranium concentrations of 1 to 4 ppm (Table 3), whereas uranium ore typically has concentrations greater than 1,000 ppm. Most uranium ore deposits in Arizona are in largely uninhabited areas on the Colorado Plateau (Wenrich and others, 1989). Many areas in Arizona contain uranium in concentrations that are far lower than those in uranium ore but significantly higher than those typical for crustal rocks. Some of these areas are within or near population centers and are known to be associated with high indoor-radon levels. These areas with anomalous uranium concentrations (6 to 50 ppm) have significant potential for producing elevated indoor-radon levels.

Most homes in the Tucson and Phoenix metropolitan areas, as well as many other parts of southern and western Arizona, are built on young, unconsolidated (loose)

ROCK TYPE	AVERAGE (ppm)	HIGH VALUE (ppm)
Basalt (crustal average)	0.5 - 1	–
Granite (crustal average)	3.0	–
Wilderness granite, Santa Catalina Mountains (19 analyses from Reynolds and others, 1980)	1.17	2.9
Oracle Granite and gneissic derivatives, Santa Catalina Mountains (9 analyses from Reynolds and others, 1980)	3.5	8.1
Granitic rocks in Prescott 15' quadrangle, including Dells Granite (13 analyses from May and others, 1982)	8.2	26.3
Lawler Peak Granite near Bagdad, Yavapai County (19 analyses total, highest 3 not included; from May and others, 1982)	14.6	51
Lawler Peak Granite (only highest 3 of 19 analyses included; from May and others, 1982)	269	551

Table 3. *Uranium content of typical basalt and granite, as well as several types of granitic rocks in Arizona, in parts per million (ppm).*

Figure 6. Contour map of gamma-radiation levels from radioactive decay of bismuth-214 (a short-lived radon daughter product) in southwestern Tucson. The dots represent measurement locations (from Spencer and others, 1987).



to poorly consolidated sand, gravel, and soil. These sediments are not known to contain anomalous uranium levels. Limestones that were originally deposited in lakes are exposed in many small areas in Arizona and are the most common type of rock with elevated uranium levels in or near population centers. Some granites also have elevated uranium levels. High indoor-radon levels have been associated with both of these rock types. Homes built on granite and decomposed granite seem to be at greater risk for elevated radon levels even if underlying rocks contain average uranium concentrations. This is probably because of the greater permeability of fractured and weathered granitic rocks (compared to other rock types), which allows a large proportion of the radon in the rock to escape.

In 1987 the Arizona Legislature appropriated $8,000 to the Arizona Geological Survey to assess the distribution and significance of populated areas with anomalous concentrations (above 6 ppm) of naturally occurring uranium. The survey focused on several populated areas of Arizona and was used by the ARRA to determine where to place charcoal canisters for indoor-radon testing. The survey contributed significantly to understanding the distribution of uranium anomalies in Arizona. During 1990 and 1991, the Arizona Geological Survey continued to study geologic aspects of radon in Arizona with funds that the EPA provided to the ARRA.

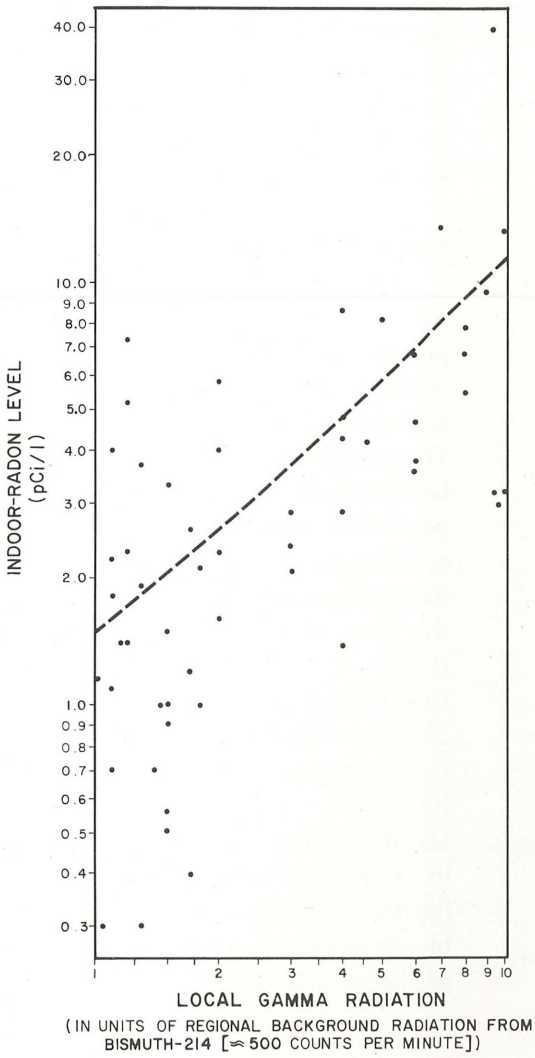


Figure 7. Plot of indoor-radon levels versus background radioactivity for homes near the Cardinal Avenue uranium anomaly. Radon levels were measured with charcoal canisters in April and May 1987. Background radioactivity (from bismuth-214) is given in units of regional (nonanomalous) radioactivity and was estimated from Figure 6.

Tucson (Cardinal Avenue)

The only rock type in the Tucson metropolitan area that is known to contain anomalous concentrations of uranium is a limestone in southwestern Tucson near the intersection of Cardinal Avenue and Valencia Road. In some areas, the limestone contains thin yellow veinlets of the uranium mineral **carnotite**. A survey of the area with a **gamma-ray spectrometer** (a uranium-prospecting instrument) revealed that uranium concentrations vary from near the background (normal) level at the edge of the anomalous area to approximately 14 times the background level at the center (Figure 6). Chemical analyses indicate that uranium concentrations are as high as 20 ppm at the center of the anomaly. Several dozen houses are built on the limestone, many of which had radon levels greater than 4 pCi/l when tested in 1987 by the Pima County Health Department. Furthermore, indoor-radon levels were generally higher toward the center of the anomaly, where underlying uranium levels are greater (Figure 7).

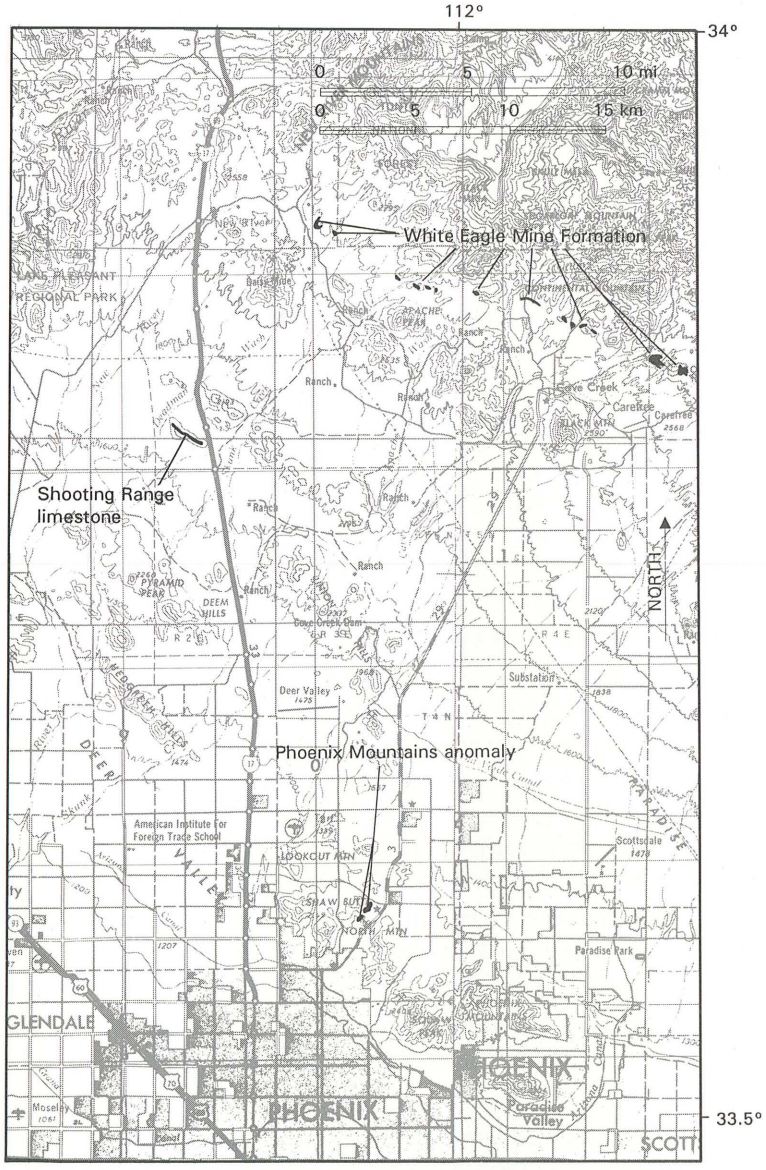


Figure 8. Map showing locations of rock types north of Phoenix that contain anomalous levels of uranium.

Phoenix (Phoenix Mountains)

The only rocks in the Phoenix metropolitan area that are known to contain anomalous concentrations of uranium are in the Phoenix Mountains just west of Cave Creek Road (Figure 8). In this area, volcanic rocks (basalt or basaltic andesite) are exposed over approximately one-eighth of a square mile and contain uranium concentrations up to approximately 12 ppm.

Cave Creek Area

Calcareous sedimentary rocks in portions of the Cave Creek area contain as much as 10 times the regional background-uranium level. These **calcareous** rocks, which contain calcium carbonate and were deposited in lakes, form a narrow discontinuous belt that extends through the northern flank of the valley where the town of Cave Creek is located (Figure 8; Doorn and Péwé, 1991). In the Cave Creek area, these rocks compose the White Eagle Mine Formation (Doorn and Péwé, 1991). Because outcrops of these rocks are small and few, they are not likely to cause high radon levels in many homes, but they could cause very high levels in a few homes. The extent of these outcrops, however, is not

fully known. Similar calcareous rocks containing elevated uranium levels are also present just west of Interstate 17 about 20 miles north of downtown Phoenix (Shooting Range limestone in Figure 8).

Verde Valley

Mudstone and soft limestone that contain anomalous levels of uranium are exposed over many square miles in Verde Valley. These rocks form the Verde Formation and were deposited when the central part of Verde Valley was a lake. The Verde Formation consists of two units: a lower unit primarily composed of soft, gray to olive-green, carbonate-rich mudstone; and an upper unit primarily composed of resistant, white, cliff-forming limestone (Figure 9; Wadell, 1972; Nations and Ranney, 1989). The lower mudstone unit typically contains anomalous uranium levels that are as high as 40 ppm, whereas the upper limestone unit is generally not anomalous in uranium (Duncan and Spencer, 1991). Mudstone underlies much of the towns of Camp Verde and Middle Verde but is not generally exposed as far north as Cottonwood.

Of 40 radon-test canisters placed in homes in the Camp Verde area during the Phase 1 and Phase 2 surveys, 4 (10 percent) had indoor-radon levels above 4 pCi/l and 3 (7.5 percent) had indoor levels above 10 pCi/l (Table 2). The high proportion of tested homes with high radon levels in the Camp Verde area, and the large area over which rocks with anomalous uranium levels are exposed, indicate that a significant number of homes in Verde Valley could have elevated indoor-radon levels.

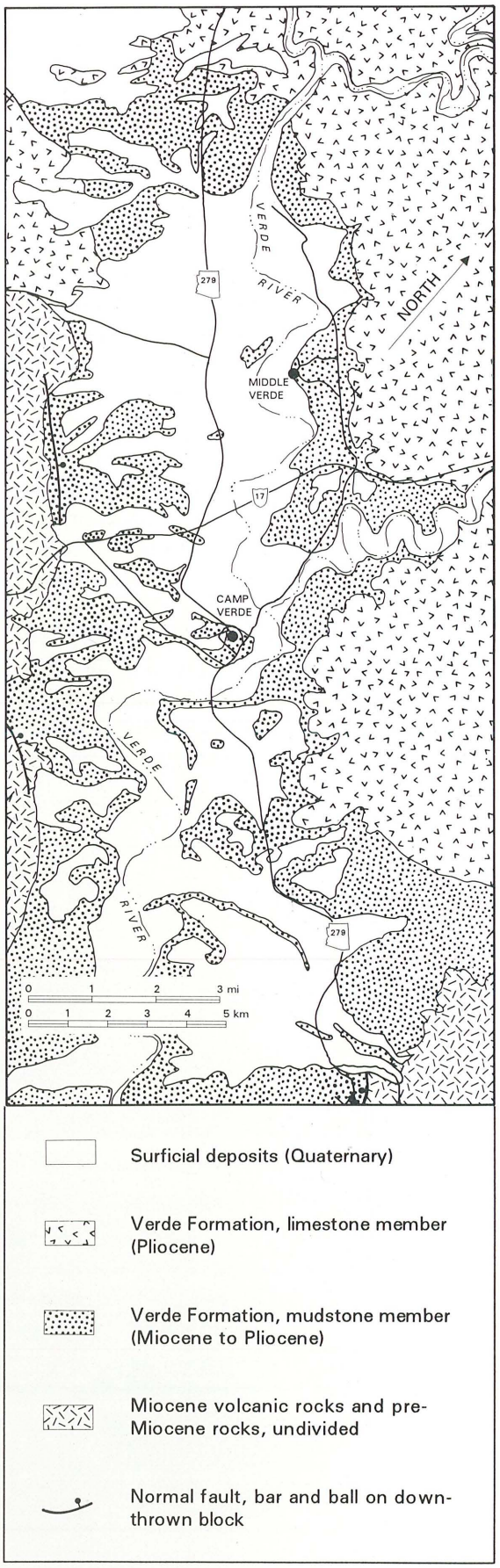


Figure 9. Simplified geologic map of the Camp Verde area showing the distribution of the two units that make up the Verde Formation. Modified from Wadell (1972), Billingsley and others (1988), Weir and others (1989), and Duncan and Spencer (1991).

Prescott (Granite Dells)

The Granite Dells, located about 5 miles northeast of Prescott (Figure 10; Krieger, 1965), is underlain by the Dells Granite, a member of a group of 1.4-billion-year-old granites that are scattered across North America. Many of these granites contain anomalous concentrations of uranium. The Dells Granite contains up to 40 ppm uranium (Proctor and others, 1987) and is exposed over an area of approximately 5 square miles (Krieger, 1965). In one survey (Kearfott, 1989), 51 homes built on the Dells Granite were tested for radon under minimum air-ventilation conditions (no open windows or running evaporative coolers). Almost 60 percent of the tested homes had indoor-radon levels above 4 pCi/l. Similar results were obtained from a survey of the Groom Creek area south of Prescott. Water from a well in the Dells Granite also contained anomalous radon concentrations, and measurements from one house indicated that turning on the shower temporarily increased indoor-radon levels (Kearfott, 1989).

One house built on the Dells Granite that was above a 240-foot-deep water well had extremely high radon levels. The well casing (a 6-inch-diameter pipe) extended upward through the floor of the house, turned 90°, and exited through a wall to the outside. A box was placed over the well casing where it extended upward through the floor. A 1-inch gap between the casing and the floor allowed radon from outside the well casing to enter the box inside the home. A charcoal canister placed inside the box yielded a radon level of 11,000 pCi/l (a world record for indoor-radon levels!). Sealing the gap between the well casing and floor and venting the subfloor space to the outside with a 1.25-inch pipe reduced indoor-radon levels to less than 5 pCi/l (Kearfott, 1989).

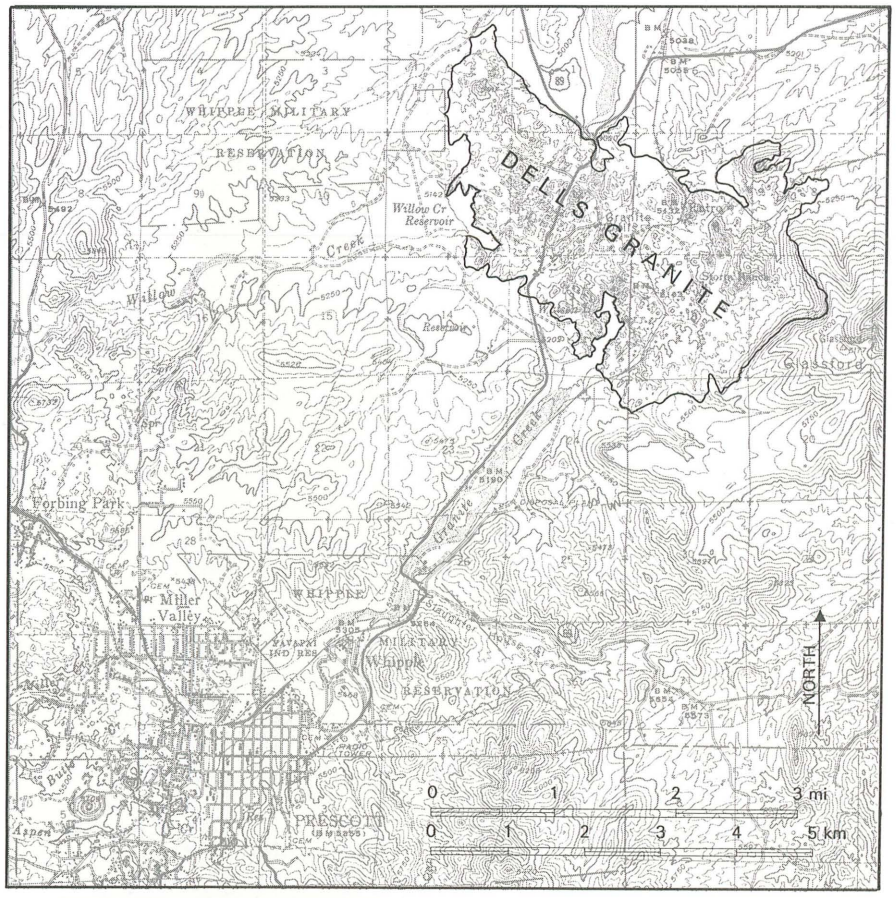


Figure 10. Map of the Prescott area showing the location of the Dells Granite (from Krieger, 1965).

How can residents of Arizona reduce radon levels in their homes?

Most studies of radon-reduction methods are directed at houses with basements or crawl spaces. Radon-reduction methods include ventilating the basement or crawl space, using fans to suck air from the basement or crawl space to the outside, and placing pipes under the home to remove radon before it flows upward into the home. Homes that are elevated from the ground so that outdoor air may flow freely underneath should have no radon problems (EPA, 1986b; NCRP, 1989).

Some homes in Arizona have underground return-flow air ducts that carry air back to air conditioners from various rooms in the house. Many of these ducts allow soil gas to be transported into the home. One study (Kearfott and others, in review) of eight of these homes in the Phoenix area showed that most had higher indoor-radon levels when air conditioners were in use and that levels in one home increased by a factor of more than 10 when the air conditioner was on. Homes with this type of duct construction should probably be tested for radon, especially in areas where uranium levels in underlying soil or rock are known or suspected to be high. Testing should be done when heaters or air conditioners are on and air is flowing through the ducts. Kearfott and others (in review) also describe duct modifications that will decrease radon intake. The EPA has recommended that sub-slab ducts be avoided in new homes (Osborne, 1988).

In general, any procedure that increases the air pressure in a home so that, at ground-floor level, it is greater than the outdoor air pressure will prevent radon entry. Under such conditions, indoor air is gently pushed down through cracks in the floor and, in turn, pushes radon into the ground and away from the home. Use of evaporative coolers makes the air pressure inside higher than outside and should decrease radon levels in the home. Indoor-radon levels are likely to be higher in the winter, when evaporative coolers are not in use and ventilation to the outside is reduced.

Most homes in Arizona have concrete-slab floors; a common method of reducing indoor-radon levels is to seal cracks in the floor so that radon cannot easily seep into the home. It is not clear, however, how effective this method is because new cracks may develop with time. Radon may even pass through some concrete slabs that have no cracks.

Methods for preventing or reducing radon entry are still being developed for buildings with concrete-slab floors. In the late 1980's, a church (Santa Cruz Lutheran Church, 6809 S. Cardinal Ave.) was built in southwestern Tucson on an area with elevated uranium levels. To prevent radon entry, the concrete-slab floor was constructed above a sheet of impermeable plastic that, in turn, overlay a layer of gravel. Perforated pipe was placed in the gravel and connected to a pipe that vented aboveground, outside the building. This appears to be an effective method of preventing indoor-radon accumulation.

Conclusion

Uranium is present in virtually all geologic materials. Radon gas, which is produced during the chain of radioactive decays that begins with uranium, is constantly being generated underground. The rate of radon production by geologic materials is directly related to their uranium content. Geologists can locate areas with anomalous uranium concentrations. Homeowners and public-health officials can take actions to reduce radon exposure to residents in these areas.

Recent surveys reveal that Arizona has lower average indoor-radon levels than most States. This is probably the result of several factors, including indoor heating, cooling, and ventilation practices associated with Arizona's relatively warm climate, as well as the absence of large areas with anomalous uranium concentrations. Several small populated areas in Arizona, however, do have anomalous uranium concentrations; the average radon level in homes in some of these areas is greater than the statewide average. Residents of these areas should take appropriate measures to test for radon in their homes and reduce levels if necessary.

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