UNIVERSITY OF NEVADA, RENO
MACKAY SCHOOL OF MINES

NEVADA BUREAU OF MINES AND GEOLOGY

BULLETIN 108

RADON IN NEVADA

JAMES G. RIGBY, JONATHAN G. PRICE,
LINDSAY G. CHRISTENSEN, DAPHNE D. LA POINTE,
ALAN R. RAMELLI, MARIO O. DESILETS,
RONALD H. HESS, AND STANLEY R. MARSHALL

1994

A detailed report of studies of radon in Nevada from 1989 through 1993, with emphasis on radon in indoor air and the hazards it poses to human health. A 1:1,000,000-scale map of indoor radon potential hazards in Nevada is included. Methods of reducing radon in homes are fully discussed and the results of applying these methods to three high-radon homes in Nevada are presented.

nbmg

Electronic edition 2002, printed on demand

For sale by the Nevada Bureau of Mines and Geology, University of Nevada, Reno

NEVADA BUREAU OF MINES AND GEOLOGY

BULLETIN 108

RADON IN NEVADA

JAMES G. RIGBY, JONATHAN G. PRICE,
LINDSAY G. CHRISTENSEN, DAPHNE D. LA POINTE,
ALAN R. RAMELLI, MARIO O. DESILETS,
RONALD H. HESS, AND STANLEY R. MARSHALL

1994

UNIVERSITY
OF NEVADA
RENO

CONTENTS

PLATE 1 *(in pocket)*

FIGURES

TABLES

ABSTRACT

This bulletin summarizes research performed over a three-year period by the Nevada Bureau of Mines and Geology (NBMG) and the Nevada Division of Health (NDOH) on radon in the state of Nevada. Funding for this research was provided in part by the U.S. Environmental Protection Agency (EPA). Measurements of indoor radon in more than 2,000 homes across the state show that close to 20% of the homes tested exceeded the EPA action level of 4.0 pCi/L (picocuries of radon per liter of air) at the time tested, the concentration above which EPA recommends that radon reduction measures be taken. This figure is about the same as the average percentage of homes nationwide that EPA has found to exceed the action level for indoor radon. Within Nevada, several communities contain high proportions of homes which exceed the action level, with nearly 60% of the homes tested for indoor radon exceeding the action level in some communities.

About 15% of the measurements of indoor radon in state-owned or state-operated buildings in Reno exceed the EPA action level, and 11% of the measurements conducted in Carson City state buildings exceed the action level for indoor radon. State offices with high indoor radon occur in generally the same geographic areas as residences with high radon.

Because most measurements were taken during cool weather (winter and early spring), when lowered indoor air pressure tends to pull radon from soils and rocks into buildings, average annual concentrations of radon were generally lower than the values presented for short-term screening tests. When weighted by population, about 10% of Nevadans are likely to live in homes with initial radon screening tests of 4.0 pCi/L or greater.

Measurements of radon in water from wells and springs, made in conjunction with the U.S. Geological Survey (USGS) and NDOH, indicate that groundwater is probably not a significant contributor to radon in the indoor air of homes and buildings in the state.

The highest concentration of radon measured in outdoor air in Nevada was 1.40 pCi/L, which is higher than the highest outdoor measurement in a national study (1.11 pCi/L), but does not pose a health hazard to most Nevadans. The mean values for the Nevada outdoor air survey and the national study were both 0.41 pCi/L. Results of radiogenic element analyses of rocks collected from various locations in the state show that, in general, a positive correlation exists between uranium and thorium in near-surface rocks and radon concentrations in soil gas and outdoor air. Additional studies have identified and delineated areas of surface rocks and soils that are potential sources of indoor radon.

A review of available results of radon testing in public elementary and secondary schools in the state reveals that Nevada may have more than twice the national average number of classrooms with radon screening measurements above the EPA action level, and about twice the national average of schools with at least one screening measurement above the action level.

Much of the above research conducted over the last three years was used to generate a map of the potential indoor radon hazard of the state. This map was prepared using a computer workstation to combine and overlay a large number of data sets to produce plate 1 of this bulletin, *Indoor Radon Potential Hazard Map of Nevada*. On the map the state is divided into three indoor radon potential hazard zones (low, intermediate, and high) to illustrate the scope of the potential radon hazard in the state: 90% of the state lies in the intermediate or high radon potential zones. This fact does not mean that every home or building in an intermediate or high zone will have high indoor radon, but it underscores the high potential for radon generation from rocks and soils over a large part of Nevada, and consequently, the potential for harmful levels of indoor radon in buildings. This map confirms the necessity for all homes and occupied buildings in the state to be tested for radon.

There is currently no legal requirement in Nevada that radon concentrations in homes or other occupied buildings be lowered to any particular level. EPA uses a conservative interpretation of studies of the health effects of radon exposure to make the following recommendations: (a) all homes should be tested and (b) indoor radon should be reduced below an average annual concentration of 4.0 pCi/L. Radon reduction methods for various home construction types are presented, with examples of some that have been successfully employed to reduce high indoor radon concentrations in Nevada homes to below the EPA action level.

INTRODUCTION

EPA estimates that between 7,000 and 30,000 lung cancer deaths in the United States each year are attributable to breathing radon gas. In fact, radon is believed to be second only to smoking as the major cause of lung cancer in the United States (U.S. Environmental Protection Agency, 1992a). The link between radon and lung cancer was first documented in underground miners in studies beginning in the 1950s (Holaday and others, 1952; Lundin and others, 1971), although earlier reports and studies had noted an increased mortality from respiratory diseases in miners (Agricola, 1556) and an increased incidence of lung cancer in underground miners (Harting and Hesse, 1879; Peller, 1939). Not until 1984, however, did it become known that radon can also occur in harmful levels in homes and buildings. In that year a home in eastern Pennsylvania was discovered to contain radon concentrations as high as those found in some underground mines (Smith and others, 1987; Wilkening, 1990). Soon, other homes with very high indoor air radon concentrations were found in this area of eastern Pennsylvania and adjacent New Jersey, an area referred to as the "Reading Prong" by geologists. Subsequently, health and environmental agencies in other areas of the country began to test homes for indoor radon, and although few homes were found to contain as much radon as the homes built on the Reading Prong, numerous homes in other states were found to contain elevated levels of radon. Based upon these findings, EPA began a cooperative program with individual states to conduct screening tests for radon in homes in order to determine the percentage of homes with elevated levels of radon.

In 1988, the U.S. Congress passed the Indoor Radon Abatement Act (Public Law 100-551, October 28, 1988), which authorized EPA to continue its state radon testing program, and which had as its ultimate goal the reduction of indoor radon concentrations in homes to concentrations in outdoor air. In late 1989, the State of Nevada applied for funding under EPA's radon program to determine the extent of the indoor radon problem in Nevada, if any.

Occurrence of Radon

Radon-222, the isotope of radon discussed in this report, is a colorless, odorless, and tasteless, naturally occurring radioactive gas. Uranium-238, which is radioactive, decays through a number of steps to form the stable, non-radioactive isotope lead-206; radon-222 is one of the intermediate decay products in this sequence, resulting directly from the decay of radium-226 (fig. 1). Each isotope shown in figure 1 spontaneously decays to the next, or daughter, isotope by emitting alpha, beta, or gamma radiation, or a combination of these. Radon-222, the only gas in the series, is formed from radium-226 as it emits an alpha particle. Because it is a gas, radon moves by diffusion from areas of higher concentration to areas of lower concentration through pores in rocks and soil, and through air and water. Ultimately, the radioactive decay process yields the isotope lead-206 which is stable (nonradioactive). Rock and soil at or near the Earth's surface provide a constant supply of radon, because its source, uranium-238, has such a long half-life, and it is relatively abundant, being the most common isotope of uranium in the Earth's crust.

Uranium occurs in varying amounts in all rocks and soils. Radon gas is constantly supplied from the ground to outdoor air, where it is generally diluted to such low concentrations that it usually does not pose a potential health risk. However, radon that moves into confined spaces, such as caves, underground mines, or the lower floors of buildings, can build up to sufficiently high concentrations to constitute a health hazard to the occupants of such spaces.

Health Effects of Radon

The only health effect known to be associated with exposure to radon is an increased risk of developing lung cancer due to inhalation of radon. No other health effects have been proven to be associated with exposure to radon. The lung cancer association with radon was first noticed in the 1950s and 1960s when various health studies detected an increased lung cancer incidence among underground uranium miners; these and other studies concluded that high concentrations of radon, such as those found in underground mines, contributed to an increased lung cancer incidence in people (National Council on Radiation Protection and Measurements, 1984; National Research Council, 1988; Stannard, 1988; Samet, 1989). Before the common use of forced ventilation in mines in the 1950s, the air of some underground uranium mines in Colorado and Utah contained radon concentrations as high as 5,000 picocuries of radon per liter of air (pCi/L) (Wilkening, 1990). After forced ventilation was instituted, these concentrations fell dramatically.

Based upon the studies of miners, EPA and others have used a model of linear extrapolation (with no threshold) from the high exposure rates experienced by underground miners to estimate the lung cancer risk for the general population due to the usually lower radon concentrations typically found in homes. Based upon this linear, no-threshold, dose-response model, EPA estimates that between 7,000 and 30,000 lung cancer deaths a year in the United States may be attributable to inhalation of radon. While other dose-response models exist (Eisenbud, 1987; National Research Council, 1991), and while not all researchers agree with the linear extrapolation-no threshold model (for example, Cohen, 1987) or with the number of lung cancer deaths estimated by EPA to be associated with radon, most national health organizations such as the Centers for Disease Control, the American Medical Association, and the American Lung Association agree with EPA's estimate.

Radon itself, which has a half-life of 3.8 days, is inhaled and then exhaled from the lungs a few seconds later, before alpha particles are emitted to damage lung tissue. Two daughter products of radon, however, polonium-218 and polonium-214, are solids which can stick to the surface cells of airways and lungs when inhaled. These isotopes of polonium, which have relatively short half-lives (3 minutes and 0.00016 seconds, respectively) emit alpha particles over a short period of time. The bombardment of surface cells of lung tissue and airways by these alpha particles causes tissue damage that may eventually result in the development of lung cancer.

Radon Entry into a Home

Radon present in rock and soil can enter a house or other building through any of several routes (fig. 2): through cracks and joints in concrete floors, around poorly sealed floor drains and sumps, through cracks and pores in hollow-block walls, and through penetrations in suspended wood floors over soil-floored crawlspaces. Radon is continually generated by radioactive decay of uranium in rock and soil and moves by diffusion from areas of relatively high concentration to areas of relatively low concentration. Radon around the foundation of a building can move into a building due to reduced pressure inside the building relative to the surrounding soil (Nazaroff, 1988). This pressure-driven flow of soil gas into a building is often accelerated in the winter, when the pressure differential between warm indoor air and cooler air in pore spaces in the surrounding soil is the greatest.

In some cases, material used in the construction of a home can be a source of radon. For example, this may be a problem if a house contains bricks or cinder blocks made of uranium-rich clay, has a fireplace built of uranium-rich stones, or uses a solar heating system in which heat is stored in large beds of uranium-containing rocks (Bruno, 1983; Ingersoll, 1983; Wilkening, 1990).

Radon can also enter a home from a private well if the water is pumped directly into a house after being in recent contact with radon-bearing rock or soil. This is usually not a problem with large community water supplies where the water is often treated and aerated before use and where it travels some distance from the well or other source to the

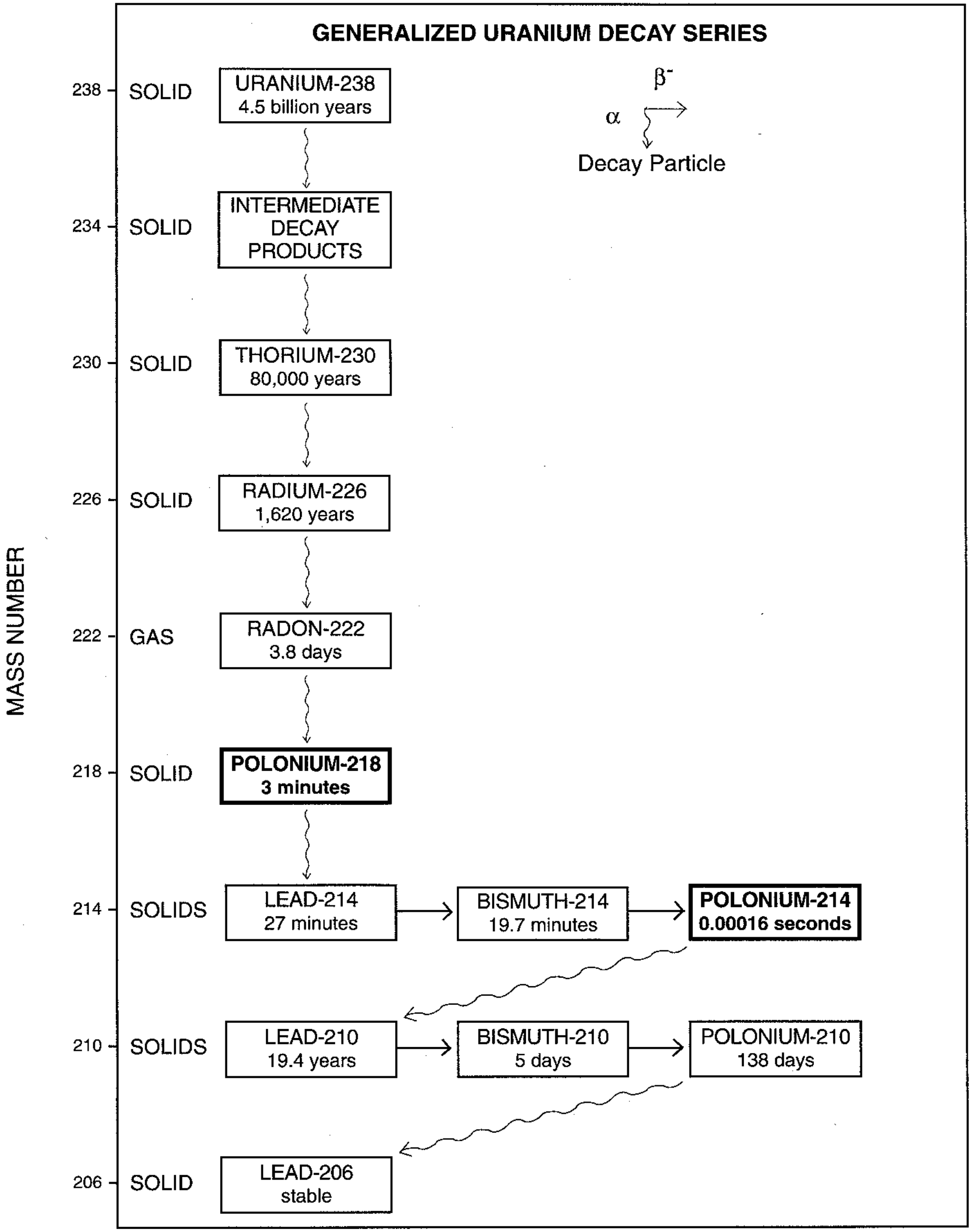


FIGURE 1.—Generalized uranium-238 decay series showing half-lives of isotopes. Radon-222, the only gas in the series, is inert and free to move through soil, air, and water without entering into chemical reactions. Polonium-218 and polonium-214 (shown in bold type) are the two radon daughters whose alpha decay causes the greatest amount of lung tissue damage when radon is inhaled. (Adapted from U.S. Environmental Protection Agency, 1987a; and National Research Council, 1991.)

point of use, losing much of its radon by degassing along the way (Cothern and Lappenbusch, 1985). For more information on radon in water, refer to the section *Radon in Water.*

The presence of high concentrations of indoor radon poses a potential health risk for occupants of not only private residences, but also schools, offices, public buildings, or any enclosed space with ground contact. Radon is present in outdoor air as well, but the concentrations are usually far less than those found indoors due to rapid mixing and dilution of soil gas with outdoor air. For more information on radon in outdoor air, including radon in the outdoor air of Nevada, refer to the section *Radon in Outdoor Air.*

Measurement of Radon

The most common unit of radon measurement in the U.S. is the picocurie of radon per liter of air, abbreviated pCi/L, which is a measure of the number of nuclear decays in a liter of air within a specified time period. One picocurie equals the radiation produced by the decay of about two radon atoms per minute. Another unit of radon measurement commonly used by the international scientific community is the Becquerel per cubic meter of air, abbreviated Bq m^{-3}. One pCi/L is equal to 37 Bq m^{-3}. Radon concentrations may also be expressed in working levels (WL), which measure the harmful decay products of radon, polonium-214 and polonium-218. The pCi/L unit of radon measurement will be used throughout this bulletin to express radon concentration.

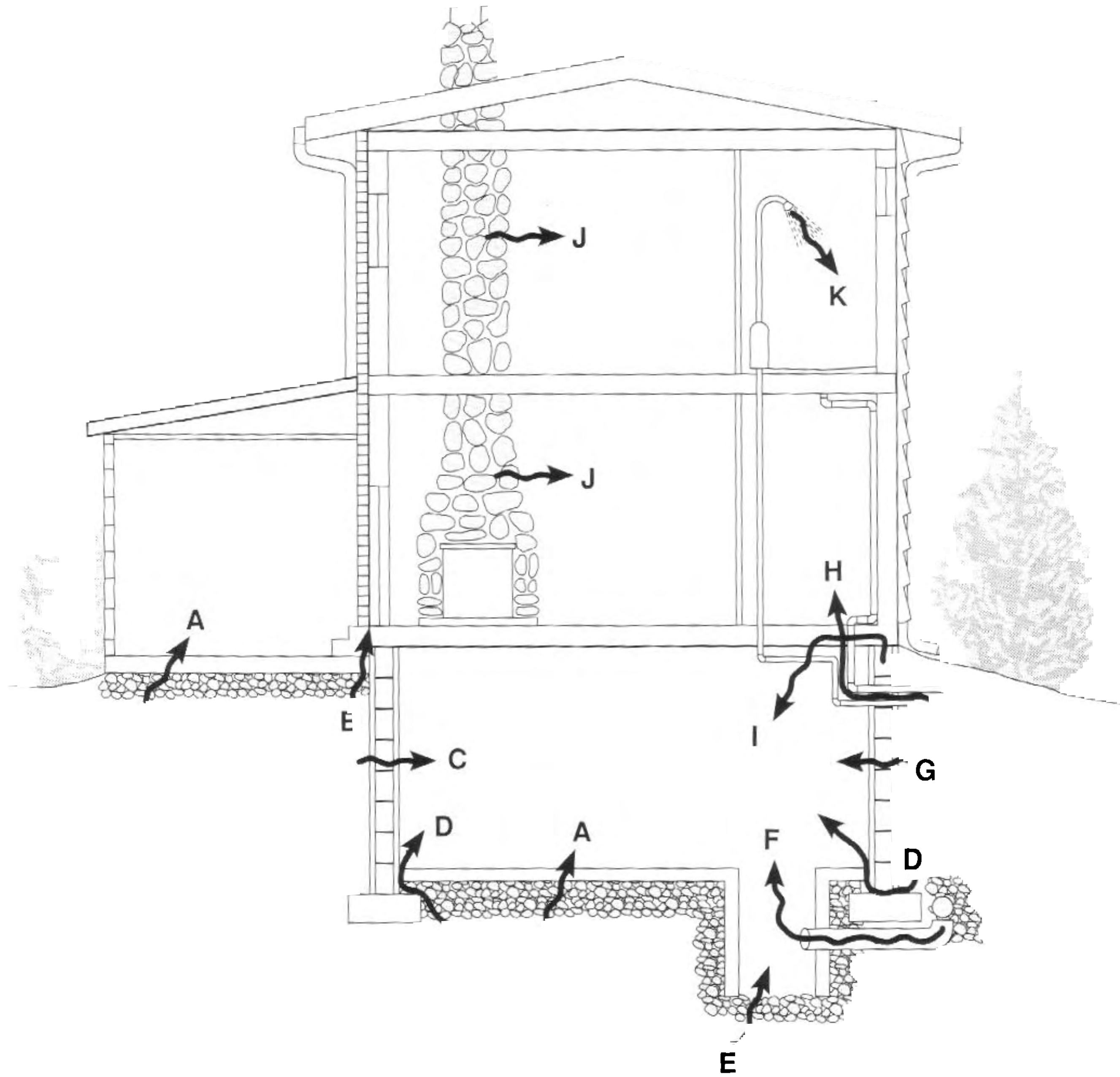
EPA recommends that the radon concentration in the indoor air of a home should be less than 4.0 pCi/L (or 0.02 WL). This is described as the EPA "action level" for indoor radon. EPA estimates that exposure to this concentration of radon for 70 years in a home will cause between one and five lung cancer deaths per 1,000 people (the likelihood of lung cancer is even higher among smokers and it also is higher for non-smokers if they live in a house where smoking occurs). EPA's choice of 4.0 pCi/L does not mean that this is a safe concentration of radon. It is, however, a concentration of radon for indoor air which EPA believes is practically obtainable in most homes. In this report, any indoor radon concentration of 4.0 pCi/L or greater is considered to be high, or elevated. The Indoor Radon Abatement Act recommends as a long-term goal the reduction of indoor radon to the level of outdoor air. This outdoor concentration of radon varies from place to place (see section *Radon in Outdoor Air*), averaging about 0.4 pCi/L nationwide (Hopper and others, 1991), and is not now practically or economically obtainable in many cases.

Indoor radon concentration can be measured using a radon detection device. Radon detection devices are classified as either passive or active. Passive devices do not require a power source to move air through them, but rather operate by the natural diffusion of air into the device for the measurement of radon concentration. Passive devices are those most commonly used in home radon testing because they are inexpensive and easy to use. The two most commonly used types of passive radon detectors are the charcoal canister and the alpha track detector. The charcoal canister is considered to be a "short-term" radon detector, measuring indoor radon concentration over a period of two to seven days. This type of detector (fig. 3) usually consists of a flat metal canister 2 to 4 inches in diameter which contains granular activated charcoal, usually covered by a filter and mesh screen (Cohen and Cohen, 1983; George, 1984). When exposed to the air, the charcoal adsorbs radon; the amount of radon adsorbed depends on the concentration of radon in the air around the canister and the duration of exposure. After two to seven days, the canister is resealed and returned to a laboratory for analysis. After analysis, the laboratory sends the user a report of the radon concentration in the air tested.

The second common type of passive radon detector is the alpha-track detector (ATD). This detector (fig. 3) usually consists of a small piece of polyester film coated with a thin layer of cellulose nitrate; the coated film is encased in a plastic or metal cylinder with filtered air holes in one end (Nakahara and others, 1980). Radon enters the detector and decays, emitting alpha particles which strike the coated film and etch tracks in the coating. At the end of the exposure period the detector is resealed and returned to the laboratory, where the film is etched with acid to expose the alpha tracks which are then counted under a microscope. The number of tracks is directly related to the radon concentration in the air to which the detector was exposed, and to the length of time of exposure. A report of the radon concentration is sent to the consumer. The ATD is considered to be a "long-term" radon detector, and is usually exposed for a period of 3 to 12 months.

A third type of passive radon detector sometimes used to obtain measurements of indoor radon is the electret ion chamber (EIC) or electret passive environmental radon monitor (EPERM). This device consists of a plastic chamber containing a thin disk of Teflon which has been given a known voltage charge (Kotrappa and others, 1988). When the device is opened, indoor air filters into the chamber. Alpha particles emitted by radon and by its subsequent daughter products in the air in the chamber form ions which are drawn to the surface of the charged disk, reducing its voltage. After exposure, the electret ion chamber is closed and taken to a laboratory where the decrease in surface voltage on the disk is measured. The change in voltage of the electret is directly proportional to the radon concentration and the exposure time, allowing calculation of the radon concentration, which is reported to the consumer. EIC or EPERM radon detectors may be used as either long- or short-term radon detectors depending on the initial voltage on the charged disk and the radon concentration to which they are to be exposed. Although fairly easy to use, the electret device is not commonly used by homeowners because of the expense of the voltage measuring device and the expertise required to properly use the electret. It is, however, a reliable passive radon monitoring device commonly used by commercial radon testers.

All three types of passive detectors are reliable for detecting radon within EPA radon measurement guidelines for the time period over which they are exposed. However, since the radon concentration of a building varies from day to day and season to season due to meteorological changes and occupants' living habits, the longer-term ATD (or electret used for extended periods) gives a more representative



MAJOR RADON ENTRY ROUTES

A. Cracks in concrete slabs
B. Spaces behind brick veneer walls
C. Pores and cracks in concrete blocks
D. Floor-wall joints
E. Exposed soil, as in a sump or crawlspace
F. Weeping (drain) tile, if drained to open sump
G. Mortar joints
H. Loose-fitting pipe penetrations
I. Open tops of block walls
J. Building materials such as some rock
K. Water (from some wells)

FIGURE 2.—Major radon entry routes into a home. Arrows indicate possible entry points and pathways of radon into a building from the surrounding soil and rock. Radon may also enter the air of a home through the water supply. In some cases, radon may be given off from certain building materials, such as fireplace rocks.

assessment of average radon content in a home or building. The charcoal canister and ATD detectors are easy for individual homeowners to use and are usually available in local hardware stores or through mail order for a cost of generally between $12 and $30 (1993 prices), which includes lab analysis and report. Whichever type of passive radon detection device is used to measure radon concentration in a home, if an initial short-term screening measurement is 4.0 pCi/L or higher, then EPA recommends either another short-term measurement be made, or preferably a long-term measurement in order to determine the annual average radon concentration in the home.

Figure 3.—Types of passive radon detectors. An alpha track detector (ATD, front) and two types of charcoal canisters (rear) are shown. *Photo by Jim Rigby.*

Active radon detection devices, also known as continuous radon monitors, use a power source to pump air through a cell attached to a machine capable of measuring alpha particle impacts and integrating this information with time, cell volume, and other variables in order to yield accurate radon concentration measurements. There are several different types of continuous radon monitors available, most of them generally too costly to be commonly used by homeowners for residential indoor radon screening measurements. They are, however, sometimes used by commercial radon mitigators in diagnostic testing of a building with a high radon concentration in order to determine the possible entry points of the radon. They are also used by researchers to verify radon measurements obtained by other methods and to monitor changes in radon concentration relative to other variables, as described in following sections.

EPA operates a Radon Measurement Proficiency program to monitor individuals and companies who are in the business of testing homes for radon, or laboratories that analyze exposed radon detectors. A consumer purchasing a radon detector, either charcoal canister or ATD, should look for words printed on the detector to the effect that the detector has met the requirements of the EPA Radon Measurement Proficiency (RMP) program, or that the product has been listed in the EPA RMP program. The RMP program's primary purpose is to make sure that the laboratories report accurate measurements to consumers. Every year, EPA issues an RMP program handbook in which all testing laboratories are listed; a copy of this handbook may be obtained from EPA or from a state health or state EPA office (in Nevada, the Radiological Health Section of the Nevada Division of Health). A detector supplied by an RMP vendor is not guaranteed to be accurate, but the RMP vendor has met certain minimum standards and quality control requirements set by EPA.

RADON STUDIES IN NEVADA

The study of radon in Nevada was initially undertaken in 1989 by NBMG and continued through 1993 in conjunction with NDOH under grants from EPA. The primary purpose of this study was to determine if radon poses a health hazard to Nevadans. A secondary purpose was to identify the source rocks and soils for radon in the state and to make these data known to the citizens of Nevada. Partial funding for this work was provided by the EPA Office of Air Toxics and Radiation, and most of the remaining funding was provided by the State of Nevada. The USGS assisted NBMG in the analysis of radon in groundwater.

NBMG Survey of 1989

Beginning in February 1989, NBMG undertook a limited screening survey of indoor radon concentrations in homes across Nevada. In this survey, short-term (7-day) charcoal canister radon detectors were purchased from the Radon Project of the University of Pittsburgh (RMP program listed) and sent to individuals who had volunteered to test for radon in their homes. This survey, while not designed to be statistically valid, nonetheless sampled most of the principal population centers of Nevada. A total of 307 detectors were returned by homeowners for analysis during the late winter and early spring of 1989. About 20% of the detectors exceeded 4.0 pCi/L, and the statewide average (arithmetic mean) was 2.9 pCi/L. These data are comparable with the results of a nationwide EPA survey of 59,000 homes in 42 states in which about 20% of the tests exceeded 4.0 pCi/L and the arithmetic mean was 3.0 pCi/L (Louise Hill, EPA, personal commun., 1993).

The limited NBMG screening survey indicated that radon did pose a potential health hazard to Nevadans and more detailed study was required. Based upon the results of this survey, NBMG contacted the Radiological Health Section of NDOH to determine if they would cooperate in a joint study of radon in Nevada with support and partial funding from the EPA's State Indoor Radon Grants (SIRG) program. After reaching a cooperative agreement, NBMG and NDOH applied to EPA for funding for a SIRG program grant to investigate indoor radon in Nevada.

EPA Indoor Radon (SIRG) Survey of 1990-1991

Upon approval by EPA of the grant request, the first phase of the joint EPA/NDOH/NBMG radon project was initiated. This project consisted of a survey of indoor radon in about 2,000 homes in the state to assess the scope of the indoor radon hazard in Nevada. The survey was designed by a subcontractor to EPA, Research Triangle Institute, to satisfy EPA's criteria that the data be statistically valid and comparable to EPA data from other states. The list of homes to be sampled in the Nevada EPA SIRG survey was selected at random by EPA from all residential telephone numbers in the state. Some areas were sampled more intensively than others. More information on the design of the survey may be found in White and others (1992).

Personnel of the Center for Applied Research at the University of Nevada, Reno telephoned homeowners on the EPA telephone list to recruit volunteers for the project. Homes eligible for the project had to be owner-occupied, single-family detached homes with a listed telephone number, and with at least one floor at or below ground level. Mobile homes were included if the owner stated that the base of the mobile home was skirted to restrict air flow under the structure (this is significant because Nevada contains more mobile homes per capita than any other state). Each qualifying home was sent one 2-day charcoal canister radon detector to be placed in the lowest livable level of the home.

In order to track seasonal variations in radon and to compare charcoal canister test results with those from long-term ATDs, 10% of the participating homeowners were sent one or more ATDs to place in their home for one year; these homeowners also received four charcoal canisters to test for radon in each season of the year that the ATDs were in place. Most of the charcoal canisters used in the EPA/SIRG survey were exposed during the first three months of 1990, similar to the NBMG survey of the previous year. Exposed charcoal canisters were analyzed at the EPA radon laboratory in Montgomery, Alabama, while exposed ATDs were returned to the vendor laboratory for analyses.

Based on the 2,065 canisters that were returned for analysis during the EPA/SIRG survey, the statewide arithmetic mean of radon concentrations in all tested homes was 2.9 pCi/L, with individual results ranging from 0.0 to 46.7 pCi/L (fig. 4). The EPA action level of 4.0 pCi/L was exceeded by about 19% of the analyzed canisters. However, based on the actual sampling rate (dependent in part on the survey design and on the success rate of telephone interviewers), population centers in the state were sampled less intensively than rural areas. For example, only 12% of the homes sampled were in Clark County where more than

TABLE 1.—*Summary of results from various indoor air radon surveys conducted in Nevada, 1989-1993.*

Survey	Area covered	Number of measurements	Mean[1] pCi/L	Highest measurement pCi/L	Percent of measurements[1] ≥4 pCi/L
NBMG screening survey, 1989 (7-day charcoal canisters)	Statewide	307	2.9	31.6	20
EPA/SIRG survey, 1990-1991 (2-day charcoal canisters)	Statewide (random)	2,065	2.9	46.7	19
EPA/SIRG survey, 1990-1991 (1-year ATDs)	Statewide (random)	243	1.4	9.4	5
NBMG-EPA State Office survey, 1992 (7-day charcoal canisters)	Reno/Sparks	125	2.1	11.8	15
NBMG-EPA State Office survey, 1993 (7-day charcoal canisters)	Carson City	134	2.2	12.8	11
NBMG-EPA targeted communities survey, 1992 (7-day charcoal canisters)	Austin	92	5.2	40.7	43
	Genoa	52	2.3	19.7	9
	Pioche	80	4.0	80.9	16
	Lake Tahoe communities: Incline Village, Zephyr Cove, Glenbrook, Stateline, Crystal Bay	38	3.2	14.4	24

[1]All numbers represent raw, unweighted data.
Table includes mobile home data.

TABLE 2.—*Distribution by county of charcoal-canister indoor air residential radon measurements, 1989-1992 surveys in Nevada.*

County	Number of measurements	Highest measurement pCi/L	Lowest measurement pCi/L	Mean[1] pCi/L	Number of measurements ≥4 pCi/L	Percent of measurements[1] ≥4.0 pCi/L
Carson City	98	31.6	0	3.7	25	26
Churchill	141	20.1	0	2.2	12	9
Clark	261	11.0	0	1.0	7	3
Douglas	154	21.9	0	3.8	44	29
Elko	258	18.0	0	2.9	56	22
Esmeralda	20	3.0	0	1.1	0	0
Eureka	37	35.4	0	3.9	9	24
Humboldt	259	43.4	0	2.3	34	13
Lander	162	46.7	0	4.3	54	34
Lincoln	234	80.9	0	4.4	67	29
Lyon	75	11.0	0	2.4	14	19
Mineral	75	23.6	0	4.2	26	35
Nye	170	17.5	0	1.6	10	6
Pershing	40	40.7	0	6.4	18	45
Storey	16	14.7	0	2.5	2	13
Washoe	495	40.6	0	2.9	98	18
White Pine	245	23.7	0	3.4	66	27
TOTAL	2,740	80.9	0	3.0	535	20

[1]All numbers represent raw, unweighted data.
Table includes mobile home data.

half of the state's population lives. After completion of the survey, Research Triangle Institute weighted the raw survey data to compensate for this variability in sampling intensity. The weighted data indicate that about 10% of Nevadans live in houses with screening tests greater than 4.0 pCi/L. These population-weighted figures were calculated by EPA using the same method used to report the data from other EPA state surveys. For Nevada, EPA based their calculations on only 1,562 radon screening tests obtained during the winter and early spring of 1990. The remaining 500 or so radon measurements from the EPA/SIRG survey of 1990-1991 were not available to EPA when EPA performed their calculations. The weighted average (arithmetic mean) of the 1,562 data subset for the state was 2.0 pCi/L and the geometric mean of this subset of the measurements was 1.0 pCi/L (White and others, 1992).

The results of the smaller, earlier NBMG survey of 1989 compared closely with those of the larger, statistically valid EPA/SIRG survey of radon in Nevada homes. Henceforth, in this report, results of both surveys, as well as subsequent surveys performed by NBMG/NDOH, will be discussed together. Table 1 lists all the major indoor radon surveys conducted by NDOH and NBMG in the state from 1989 through early 1993.

Nevada communities in which ten or more residential indoor radon measurements were obtained in the 1989 to 1992 surveys are shown in figure 5; the figures on the map represent the percentages of tests in each community that exceed the EPA action level of 4.0 pCi/L. A high proportion of the measurements exceed the action level in several of the state's communities. Most of the communities in which a high proportion (>20%) of the measured homes exceed the action level are situated in either the northern one-half of the state (Reno, Zephyr Cove, Carson City, Minden, Gardnerville, Yerington, Hawthorne, Lovelock, Austin, Orovada, Wells, Elko, Carlin, Eureka, and Ely), or in the southeastern part of the state (Pioche, Panaca, and Caliente). As will be discussed later in this report, these observations can be explained primarily on the basis of varying geology and climate.

Table 2 shows the results of the 1989 through 1992 surveys by county. The homes in nine of the state's 17 counties contain indoor radon in excess of the EPA action level in at least 20% of the tested homes. These counties (Pershing, Mineral, Lander, Lincoln, White Pine, Carson City, Douglas, Eureka, and Elko) have recently been designated by EPA as counties that have the highest potential for

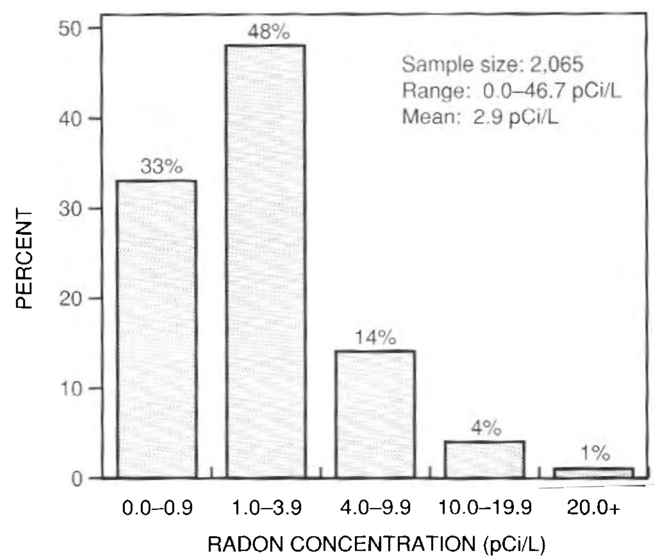


FIGURE 4.—Results of 1990-1991 EPA/SIRG indoor radon survey in Nevada. Data represent 2,065 screening test results using 2-day charcoal canisters in Nevada homes, including mobile homes. Measurements were made in the lowest livable level of homes and most measurements were made in winter and early spring.

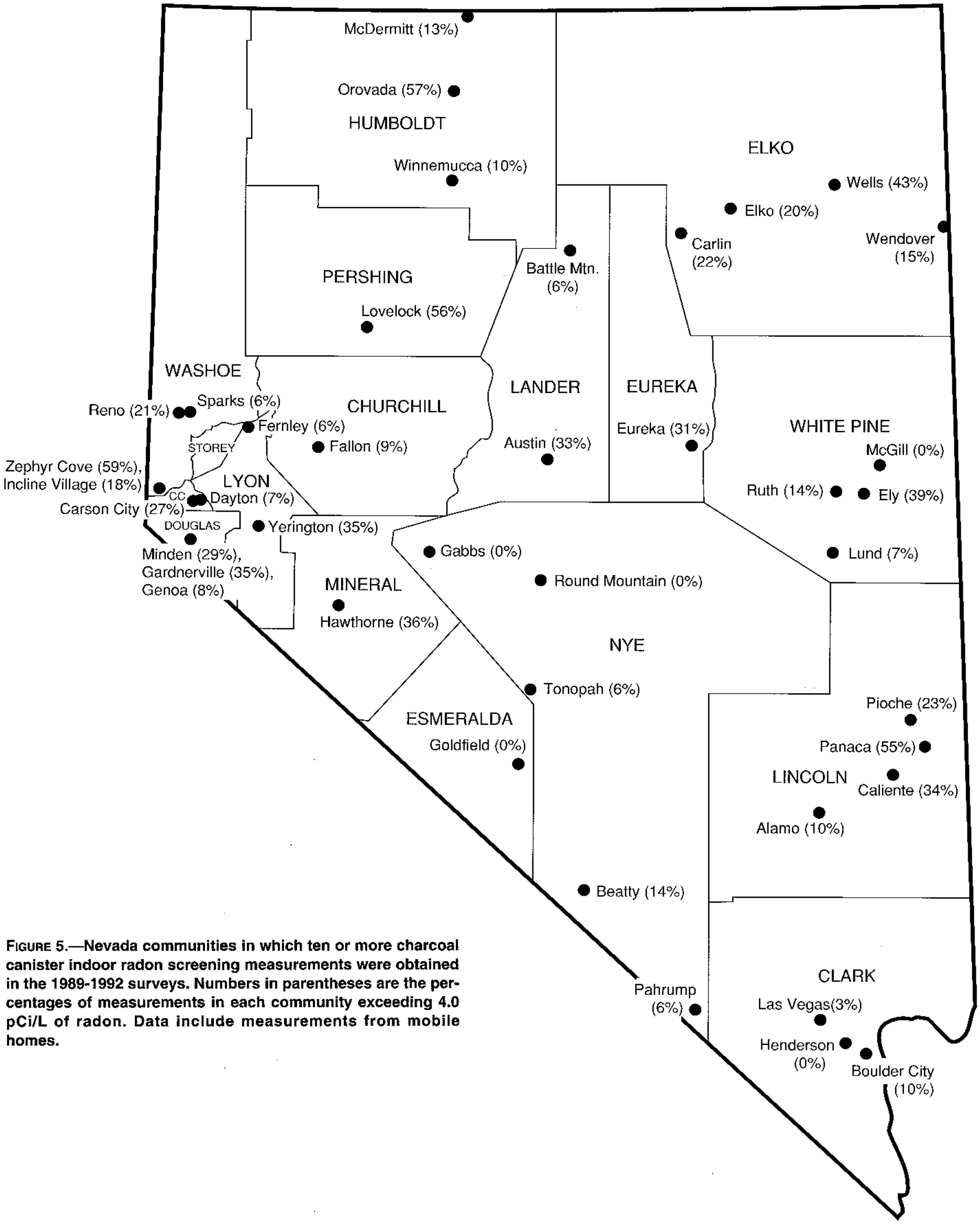


FIGURE 5.—Nevada communities in which ten or more charcoal canister indoor radon screening measurements were obtained in the 1989-1992 surveys. Numbers in parentheses are the percentages of measurements in each community exceeding 4.0 pCi/L of radon. Data include measurements from mobile homes.

health hazard from indoor radon. All other counties in Nevada except for Clark County are designated by EPA as having intermediate potential health hazard due to indoor radon, while Clark County is designated by EPA as having the lowest health hazard due to indoor radon (U.S. Environmental Protection Agency, 1993a).

COMPARISON OF ATD AND SEASONAL CHARCOAL CANISTER RESULTS

As mentioned earlier, 10% of the homes tested in the EPA/SIRG survey of 1990-1991 received one or more one-year ATDs and a charcoal canister for each of the four seasons of the year. The results of the indoor radon measurements based upon the ATDs are somewhat different than the results based upon the charcoal canister measurements. A total of 243 ATDs were properly exposed and returned for analysis representing 122 homes. Of the 243 ATDs properly exposed and returned for analysis, 12 ATDs (about 5%) exceeded the EPA action level of 4.0 pCi/L of radon. This figure of 5% can be compared to the figure cited previously of 19% of the charcoal canister screening tests which exceeded 4.0 pCi/L in the canister-only part of the EPA/SIRG survey (see table 1). Because the exposure period of the ATDs was one year, the ATD figures represent annual average radon concentrations in those homes, whereas the statewide charcoal canister survey data is based mainly on short-term winter measurements which are typically higher than the annual average radon measurements obtained with the ATDs. The figure of 5% of homes with high annual average radon concentration may, however, not be representative of the entire state because of the relatively small number of homes (122) measured with ATDs.

Table 3 compares the average of ATD measurements with the average measurements from four charcoal canisters exposed in each season for those participants in the EPA/SIRG survey that received and returned both types of

TABLE 3.—*Comparison of ATD and seasonal charcoal-canister indoor air residential radon measurements (pCi/L), 1990-1991 EPA/SIRG survey.*

House no.	ATDs			CHARCOAL CANISTERS[1]					CAN/ATD[2]
	#1	#2	Average	Winter	Spring	Summer	Fall	Average	
SRNV20167	9.0	9.3	9.2	18.6	13.7	11.3	10.5	13.5	1.5
SRNV20198	6.8	7.1	7.0	17.2	13.8	7.6	0.0	9.7	1.4
SRNV20014	5.8	4.8	5.3	5.2	8.8	6.2	2.2	5.6	1.1
SRNV20069	5.4	—	5.4	8.4	12.1	8.4	0.4	7.3	1.4
SRNV20190	4.3	5.7	5.0	11.0	3.9	2.9	0.9	4.7	0.9
SRNV20113	4.1	—	4.1	5.5	5.3	1.9	5.2	4.5	1.1
SRNV20150	3.9	—	3.9	4.0	6.6	5.6	2.2	4.6	1.2
SRNV20019	3.5	3.2	3.4	5.0	2.8	3.6	1.3	3.2	0.9
SRNV20186	3.2	—	3.2	3.1	4.0	3.3	4.5	3.7	1.2
SRNV20017	3.0	—	3.0	4.0	16.6	2.3	1.9	6.2	2.1
SRNV20187	2.9	2.5	2.7	3.5	4.6	1.4	1.4	2.7	1.0
SRNV20174	2.8	—	2.8	3.7	1.2	3.0	4.5	3.1	1.1
SRNV20162	2.6	—	2.6	6.7	4.0	3.2	0.7	3.7	1.4
SRNV20183	2.6	2.0	2.3	5.5	4.3	2.0	0.8	3.2	1.4
SRNV20018	2.4	2.3	2.4	4.1	13.6	2.6	0.3	5.2	2.2
SRNV20175	2.3	2.7	2.5	5.8	1.8	0.4	0.7	2.2	0.9
SRNV20052	2.0	1.7	1.9	2.7	1.9	1.4	0.7	1.7	0.9
SRNV20022	1.9	2.4	2.2	5.3	2.1	0.5	5.2	2.1	1.0
SRNV20056	1.9	1.8	1.9	3.8	4.9	0.3	2.1	2.8	1.5
SRNV20181	1.9	—	1.9	3.6	1.5	1.3	0.9	1.8	0.9
SRNV20121	1.6	0.8	1.2	1.2	1.0	0.1	0.7	0.8	0.7
SRNV20114	1.6	1.7	1.7	2.2	1.9	1.3	1.4	1.7	1.0
SRNV20189	1.5	1.9	1.7	2.9	2.0	2.3	0.0	1.8	1.1
SRNV20100	1.4	—	1.4	2.7	3.0	0.1	0.4	1.5	1.1
SRNV20071	1.3	1.5	1.4	5.0	3.2	0.9	0.5	2.4	1.7
SRNV20112	1.2	1.2	1.2	1.8	0.2	0.1	0.5	0.7	0.6
SRNV20104	1.2	0.8	1.0	1.3	2.0	1.3	1.4	1.5	1.5
SRNV20026	1.1	1.3	1.2	2.1	2.5	1.2	0.0	1.5	1.3
SRNV20096	1.0	0.9	1.0	2.7	2.6	2.1	0.8	2.1	2.1
SRNV20102	0.9	1.2	1.1	1.9	2.2	0.0	0.6	1.2	1.4
SRNV20193	0.8	1.1	1.0	2.3	0.9	1.1	0.6	1.2	1.2
SRNV20051	0.7	0.7	0.7	1.6	1.3	0.2	0.0	0.8	1.1
SRNV20041	0.7	0.8	0.8	2.8	2.5	1.3	0.4	1.8	2.3
SRNV20032	0.6	0.7	0.7	2.0	1.3	0.8	0.6	1.4	2.0
SRNV20070	0.5	0.6	0.6	1.2	0.9	0.6	0.2	0.7	1.2
SRNV20131	0.4	0.6	0.5	1.4	1.0	0.0	0.0	0.6	1.2
SRNV20148	0.4	0.5	0.5	2.0	0.9	0.7	0.7	1.1	2.2
SRNV20179	0.4	0.3	0.4	2.6	0.4	0.4	0.9	1.1	2.8
SRNV20191	0.3	1.1	0.7	2.3	1.9	0.0	0.7	1.2	1.7
AVERAGE			2.3	4.3	4.1	2.2	1.5	3.0	1.3

[1]Winter (December, January, February), Spring (March, April, May), Summer (June, July, August), Autumn (September, October, November)

[2]CAN/ATD = ratio of average of ATDs to average of canisters by house.

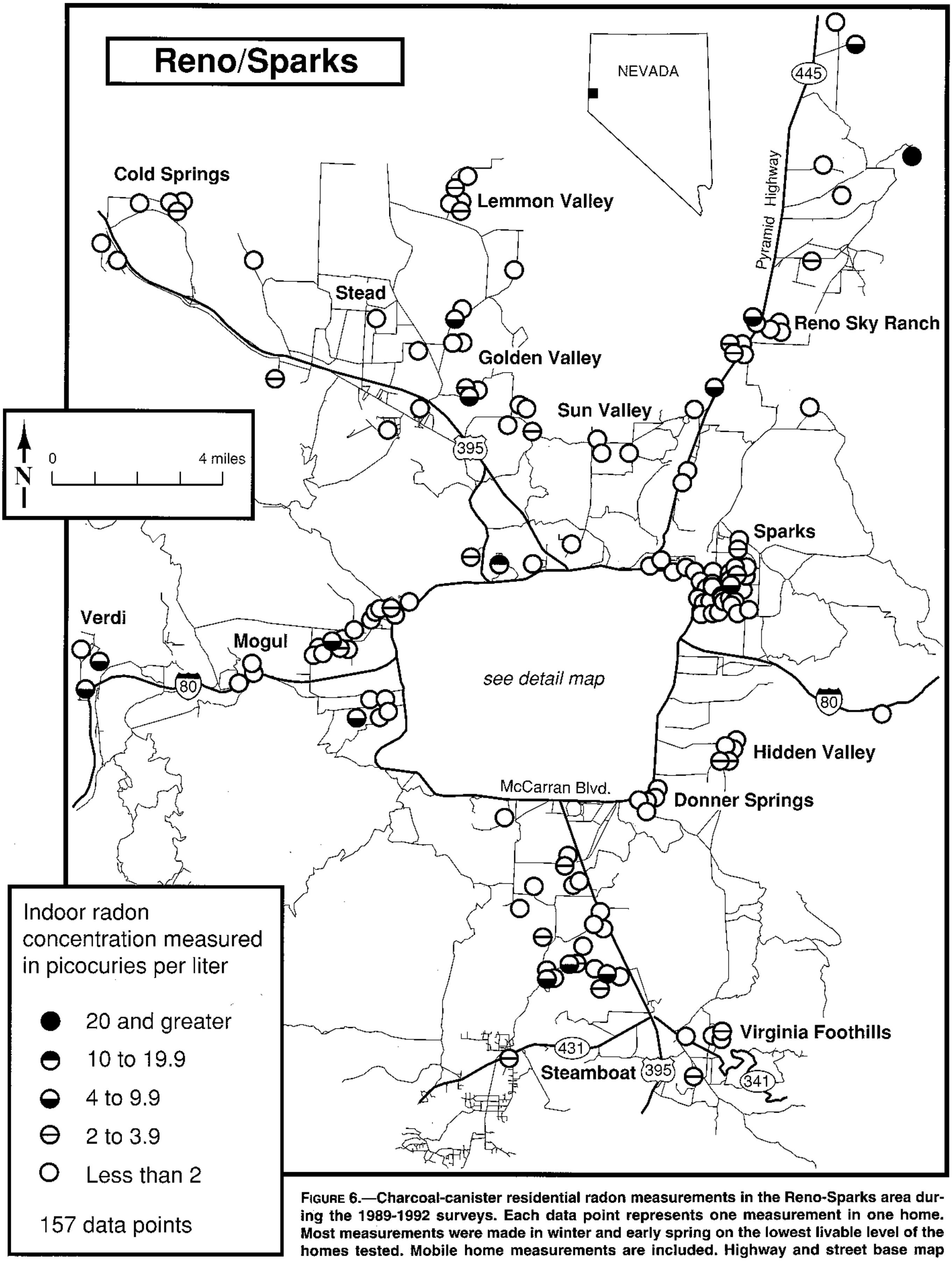


FIGURE 6.—Charcoal-canister residential radon measurements in the Reno-Sparks area during the 1989-1992 surveys. Each data point represents one measurement in one home. Most measurements were made in winter and early spring on the lowest livable level of the homes tested. Mobile home measurements are included. Highway and street base map adapted from U.S. Census Bureau TIGER file.

detectors. This table shows data collected from 39 homes in Nevada which contained one or two ATDs as well as four seasonal charcoal canisters. Of the 122 homeowners who returned ATDs, only 39 of them exposed their seasonal canisters in the correct season throughout the year that the ATDs were in place. As shown in this table, the average radon concentration measured by ATDs from those 39 homes is 2.3 pCi/L, while the average of the four seasonal canisters from the same 39 homes is 3.0 pCi/L; the overall ratio of the average of the seasonal canister measurements to the average of the ATD measurements is 1.3. In other words, the average of the seasonal canister measurements, as a whole, was 130% of the average of the ATD instruments for the same group of homes. There is, however, a wide variation in the ratio of average seasonal canister radon concentration to average ATD radon concentration for each individual home, ranging from about 0.6 to 2.8 (about 60% to 280%), as shown in the last column of table 3.

The differences seen in table 3 in the average yearly radon concentrations measured in these homes by ATD versus charcoal canister detectors may be explained by the fact that the four seasonal charcoal canisters used in each home were exposed to the air in these homes for a only few days each season. In effect, the charcoal canisters take brief snapshots only of the indoor radon concentrations which vary from day to day and season to season. By comparison, the ATDs in these homes were continuously accumulating data (alpha tracks) every day of the year, averaging out the extreme high and low radon concentrations detected by the charcoal canisters.

The charcoal canister measurements shown in table 3 also demonstrate the variation in indoor radon concentration by season. The average indoor radon concentration for all 39 homes for the winter is 4.3 pCi/L, while the averages for all the other seasons of the year are less than this, with the lowest seasonal average occurring in the fall (1.5 pCi/L). This seasonal variation in indoor radon concentrations will be discussed more fully in the section entitled *Factors Affecting Indoor Radon.*

LOCAL VARIATIONS IN INDOOR RADON IN THREE NEVADA POPULATION CENTERS

Maps of the larger population centers in the state (Las Vegas, Reno-Sparks, Carson City) illustrate the distribution of individual indoor charcoal canister radon measurements collected in all surveys done by NBMG from 1989 through 1992 (figs. 6-8). These maps show the distribution of residential indoor radon measurements in five ranges of radon

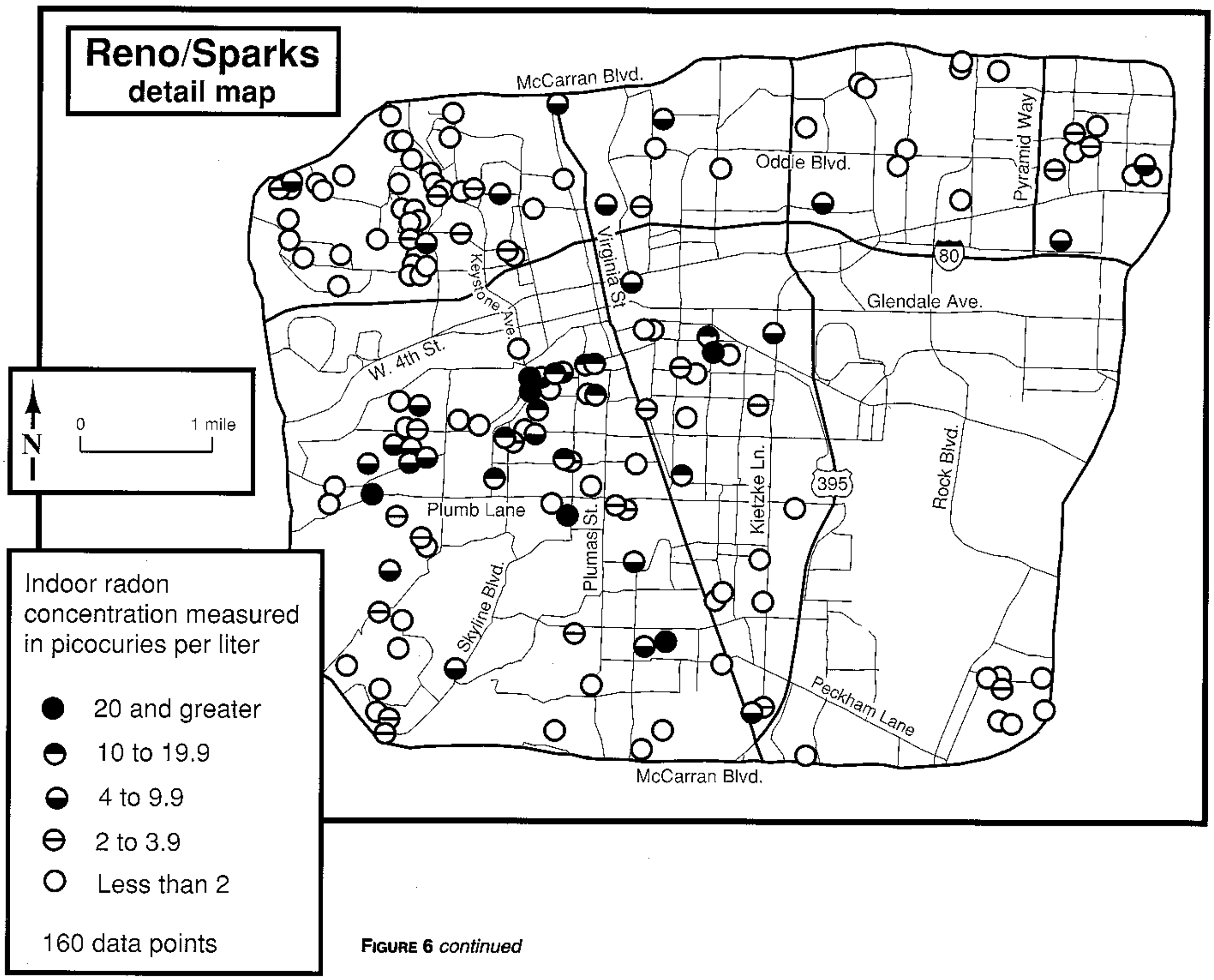


FIGURE 6 *continued*

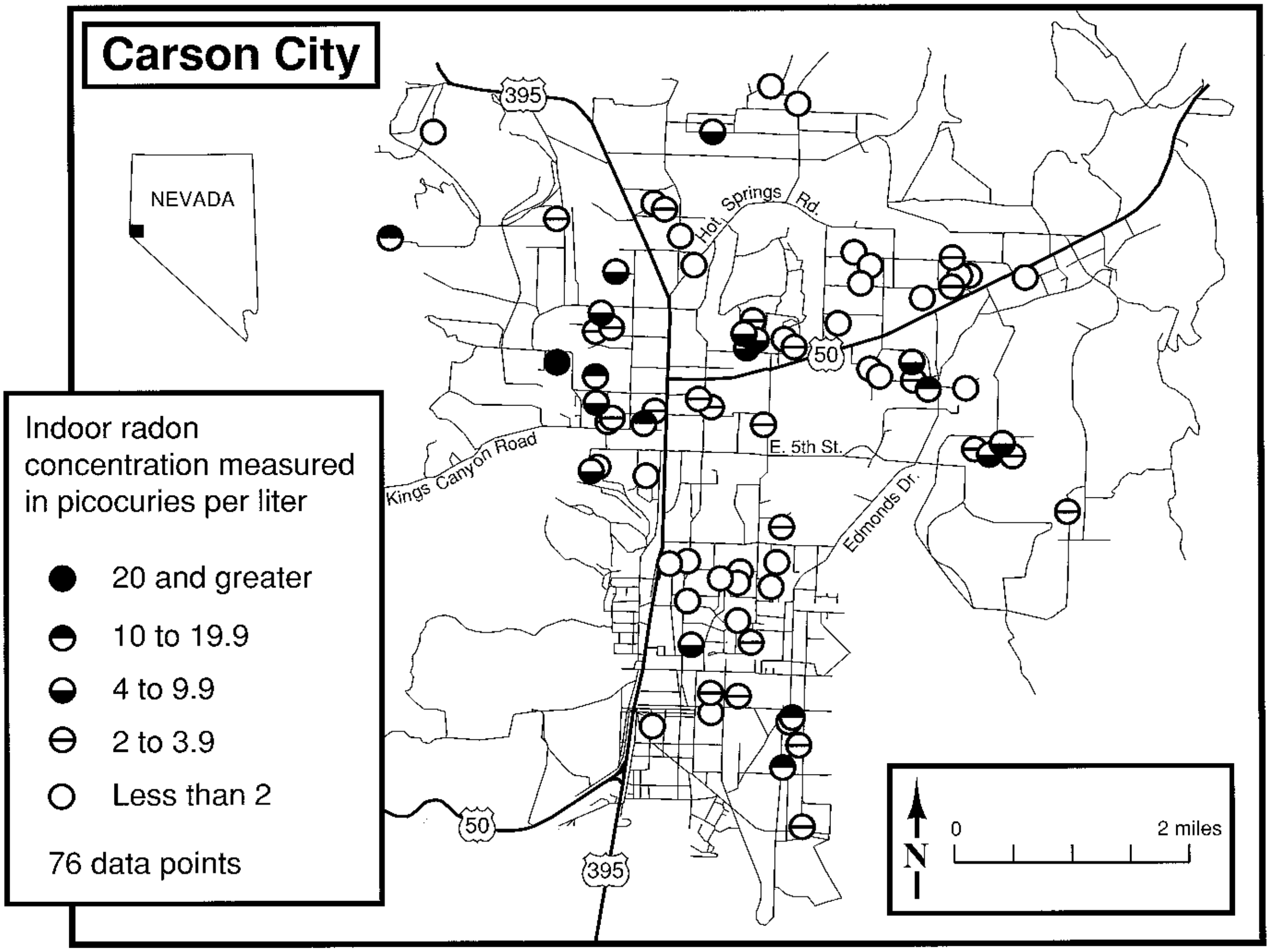


FIGURE 7.—Charcoal-canister residential radon measurements in Carson City during the 1989-1992 surveys. Each data point represents one measurement in one home. Most measurements were made in winter and early spring on the lowest livable level of the homes tested. Mobile home measurements are included. Highway and street base map adapted from U.S. Census Bureau TIGER file.

concentration: less than 2 pCi/L, 2-3.9 pCi/L, 4-9.9 pCi/L, 10-19.9 pCi/L, and 20 pCi/L and above.

Figure 6 shows the indoor radon distribution in the adjacent cities of Reno and Sparks. About 21% of the measurements with charcoal canisters in Reno from 1989 to 1992 had radon concentrations over 4.0 pCi/L, as did 6% of the measurements in Sparks (see fig. 5). The highest concentration of indoor radon measured in Reno-Sparks in 1989 to 1992 was 40.6 pCi/L. Subsequent measurements of indoor radon made in February and March 1993 in targeted high hazard areas in Reno and Sparks were as high as 177.5 pCi/L. The southwestern part of Reno contains the highest density of homes with radon concentrations exceeding 4.0 pCi/L (fig. 6 detail map). In particular, the area between Interstate 80 (I-80) on the north and McCarran Boulevard on the south, and between Virginia Street on the east, and McCarran Boulevard on the west contains a high proportion of homes with elevated indoor radon concentrations. Sparks and those portions of Reno outside the boundaries of this area generally contain a smaller percentage of homes with elevated levels of radon, although a few scattered clusters of homes with elevated indoor radon possibly indicative of potentially high radon areas do exist outside the area mentioned above. The parts of Reno that contain large percentages of homes with elevated radon are underlain, for the most part, by Quaternary gravels which include terrace gravels, alluvial fan gravels, glacial outwash, and pediment gravels (Bonham and Bingler, 1973; Bonham and Rogers, 1983). The clasts comprising many of these gravels are of granitic and volcanic composition which can be relatively enriched in uranium-bearing minerals. Parts of southwest Reno also contain numerous geologic faults of various types and ages. Some faults act as conduits for the transport of radon from source rocks to foundations of homes built near the faults (King, 1978, 1980; King and others, 1991). This may be a factor in the large proportion of homes in southwest Reno with elevated radon levels, although the mere presence of faults does not predict elevated indoor radon levels, because many areas with dense concentrations of faults have no such elevated radon levels. Figure 6 indicates that the community of Verdi may have the potential for having a large proportion of homes with elevated indoor radon, but too few measurements are available from Verdi to support a definitive conclusion.

Figure 7 shows the distribution of indoor radon measurements in Carson City. Overall, about 27% of the measurements in Carson City from 1989 to 1992 had radon concentrations over 4.0 pCi/L (see fig. 5), and the highest concentration of indoor radon measured was 31.6 pCi/L. A large proportion of the tested homes in the western portion of Carson City (west of U.S. Highway 395) exceed 4.0 pCi/L of radon and the highest radon measurements in Carson City are from this area. This part of Carson City is underlain by alluvium and alluvial fan sediments and gravels, derived mainly from granitic rocks of the Carson Range (granodiorite of Cretaceous age) located immediately west of Carson City (Trexler, 1977). There may also be three or four smaller, localized areas of Carson City containing a higher than normal proportion of homes with elevated indoor radon. One area is located along the north side of U.S. Highway 50 about 1 mile east of downtown Carson City. Two other areas are located east of this area: one is south of Highway 50 and north of East 5th Street, about 2 miles east of Highway 395, while the other is at the east terminus of East 5th Street about 3 miles east of Highway 395 and 1 1/2 mile south of Highway 50. A fourth possible high hazard indoor radon area is in southeastern Carson City about 1 1/2 miles east of the southern junction of Highways 50 and 395. All of these areas are near outcrops of bedrock consisting of predominantly metavolcanic rocks of Triassic-Jurassic age (Moore, 1969). The area north of Highway 50 also contains faults cutting Quaternary alluvium.

Figure 8 shows the distribution of indoor radon measurements in the Las Vegas, North Las Vegas, and Henderson area. Overall, only about 3% of the measurements in Las

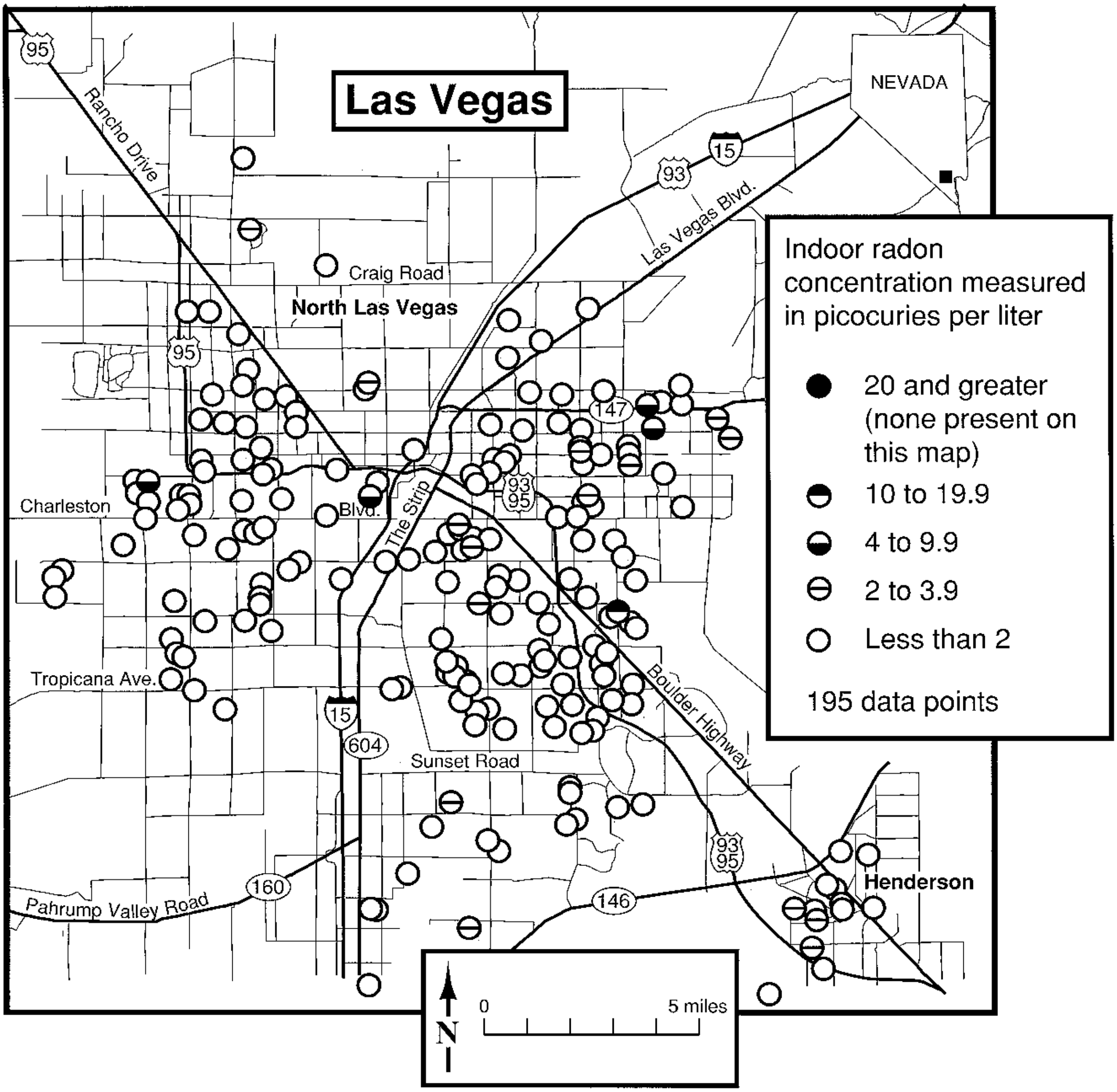


FIGURE 8.—Charcoal-canister residential radon measurements in Las Vegas during the 1989-1992 surveys. Each data point represents one measurement in one home. Most measurements were made in winter and early spring on the lowest livable level of the homes tested. Mobile home measurements are included. Highway and street base map adapted from U.S. Census Bureau TIGER file.

Vegas (including North Las Vegas) had radon concentrations over 4.0 pCi/L, with none above 4.0 pCi/L in Henderson. Inspection of figure 8 indicates that very few homes are over the EPA action level. In the eastern part of Las Vegas, between Las Vegas Boulevard on the north and the Boulder Highway on the south, there is a loosely scattered cluster of a few homes with elevated indoor radon concentrations of which the highest measurement is 11.0 pCi/L. This area is centered on the eastern terminus of State Route 147 (Lake Mead Boulevard). The homes of this region are built on alluvium of the Las Vegas Valley, most of which was derived from Las Vegas Wash to the northwest. Frenchman Mountain, located 6 to 7 miles east of Las Vegas, is composed predominantly of various Paleozoic-age limestones and dolomites and lesser amounts of shale and Precambrian gneiss (Matti and others, 1993). The gneiss may contain some uranium-bearing minerals which would be a potential source of indoor radon in homes built on detritus from Frenchman Mountain.

Post-EPA/SIRG Survey Radon Studies and Activities

Since the completion of the EPA/SIRG charcoal canister and ATD survey in Nevada in 1991, NBMG and NDOH obtained additional EPA/SIRG funding to continue to investigate radon in Nevada, and NBMG has conducted indoor radon tests in additional homes in the state, as well as in offices occupied by state workers in Reno, Sparks, and Carson City. Radon in the pore spaces of soil (soil-gas radon) has been measured at numerous sites in the state, as has radon in outdoor air (ambient-air radon) of the state. NBMG has also collected and tabulated available information on radon measurements from public schools, and has assisted the USGS in obtaining radon measurements in groundwater in Nevada.

Beginning with the second year of EPA-funded activities, a major element of the state's scientific effort has been to identify those areas in Nevada that have the geologic potential to generate significant amounts of radon that could cause elevated indoor radon concentrations in homes built in these areas. A map of potential radon hazard in Nevada was generated in order to graphically display the regions of differing potential relative hazard due to indoor radon in a form most useful to the greatest number of people. In order to do this most efficiently, GIS (geographic information system) technology was used on a high-capacity computer to assemble, catalog, and compare disparate types of information and to construct maps and overlays of the various data sets. In this manner, after all the data have been entered into the computer databases, the GIS software user can more easily evaluate whether correlations exist among the different data sets. The final goal of this technology as applied to the radon program was to develop an Indoor Radon Potential Hazard Map of Nevada, showing areas of relative potential for indoor radon based upon various types of data (such as geology, soils, uranium content of near surface rocks and soils, and indoor radon concentrations). The GIS procedures used in the development of this map are described in the section on *Indoor Radon Potential Hazard Map.*

INDOOR AIR SURVEY OF TARGETED COMMUNITIES

The EPA/SIRG indoor air survey of the state found several communities to have a high percentage of homes with elevated levels of radon. In order to further investigate the extent of the radon problem in some of these communities, NBMG selected three towns to participate in an intensive indoor radon survey. The communities of Austin (1990 population 990), Genoa (pop. 4,158, including Jacks Valley), and Pioche (population 1,604) were selected because of their relatively small populations, their diverse geologic settings, and the relatively high percentage of tested homes containing radon in excess of 4.0 pCi/L from the NBMG and EPA/SIRG screening surveys (Austin: 41%; Genoa: 100%, but with too few measurements to be statistically significant; Pioche: 39%). Every resident with a listed telephone number in these communities was contacted and asked to participate. In February 1992, 7-day charcoal canisters purchased from Alpha Spectra, Inc. of Lakewood, Colorado (an RMP listed company) were sent to more than 300 homeowner volunteers in these three communities, as well as to several other homeowners in western Nevada where previous indoor radon data were lacking or where previous data suggested high indoor radon potential; communities situated along the shore of Lake Tahoe were included in this survey.

Results of this survey are as follows: 43% of the canisters returned from the town of Austin contained radon in excess of 4.0 pCi/L, 9% from the town of Genoa, and 16% from the town of Pioche. The highest radon concentration was 80.9 pCi/L (the highest indoor radon concentration measured in any of the NBMG/NDOH radon surveys through 1992) from the town of Pioche, while Austin had a high of 40.7 pCi/L and Genoa a high of 19.7 pCi/L (see table 1).

Figure 9 shows the distribution of indoor radon measurements obtained in the 1992 targeted survey for the town of Genoa. About 9% of the measurements in Genoa exceeded 4.0 pCi/L of radon in this survey (see table 1). Of all the measurements for indoor radon made in Genoa between 1989 and 1992, only 8% exceeded the EPA action level (see fig. 5). The homes that do exceed 4.0 pCi/L occur mostly on the west side of Genoa and State Route 206 (Main Street in Genoa). All of these homes lie within about 0.1 mile of the Genoa fault, a major, range-bounding fault which may be a factor in the distribution of high-radon homes in Genoa. Unlike the Carson Range near Carson City, the Carson Range in the vicinity of Genoa is composed mostly of non-granitic rocks consisting predominantly of Triassic and Jurassic schists and metavolcanic rocks, although Cretaceous granodiorite crops out farther to the west in the Carson Range (Pease, 1980). The lower percentage of tested homes with elevated radon in Genoa compared to Carson City, 12 miles to the north, is probably attributable in part to the difference in origin of the source rocks for the valley fill on which most of the homes are built: granitic Carson Range rocks west of Carson City, and metavolcanic rocks in the Carson Range west of Genoa. The highest concentration of indoor radon measured in Genoa to date has been 19.7 pCi/L.

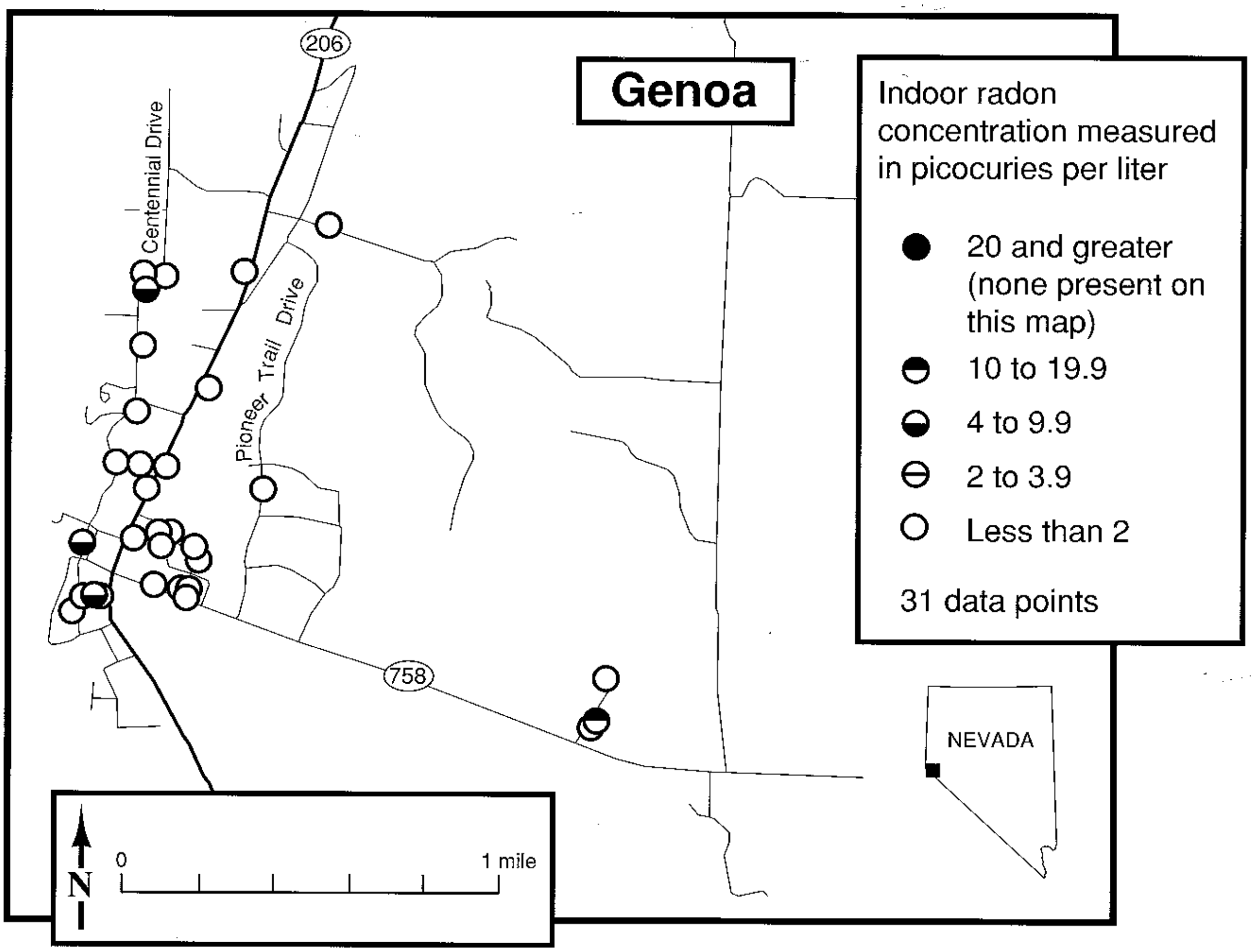


FIGURE 9.—Charcoal-canister residential radon measurements in Genoa during the 1992 targeted survey. Each data point represents one measurement in one home. Most measurements were made in February and March on the lowest livable level of the homes tested. Mobile home measurements are included. Highway and street base map adapted from U.S. Census Bureau TIGER file.

The discrepancy between the percentage of homes measured exceeding 4.0 pCi/L in Genoa during the EPA/SIRG survey (100%) and the percentage in the targeted survey (9%) is probably because only two homes were sampled in the earlier survey and these two homes, although having a Genoa zip code, were located several miles south of Genoa in an area of much different geology. Another reason why the percentage of homes with elevated radon was not as high as expected in this survey for Genoa (and perhaps Pioche and Austin as well) may be due to the weather at the time of testing. Most of the measurements of indoor radon in the EPA/SIRG survey were obtained mainly during the late winter of 1989-1990 when conditions were relatively cold in the state, whereas the targeted survey of the three communities was conducted beginning in late February 1992 when daytime temperatures in northwestern Nevada (Carson City; no weather station for Genoa) reached 67°F and stayed warm for most of the test period. These warm temperatures probably prompted the occupants of many of the homes to increase outside ventilation into their homes, thus diluting indoor radon concentrations.

Figure 10 shows the distribution of indoor radon measurements from the 1992 targeted community survey for Austin. About 43% of the measurements in Austin exceeded 4.0 pCi/L in this survey (see table 1). In all the measurements made for indoor radon in Austin between 1989 and 1992, 33% exceeded the EPA action level (see fig. 5). Homes containing elevated radon concentrations appear to be distributed in all parts of Austin, showing no distinct pattern. This is probably attributable in part to the fact that all of Austin and the surrounding area of the Toiyabe Range is underlain by the same granitic rock type (Jurassic quartz monzonite; Stewart and others, 1977). As granitic rocks can contain relatively large amounts of uranium-bearing minerals, they are a common source of radon. The highest concentration of indoor radon measured in Austin to date has been 40.7 pCi/L. It should be noted that figure 10 includes mobile home data; many of the radon concentrations less than 4.0 pCi/L in Austin were measured in mobile homes.

Figure 11 shows the distribution of indoor radon measurements from the 1992 targeted community survey

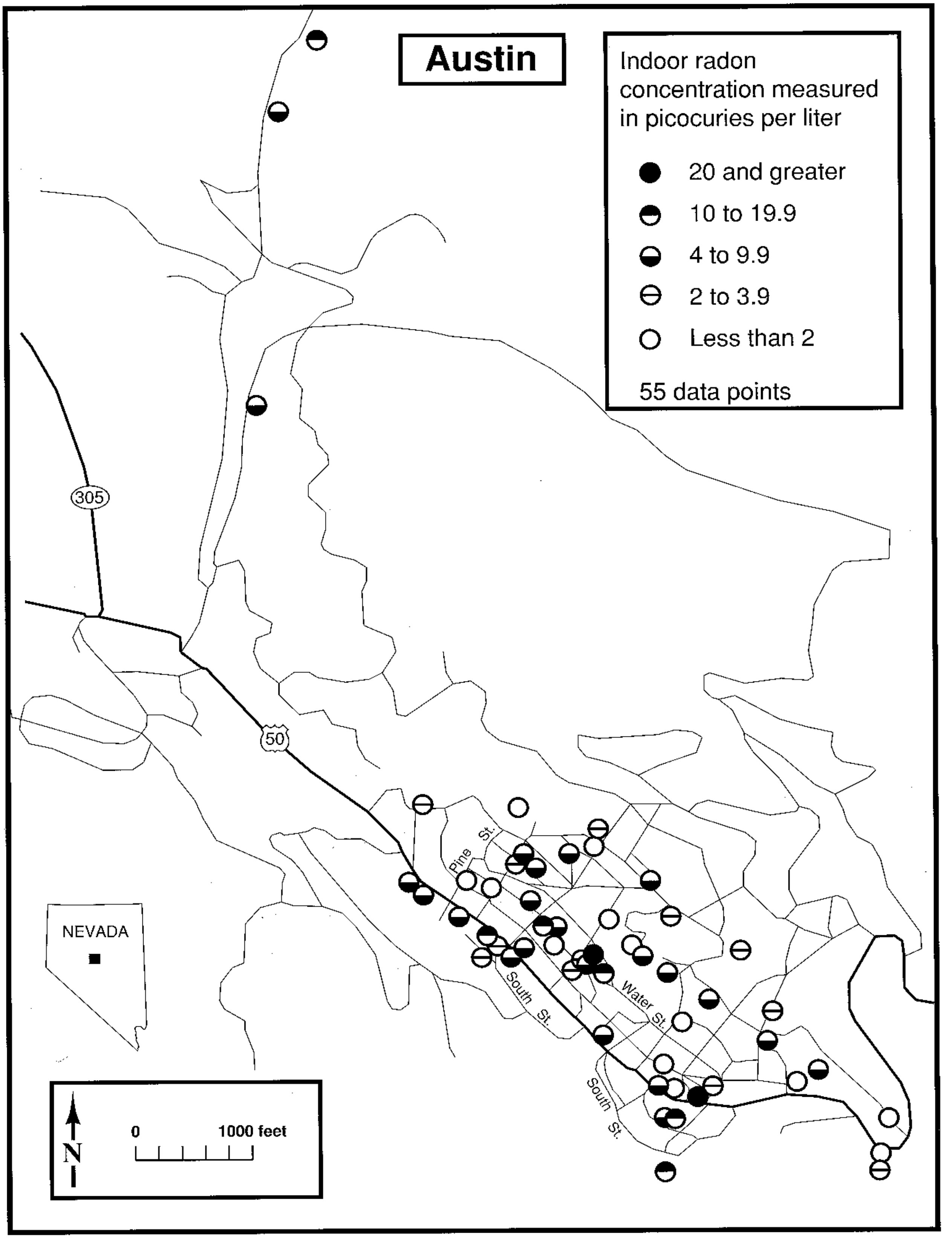


FIGURE 10.—Charcoal-canister residential radon measurements in Austin during the 1992 targeted survey. Each data point represents one measurement in one home. Most measurements were made in February and March on the lowest livable level of the homes tested. Mobile home measurements are included. Highway and street base map adapted from U.S. Census Bureau TIGER file.

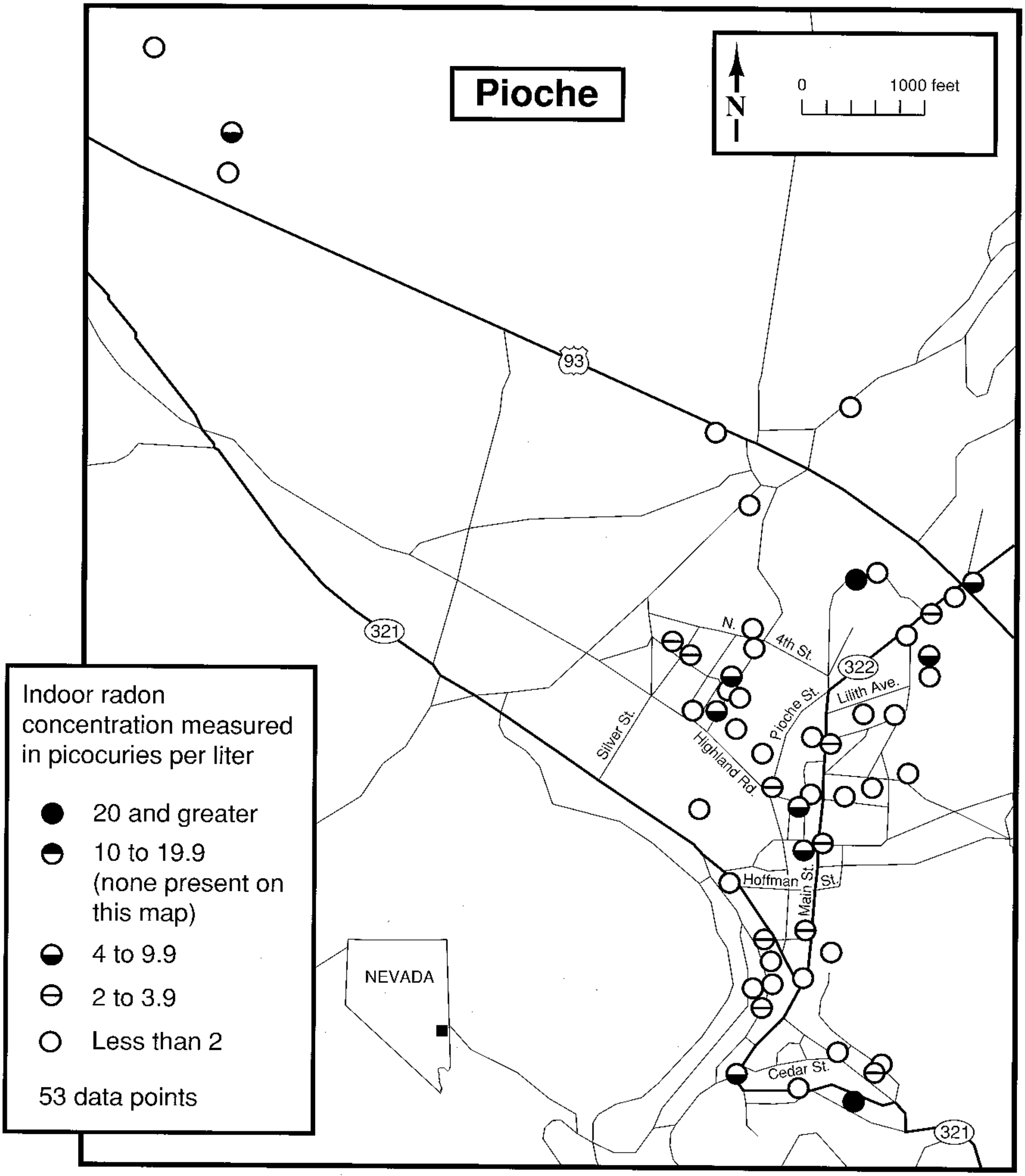


FIGURE 11.—Charcoal-canister residential radon measurements in Pioche during the 1992 targeted survey. Each data point represents one measurement in one home. Most measurements were made in February and March on the lowest livable level of the homes tested. Mobile home measurements are included. Highway and street base map adapted from U.S. Census Bureau TIGER file.

for Pioche. About 16% of the measurements in Pioche exceeded 4.0 pCi/L in this survey (see table 1). Of all the measurements of indoor radon in Pioche between 1989 and 1992, 23% exceeded the action level (see fig. 5). No distinct trend or pattern in the distribution of sampled homes with elevated radon in this survey can be seen; a few occur in the northern part of the town, two in the center of town, and two to the south of town. Pioche is situated in the Pioche Hills which are composed predominantly of Cambrian quartzite, with Cambrian limestone and dolomite in the vicinity of Pioche (Tschanz and Pampeyan, 1970). Igneous rocks have been detected in underground mines and in mineral exploration drill holes in the Pioche area. The Pioche Hills are cut by numerous faults and mineralized veins also.

As there is no obvious uranium-rich source rock for radon at the surface, it is possible that other factors such as proximity to faults and porosity and permeability of the soil or home construction foundation type exert a controlling influence over the distribution of homes with high indoor radon in Pioche. The percentage of homes exceeding 4.0 pCi/L in Pioche in the 1992 targeted survey was not as large as that found in previous surveys. Part of the reason for this may be due to the relatively warm temperatures in Pioche during the 1992 testing period. Air temperatures in nearby Caliente (no weather station for Pioche) hit a high of 68°F during the testing period and remained warm throughout the testing period, probably resulting in increased ventilation with outside air and decreased use of furnaces during the 1992 test period.

Several small communities surrounding the Nevada shore of Lake Tahoe were also targeted for indoor radon measurements in the February 1992 survey. These communities included Incline Village, Glenbrook, and Zephyr Cove. Homes in the communities of Crystal Bay and Stateline also received canisters. None of these communities were well represented in the 1990-1991 EPA/SIRG survey.

Figure 12 shows the distribution of indoor radon measurements from these communities from all surveys. Of the measurements made from 1989 to 1992, 59% exceeded 4.0 pCi/L in Zephyr Cove, 44% in Glenbrook, 18% in Incline Village, and none exceeded 4.0 pCi/L in Crystal Bay or Stateline (but there was only one measurement from each of these two communities). About 38% of all indoor radon measurements made in the Lake Tahoe area communities between 1989 and 1992 exceeded the EPA action level (24% in the 1992 targeted survey only; see table 1).

Most of these communities lie on, or very close to, granitic bedrock (Cretaceous granodiorite and related igneous rocks) of the Sierra Nevada batholith.

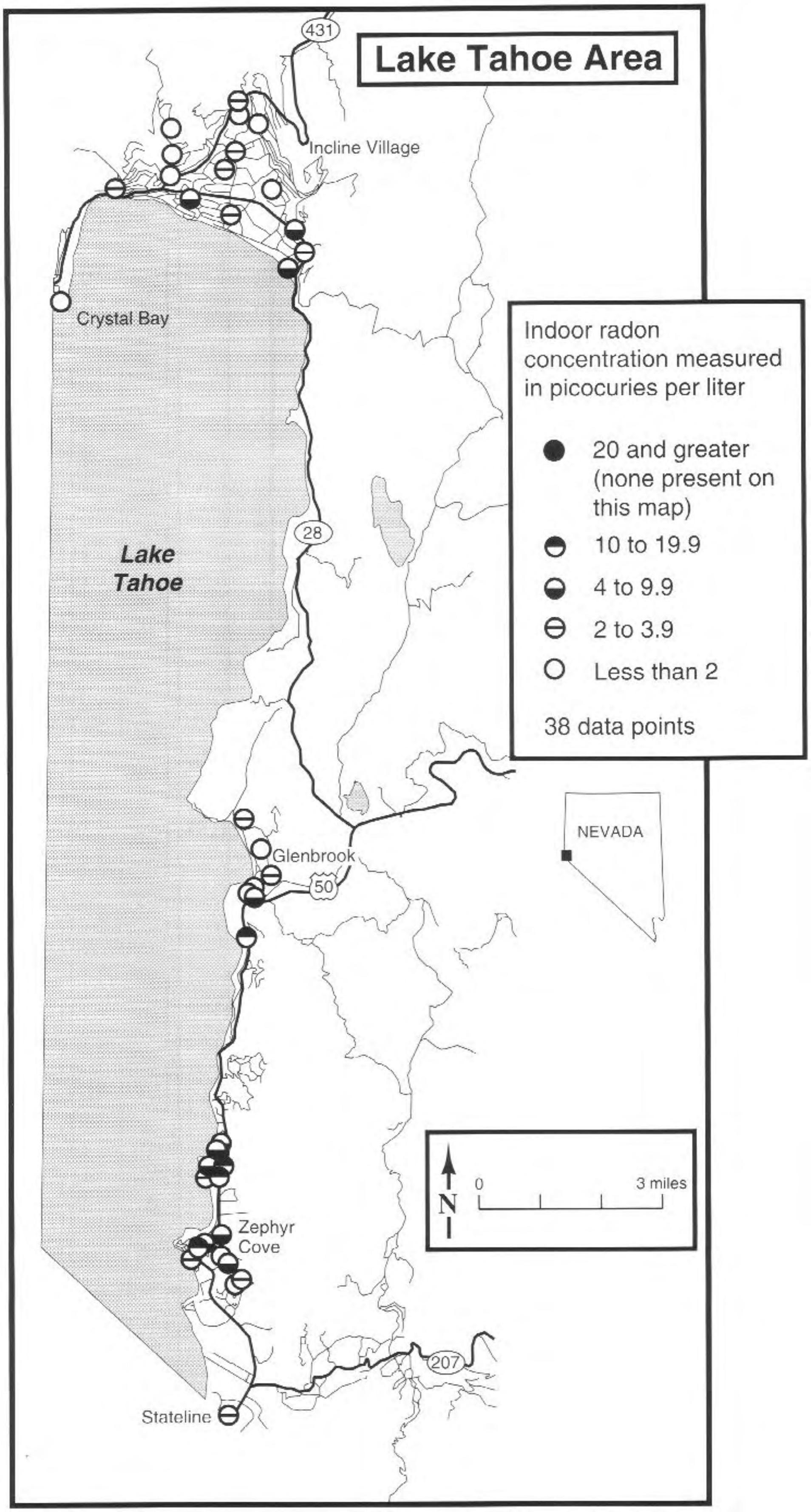


FIGURE 12.—Charcoal-canister residential radon measurements in the Lake Tahoe area during the 1989-1992 surveys. Each data point represents one measurement in one home. Most measurements were made in February and March on the lowest livable level of the homes tested. Mobile home measurements are included. Highway and street base map adapted from U.S. Census Bureau TIGER file.

Zephyr Cove is underlain by granodiorite bedrock, with arkosic alluvium (derived from weathering of granitic rocks) and organic-rich marsh deposits occurring locally (Grose, 1985; Otton and others, 1989). Stateline is underlain mostly by Quaternary-age alluvium derived wholly, or in part, from nearby outcrops of granodiorite (Bonham and Burnett, 1976). Part of Stateline is underlain by artificial fill of unknown origin (Bonham and Burnett, 1976). Most of Glenbrook is also underlain by alluvium derived either from Cretaceous granodiorite and related igneous rocks, or from Tertiary volcanic rocks (latite and trachyte) and Triassic to Jurassic-age metamorphosed volcanic rocks and monzogranite (Grose, 1985). The southern part of Glenbrook, where most of the homes are located, is underlain by Cretaceous granodiorite and related igneous rocks only (Grose, 1985). Most of Incline Village is underlain by Quaternary arkosic alluvial and fluvial deposits with nearby outcrops of Cretaceous granodiorite and andesitic volcanic rocks of the Kate Peak Formation (Thompson and White, 1964; Grose, 1986). Crystal Bay is underlain by Cretaceous granodiorite with volcanic rocks of the Kate Peak Formation occurring nearby (Grose, 1986). Some faults occur within or close to some of these Lake Tahoe communities and may be a factor in localized high indoor radon concentrations.

Near-surface, organic-rich, marsh sediments in the Zephyr Cove area have been found to contain very high concentrations of uranium (82 to 2,100 parts per million, reported in a study by Otton and others, 1989). This is undoubtedly a contributing factor in the high proportion of tested homes with elevated radon in the Zephyr Cove area. Although the granitic rocks of the Sierra Nevada batholith in the Zephyr Cove area are not particularly high in uranium compared to granitic rocks elsewhere, they are still almost certainly the source of the uranium in the marsh deposits and, ultimately, the indoor radon in the homes of the community.

NEVADA STATE OFFICE BUILDING RADON SURVEYS

Part of NBMG/NDOH activity under the EPA radon grant was to conduct an indoor air radon survey of state office buildings in Reno, Sparks, and Carson City. This was done to determine the percentage of state offices with elevated concentrations of radon in the workplace and to determine whether indoor air radon concentrations in these public buildings follow local patterns similar to those seen in residential indoor radon concentrations. State offices in Las Vegas were not tested because the residential radon surveys discussed previously indicated that radon is a minor problem in Las Vegas relative to the Reno and Carson City areas.

The Reno-Sparks state building screening survey was conducted by NBMG during March 1992 using 7-day charcoal canisters obtained from EPA. This survey tested nearly all office buildings owned or leased by the state in the Reno-Sparks metropolitan area, including buildings of the University of Nevada, Reno, and Truckee Meadows Community College in Reno. About 15% of the 125 measurements in this survey exceeded 4.0 pCi/L. The range in measurements was 0.1 to 11.8 pCi/L and the arithmetic mean was 2.1 pCi/L (see table 1). In June and July 1992, ATD detectors obtained from EPA were placed in those offices exceeding 4.0 pCi/L and exposed for one year in order to retest the measurements obtained with the short-term charcoal canisters. Of the 36 one-year ATD measurements taken in 18 state-occupied buildings, 15 (42%) were 4.0 pCi/L or higher. Twelve of the 18 buildings retested (67%) yielded one or more ATD measurements of 4.0 pCi/L or higher. The highest one-year ATD measurement in a state-occupied office in Reno-Sparks was 17.8 pCi/L.

In January 1993, NBMG conducted a similar state office radon screening survey in Carson City. In that survey, using 7-day charcoal canisters obtained from EPA, about 11% of the 134 measurements were in excess of 4.0 pCi/L. The range in measurements was 0.3 to 12.8 pCi/L, and the arithmetic mean was 2.2 pCi/L (see table 1).

Although state offices are not uniformly distributed in Reno-Sparks or in Carson City, the distribution of the elevated indoor radon measurements in state offices in Reno-Sparks and Carson City, in general, correspond to the distribution of elevated measurements seen in the residential surveys of these communities (see figs. 6 and 7). In Reno-Sparks, two state offices with elevated indoor radon are located in southwest Reno, corresponding to an area of high radon in homes. In addition, there are a few state offices with elevated indoor radon concentrations in adjacent south Reno near the southern terminus of Kietzke Lane where one of two homes tested had elevated indoor radon. A cluster of state offices with elevated radon also occurs on the campus of the University of Nevada, Reno located in north Reno just east of Virginia Street between McCarran Boulevard and I-80, and another cluster is east of Highway 395 just south of I-80 in southwest Sparks (no homes were tested in this area in any of the residential surveys).

Most state offices in Carson City are located near downtown Carson City and along the east side of Highway 395. Some of the offices east of Highway 395 in Carson City were found to contain elevated levels of radon. No homes are present within this immediate area, but this area is adjacent to the area of western Carson City which contained a high proportion of tested homes with elevated indoor radon as shown in figure 7 (a single state office with elevated radon was found in western Carson City as well). Two state offices with elevated radon are located north of Highway 50, about 0.25 mile east of Highway 395 near an area with elevated residential indoor radon, and a single state office with elevated indoor radon was found in southeastern Carson City near an area of homes with elevated indoor radon as shown on figure 7.

RADON TESTING IN NEVADA PUBLIC SCHOOLS

One of the goals of the Nevada SIRG study was to report on the extent and results of radon testing in Nevada public schools. To assess the extent of radon testing in Nevada schools, radon test results were requested in October 1992 from the school districts in all 17 counties of the state (for location of counties, see fig. 5). The initial request was followed by additional letters and phone calls over the next few months to those districts that did not respond. Most of the data used to compile the following report are in written form, but some information was obtained by telephone conversations with school district personnel where written data were unavailable.

Fourteen of the 17 county school districts in Nevada had done some radon testing in school buildings, the exceptions being Lincoln, Lyon, and Nye Counties. Letters were sent to the superintendents of these three school districts advising them of the potential for elevated indoor radon concentrations in the state, suggesting that they test their school buildings for radon, and providing them with literature on radon in Nevada and lists of suppliers of radon test kits. Of the 14 counties that had tested for radon, written reports of test results were received from 13 of the school districts, although some were incomplete. Storey County reported that radon testing had been done, but they could not find the results.

Mineral County School District tested its six schools but could not find a complete copy of their results. Their records indicate, however, that 158 charcoal canister screening tests were done in spring of 1990, and that two of the test results were greater than the EPA action level of 4.0 pCi/L. The rooms with the two high measurements were retested using long-term alpha track detectors which yielded measurements less than 4.0 pCi/L.

Carson City School District contracted with a commercial radon testing company to test for radon in fall 1989. All 11 schools were tested using 448 charcoal canister screening tests, of which 37 yielded measurements higher than 4.0 pCi/L. At least one result greater than 4.0 pCi/L was obtained in each of eight schools. No confirmatory follow-up-long-term testing was reported.

In March 1990, Churchill County School District contracted with a commercial radon testing company to do 360 charcoal canister screening tests in all six schools. Of these, five canisters from three schools yielded measurements higher than 4.0 pCi/L. The radon testing company recommended confirmatory follow-up testing of the five high measurements.

Clark County School District, working in conjunction with the Las Vegas EPA radon laboratory, has done extensive charcoal canister screening tests and follow-up tests in 14 of its 170 schools, mainly in 1989 and 1991. Sixty-three permanent buildings (145 buildings including portable classrooms) were tested at 14 schools. Of the 529 classrooms initially tested, eight detectors from three schools yielded results higher than 4.0 pCi/L. Three of these screening tests were at Las Vegas High School, where the radon problem was remediated using sub-slab radon reduction measures as part of a renovation project. School district personnel reported that post-mitigation testing indicated that radon concentration in all rooms in Las Vegas High School was less than 2.0 pCi/L (a Clark County School District radon guideline consisting of 50% of the EPA recommended action level of 4.0 pCi/L). School district personnel also reported that of the 529 classrooms initially tested, retesting showed that only five rooms remained above 4.0 pCi/L, and none exceeded 6.0 pCi/L. Thirty-six rooms were between 2.0 and 4.0 pCi/L. Systematic remedial work was done in rooms with elevated radon concentrations by adjusting air handlers to increase the fresh air exchange rate. Retesting of these schools and testing of new schools in Clark County was planned.

Douglas County School District hired a commercial radon testing company to make radon screening tests in all rooms of all nine schools in December 1990. Of 534 tests, 152 exceeded the EPA recommended action level, and every school tested had at least four test results exceeding the action level. Retesting was done at all screening test sites that exceeded the 4.0 pCi/L EPA action level, as well as at some additional sites (168 retests in all). Of the 141 retests which were retrieved and analyzed, 19 exceeded the 4.0 pCi/L action level.

The highest measurements in Douglas County were from Zephyr Cove Elementary School where one initial screening test result was 25.4 pCi/L, and later testing yielded a radon concentration of 38.0 pCi/L. Follow-up testing of elevated results at Zephyr Cove Elementary School using long-term ATD radon detectors over a one-month period in winter 1991 confirmed initial high screening measurements in several rooms. A sub-slab suction radon reduction system using four separate suction points and fans was installed at Zephyr Cove Elementary School during the summer of 1992. Post-mitigation radon testing yielded consistent results of 2.0 pCi/L or less with occasional spikes to 6.0 pCi/L.

Douglas County School District purchased two continuous radon monitors to do spot-check radon monitoring at Zephyr Cove Elementary School and at other schools in the district. School district personnel reported plans for additional long-term confirmatory radon testing and radon mitigation in other schools with elevated radon test results.

Elko County School District contracted with a commercial radon testing company to test school buildings for radon in spring 1991. All 20 schools were tested using 572 charcoal canisters, of which only six tests (in two schools) exceeded the EPA recommended action level. The highest of these measurements was only 4.7 pCi/L. The radon testing company recommended confirmatory follow-up testing of the six elevated measurements.

Esmeralda County School District employed a commercial radon testing company to test their three schools for radon in fall 1990. Twenty-four charcoal canister screening tests were done in the three schools. No test results were over the EPA action level and no confirmatory follow-up testing was recommended.

Eureka County School District purchased 28 charcoal canister test kits from a commercial radon testing company for screening tests in the two schools in the county in fall 1989. Two test results in each school exceeded the EPA action level, with the highest measurement being 4.6 pCi/L. Follow-up charcoal canister tests were done in January 1990 at the sites of the elevated measurements with resultant radon measurements all less than 2.0 pCi/L.

Humboldt County School District conducted 200 charcoal canister screening tests for radon in all 12 schools in summer 1990. Sixteen of the test measurements were above 4.0 pCi/L, located in six of the schools. The highest measurement was 8.1 pCi/L. Follow-up measurements were made in the schools with high screening tests using ATDs over a 10-month period from September 1990 through June and July 1991. All follow-up radon measurements were less than 3.0 pCi/L.

Lander County School District conducted simultaneous charcoal canister and ATD radon tests in their six schools beginning in October 1989. Four of the 24 ATD radon tests (representing three different schools) were over the 4.0 pCi/L EPA action level. The highest of these measurements was 13.0 pCi/L. The six charcoal canister tests, one in each school, were all under the 4.0 pCi/L. Confirmatory follow-up testing of the rooms with elevated screening measurements was recommended but the school district did not report that it had been done.

Pershing County School District conducted 94 charcoal canister screening tests for radon in their four schools in December 1989. Twelve of the test measurements were elevated in two of the schools. The highest measurement was 13.6 pCi/L. The superintendent of the school district reported that follow-up testing was done in February 1991, but the results could not be found.

White Pine County School District first purchased 30 ATDs for use in testing for radon in their eight schools, which they did from March 1990 to May 1991. Fifteen detectors (representing five schools) yielded measurements over 4.0 pCi/L. The highest of these measurements was 9.5 pCi/L. After the initial screening tests were done, additional testing was undertaken in July 1991 using 30 short-term charcoal canister tests which yielded test results all below 4.0 pCi/L. It was unclear from the charcoal canister test report supplied by school district personnel which rooms in which schools had been tested. The school district did not report that any radon-reducing measures had been taken in the buildings with elevated ATD measurements.

Washoe County School District conducted an extensive and systematic radon testing and mitigation program in its 72 schools. The radon testing program began in February 1990. Between 1990 and 1993, results were received from 1,938 three-month ATD screening tests in 47 schools, and about 500 more tests per year were planned until all of the district's 72 schools and additional administrative buildings are tested. Fifty-one of the screening test measurements exceeded the EPA action level of 4.0 pCi/L. Eleven of the schools had one or more measurements over this level. The highest of these measurements was 13.2 pCi/L. All initial measurements were made over periods of three to four months during the winter and spring months. All rooms with measurements over the EPA recommended action level were retested using ATDs over a full nine-month school year. Remedial measures were implemented in rooms with long-term retests above the action level to reduce radon concentrations below the EPA action level of 4.0 pCi/L.

Washoe County School District personnel reported that radon reduction procedures were successful at Incline Elementary School where several rooms had yielded consistently high radon measurements. The air handlers in the school were serviced to increase entry of fresh air into the rooms, thus diluting radon concentrations. Subsequent testing using ATDs over a five-month period from December 1991 to May 1992 showed all rooms to have radon concentrations less than 4.0 pCi/L.

At several other Washoe County schools with elevated radon screening results, inspection revealed gaps and cracked packing around pipe penetrations through the concrete slab into the earth below. School personnel planned to do extensive sealing and subsequent ATD retesting for an entire school year at these locations, with additional mitigation work to follow if elevated radon levels persist.

A summary of radon testing done in Nevada public schools is shown in table 4. These figures should be used only as a general guide to the approximate amount of radon testing done in Nevada public schools, because some of the reports from the school districts were unclear as to the exact number of tests done and the number of buildings tested. According to the reports received from the school districts, 312 (6%) of the 4,945 initial screening tests made in Nevada schools were higher than 4.0 pCi/L. Usually only one test was done per room, so about 6% of the tested schoolrooms in Nevada showed elevated levels of radon from initial screening tests (some of these have since retested at lower levels and some have been mitigated). This can be compared to a nationwide screening survey of randomly selected U.S. schools done by the EPA during the 1990-1991 school year which found that 2.7% of the nation's schoolrooms yielded short-term radon screening test results above the EPA action level of 4.0 pCi/L (U.S. Environmental Protection Agency, 1993b). However, 56 (38%) of the 148 schools tested in Nevada had at least one screening test higher than the EPA action level, compared to 19.3% of schools nationwide with at least one room higher than the action level, according to the same survey. Thus, overall, Nevada has more than twice the national average of schoolrooms with radon screening tests over the action level and about twice the national average of schools with at least one screening test over the EPA action level. Some of these buildings have had follow-up radon testing which yielded lower results, and the radon problem has been resolved in some since the screening tests were done. It is also important to note that these figures are not weighted to take into account differences in population density across the state. Most of the state's population resides in Clark County, where recent testing indicates that only 5 out of 529 classrooms (<1%), and 2 out of 14 schools (14%) have elevated radon concentrations. Thus the total percentage of Nevada's school children exposed to elevated radon levels is probably far less than might be deduced from table 4.

RADON IN SOIL GAS

In order to obtain basic information on concentrations of radon in soil gas in Nevada and to determine whether these correlate with concentrations of radon in the indoor air of homes, a number of studies were undertaken to measure soil-gas radon concentrations in the near-surface soils of the state. Soil is generally the largest source of indoor radon because radon is derived from the decay series of uranium contained in the soil and underlying bedrock. Some studies have indicated that there may be a rough correlation between soil-gas radon concentrations and indoor air radon concentrations in homes (Åkerblom, 1986;

TABLE 4.—*Summary of radon testing in Nevada public schools.*

County	Number of rooms over 4.0 pCi/L/number of rooms tested	Number of schools with at least one measurement over 4.0 pCi/L/number of schools tested	Type of detector used in screening tests	Season tested	Highest screening test pCi/L	Retesting, mitigation, comments
Carson City	37/448	8/11	CC	Fall 1989	9.5	No retesting or mitigation reported.
Churchill	5/360	3/6	CC	Fall 1990	7.1	No retesting or mitigation reported.
Clark	8/529	3/14	CC	Winter, 1989, 1991	6.7	Three elevated measurements were from Las Vegas High School where mitigation was done; retested <2.0 pCi/L.
Douglas	152/534	9/9	CC	Winter 1990, 1991	25.4	Retested with ATDs; only 19 retests >4.0 pCi/L. A sub-slab suction radon reduction system was installed at Zephyr Cove Elementary School; retested <2.0 pCi/L with occasional spikes to 6.0 pCi/L in spot-check monitoring.
Elko	6/572	2/20	CC	Spring 1991	4.7	No retesting or mitigation reported.
Esmeralda	0/24	0/3	CC	Fall 1990	1.0	No retesting or mitigation recommended.
Eureka	4/28	2/2	CC	Fall 1989	4.6	Retested with charcoal canisters; all retests <2.0 pCi/L.
Humboldt	16/200	6/12	CC	Summer 1990	8.1	Retested with one-year ATDs; all results were <3.0 pCi/L.
Lander	4/30	3/6	ATD and CC	Fall 1989	13.0	No retesting or mitigation reported.
Lincoln	—	—	—	—	—	No testing reported.
Lyon	—	—	—	—	—	No testing reported.
Mineral	2/158	2/6	CC	Spring 1990	?	Retested the two sites with elevated measurements with ATDs; results were <4.0 pCi/L.
Nye	—	—	—	—	—	No testing reported.
Pershing	12/94	2/4	CC	Winter 1989	13.6	Retesting was reportedly done with no elevated radon levels found, but results could not be found.
Storey	—	—	—	—	—	Testing was reportedly done, but no copy of results was available.
Washoe	51/1938	11/47	ATD	Winter and Spring 1990-1993	13.2	Program is still in progress with about two-thirds of the schools tested to date. Retesting and mitigation of schools with elevated measurements is being done with most tests now <4.0 pCi/L.
White Pine	15/30	5/8	ATD	March 1990-April 1991	9.5	Retested with 30 short-term charcoal canister tests in July 1991; all results were less than 1.3 pCi/L.
Total (all counties)	312/4945	56/148				

Gundersen and others, 1987, 1988; Brookins, 1991; Gundersen, 1991; Reimer and others, 1991).

In 1991, NBMG began measuring soil-gas radon concentrations at one-meter (3.3 feet) depth using an active sampling technique. The sampling method consists of pounding a small diameter, thick-walled, hollow carbon-steel tube into the ground to a depth of 2.5 to 3.3 feet. This is generally below the depths at which soil is affected by meteorological variables and at a depth where lower soil horizons are generally encountered. This sampling method disturbs the soil less than other methods of obtaining soil-gas radon measurements such as burial of passive detectors. After the soil probe is pounded into the ground, an airtight collar containing an O-ring and septum is attached to the open end of the probe. The tube is then flushed and a sample of air in the pore spaces of the soil encountered by the tip of the probe is extracted using a syringe. The soil-gas sample is then injected into an evacuated scintillation cell (a Lucas cell) of an electronic alpha-particle scintillometer for analysis (Lucas, 1957). Details on this sampling method can be found in Reimer (1991). The alpha scintillometer used in the NBMG investigations of soil-gas radon is a Pylon Electronics Inc. model AB-5 using Pylon model 110-A and 300-A Lucas cells; manufacturer instructions were followed in the analysis of all samples using this equipment, and all samples were collected and analyzed in accordance with the quality assurance (QA) guidelines outlined in the EPA-approved NBMG QA document.

Analyses of soil-gas radon and relations with underlying geology consist of three studies in west-central Nevada and one statewide study. The three west-central Nevada studies include: 1) an ongoing analysis of correlations between indoor and soil-gas radon concentrations in west-central Nevada, including the Reno area; 2) analysis of glacial outwash surfaces and fault scarps of the Mt. Rose alluvial fan complex near Reno; and 3) analysis of soil gas in the Lovelock area, which is located on fine-grained alluvial and lacustrine deposits. The statewide study consisted of soil-gas radon measurements taken as part of the ambient air radon survey discussed in the section *Radon in Outdoor Air*. In all studies most measurements were made during the summer, when the soil was dry.

Interpretations of soil-gas radon data derived from these studies and discussed below are preliminary; additional data are needed for more complete evaluations. However, some relations are apparent and are probably valid in most cases. The following general statements can be made: 1) in all cases, there is considerable variability in soil-gas radon concentrations; 2) observed differences in soil-gas radon concentrations often have apparent logical reasons, given the characteristics of individual sample locations; 3) soil-gas radon has a definite relationship to underlying geology; 4) influences of sample depth, soil moisture, and soil permeability described by others were observed and verified during these studies.

Comparison of Soil-Gas Radon and Geologic Units in and around Reno

Soil-gas radon was measured at several sites in and around the Reno-Carson City-Lake Tahoe area of western Nevada for comparison with indoor radon concentrations (see section on *Local Variations in Indoor Radon in Three Nevada Population Centers*). The soil-gas radon measurements obtained from this study, some of which are average values for multiple samples from the same site, have been examined for correlations with underlying geology.

Soil-gas radon measurements are plotted on a simplified geologic base (fig. 13) as an illustrative guide, but for quantitative analysis (table 5) were related to geology using the most detailed geologic maps available, in most cases the 1:24,000-scale, $7^1/2'$ quadrangle series published by NBMG. As shown in figure 13, geology is divided into six simplified geologic units. There appear to be some definite correlations between soil-gas radon concentrations and underlying geology (table 6), although all of the defined geologic units show considerable variability and the data subsets are in most cases too small to make statistically valid comparisons.

In general, the apparent differences between defined geologic units are logical and fit known geologic characteristics. Siliceous igneous rocks (granitic rocks and rhyolites) are often relatively high in uranium and therefore have

TABLE 5.—*Summary statistics for western Nevada soil-gas radon measurements (pCi/L).*

Unit	Number of measurements	Mean	Standard deviation	Median	Minimum	Maximum
gr	7	3,400	3,030	2,350	480	8,070
Tv	9	1,550	1,300	1,000	370	3,920
Qog	34	1,370	1,180	1,100	300	6,180
Qal	30	900	850	610	130	3,830
gr plus gr subunit	14	2,410	2,440	1,500	440	8,070
Qal minus sites near bedrock	11	610	290	520	130	1,110
Tk plus Ta plus Tk subunit	8	690	240	650	370	1,100
Spanish Springs study area	6	4,680	2,320	3,590	2,790	8,070
North valleys	9	490	200	480	190	900

TABLE 6.—*Soil-gas radon concentrations and underlying geology at sampling sites in and around Reno, Nevada.*

Sample no.	pCi/L	Unit	Subunit	Nearby bedrock	Detail
177	8,070	gr			
177a	7,150	gr			
178	3,250	gr			
122	2,350	gr			
136	1,660	gr			
133	870	gr			Mzsm
147	480	gr			Mzgd
132	890	mvs	gr		Mzmv/Mzsm
130	3,830	Qal	gr		
123	3,440	Qal		Tk	Qsu
129	2,120	Qal		gr	
113	1,340	Qal	gr		Qsu
174	1,310	Qal		gr	Qa
112	1,290	Qal		Tk	Qfsb
163b	1,110	Qal			Qa
119	980	Qal			Qfg
140	900	Qal		gr	Qg
168	870	Qal			Qa
134	820	Qal	gr		Qbo
120	810	Qal		Tk	Qfvo
124	730	Qal		gr	Qsd1
165	710	Qal			
166	630	Qal	Tk		
164a	590	Qal	Tk		
144	580	Qal	gr		Qws
116	530	Qal			Qld
155	520	Qal			
114	510	Qal			Qsu
167	470	Qal			
117	470	Qal		Tv	Qld
146	450	Qal			Qfb
141	440	Qal	gr		Qg
118	390	Qal		Tv	Qld
135	390	Qal			Qoa
142	300	Qal		gr	Qa
AA2	220	Qal	mvs		Qfcb
145	190	Qal		gr	Qfg
115	130	Qal			Qld
156	6,180	Qog			Qdo
150b	4,240	Qog			Qdo
150a	3,260	Qog	Qdo		
175	2,060	Qog	gr		Qoa
161	1,950	Qog			Qgo2
160	1,930	Qog			Qdo
126	1,760	Qog		Tk	Qgo2
162	1,710	Qog			Qdo
128	1,610	Qog			Qdm
125	1,510	Qog		Tk	Qgo2
111b	1,420	Qog			Qdo
152	1,290	Qog			Qto
AA1	1,240	Qog			Qoa
169	1,220	Qog			Qdo
11	1,210	Qog			Qdm
137	1,210	Qog			Qpf
110	1,100	Qog			Qdo
172	1,090	Qog			Qdm
107	1,000	Qog			Qdo

TABLE 6.—*Soil-gas radon concentrations and underlying geology at sampling sites in and around Reno, Nevada (continued).*

Sample no.	pCi/L	Unit	Subunit	Nearby bedrock	Detail
157	990	Qog			Qt4
158	980	Qog			Qdo
109a	940	Qog			Qdo
127	930	Qog		Tk	Qgo2
151	920	Qog			Qdo
159	700	Qog			Qdo
111a	560	Qog			Qdo
163a	550	Qog			Qdo
143	550	Qog			Qsw
148	500	Qog			Qp
108	450	Qog			Qdo
170	420	Qog			Qpf
149	370	Qog			Qpf
109b	370	Qog			Qdo
171	300	Qog			Qoa
139	1,100	Ta			Ta
121	1,000	Ta			
131	660	Ta			Thl
179a	3,920	Tv			
176a	2,910	Tv			
176	2,790	Tv			
173	660	Tk			Tku
154	510	Tk			Tkfb
164b	370	Tk			
138	370	Ts			Th
153	290	Ts			Th2

Notes:
Unit = underlying geologic unit
Units listed: gr = granitic rocks; mvs = metavolcanic and metasedimentary rocks; Qal = younger Quaternary sediments; Qog = older Quaternary gravels; Ta = Alta Formation volcanic rocks; Tv = Tertiary volcanic rocks, undivided; Tk = Kate Peak Formation volcanic rocks; Ts = Tertiary fluvial and lacustrine sedimentary rocks
Subunit = secondary geologic unit in proximity to sample location
Detail = geologic unit as described on detailed maps (7.5′ quadrangles)

elevated radon-producing potential. Of the defined units, granitic rocks (gr) show the highest average level of radon (3,400 ± 3,030 pCi/L), although both this high average level and the high variability largely result from inclusion of very high concentrations measured in a single area (that is, the western side of the Pah Rah Range, immediately northeast of Spanish Springs Valley, fig. 13). Three sites located on small outcrops of rhyolitic volcanic rocks overlying granitic rocks in this same area also have very high concentrations of radon (2,910; 2,790; and 3,920 pCi/L) and similarly skew the average concentration and variability for volcanic rocks.

The average soil-gas radon level for sites located on Quaternary alluvium (Qal) is relatively low (900 ± 850 pCi/L). If Qal sites located near bedrock exposures are not considered, this relation is even stronger (610 ± 290 pCi/L). Sites located on older alluvium (Qog) show a significantly higher average radon level (1,370 ± 1,180 pCi/L) than do those located on the younger Qal units. This is probably due to the predominance of glacial outwash gravels containing abundant granitic and volcanic clasts at the Qog sites.

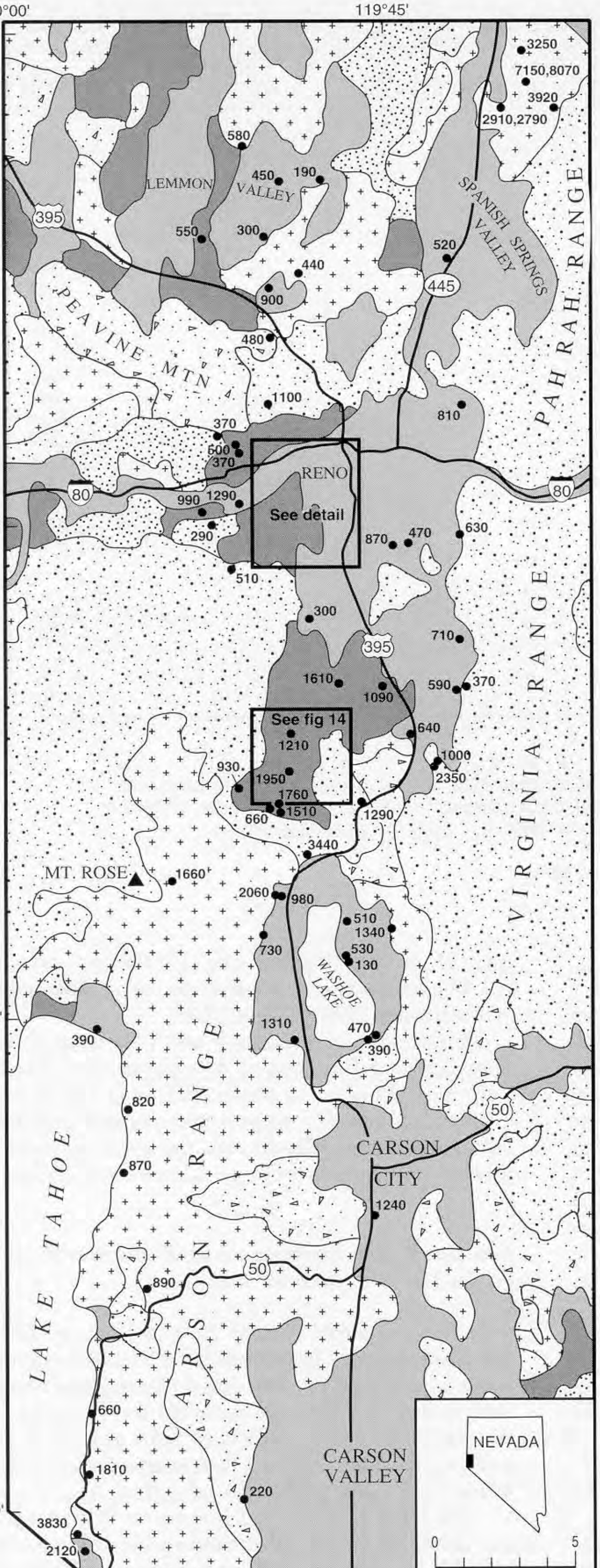
Sites located on volcanic rocks (Tv) have an intermediate average soil-gas radon level (1,550 ± 1,300 pCi/L), but if the Tv data subset is limited to sites on or near andesitic rocks (Kate Peak (Tk) and Alta (Ta) Formations) which are low in uranium relative to rhyolitic rocks, the average level is much lower (690 ± 240 pCi/L).

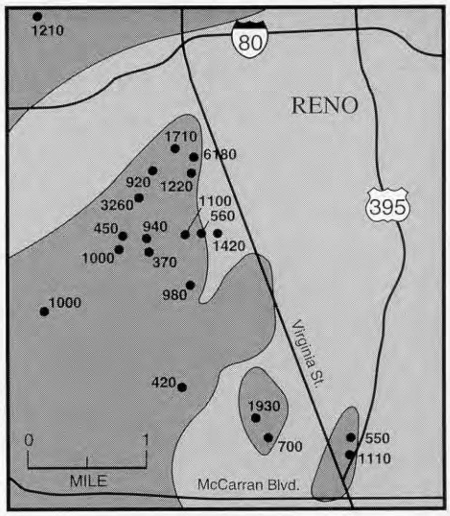
The Tertiary sedimentary unit (Ts) is composed predominantly of fine-grained deposits of the Hunter Creek Formation. Low radon concentrations at two sample sites (370 and 290 pCi/L) suggest that this unit may have low radon-generating potential, but the small number of samples is insufficient to prove a consistent relationship.

Soil-Gas Radon Analyses across Fault Scarps on the Mt. Rose Alluvial Fan

Over the period August 1991 to February 1992, soil-gas radon samples from three sites located on glacial outwash surfaces of the Mt. Rose alluvial fan complex in west-central Nevada were collected and analyzed. Two of these sites, one each on Donner Lake and Tahoe outwash surfaces, straddle Holocene fault scarps. Samples were collected along linear profiles crossing these faults.

The study had two principal goals: 1) to compare soil-gas radon from surficial deposits with differing lithology and soil development; and 2) to determine whether elevated concentrations of soil-gas radon occur along these Holocene





Qal Younger Quaternary sediments. Predominantly stream deposits and alluvial fans; includes lacustrine deposits in valleys northwest of Reno.

Qog Older Quaternary gravels. Includes terrace, alluvial fan, glacial outwash, and pediment gravels.

Ts Tertiary fluvial and lacustrine sedimentary rocks. Includes diatomite, sandstone, siltstone, mudstone, shale, and conglomerate; commonly tuffaceous.

Tv Tertiary volcanic rocks, undivided. Includes pyroxene andesites to rhyodacites of the Kate Peak Formation, pyroxene and hornblende andesites of the Alta Formation, and rhyolite to quartz latite. Includes basaltic andesite in Pah Rah Range.

gr Granitic rocks. Predominantly Cretaceous granodiorites; includes minor Tertiary granitics.

mvs Triassic and Jurassic metavolcanic and metasedimentary rocks.

• Site of radon measurement in soil gas. Numbers represent radon in picocuries/liter. Two numbers indicate two measurements taken within 100 feet of each other.

FIGURE 13.—Generalized geologic map and soil-gas radon measurements in west-central Nevada. Simplified geologic units are shown for illustrative purposes; geologic relations discussed in text and listed in tables 5 and 6 are taken from more detailed geologic maps and may not match this simplified representation. The location of figure 14 is shown on map.

fault traces. Faults often serve as permeable conduits through which fluids circulate, leaching uranium from rocks at depth and transporting it to the surface.

Glacial outwash deposits of the Mt. Rose alluvial fan complex

The surficial geology of the Mt. Rose alluvial fan complex is dominated by glacial outwash deposited by meltwater from small glaciers in the Carson Range (Bonham and Rogers, 1983). Based on soil development and weathering of boulders, the fan surface in general consists of Donner Lake outwash deposits north of Whites Creek and Tahoe outwash deposits south of Whites Creek (fig. 14).

Donner Lake outwash in the Mt. Rose fan area is derived from major streams draining alpine glaciers in the Carson Range and is composed of poorly sorted large pebble gravel, with cobbles and boulders common. Clasts are dominantly volcanic, with minor granitics. Clasts are highly rounded and boulders are deeply to completely weathered. The Donner Lake outwash deposits have strongly developed soil profiles 7 to 10 feet thick. Soils typically include a thick argillic B-horizon and a weakly to strongly developed siliceous and calcic duripan 3 to 7 feet thick (Bonham and Rogers, 1983). The original topographic forms of Donner Lake glacial moraines in the Carson Range have been completely destroyed by erosion (Thompson and White, 1964).

Tahoe outwash in the Mt. Rose fan area is also derived from streams draining alpine glaciers in the Carson Range, principally the Whites Creek and Galena Creek drainages. In this area, Tahoe outwash is predominantly sandy, cobble to boulder gravel containing a mixture of volcanic and granitic clasts. Relative to the Donner Lake outwash, boulders are less weathered, argillic B-horizons are typically thinner, and duripans are generally absent. Being younger, Tahoe glacial moraines are inset into Donner Lake moraines and are better preserved. Lateral moraines are well preserved, but end moraines are lacking, making it difficult to determine the lowest elevation that the glaciers reached. Tahoe morainal deposits are mapped as low as 6,250 feet elevation along Galena Creek (Thompson and White, 1964), within 0.6 mile of the southwest corner of the map shown in figure 14.

Faulting in the Mt. Rose study area

The glacial outwash deposits dominating the surficial geology of the Mt. Rose alluvial fan complex are displaced by a broad network of faults. These faults are part of the frontal fault zone bounding the east side of the Carson Range, one of the principal active fault zones in the urbanized region of west-central Nevada (Reno-Carson City-Lake Tahoe area). The study area is located in a complex nested graben about 1.2 miles wide between the Carson Range and Steamboat Hills (fig. 14), just southwest of Reno. The faults comprising this graben have formed prominent fault scarps that are at least in part of Holocene age (Szecsody, 1983).

Mt. Rose soil-gas radon results

Site MTR-1 is located on a Donner Lake outwash surface, immediately north of Whites Creek (fig. 14). This site was abandoned after four sampling attempts, because a bouldery and clayey stone layer at about 2-foot depth is quite resistant to soil probe emplacement and has a very low gas permeability, making it difficult to draw soil-gas samples.

Seventeen samples were taken from site MTR-1 along an 800-foot-long profile (table 7 and fig. 15). Four of these samples were collected along an east-facing fault scarp, seven were taken from the downthrown side of the fault, and six were taken from the upthrown side. The radon concentration for the total data set of 17 samples averaged 480 ± 170 pCi/L.

Radon concentrations were highest along the fault scarp (see fig. 15), averaging 690 ± 150 pCi/L, whereas averages for the remaining sites ranged from 190 ± 40 pCi/L to 490 ± 190 pCi/L. While the slightly elevated radon along the fault could be due to greater transmissivity of radon from some source at depth cut by the fault, it could also be solely a surficial effect of soil permeability. The very low permeability of this soil indicated by the difficulty in drawing a soil-gas sample may greatly inhibit transmission of soil gas. Increased permeability where the soil is disturbed by recent faulting could cause radon to collect and become concentrated along the fault zone.

Site MTR-2 is located on a Donner Lake outwash surface and consists of a single sample location adjacent to a residence which was under construction in 1992. A stone layer similar to that at site MTR-1 is present at site MTR-2, but it is not as resistant to soil probe emplacement or sample extraction as at site MTR-1.

Three samples taken from site MTR-2 averaged 1,360 ± 240 pCi/L (table 7), which is very similar to site MTR-3 and significantly higher than site MTR-1. Somewhat greater soil-gas permeability, relative to site MTR-1, may be the cause of the higher average radon level.

Site MTR-3 is located on a Tahoe outwash surface and consists of ten sample locations along an east-west profile about 1,700 feet long. The profile obliquely crosses State Route 431 (fig. 14) and includes two east-facing fault scarps and one west-facing fault scarp. The outwash deposits at this location are very bouldery, making soil probe emplacement difficult, but a lack of the stone layer characteristic of the Donner Lake surface made it possible with persistence.

Forty-one samples were collected from site MTR-3 (table 7 and fig. 15). The soil-gas radon concentration for the total data set of 41 samples averaged 1,330 ± 660 pCi/L. Averages for individual sample locations ranged from 440 ± 110 pCi/L to 2,510 ± 260 pCi/L. Radon concentrations along the two east-facing fault scarps were typical for site MTR-3, averaging 1,150 ± 290 pCi/L and 1,180 ± 340 pCi/L.

Samples from the west-facing fault averaged 440 ± 110 pCi/L, which was by far the lowest concentration for site MTR-3. The very low radon concentrations measured across

TABLE 7.—*Mt. Rose fan study area soil-gas radon statistics.*

Distance from west end (ft)	Mean pCi/L	Standard deviation	Number of samples	
Site: MTR-1				
0	460	60	2	
200	460	130	3	
280	190	40	2	
400	690	150	4	fault
540	320	—	1	
600	340	110	3	
800	490	190	2	
AVERAGE	480	170	17	
Site: MTR-2				
0	1,360	240	3	

Distance from west end (ft)	Mean pCi/L	Standard deviation	Number of samples	
Site: MTR-3				
0	2,330	580	4	
200	1,020	190	6	
400	1,150	290	6	east-facing fault
600	1,180	340	5	east-facing fault
750	1,120	—	1	
800	1,140	320	5	
1,000	2,510	260	4	
1,250	1,250	50	2	
1,500	440	110	5	west-facing fault
1,700	1,540	80	3	
AVERAGE	1,330	660	41	

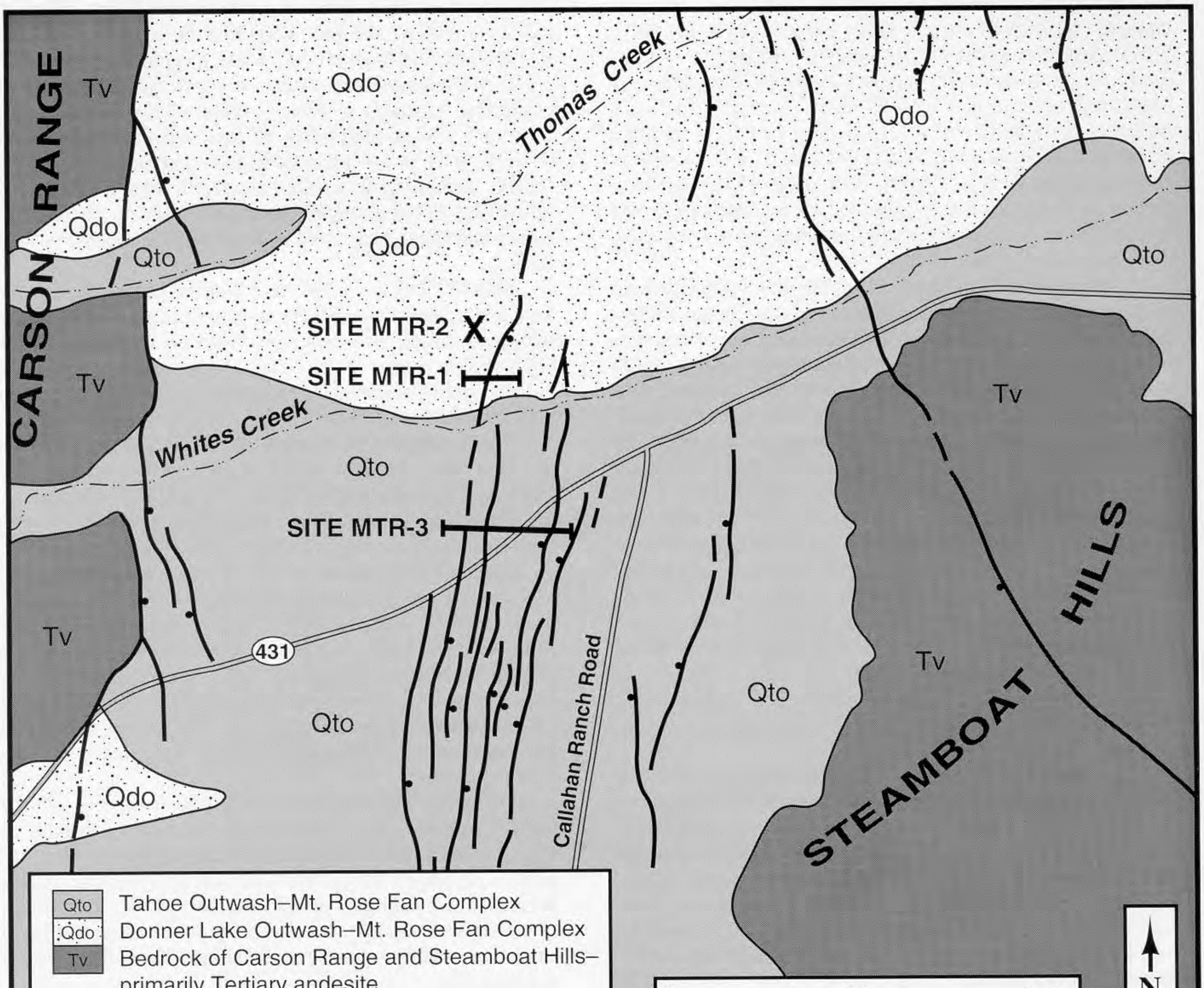
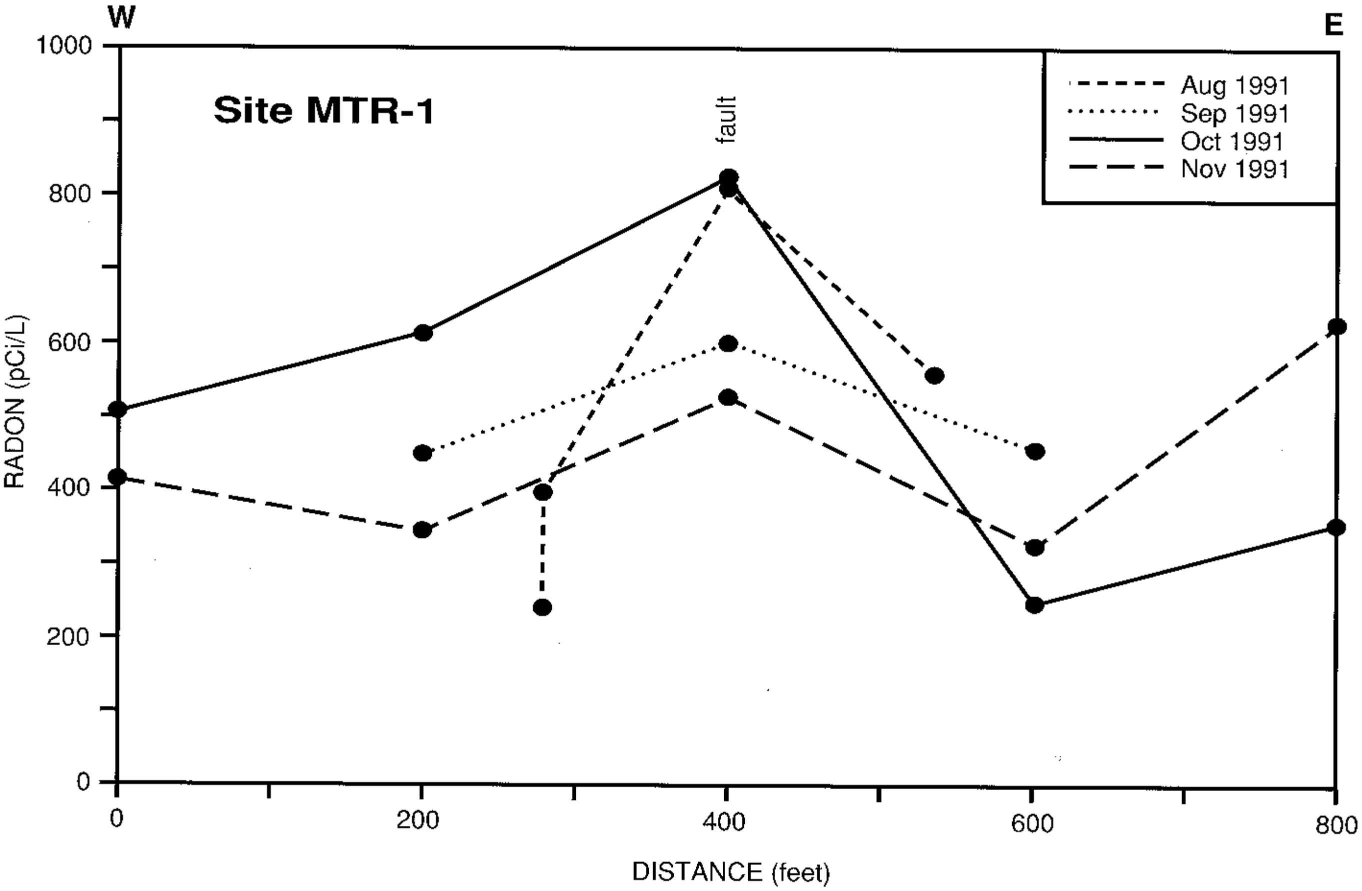


FIGURE 14.—**Generalized geologic map of the Mt. Rose soil-gas radon study area. Sites MTR-1 and MTR-3 consist of east-west profiles containing multiple sample locations (see table 7). Galena Creek lies just beyond the southern edge of map.**



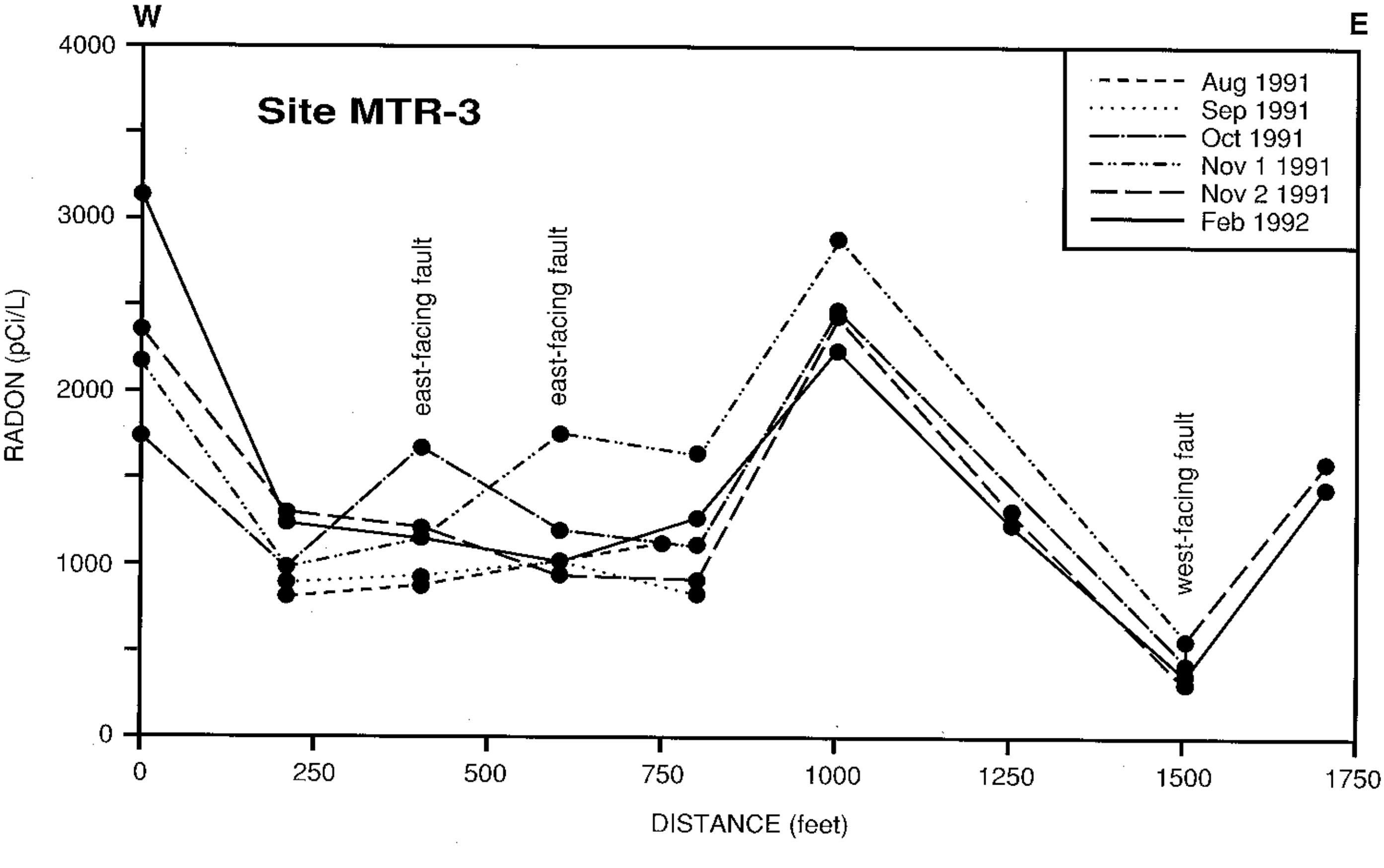


FIGURE 15.—Graphs showing soil-gas radon measurements (pCi/L) at sites MTR-1 and MTR-3, Mt. Rose study area. Locations of sites on late Quaternary fault scarps are indicated.

the trace of this west-facing fault are possibly due to a localized extremely high soil permeability due to recent fault activity. The fault trace can be discerned as an abrupt contact between bouldery outwash and sandy grus present on the downthrown side. The grus is very loose and the soil probe can almost be pushed into the ground by hand. Soil permeability at this location along the fault may be so high that radon in soil gas is diluted by ambient air to a greater depth than normal, and is also rapidly vented to the atmosphere.

Discussion on Mt. Rose study area

Soil-gas radon in the Mt. Rose alluvial fan area appears to vary depending on surficial geology, but the exact reason why is not immediately obvious. Average soil-gas radon concentrations at site MTR-1 (Donner Lake outwash) are consistently lower than those at site MTR-3 (Tahoe outwash). This may indicate a real difference in terms of radon generation between the two deposits, or it may be an effect of lower permeability of the Donner Lake soil. The radon concentrations at site MTR-2 (Donner Lake outwash) are more similar to site MTR-3 and therefore do not support a consistent surface-dependent difference, and the observed difference may be solely due to the extremely low soil permeability at site MTR-1.

The samples taken from fault scarps showed some minor differences relative to those from surfaces on either side of the faults. This may reflect upward transport of uranium from depth, but it may also be due to soil permeability conditions. A single fault trace sampled at site MTR-1 showed a slightly elevated radon concentration relative to the surrounding unfaulted surface, but ease of soil probe emplacement suggests the tight Donner Lake soil is disturbed by Holocene faulting, thereby slightly increasing soil permeability. At site MTR-3, two of three faults sampled have radon concentrations that are average for the site, whereas the third fault has the lowest concentration sampled in the Mt. Rose fan area. Ease of soil probe emplacement suggests the soil along the lower part of this third fault scarp is extremely loose, with very high soil permeability causing rapid venting of radon to the atmosphere.

Soil-Gas Radon Analyses in the Lovelock Area, West-Central Nevada

Results of the 1989 NBMG screening survey and the 1990-1991 EPA/SIRG survey indicated that residences in Lovelock, west-central Nevada, have a higher than average incidence of radon exceeding the EPA recommended action level of 4.0 pCi/L (Rigby, 1991). This finding was unexpected, because Lovelock is situated on fine-grained lacustrine deposits of the pluvial Lake Lahontan basin. Elevated concentrations of radon in Nevada are more typically related to the occurrence of granitic or siliceous volcanic rocks.

In an attempt to define the areal distribution and possible underlying causes of elevated indoor radon concentrations in the Lovelock area (56% of NBMG survey tests exceed 4.0 pCi/L), additional indoor measurements and analyses of soil-gas radon were undertaken.

Geologic setting of the Lovelock area

Lovelock, which has a population of about 2,000, is located in west-central Nevada, about 90 miles northeast of Reno. Lovelock is in the central part of Upper Valley, the northeastern part of the Humboldt Sink subbasin of the Late Pleistocene Lake Lahontan basin. At its high stands, Lake Lahontan covered much of northwestern Nevada.

Surficial geology in the Lovelock area is dominated by fine-grained lacustrine (lake) and paludal (marsh) deposits and overbank alluvium from the Humboldt River. Because the Humboldt Sink subbasin is one of the lowest parts of the Lake Lahontan system, the uppermost lacustrine deposits in the Lovelock area are part of the Holocene Fallon Formation (Morrison, 1964). From artifacts found in the area, it is known that during interpluvial periods this was at times a marshy area created by flow from the Humboldt River into the Humboldt Sink subbasin (Morrison and Davis, 1984).

The West Humboldt Range bounds the southeast side of Upper Valley and consists of Mesozoic metasedimentary and Cenozoic sedimentary and volcanic rocks (Johnson, 1977). The Mesozoic rocks are dominated by mudstones and minor fine-grained sandstones of the Lower Jurassic to Triassic Auld Lang Syne Group, which have been metamorphosed to phyllite, argillite, and quartzite.

The Trinity Range bounds the northwest side of Upper Valley and consists of Mesozoic metasedimentary (Auld Lang Syne Group) and granitic rocks, and Cenozoic rhyolites and tuffaceous sedimentary rocks.

Quaternary alluvial fan aprons are present on both the southeast and northwest sides of Upper Valley and consist of sediments derived from the West Humboldt and Trinity Ranges, respectively.

Preliminary results of soil-gas radon analyses

Soil-gas samples collected from 45 sites in and around Lovelock were analyzed for radon concentrations. Measurements ranged from 220 to 2,500 pCi/L (fig. 16). Although data points are rather sparse to support confident interpretations, soil-gas radon concentrations are highest along a north-trending zone that roughly parallels the axis of the valley and overall trend of the Humboldt River through this area.

Discussion of possible uranium accumulation in tule clays

From communication with local residents and subsequent examination of water-well logs, it was found that shallow organic-rich clay layers are present within the fluviolacustrine stratigraphy. A residential well encountered such a layer within 7 to 10 feet of the surface and a weakly organic horizon is exposed less than 7 feet below the surface in nearby cut banks of the Humboldt River. Where reported on well logs, these layers are typically described as black clay or tule clay. Elevated radon concentrations may be due to uranium accumulation in these organic-rich clay layers, although the young age of these sediments (at most a few thousand years) would limit the amount of accumulated uranium.

Uranium concentration associated with organic matter is well established and typically occurs in an anoxic, reducing environment. Kochenov and others (1965) concluded that uranium can be concentrated in peat bogs from circulation of groundwater containing uranium near background concentrations. As mentioned in the section on *Indoor Air Surveys of Targeted Communities*, Otton and others (1989) found high concentrations of uranium in marshes and organic-rich sediments near Zephyr Cove at Lake Tahoe. Although more work needs to be done, it is possible that the elevated soil-gas radon and the large percentage of high indoor air radon concentrations in Lovelock may be the result of uranium accumulation in organic-rich clays underlying the area.

RADON IN OUTDOOR AIR

Another facet of Nevada's radon study program consisted of the measurement of radon in outdoor air in the state. Although not a part of the activities of the EPA/SIRG radon program in Nevada, the determination of radon concentration in outdoor air is important because the Indoor Radon Abatement Act passed by Congress in 1988 states that the eventual goal of the EPA radon program should be the lowering of indoor air radon concentrations in homes to ambient air levels. Before NBMG began its study of outdoor air radon concentrations, the only systematic measurements of radon in the outdoor air of the United States consisted of a study of outdoor air at one site in each of the 50

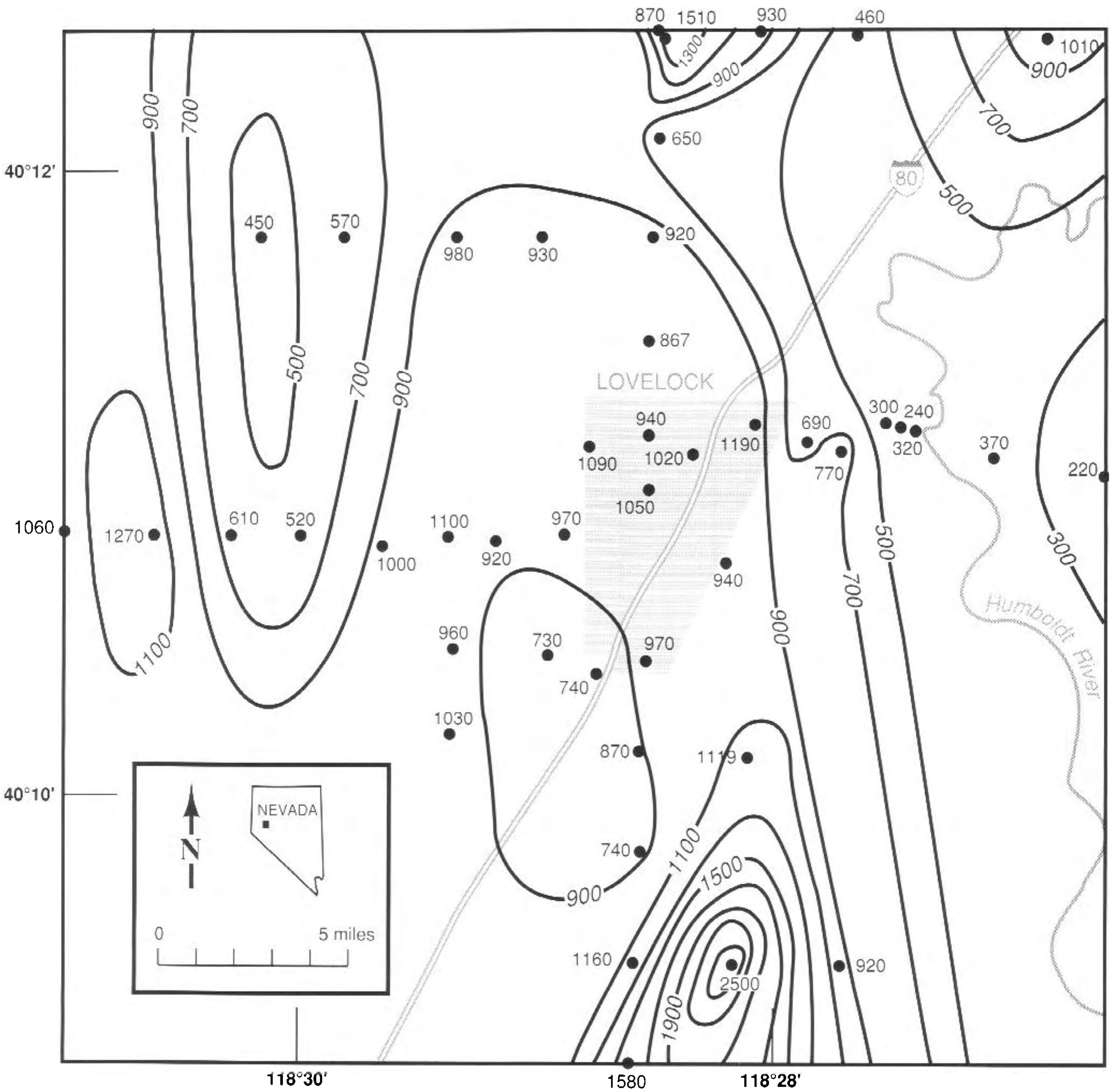


FIGURE 16.—Soil-gas radon measurements (pCi/L) from the Lovelock study area. The isopleths are based on sparse data, and should be disregarded in areas lacking data.

TABLE 8.—*Comparison of radon concentrations in outdoor air at nominal height of 1 meter (3.3 feet) above the surface.*

Location	Radon in outdoor air, pCi/L		Reference
	Average	Range	
Continents	0.2	—	Wilkening (1990)
Oceans	0.001	—	Wilkening (1990)
Great Britain	0.1	—	Wrixon and others (1988)
Chester, New Jersey	0.22	—	Harley (1978)
Socorro, New Mexico	0.24	—	Wilkening (1959)
USA (50 measurements)	0.4	0.06-1.1	Hopper and others (1991)
Nevada (50 measurements)	0.4	0.07-1.4	this study

states; this study found a yearlong average radon concentration of about 0.4 pCi/L for the 50 locations (Hopper and others, 1991). The single site for Nevada in this study was in Las Vegas. Before this study, most researchers and the EPA had assumed that the average outdoor air concentration in the United States was about 0.1 to 0.4 pCi/L (Wilkening, 1959; Harley, 1978; Wrixon and others, 1988; National Council on Radiation Protection and Measurement, 1988; Wilkening, 1990; Gunby and others, 1993), although individual outdoor measurements as high as 35 to 40 pCi/L have been reported within a few feet of the ground in an unusual, man-distributed area in Florida (Tyson and others, 1993). Some of the average global outdoor air radon data from the above studies are summarized in table 8.

Radon in outdoor air was measured at 50 sites in Nevada (Price and others, 1994). Sites were selected to obtain data from (a) different rock types and (b) principal population centers in Nevada. Data were collected in 26 towns and at 24 remote sites (table 9 and fig. 17). In all cases at least a thin (1 foot) layer of soil overlies the rocks. Results of the National Uranium Resource Evaluation program of the U.S. Department of Energy were used to select some sites with relatively high uranium concentrations in the surface rocks and soils (fig. 18). Gamma scintillometers were used to confirm locations with high uranium concentrations.

Measurements were taken using the methods and quality assurance procedures described by Hopper and others (1991) in the national ambient radon study. Measuring devices were borrowed from Richard D. Hopper at the EPA radon laboratory in Las Vegas. At each site, three short-term EICs (electret ion chambers) were placed in ventilated shelter boxes 1.0 meter (3.3 feet) above the ground (fig. 19). The EICs were exposed for a minimum of

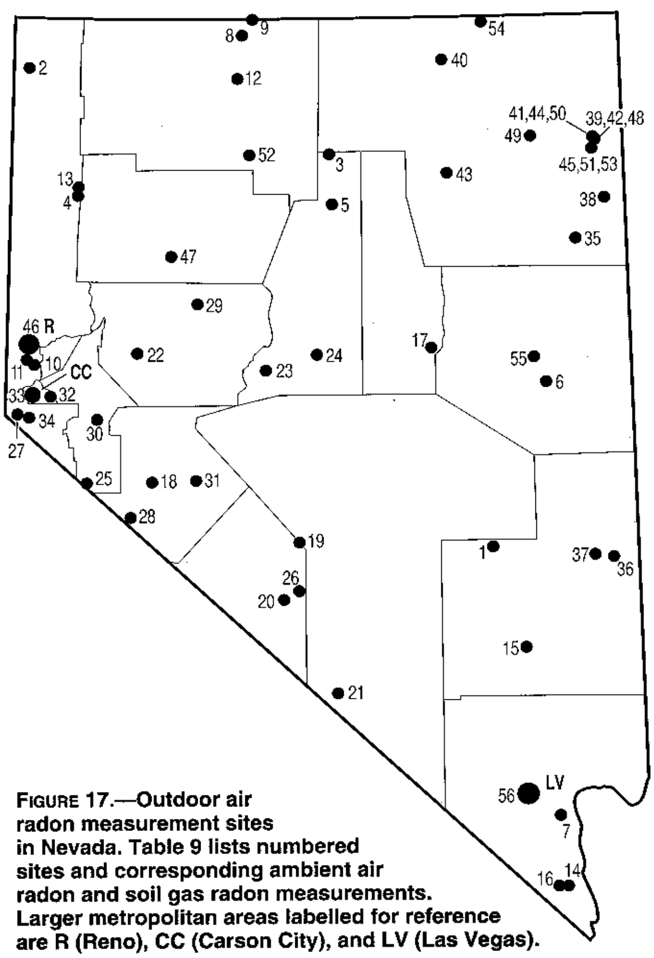


FIGURE 17.—Outdoor air radon measurement sites in Nevada. Table 9 lists numbered sites and corresponding ambient air radon and soil gas radon measurements. Larger metropolitan areas labelled for reference are R (Reno), CC (Carson City), and LV (Las Vegas).

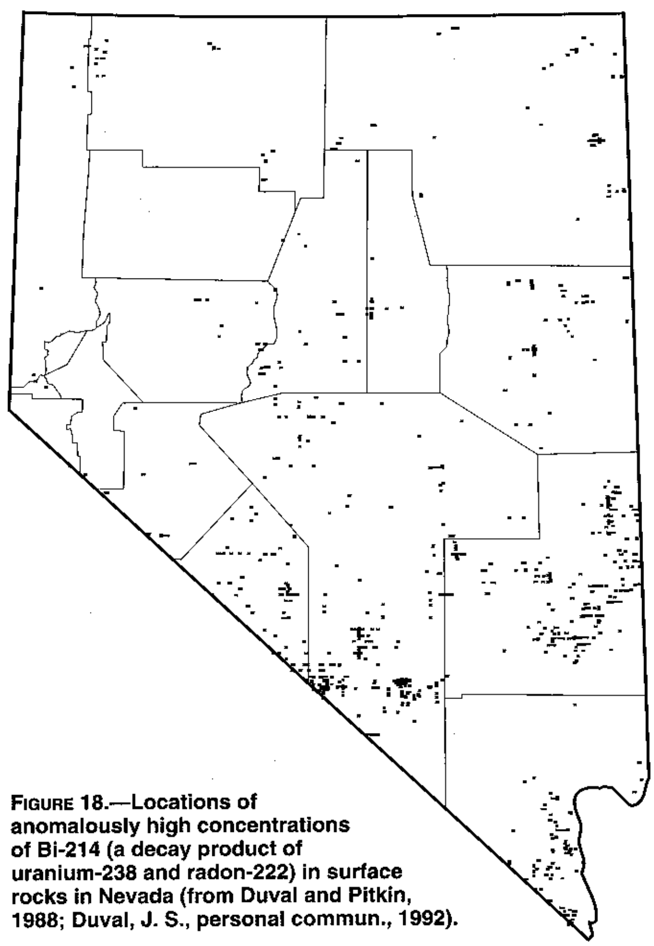


FIGURE 18.—Locations of anomalously high concentrations of Bi-214 (a decay product of uranium-238 and radon-222) in surface rocks in Nevada (from Duval and Pitkin, 1988; Duval, J. S., personal commun., 1992).

TABLE 9.—*Radon concentrations in outdoor air and soil gas in Nevada and uranium and thorium in corresponding rock samples.*

Site no.	Location	Percentage of homes with indoor radon ≥4.0 pCi/L	Soil gas pCi/L	Outdoor air pCi/L	U ppm	Th ppm
	TOWNS					
27	Zephyr Cove	59	1,800	0.88	6.2	33
12	Orovada	57	420	0.58	—	—
47	Lovelock	56	1,500	0.73	—	—
24	Austin	33	2,400	0.47	4.4	11
6	Ely	39	1,400	0.13	—	—
49	Wells	43	1,200	0.44	—	—
37	Pioche	23	720	0.20	—	—
18	Hawthorne	36	810	0.39	—	—
30	Yerington	35	2,100	0.62	—	—
17	Eureka	31	380	0.39	—	—
33	Carson City	27	1,200	0.46	—	—
46	Reno	21	1,000	0.32	—	—
43	Elko/Lamoille	20	340	0.26	—	—
52	Winnemucca	10	340	0.43	—	—
9	McDermitt	13	940	0.63	—	—
7	Boulder City	10	na	0.45	2.0	15
22	Fallon	9	1,100	0.39	—	—
34	Genoa	8	220	0.51	—	—
19	Tonopah	6	440	0.07	—	—
5	Battle Mountain	6	460	0.30	—	—
56	Las Vegas	3	510	0.17	—	—
26	Goldfield	0	740	0.41	—	—
2	Vya	tf	370	0.27	4.0	12
54	Jarbidge	tf	na	0.58	6.6	37.5
4	Gerlach	tf	480	0.31	—	—
16	Searchlight	tf	290	0.28	—	—
	REMOTE SITES					
35	Dolly Varden Range	—	4,600	1.40	9.0	70
55	Egan Range	—	2,200	0.26	5.0	27
51	Toano Range - S, 0.5 m	—	na	0.52	—	—
45	Toano Range - S, 1.0 m	—	na	0.48	—	—
53	Toano Range - S, 2.0 m	—	na	0.45	—	—
39	Toano Range - C, 0.5 m	—	—	0.45	—	—
48	Toano Range - C, 1.0 m	—	2,100	0.55	—	—
42	Toano Range - C, 2.0 m	—	—	0.27	—	—
44	Toano Range - N, 0.5 m	—	na	0.15	—	—
41	Toano Range - N, 1.0 m	—	na	0.19	—	—
50	Toano Range - N, 2.0 m	—	na	0.15	—	—
31	Gabbs Valley Range	—	1,600	0.33	4.8	38
40	Wild Horse Reservoir	—	1,400	0.77	—	—
23	Smith Creek Valley	—	960	0.55	—	—
32	Hackett Canyon	—	970	0.49	—	—
1	Garden Valley	—	860	0.67	—	—
11	Mt. Rose fan	—	870	0.26	—	—
36	Echo Canyon	—	860	0.18	—	—
21	Bullfrog Hills	—	830	0.30	4.2	21
10	Steamboat Hot Springs	—	640	0.48	—	—
20	Montezuma Range	—	550	0.46	8.8	30
8	Hoppin Peak	—	450	0.08	8.3	18
3	Izzenhood Ranch	—	360	0.30	9.0	23.5
15	Pahranagat	—	320	0.50	—	—
14	Fourth of July Mountain	—	250	0.27	2.4	16
28	Spring Peak	—	250	0.16	1.6	6
13	Granite Range	—	240	0.16	2.8	7
29	Coppereid, Stillwater Range	—	na	0.49	6.9	30.5
25	Sweetwater Flat	—	na	0.43	8.5	31.5
38	Goshute Mountains	—	na	0.21	5.8	5.6

na = not analyzed; tf = too few homes (<10) measured to calculate percentages.

FIGURE 19.—Ventilated shelter box used to house radon detection instruments used in ambient air survey, located 1.0 m above ground level. *Photo by Jim Rigby.*

30 days during July and August 1992. Seasonal variations in outdoor radon have been recognized by Gesell (1983) and Hopper and others (1991). The monthly (Gesell, 1983) and quarterly (Hopper and others, 1991) extremes at any given site rarely differed by more than a factor of 4. In order to minimize any possible seasonal effects in this investigation in Nevada, all measurements were made during about the same one-month interval. All measuring devices were placed in the field over a period of about six days, then retrieved in about the same amount of time, beginning one month after placement.

Because the EIC measures both alpha and gamma radiation, three thermoluminescent dosimeters (TLDs) were also placed in each shelter to measure background gamma radiation. Results from the TLDs were subtracted from the EIC results using the method recommended by the manufacturer. To determine whether the EICs had been exposed to anomalous gamma radiation in transport to the measurement sites, additional TLDs were transported with the three vehicles used to distribute and retrieve the shelters. All EICs and TLDs were analyzed at the EPA Las Vegas facility. Hopper and others (1991) reported a limit of detection of 0.054 pCi/L for the EICs.

Measurements were made at 0.5, 1.0, and 2.0 meters (1.7, 3.3, and 6.6 feet) above the ground surface at three sites in the Toano Range in northeastern Nevada. Two of the three sites (Toano Range-S and Toano Range-C in table 9) are above outcrops of an unusually uranium-rich rhyolite (silica-rich volcanic rock). Price and others (1992) determined an average uranium concentration in this rock of 46 parts per million by weight, about 26 times the normal abundance of uranium in the earth's crust (Mason, 1966). A two-day charcoal canister placed at ground level in August 1991 recorded an outdoor radon concentration of 17 pCi/L at one of the outcrops. The measurements at multiple heights were designed to determine whether radon flux from the ground is well mixed with ambient air at breathing heights for humans.

Measurements of radon in soil gas were made at most sites using the apparatus and procedures described in the section *Radon in Soil Gas*.

Results of the survey of radon in outdoor air in Nevada are listed in table 9. Results were compared to those from the national ambient radon study of Hopper and others (1991). The Nevada results range from 0.07 to 1.40 pCi/L, slightly broader than the 0.06 to 1.11 pCi/L range in the national study. The median of all 50 measurements taken at a height of 3.3 feet in the Nevada survey is 0.40 pCi/L, essentially the same as the median of 0.39 pCi/L in the national survey, for which measurements were also made at a height of 3.3 feet. The average value for both surveys is 0.41 pCi/L.

The national ambient radon study of Hopper and others (1991) determined four quarterly results at each site and therefore may not be directly comparable to the Nevada survey, for which measurements were made for only one month. However, Hopper and others (1991) noted little difference among quarterly results. The Las Vegas site was sampled in both surveys. Our one-month result for this site was 0.17 ± 0.07 pCi/L, whereas the average of four quarterly results in the national study of Hopper and others (1991) was 0.22 ± 0.08 pCi/L.

Because some of the sites were selected for their proximity to known high concentrations of uranium in outcropping rocks, the Nevada results may be biased toward higher values. Nonetheless, the mean value for 26 Nevada towns, which provide a random sample by location, is the same as the mean for the entire data set of 50 sites.

The variations in radon concentrations in outdoor air in Nevada can generally be correlated with different concentrations of radon in soils and of uranium and its daughter products in rocks. Radon in soil gas is an indirect measurement of the radon concentration in the soil and in the underlying rocks from which the soil is derived. In addition to the concentration of radon in soils and underlying rocks themselves, the grain size, mineralogy, porosity, permeability, and moisture content of the soil combine to determine how much of the available radon actually enters the soil gas (Wilkening, 1990; Nazaroff, 1992). Silica-rich igneous rocks (rhyolites and granites) appear to be the main sources of high levels of radon in outdoor air in Nevada. Most of the areas identified by the National Uranium Resource Evaluation program (fig. 18) as having anomalously high concentrations of bismuth-214 at the ground surface are underlain by these rock types. As indicated by the measurements of radon at multiple heights in the Toano Range (table 9), the air at 2 meters (6.6 feet) above the ground surface still reflects the underlying geology.

A weak correlation between radon in soil gas and radon in outdoor air in Nevada is evident in figure 20. Sites with the highest concentrations of radon in outdoor air (towns of Zephyr Cove, Lovelock, and Yerington, and remote sites in the Dolly Varden Range, Wild Horse

Reservoir, and Garden Valley) generally have relatively high values of radon in soil gas, and sites with the lowest concentrations of radon in outdoor air (towns of Tonopah, Las Vegas, Ely and remote sites at Hoppin Peak, Spring Peak, and the Granite Range) generally have relatively low values of radon in soil gas (table 9).

A statistical measure of the degree of linearity for a set of data is the Pearson correlation coefficient (Sinclair, 1986). The closer the Pearson correlation coefficient is to zero, the weaker the correlation; the closer the coefficient approaches 1 or -1, the stronger the linear relationship. The Pearson correlation coefficient for the set of 43 data points in figure 20 is 0.67. According to Sinclair (1986), a Pearson correlation coefficient greater than 0.30 is significant at the 95% confidence level for this number of data points. Removal of the highest data point would reduce the correlation coefficient to 0.42 (for 42 data points), which is still a significant correlation.

Towns in which more than 20% of the tested homes have indoor-air radon concentrations greater than or equal to 4.0 pCi/L (Rigby, 1991) generally have relatively high soil-gas radon, relatively high outdoor-air radon, or both (table 9). This observation is easily explained by the fact that the geological conditions that give rise to high concentrations of radon in soil gas also are responsible for the high concentrations in homes and in outdoor air.

These data indicate a clear link between the underlying geology and the concentration of radon in outdoor ambient air at a height of 3.3 feet. Outdoor air radon concentrations as high as 1.4 pCi/L were measured (Price and others, 1994), which is 35% of the EPA action level for indoor air of 4.0 pCi/L. The silica-rich igneous rocks of Nevada are among the most uraniferous of the common rock types.

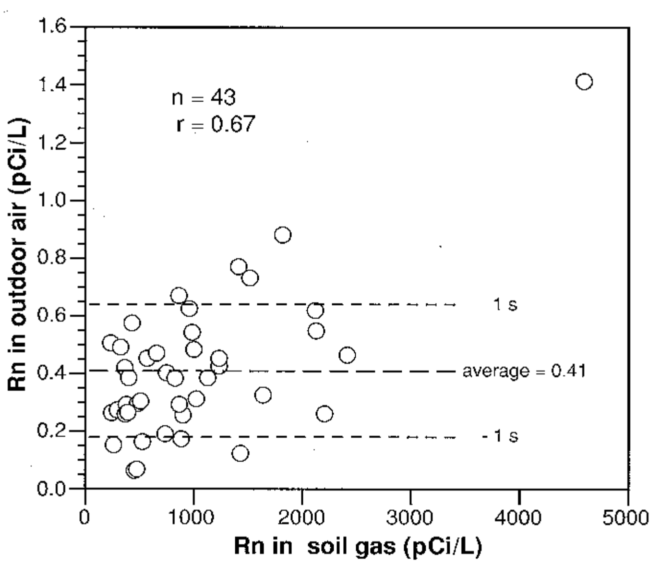


FIGURE 20.—Plot of radon in soil gas against radon in outdoor air for sample sites in Nevada at which both measurements were made. Outdoor air measurements were taken at 3.3 feet above ground level, and soil gas measurements were made between 2.5 and 3.3 feet below ground level. n = number of measurements; r = Pearson correlation coefficient; s = standard deviation.

Uncommon rocks, such as uranium ores, could yield higher radon fluxes from the ground, but the area covered by these uncommon rock types is likely to be small (usually less than a few acres). Radon concentrations in outdoor air as high as the indoor action level are unlikely in Nevada, except perhaps during unusually stagnant air conditions or in local areas with exceptionally high concentrations of radon in soils and rocks.

In order to investigate the link between underlying geology and radon in soil gas and outdoor air, rock samples collected from 18 of the outdoor air radon measurement sites were analyzed for the radiogenic elements uranium and thorium; soil-gas radon measurements were available from 13 of these sites. Figure 21 displays graphs of the whole rock uranium and thorium analyses (performed by neutron activation analysis at Chemex Labs, Sparks, Nevada) plotted against outdoor air radon concentration (upper graphs) and soil gas radon concentration (lower graphs); table 9 lists the data used in these graphs. Positive correlations are apparent between uranium and thorium contents in the rocks from the sites and radon concentrations in corresponding outdoor air and in soil gas. Specifically, the Pearson correlation coefficient (Sinclair, 1986) is 0.46 for uranium, and 0.84 for thorium from the rocks versus outdoor air radon concentration, while it is 0.35 for uranium, and 0.79 for thorium from the rocks versus soil gas radon concentration. According to Sinclair (1986), Pearson correlation coefficients greater than 0.44 and 0.51 are significant at the 95% confidence level for the number of data points in the rock-to-outdoor air and rock-to-soil gas comparisons, respectively.

It is apparent that thorium exhibits a substantially better correlation with radon concentrations in soil gas and in outdoor air than does uranium. This correlation is to be expected because uranium dissolves readily in an oxidizing surface environment. Thorium, however, generally is immobile in the surface environment. For this reason, rocks at the surface of the earth tend to have had a portion of their initial uranium content leached relative to thorium.

Thus, a rock with relatively high initial concentrations of uranium and thorium may, after undergoing a period of chemical weathering when exposed at the surface, still have a relatively high thorium content remaining, but will tend to be depleted in uranium. Even though this rock may be depleted in uranium relative to thorium, it will still tend to have a relatively high radon content and, everything else (such as grain size, porosity, and mineralogical distribution of radon) being equal, will tend to emit large amounts of radon to the surrounding soil gas and to the air.

Other factors such as soil permeability or water content may affect the correlation of radon in soil gas or outdoor air with the content of radiogenic elements in the rocks. High soil gas permeability may allow radon and other soil gases to escape more easily to the atmosphere, resulting in a low soil gas radon value despite high uranium or thorium content in the parent material. In addition, high water content in the soil can fill soil pore spaces thus decreasing the permeability of the soil to gases and restricting soil gas flux and escape to the atmosphere. Such possible influences are suggested by relatively low soil-gas radon concentrations obtained at some of the

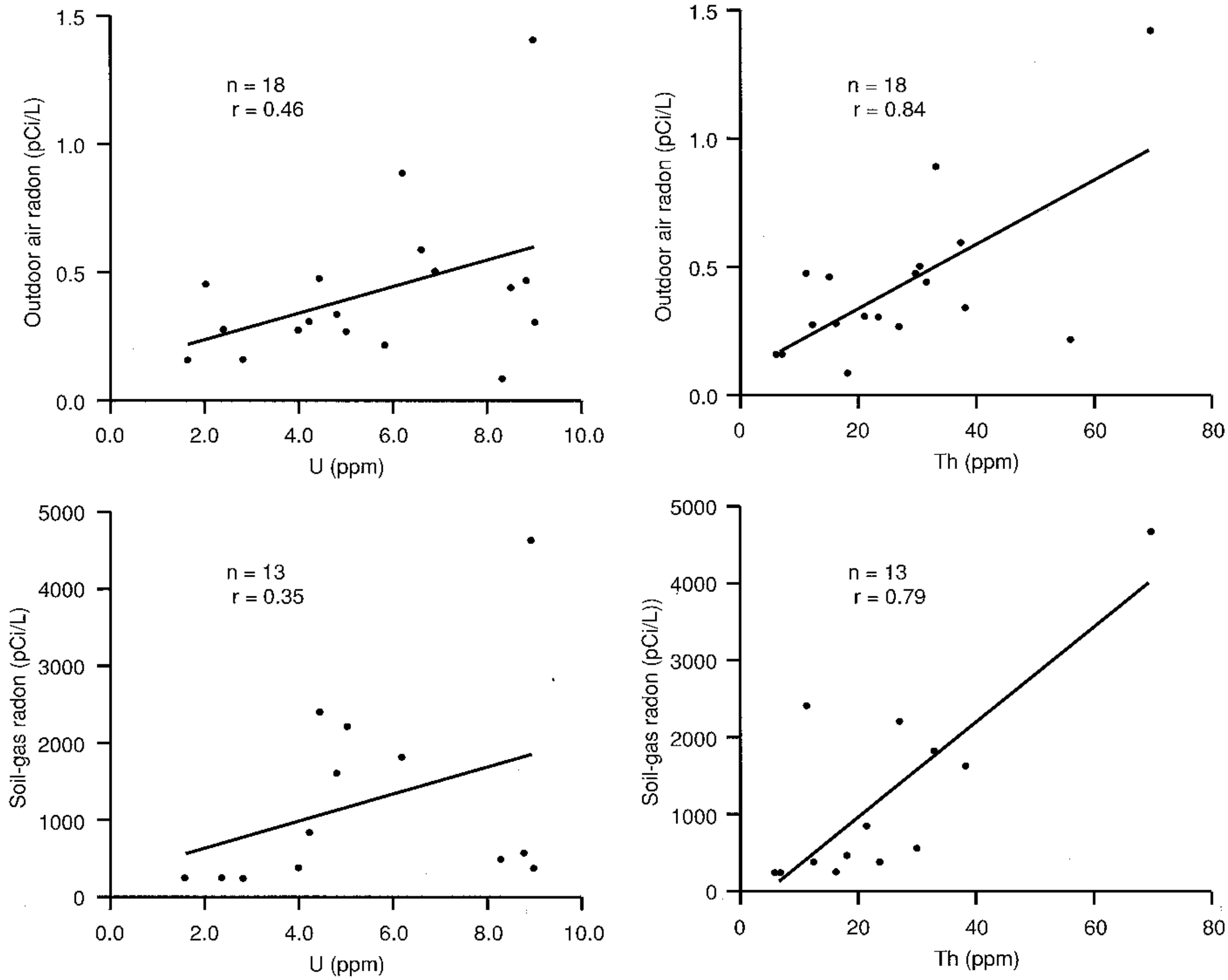


FIGURE 21.—Radon concentration in soil gas and outdoor air in relation to whole-rock uranium and thorium content measured at selected outdoor-air sampling sites across Nevada. n = number of measurements; r = Pearson correlation coefficient.

sites despite relatively high uranium or thorium contents in the corresponding rocks collected at the sites (see fig. 21 and table 9). No sites, however, exhibited the inverse relation, that is, sites with high radon concentrations in soil gas or outdoor air and low uranium or thorium contents in corresponding rock samples.

RADON IN WATER

Radon is found in water and can enter indoor air of homes by degassing at the point of use in the home (such as at showers and faucets). Because radon is a gas and easily escapes from water that comes in contact with air, water in lakes, rivers, and reservoirs usually contains very little radon. Homes that rely on surface water normally do not have any significant fraction of indoor radon derived from their water source because most of the radon in the water will have escaped before it reaches the home. Radon can, however, be highly concentrated in groundwater in contact with uranium-rich rocks. Homes that use groundwater from private wells, or from small public water works which have closed systems and short transport times, may have significant potential for indoor radon derived from the water supply (Cothern and Lappenbusch, 1985; Hess and others, 1985; Nazaroff and others, 1987).

At present, there is no known health hazard associated with the consumption of water containing radon. However, radon dissolved in water is released into the air in a home during showering, laundering, and dishwashing, for example, and contributes to the overall indoor air radon concentration of the home. Radon concentrations in groundwater can be very high compared to indoor radon; concentrations of several thousands to about 1 million (Hess and others, 1983) and 3 million pCi/L (Phil Nyberg, personal commun., 1990) have been measured across the country. On the basis of typical home size and use, it is estimated that well water containing 10,000 pCi/L of water will contribute 1 pCi/L of air to the indoor air of a home (Milvy and Cothern, 1990). That is, the groundwater from the well would have to contain a radon concentration of about 40,000 pCi/L for indoor air of the home to reach the EPA action level of 4.0 pCi/L if there were no other source of indoor radon.

Although groundwater radon was not a part of the EPA/SIRG funded radon program in Nevada, NBMG cooperated with USGS in the measurement of radon in groundwater in Nevada. Between 1986 and 1989, personnel of the USGS Water Resources Division in Carson City measured the radon concentration in 278 wells and springs in west-central Nevada and from three other areas of Nevada (Lico, 1991). Figure 22 shows the location of 446 wells and springs in Nevada measured for radon concentration or gross alpha and beta particle radioactivity, including the 278 wells and springs in the USGS study. Appendix A lists these locations by latitude and longitude within each county, gives the radon concentration or gross alpha and gross beta measurement in picocuries per liter, identifies the source of the water (well or spring), and identifies the agency reporting the measurement. Some of the numbers are averages of several measurements from closely spaced wells, or averages of measurements from a single well made over a period of several years.

As shown in appendix A, most of the measurements of radon in water in the state are relatively low, with a maximum concentration of 16,000 pCi/L found in water from a well near Zephyr Cove in the USGS study (Lico, 1991) discussed above. It is not possible to predict the radon concentration of the water in the wells and springs with only gross alpha and beta radioactivity measurements. However, EPA has set standards for gross alpha and gross beta particle radioactivity in potable public water; the water must not exceed 15 pCi/L gross alpha particle radioactivity and must not exceed 50 pCi/L gross beta particle radioactivity (Larry Roundtree, personal commun., 1993). If the tested water exceeds 15 pCi/L gross alpha particle radioactivity, the water must undergo additional tests for isotopes of radium and uranium to determine whether the water is within compliance of the alpha particle standard. As is evident from appendix A and from figure 22, most of the measurements of radon or alpha and beta particle radioactivity in water have been made in western Nevada, with too few measurements from the remainder of the state to determine whether the range in radon concentrations noted in appendix A is representative of the entire state.

The results of the studies shown in figure 22 and appendix A indicate that radon in groundwater is not an important potential contributor to radon in indoor air of homes in Nevada. At present, the most radon-rich water measured in the state is the 16,000 pCi/L water obtained from the well in the USGS study from the Lake Tahoe basin; this water, if used in a home, would contribute only an additional 1.6 pCi/L of radon to the indoor air of the home.

Radon in Nevada groundwater has also been studied by Otton and others (1989), who found radon concentrations up to 345 pCi/L from springs thought to represent groundwater in the Lake Tahoe basin. Horton (1985) found concentrations of radon up to 1,348 pCi/L in the public drinking-water supplies in the Gardnerville, Reno, and Yerington areas.

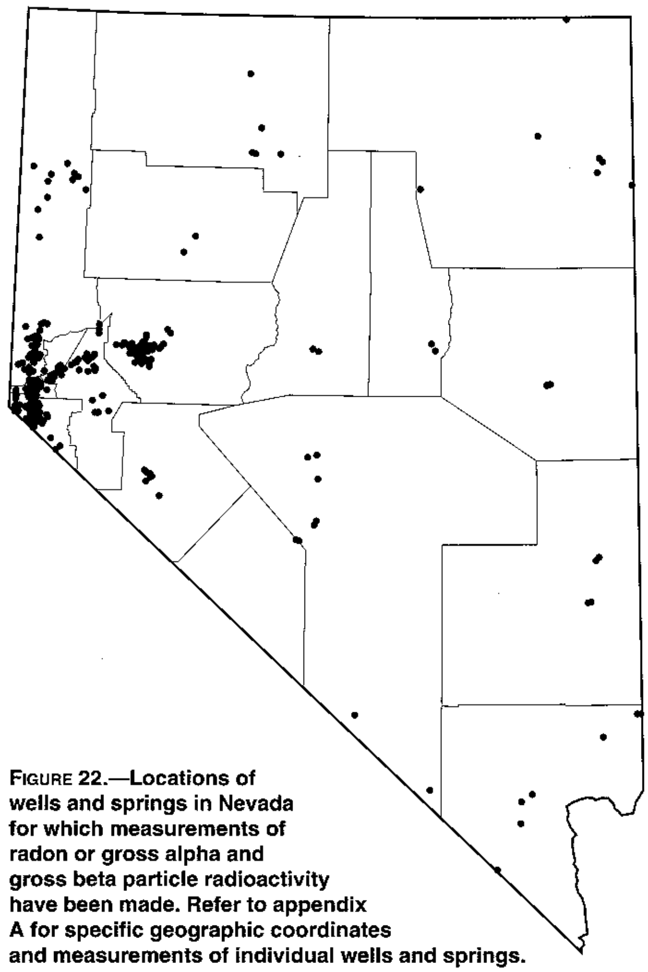


FIGURE 22.—Locations of wells and springs in Nevada for which measurements of radon or gross alpha and gross beta particle radioactivity have been made. Refer to appendix A for specific geographic coordinates and measurements of individual wells and springs.

Currently, no federal standards exist for radon in public drinking water supplies, although EPA is studying the issue in an attempt to come up with a recommended guideline for radon in public water supplies.

If residential well water is found to contain high radon concentrations, there are several methods of removing radon from the water. Two of these which are in common use are aeration systems and granular activated charcoal filtration systems. For detailed information about these types of systems, see Lowry and Lowry (1987) and in Lowry and others (1987).

Factors Affecting Indoor Radon

TIME OF MEASUREMENT (SEASONAL)

Numerous studies (Fleisher and Turner, 1983; Toohey and others, 1985; Wilkening, 1986) have shown that radon concentrations in homes are generally higher during the winter months. This is mainly because of two factors, the first of which is due to the habits of the occupants only, while the second is due to the habits of the occupants in conjunction with interactions between the atmosphere and the soil around the home. The first reason for this seasonal

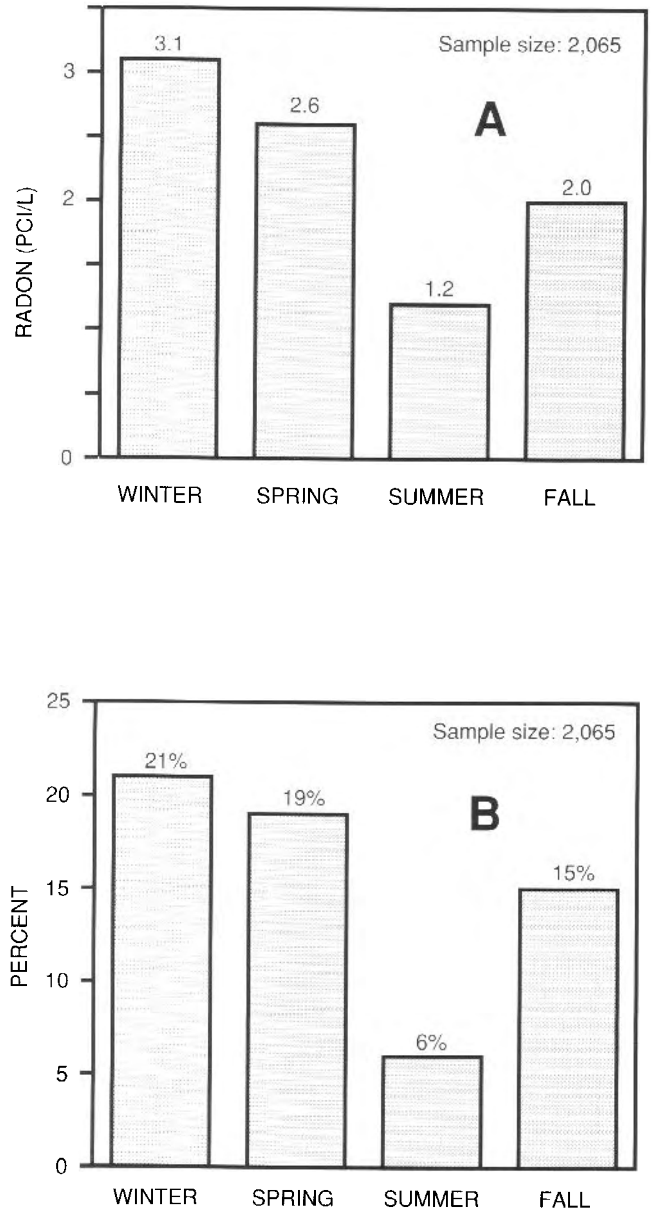


FIGURE 23.—Average radon concentration by season in homes (including mobile homes) tested during the 1990-1991 EPA/SIRG indoor radon survey (A), and the percentage of these homes exceeding the EPA action level during each season (B). Winter includes December, January, and February. Spring includes March, April, and May. Summer includes June, July, and August. Fall includes September, October, and November. Data consist of 2,065 measurements: 1,601 in the winter, 260 in the spring, 130 in the summer, and 74 in the fall.

variation is that homes are usually less ventilated in the winter, especially at more northern latitudes, due to cold weather. This reduces the amount of outside air circulation into the home, thus permitting radon to build up to higher concentrations than in warmer months when windows and doors are open more often.

The second reason for higher indoor radon concentrations in winter is that most homes use artificial heating to keep interiors warm. In heating a home with a central furnace, air inside the home is warmed and rises, resulting in a reduction of indoor air pressure in the lower parts of the home. If the soil gas pressure in ground adjacent to the foundation is higher than the indoor pressure, soil gas can more easily flow upward and into the basement or lower level of the home through cracks, joints, and pores in the foundation. This process, sometimes referred to as stack effect, causes more radon to be drawn into the building from surrounding soil in the colder parts of the year. This process, in conjunction with reduced ventilation during colder weather, can result in wintertime indoor radon concentrations that are significantly higher than those in the same home or building in other seasons. The stack effect can be reduced by the installation of ductwork to provide outside make-up air for combustion appliances, further described in the section on *Reducing Radon in Homes*.

Results of the radon testing by NBMG and NDOH in Nevada reflect this seasonal variation. Figure 23A shows the indoor radon concentrations of homes tested in the 1990-1991 EPA/SIRG indoor survey by season. During the winter (here defined as the months of December, January, and February), the indoor radon concentration of all homes tested in these surveys averaged 3.1 pCi/L, higher than during any other season. Significantly, the average winter radon concentration is almost three times as high as the average summer (here defined as the months of June, July, and August) radon concentration. Figure 23B shows the percentage of homes that exceed the EPA action level of 4.0 pCi/L in each season. The greatest number of tested homes exceed the action level in the winter, and the fewest exceed the action level in the summer.

Not only do average measurements for seasons vary, but indoor radon concentrations in individual homes can vary dramatically by season as well. Figure 24 shows the indoor radon concentration by season for three Nevada homes tested during the 1990-1991 EPA/SIRG survey. A home in Gardnerville had a relatively high winter radon concentration (18.6 pCi/L) which declined somewhat in the spring and summer, reaching a low in the fall (10.5 pCi/L). In all seasons of the year, however, measurements remained above the EPA action level of 4.0 pCi/L. A home in Hawthorne had a high winter radon concentration (16.6 pCi/L) similar to the Gardnerville home, but by spring, the radon had declined dramatically to below the EPA action level, staying below the action level during the summer when it reached the low for the year (1.9 pCi/L). Subsequently, radon concentration in this home increased somewhat in the fall to the action level. A third home, located in Pioche, had a winter radon concentration that was relatively high (2.5 pCi/L) compared to the spring and summer concentrations, but the actual high (2.8 pCi/L) occurred in the fall. As in the Hawthorne home, the low for the Pioche home occurred in the summer (0.4 pCi/L), but unlike the Hawthorne home, all measurements remained below the action level throughout the year.

Other factors that may affect indoor air radon concentrations from season to season are interactions between the atmosphere and the soil around the home. These include changes in air pressure, precipitation, and possibly air temperature and wind speed. Lowered air pressure has been shown to cause an increase in soil-gas radon near the surface (Kovach, 1945; Kraner and others, 1964; Jaacks, 1984; Schery and others, 1984), which may permit more radon to enter a home during times of the year when air pressure is lower. However, although lowered air pressure may increase near-surface soil-gas radon, a corresponding effect on indoor radon concentrations may not be apparent due to dynamics of house heating and cooling and occupant activity which may change indoor pressure relative to the soil more than the effects of outdoor air pressure changes.

Precipitation increases soil moisture, which has been shown to increase the rates of radon outgassing from the soil up to certain soil moisture contents; beyond this, the radon concentration in the soil tends to decrease (Damkjaer and Korsbech, 1985; Lindmark and Rosen, 1985). A high soil-water content tends to lower soil permeability to gas, thus blocking radon from escaping upward to the surface. In many parts of the country, certain periods of the year are wetter than others so indoor radon may be higher in homes during the wetter times of the year due partly to this effect. Soil-gas radon has been shown to increase as air temperature (and hence soil temperature) decreases, and to decrease when air temperature increases (Kovach, 1945; Ball and others, 1983; Jaacks, 1984). High or gusting winds tend to increase radon flux from the soil surface, decreasing the radon concentration in the soil (Smyth, 1912; Kovach, 1945; Kraner and others, 1964; Jaacks, 1984). A review of atmospheric and soil factors affecting seasonal radon concentrations can be found in Asher-Bolinder and others (1991). Rigby and La Pointe (1993) reported on wind and air pressure effects on indoor radon in two homes in Nevada which had been remediated for high radon concentrations.

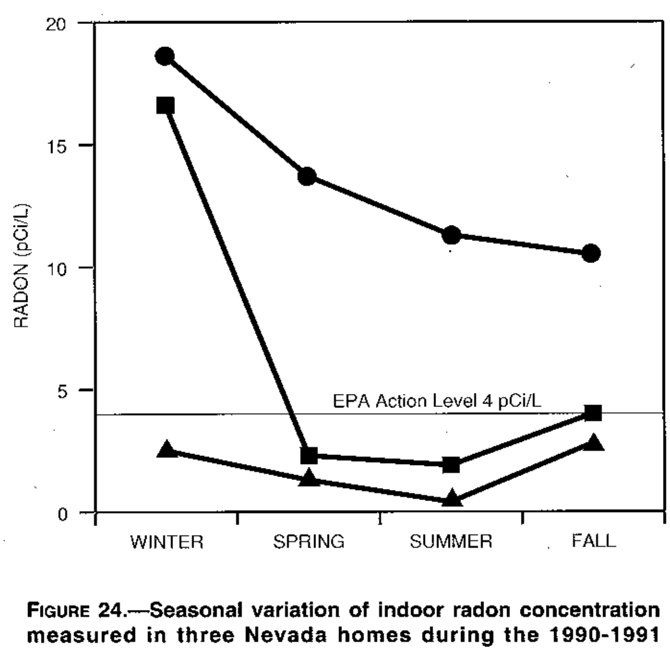


FIGURE 24.—Seasonal variation of indoor radon concentration measured in three Nevada homes during the 1990-1991 EPA/SIRG indoor radon survey. Measurements on the top line (circles) were made on the ground floor level of a home in Gardnerville; measurements on the middle line (squares) were made on the ground floor level of a home in Hawthorne; and measurements on the bottom line (triangles) were made on the ground floor level of a home in Pioche.

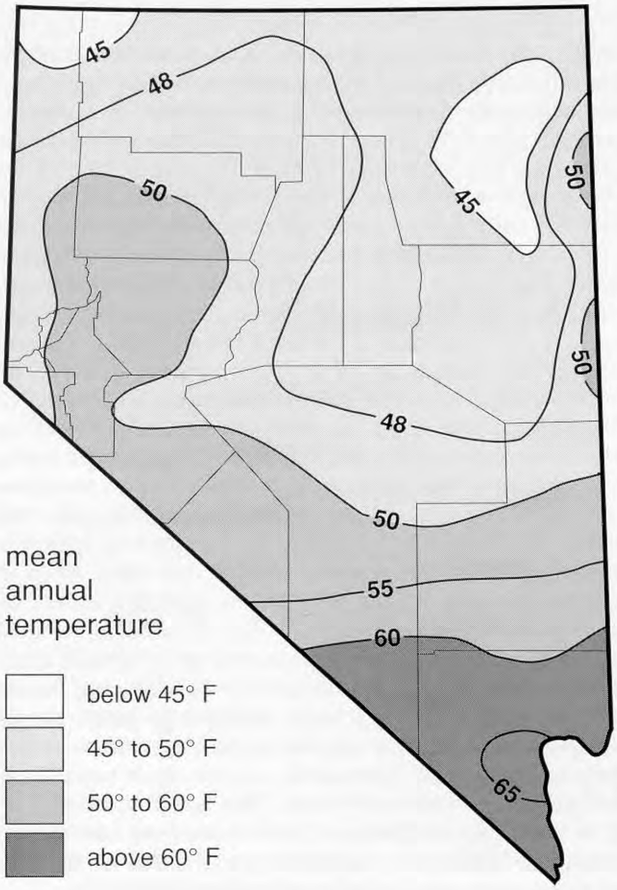
In general, many of the results of the indoor radon surveys in Nevada can be explained by temperature variations superimposed upon underlying geological factors. Most of the state's communities with a high proportion of homes exceeding the EPA action level are in northern Nevada and the rest are in southeastern Nevada. The distribution of the high indoor radon communities in northern Nevada may be related to generally cooler temperatures throughout the year (see fig. 25) and especially during the winter heating season when most of the residential survey measurements were obtained. As these maps show, there is a high gradient in both mean annual temperature and mean January temperature between northern and southern Nevada. As discussed above, where outside temperatures tend to be lower, occupants are more likely to keep the windows, doors, and crawlspace vents of their homes closed more, thus increasing the likelihood that indoor radon concentrations will build up to higher levels. This is especially true during the winter when it is often cool enough for homes in northern Nevada to be heated most of the time, while in southern Nevada, it may be warm enough that homes do not require additional heating (fig. 25). In addition, some of the results of the residential radon surveys in Nevada could be explained, in part, by variation in rainfall, and hence, soil moisture. There is a large variation in mean annual precipitation within Nevada, but unlike temperature, which tends to vary mostly from north to south, most variation in precipitation is from east to west. This factor is due primarily to the marked differences in elevation from east to west which is related to the preponderance of north-south trending mountain ranges and adjacent valleys in the state.

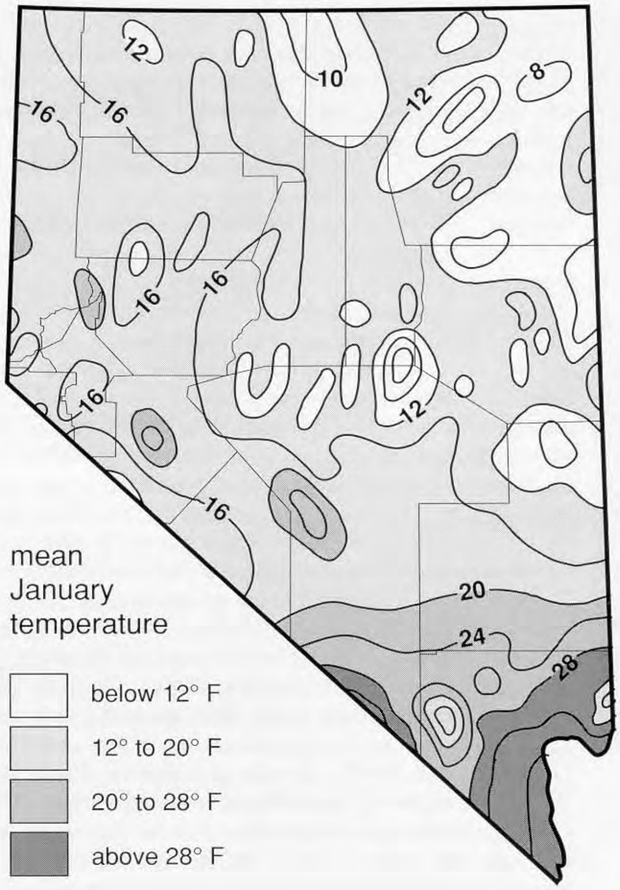
In summary, indoor radon concentrations in Nevada vary widely from season to season, generally being highest in winter, and lowest in summer. Some of this seasonal variation in indoor radon concentration may be attributable to the living habits of the residents, while some may be attributable to seasonal variations in meteorological factors.

TIME OF MEASUREMENT (DAILY)

Generally, indoor air radon concentrations are higher during the night than during the day; this effect may be due, in part, to the habits of the occupants of the home. Most occupants keep the doors and windows of their homes closed at night so that radon seeping into the house builds up during the night, frequently reaching peak concentration in early morning. The on and off cycling of central heating and cooling systems can also induce daily changes in indoor radon concentrations.

Interactions between the atmosphere and the soil can cause daily variations in the concentration of soil-gas radon similar to seasonal variations. For example, solar heating of the ground surface during the day, combined with the cooling of the ground surface at night, results in an accumulation of radon near the surface at night. When the sun heats the ground surface the following day, the near-surface air is warmed, becomes less dense, and rises, transporting radon with it. This process results in a night time concentration of radon that is relatively high near the ground surface, and a day time concentration that is relatively low (Wilkening, 1959, 1982). This process may have some effect on the





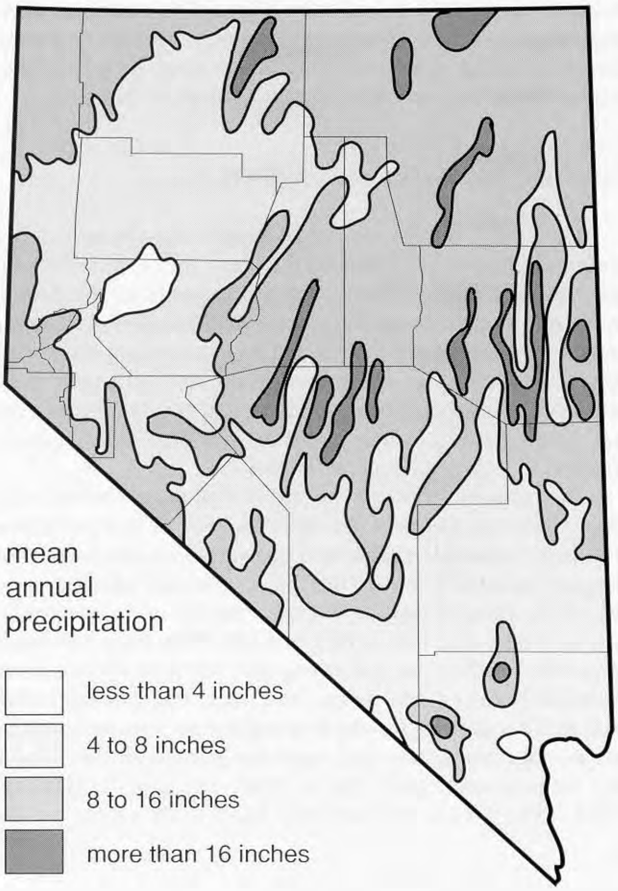


Figure 25.—Mean annual temperature, mean January temperature, and mean annual precipitation in Nevada (modified from Houghton and others, 1975).

amount of radon seeping into a home over the course of a day. Day to day changes in atmospheric pressure and precipitation have also been shown to cause daily changes in the rate of flux of radon from the soil (Kraner and others, 1964; Clements and Wilkening, 1974), which may influence the daily amount of radon entering a home. A review of atmospheric and soil factors affecting daily radon concentrations can be found in Asher-Bolinder and others (1991).

One example of diurnal variations in indoor radon concentration is shown in figure 26. This graph shows variations in radon concentration measured for a period of one week in a basement room that NBMG uses for storage. The figure shows daily cycle in radon concentrations in this room between late-evening lows (generally between 9:00 p.m. and midnight), and daytime highs (either at 9:00 a.m. or between 1:00 and 4:00 p.m.). These variations can be correlated with daily ventilation and heating patterns in the building.

CLIMATIC FACTORS

The Nevada radon work includes empirical observations of correlations between mean indoor radon concentrations and several meteorologic factors (outdoor air temperature, barometric pressure, precipitation, and wind speed) in Nevada cities with widely varying climates. Communities chosen for study were those which had the largest number of indoor radon measurements for statistical calculation of means, the most widely varying climatic factors, and state meteorological stations from which climatological data were available for the indoor radon measurement periods. Reno-Sparks, Winnemucca, and Las Vegas fit these criteria. Elko and Ely were also considered but lacked sufficient data to provide mean indoor radon concentrations for measurement periods throughout the year.

Data from the EPA/SIRG indoor radon survey begun in 1990 were sorted by zip code and dates of measurement. Only ground-level first floor measurements from the EPA/SIRG survey were used, spanning the time period between mid January and late December 1990. Mobile home data were not used. Because most measurements were obtained during the early months of the year (January-March), means for these months were compared to meteorological factors week by week. Later in the year when fewer indoor measurements were made, data were compared over longer periods of time (usually a month) to obtain sufficient data points to calculate mean indoor radon concentrations. For each measurement period, indoor radon concentrations which deviated from the mean by 2 or more standard deviations were omitted to remove the influence of anomalous values.

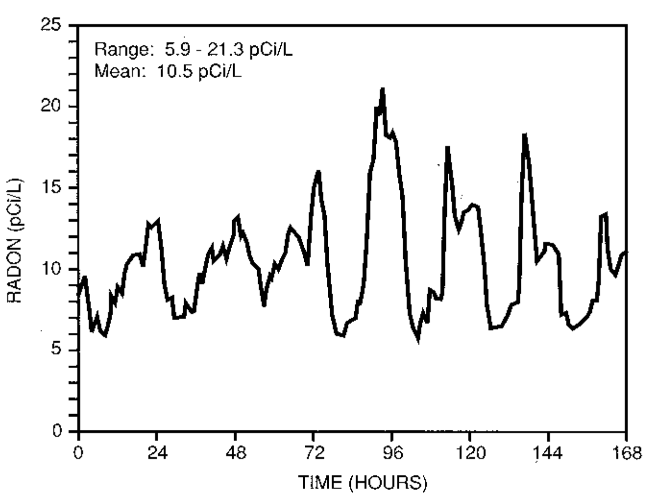


FIGURE 26.—Variations in indoor radon concentration over a one-week period, measured hourly using a continuous radon monitor. Measurements were made under closed conditions in a basement room of the Scrugham Engineering-Mines building at the University of Nevada, Reno starting at 4 p.m. on September 7, 1990. (The room is unoccupied and generally used only for storage.)

Monthly summaries of 1990 local climatological data for Reno, Winnemucca, and Las Vegas were obtained from the National Weather Service to calculate mean meteorological factors for the radon measurement periods. The monthly meteorological summaries showed that wind speed and precipitation were too sporadic and variable to show any meaningful variations from one radon measurement period to the next. Mean outdoor temperature and mean barometric pressure for the radon measurement periods were plotted for each of the three cities studied and are shown in figures 27, 28, and 29.

In Reno-Sparks, there is generally an inverse relationship between mean outdoor temperature and mean indoor radon (fig. 27B). Values for mean indoor radon bottom out at about 0.4 pCi/L during the warm months of the year when indoor radon concentrations approach outdoor ambient air levels. It is interesting to note in the more closely spaced measurement periods early in the year that there appears to be a slight lag time of a few days after outdoor temperatures rise or fall for indoor radon levels to react accordingly. This is probably due to the time required for indoor radon levels to equilibrate after a change in outdoor air temperature affects soil gas flux rates. The effect of barometric pressure on mean indoor radon concentrations is much less obvious in the Reno-Sparks data, but there is a general positive correlation between mean barometric pressure and mean indoor radon concentration (fig. 27A). Large fluctuations in mean barometric pressure from week to week during the early months of the year make correlation during this time period difficult. Also, soil gas entry into a house is affected by numerous factors such as changes in the pressure caused by use of vent fans, furnaces, and other combustion appliances which may mask the effects of small changes in outdoor barometric pressure on indoor radon.

In Winnemucca, the relationships between mean indoor radon concentration, mean outdoor temperature, and mean barometric pressure are similar to those observed in Reno-Sparks. Mean indoor radon concentrations show a general positive correlation with mean barometric pressure over the whole year (fig. 28A), although rapid fluctuations in the early months of the year make correlation difficult over this time period. As in the Reno-Sparks data, an inverse relationship between mean outdoor temperature and mean indoor radon is clear from figure 28B.

In Las Vegas, a similar inverse relationship between mean outdoor temperature and mean indoor radon concentration is observed (fig. 29B) with a similar lag time of a few days seen in the more closely spaced measurement periods in the early months of the year. The drop in radon levels over the hot summer months is somewhat less pronounced in Las Vegas than it is in Reno-Sparks, probably due in part to the fact that the extreme summer temperatures cause more houses in Las Vegas to be closed up and air conditioned than in Reno-Sparks during the same months. A positive correlation between mean barometric

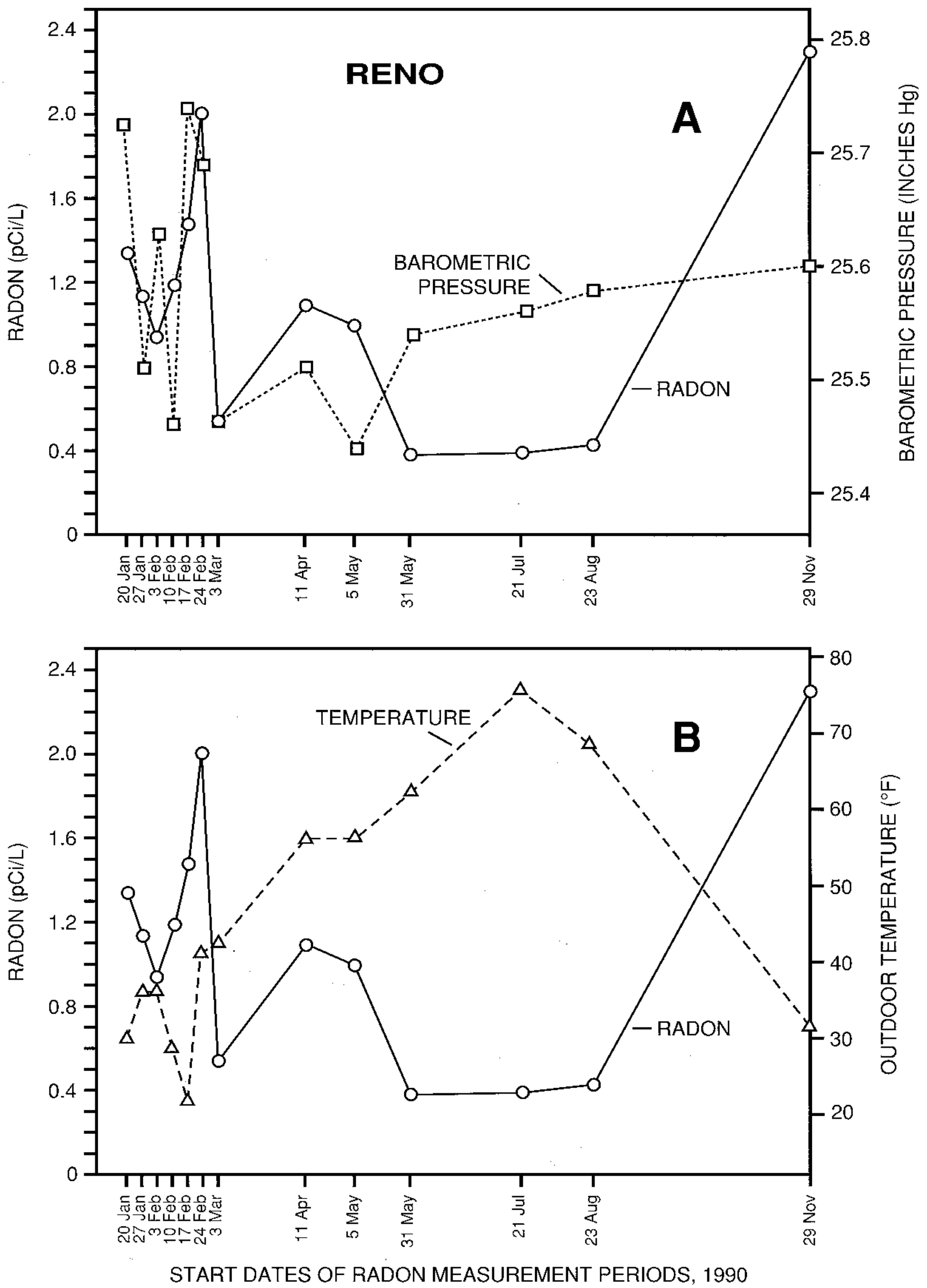


FIGURE 27.—Variations in mean indoor radon in Reno-Sparks with mean barometric pressure (A) and mean outdoor temperature (B) for radon measurement periods during 1990-1991 EPA/SIRG survey. Only ground floor measurements are used; mobile home data are not included. Total number of radon measurements used in calculating means is 198.

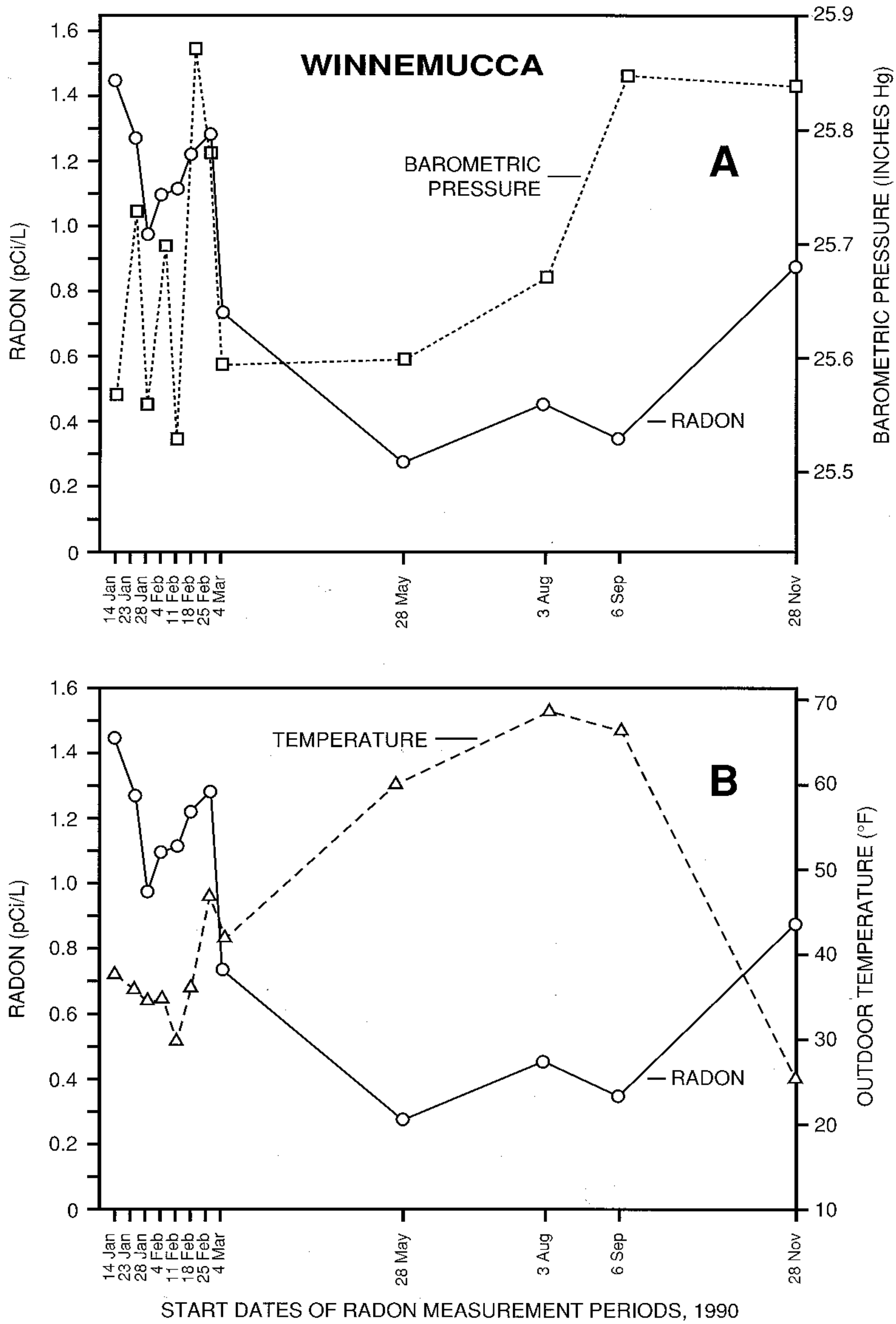


FIGURE 28.—Variations in mean indoor radon in Winnemucca with mean barometric pressure (A) and mean outdoor temperature (B) for radon measurement periods during 1990-1991 EPA/SIRG survey. Only ground floor measurements are used; mobile home data are not included. Total number of radon measurements used in calculating means is 145.

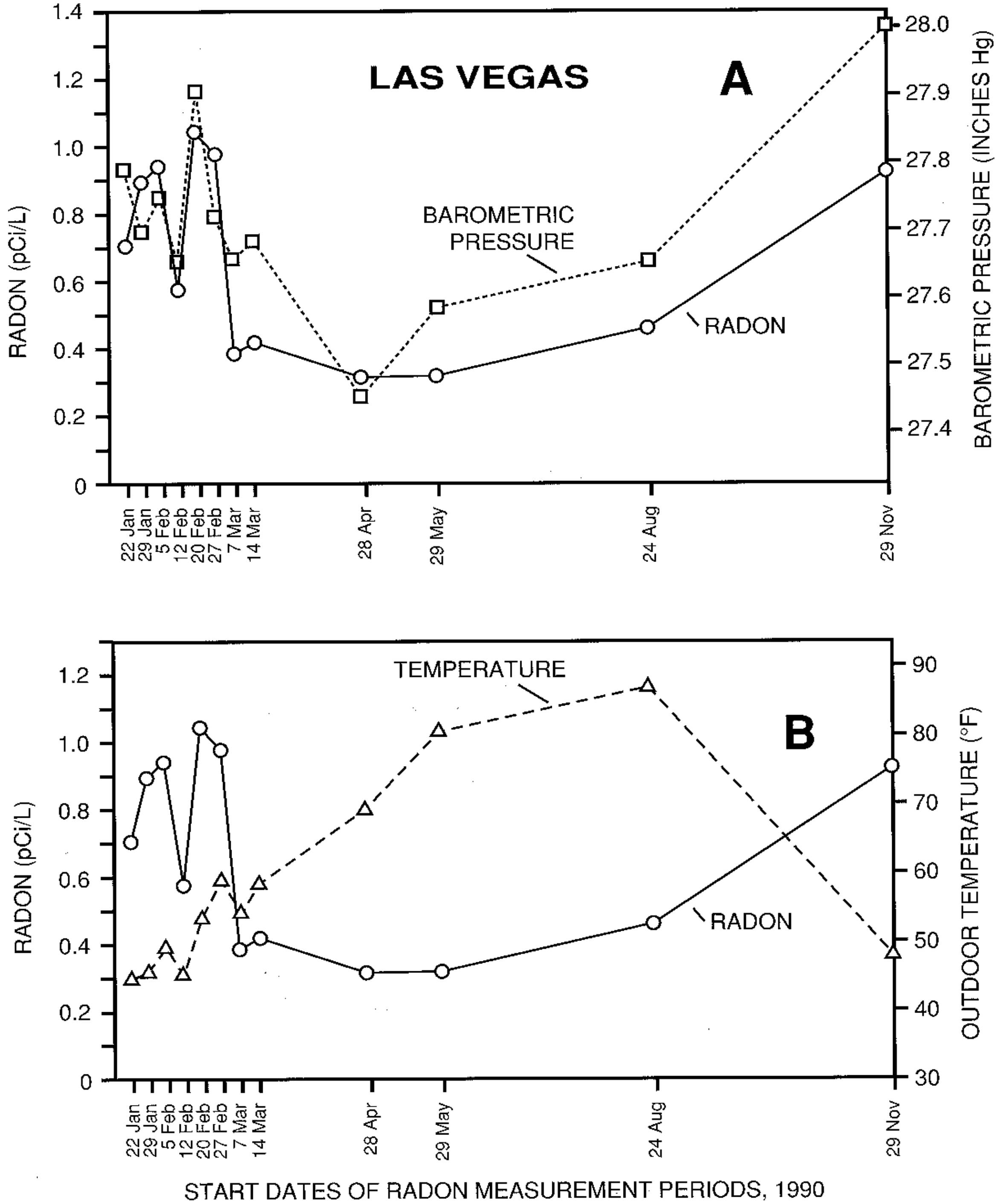


FIGURE 29.—Variations in mean indoor radon in Las Vegas with mean barometric pressure (A) and mean outdoor temperature (B) for radon measurement periods during 1990-1991 EPA/SIRG survey. Only ground floor measurements are used; mobile home data are not included. Total number of radon measurements used in calculating means is 194.

TABLE 10.—*Results by floor of charcoal-canister indoor air residential radon measurements, 1990-1991 EPA/SIRG survey.*

Placement	Number of measurements	Highest pCi/L	Lowest pCi/L	Mean[1] pCi/L	No. ≥4.0 pCi/L	Percent[1] ≥4.0 pCi/L
Basement	440	46.7	0.0	6.5	224	50.9
Crawlspace	18	9.8	0.0	3.1	5	27.8
Ground floor	1,584	26.3	0.0	1.9	166	10.5
Second floor	13	7.5	0.0	1.6	1	7.7
TOTAL	2,055	46.7	0.0	2.9	396	19.3

[1]All numbers represent raw, unweighted data.
Table includes mobile home data.

pressure and mean indoor radon concentration (fig. 29A) is more evident in Las Vegas than in either Reno-Sparks or Winnemucca, especially during the cooler months of the year. This may be due in part to the warmer Las Vegas winters requiring less use of furnaces than in both Reno-Sparks and Winnemucca during the winter months, thus reducing the masking effect of house dynamics on mean indoor radon concentrations. Also, there was less fluctuation in mean barometric pressure from measurement period to measurement period in Las Vegas than in the northern cities during the winter months.

Although the seasonal pattern of variation in indoor radon concentration is similar in Reno-Sparks, Winnemucca, and Las Vegas, the overall values for mean indoor radon concentrations for Las Vegas are generally lower than those in Reno-Sparks and Winnemucca. This is probably attributable to the lower geologic potential for radon in the Las Vegas area as compared to the Reno and Winnemucca areas as seen in plate 1, which shows the potential indoor radon hazard in Nevada. Another factor in the overall lower indoor radon concentrations in the southern, warmer part of the state may be the increased tendency of residents to ventilate homes during more months of the year than in the north.

Climate plays a significant role in determining the radon concentration in indoor air. Given similar geology and soil permeability, radon tends to be lower in areas with warmer and drier climates, and lower during the warmer months in both northern and southern Nevada communities, due mainly to heating, ventilation, and air conditioning practices of residents.

LOCATION OF MEASUREMENT (FLOOR)

The single largest source of indoor radon in most homes is the soil or rock on which the home is built. Thus the lowest floors of homes which are in direct contact with the soil or rock generally contain the highest concentrations of radon. The indoor radon measurements conducted by NBMG and NDOH in Nevada demonstrated the floor by floor differences in radon concentration in homes. Table 10 shows the number of indoor radon measurements from the EPA/SIRG survey made on each floor as well as the high, low, and average values for each floor and the number and percentage exceeding 4.0 pCi/L by floor. The highest average radon concentration occurred in basements (6.5 pCi/L), followed by crawlspaces (3.1 pCi/L), ground-level first floors (1.9 pCi/L) and second floors (1.6 pCi/L). The data for crawlspaces and second floors may not be statistically significant due to the small number of measurements from these locations. Furthermore, the basements which were tested exceeded 4.0 pCi/L more often than any other floor tested (50.9% versus 27.8% for crawlspaces, 10.5% for ground-level first floors, and 7.7% for second floors). These data corroborate the findings of other workers that radon concentrations tend to be highest on the lower floors of a home.

TYPE OF FOUNDATION AND AGE OF HOME

Some studies have shown that the type of foundation underlying the home affects indoor radon concentrations (Rundo and others, 1979; Cohen, 1986). The data from the indoor radon surveys in Nevada support these studies. For example, table 11 shows the average indoor radon concentration on the ground-level first floors of homes from the 1989-1992 indoor radon surveys which reported foundation type (basement, crawlspace, slab-on-grade, and mobile homes). The average of ground-level first floor measurements was 4.9 pCi/L in homes with basements, 2.4 pCi/L on ground-level first floors in homes with crawlspaces, and 1.9 pCi/L on ground-level first floors of homes with a slab-on-grade foundation. Mobile homes (usually having only a ground floor) averaged only 1.2 pCi/L. Also shown on table 11 is the percentage of measurements exceeding 4.0 pCi/L for each foundation type. The ground-level first floors of homes with basements exceeded 4.0 pCi/L 33.0% of the time, ground-level first floors of homes

TABLE 11.—*Ground-level first floor charcoal-canister indoor air radon measurements in homes reporting foundation type, 1989-1992 surveys in Nevada.*

Foundation type	Number of measurements	Mean[1] pCi/L	Percent[1] ≥4.0 pCi/L
Basement	106	4.9	33.0
Crawlspace	749	2.4	14.7
Slab-on-grade	341	1.9	9.4
	1,196	2.5	14.8
Mobile homes	420	1.2	4.0
	1,616	2.1	11.7

[1]All numbers are raw, unweighted data.

with crawlspaces exceeded 4.0 pCi/L 14.7% of the time, and ground-level first floors of homes with slab-on-grade foundations exceeded 4.0 pCi/L only 9.4% of the time. Mobile homes exceeded 4.0 pCi/L only 4.0% of the time.

The data from the Nevada surveys support previous studies that suggest that foundation type can influence indoor radon concentrations. Homes with basements are thought to contain higher concentrations of radon due to the larger surface area in contact with the soil that the basement creates. This relatively large soil contact area can collect radon from a larger volume of soil beneath the house, and radon then can diffuse throughout the house, increasing the overall indoor concentration. Homes with slab-on-grade foundations have less soil contact area and collect less radon. Homes with crawlspaces can approach the soil contact area of basements, but most crawlspaces contain vents which provide outside ventilation into the crawlspace, and crawlspaces are often above grade with less stem-wall soil contact than basement walls.

The generally low average indoor radon concentration in mobile homes is also evident from this table. For Nevada, this fact is significant because about 15% of the privately owned, single family homes in the state are mobile homes (Maude Narol, oral commun., 1993). This should not be interpreted as indicating that no mobile homes have radon problems; those with tightly sealed skirting or poor ventilation can be subject to the same potential radon hazards as homes with permanent foundations. Results of screening tests in some mobile homes, especially in the town of Austin, did exceed the EPA action level of 4.0 pCi/L of radon. A total of 376 mobile home measurements were included in the 1990-1991 EPA/SIRG survey of the state.

Some studies (for example, Cohen, 1986, 1991) have shown that the age of the home may be a factor in indoor radon concentrations, while other studies (for example, Cohen, 1985) have not been able to document this correlation. The data from the 1990-1991 SIRG survey in Nevada were examined for possible correlations with age of the home but no correlations were found.

Indoor Radon Potential Hazard Map

One of the primary objectives of the Nevada radon studies was to produce a map of Nevada showing relative potential for elevated levels of indoor radon in buildings constructed in the state. This map, entitled Indoor Radon Potential Hazard Map of Nevada (plate 1) was produced using GIS techniques and databases described in this section.

GIS METHODS

A Geographic Information System (GIS) is an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information (definition from Environmental Systems Research Institute, Inc., 1990). In simple terms, a GIS is a method of digitally storing and analyzing geographic data composed of two parts: map features and attributes. Map features are points (such as sample locations), lines or arcs (roads, rivers) and areas or polygons (soil units, geologic formations). Associated with the map features are attribute data such as analytical values for points, names for roads, or rock types for geologic polygons. A set of thematic map features and attributes (such as geology) is called a coverage.

The first part of creating coverages is the capturing of map features. One method is to create a digital version of a hard copy map by scanning or manually digitizing. Another method is the generation of features defined by Cartesian coordinate input. After features are entered and edited, topology is generated. Topology is the spatial relationship between connecting or adjacent map features. For example, the topology of a line includes its beginning point, ending point, and what lies on either side of the line. Once thematic coverages are created, various analytical techniques can be used to overlay, query, and manipulate data between coverages. Mathematical and statistical operations can be performed on numerical attributes. Point and polygon coverages can be intersected to form a point coverage with the attributes of the original point coverage and those of the polygons which they overlay. The union of two polygon coverages creates a new polygon coverage that has the attributes of the two parent coverages.

Software and Hardware

GIS processing of the radon data used the software package ARC/INFO produced by Environmental Systems Research Institute, Inc. (ESRI). Versions 5.0.1 through 6.1.1 were run on a Sun workstation network consisting of a SPARC Station 2 server and two SPARC Station IPC terminals. In addition three PC DOS compatible microcomputers running PC ARC/INFO revisions 3.3 and 3.4D were used for digitizing, editing, and preliminary analysis of data. Manual digitizing was done on two CalComp 9500 series digitizing tablets. Hard copy plots were produced using an HP-7585B pen plotter.

SOURCES OF DATA

The data used in developing the radon project GIS coverages were acquired from published sources, data developed by other agencies, and the results of NBMG studies. Descriptions of the coverages used and the methods of creation follow.

Indoor Radon

The results of three indoor radon residential surveys conducted by NBMG (1989 NBMG screening survey, 1990-1991 EPA/SIRG survey, and 1992 NBMG targeted community survey) were entered as point coverages. Homes were located on published street or topographic maps using data from forms filled out by the resident at the time of testing, by telephone contact with the resident, or by visual location where necessary.

Home locations were converted into a point coverage by on-screen digitizing with a road network background coverage. The digital road network used in locating homes was the U.S. Census Bureau *Topologically Integrated Geographic Encoding and Referencing* (TIGER) data format. TIGER was created to support census programs and surveys. It consists of geographic and political data such as surface hydrology, roads, voting districts, and census tracts for each county. The hydrology and roads were digitized from USGS 1:100,000 scale maps. The accuracy of the TIGER coverages is no greater than the standards for the original map data (U.S. Bureau of Census, 1990a, 1990b).

Indoor radon point coverages were created and attribute data were entered for each county. Attribute data included: house identification number, indoor radon measurement in pCi/L, placement of canister (basement, crawlspace, ground floor, or second floor), and house type (single family or mobile home). For homes with more than one measurement, the measurement and placement for each canister were entered. County coverages were joined into statewide coverages, one for each of the three surveys. The total numbers of homes located in each of the surveys are:

1989 NBMG screening survey	252
1990-1991 EPA/SIRG survey	1,657
1992 targeted community survey	186

Because the indoor radon potential hazard map was to be an assessment of the potential for radon in living areas of buildings with permanent foundations, measurements made in crawlspaces and mobile homes were removed from the indoor data set. The resulting data points used in the analysis are:

1989 NBMG screening survey	229
1990-1991 EPA/SIRG survey	1,452
1992 targeted community survey	150
Total data points used	1,831

National Uranium Resource Evaluation

The aerial gamma-ray data used in this study are from the U.S. Department of Energy National Uranium Resource Evaluation (NURE) program (1975-1983). The following description of the data collection and processing is adapted from Duval and Pitkin (1988).

Aerial surveys of the 1 × 2° quadrangles of the state were flown at a nominal altitude of 400 feet above the surface. East-west flight line spacing was 1 to 3 miles with north-south tie lines spaced 12 to 15 miles. Uranium (as measured by its daughter product, the isotope bismuth-214), potassium (as measured by the isotope potassium-40), and thorium (as measured by the isotope thallium-208) were measured continuously with gamma-ray spectrometers with accumulated data downloaded about every 200 feet, resulting in a raw data set consisting of a series of measurements taken every 200 feet along the flight line. Measurements represent radiation emanating from the surface to a depth of about 18 inches. The data were corrected for background cosmic radiation, altitude variation, and airborne bismuth-214. The gamma-ray systems were calibrated such that measurements could be expressed as concentrations of parts per million equivalent uranium (ppm eU), percent potassium (%K), and parts per million equivalent thorium (ppm eTh)[1].

Figure 30 is one of the published versions of the uranium concentration data. Joseph Duval of the USGS provided NBMG an aerial radiometric data set for the state of Nevada from the national data set. The data given to NBMG had been processed from the original measurements along the flight line to one point measurement about every 600 feet. The process consisted of the following steps (J. Duval, personal commun., 1992):

1. A 5-point median filter for removing spikes.
2. A 17-point gaussian filter for smoothing purposes.
3. All data with negative values were set to a value slightly above zero.
4. All data with altimeter readings greater than 650 feet above the ground were discarded as being statistically unreliable.

The NURE data set consists of longitude, latitude, percent potassium (%K), parts per million equivalent uranium (ppm eU), and parts per million equivalent thorium (ppm eTh) at each of the points. Point coverages were generated for each of the 1 × 2° quadrangles of the state (18 total) and attributed for ppm eU (potassium and thorium were not used in this part of the study). The separate coverages were then joined into a statewide coverage with a total of 534,580 data points. The range in values of these points is 0.0 to 69.2 ppm eU, the mean is 2.7 ppm eU, and the standard deviation is 1.1 ppm eU.

Another factor that could be considered in the evaluation of potential for generating radon is the proximity of a site to known uranium deposits. Figure 31 shows the distribution of major uranium deposits in Nevada. These include all mines with major or minor production and prospect areas containing sufficient concentrations of uranium to be potentially minable under favorable economic conditions (Garside, 1973, 1979; Mineral Resources Data System, 1993). The area surrounding each of these deposits that would be affected by radon emanating from the uranium in that deposit, however, is so small as to be insignificant on a county or statewide scale. Any single uranium deposit results in a potential radon hazard extending at most only several hundred yards beyond the periphery of the deposit, and the likelihood of construction of a large number of dwellings in that area is small, although it has occurred in at least one community in the eastern United States (Otton, personal commun., 1993). The NURE data provide a much more complete regional coverage for assessment of near-surface uranium content than do the locations of individual uranium deposits, and for this reason, the NURE data were used in the GIS development of the indoor radon potential hazard map of

[1]"Equivalent" means that equilibrium is assumed between parent and daughter isotopes of uranium. Although surface processes can cause disequilibrium among uranium, radium, radon, and bismuth isotopes, the map of equivalent uranium as measured by bismuth-214 is a fairly accurate measurement of radon in the upper several inches of the soil.

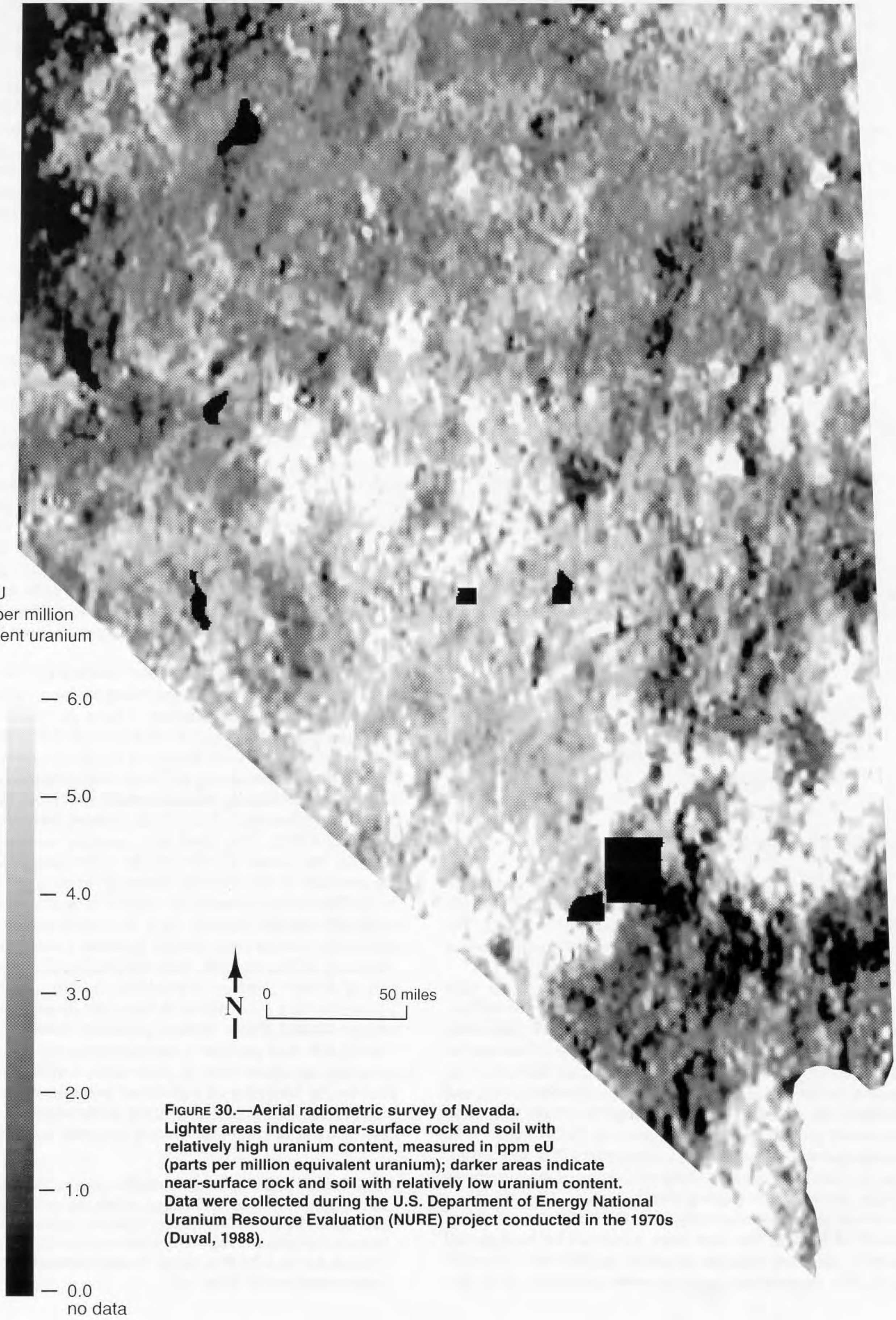


FIGURE 30.—Aerial radiometric survey of Nevada. Lighter areas indicate near-surface rock and soil with relatively high uranium content, measured in ppm eU (parts per million equivalent uranium); darker areas indicate near-surface rock and soil with relatively low uranium content. Data were collected during the U.S. Department of Energy National Uranium Resource Evaluation (NURE) project conducted in the 1970s (Duval, 1988).

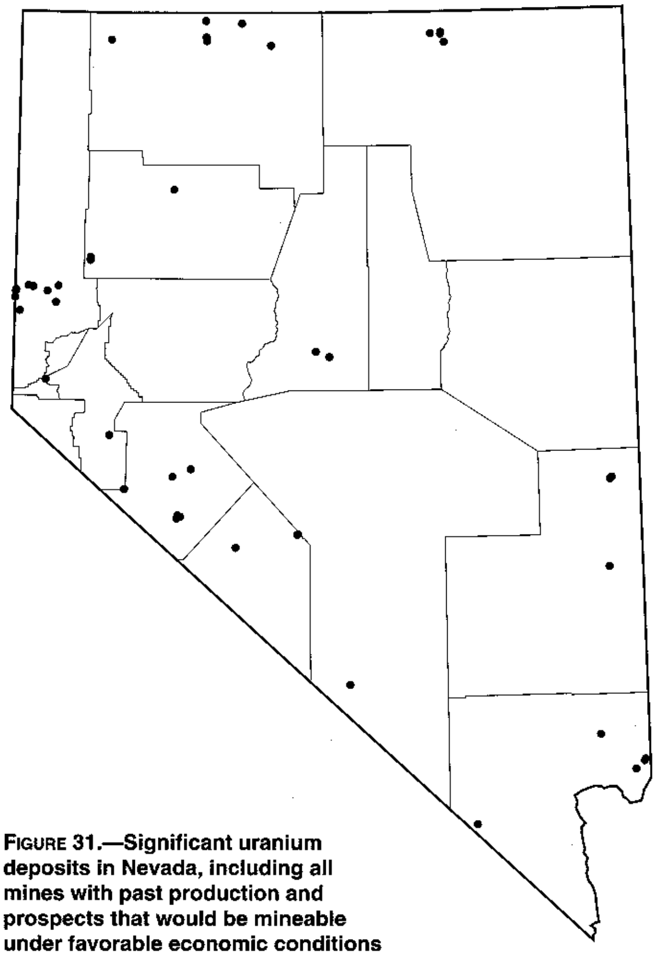


FIGURE 31.—Significant uranium deposits in Nevada, including all mines with past production and prospects that would be mineable under favorable economic conditions (Garside, 1973, 1979; U.S. Geological Survey, 1993).

Nevada. All but one of the uranium deposits shown in figure 31 do, however, fall within NURE zones of 2.0 ppm eU or more, thus placing them in the intermediate to high zones for potential indoor radon hazard (see following section on the *Hazard Zone Criteria*).

Geology

The statewide geologic base used in the analysis was a 1:500,000-scale geologic map of Nevada (Stewart and Carlson, 1978); a digitized representation of this map was produced by the USGS (Turner and Bawiec, 1991). The coverage consisted of arcs representing faults or geologic contacts and polygons attributed for geologic formations. For analytical purposes in this report, a simplified version was created in which fault lines that did not define polygon boundaries were deleted and large polygons of Quaternary alluvium were divided into smaller polygons to meet the polygon size limitations of the ARC/INFO software used. Totals for the simplified coverage were 20,151 polygons and 102 geologic formations. Figure 32 is a highly simplified version of the resulting digital geology coverage at an approximate scale of 1:3,250,000.

Soils

The statewide soils coverage was the U.S. Soil Conservation Service (SCS) State Soil Geographic Data Base (STATSGO). The STATSGO Data Users Guide (U.S. Department of Agriculture, 1991) states "STATSGO was compiled at 1:250,000 and designed to be used primarily for regional, multistate, state, and river basin, resource planning, management, and monitoring. The following procedure on the creation of the database is condensed from the Data Users Guide. The soil data were compiled on 1:250,000-scale USGS topographic maps. Data from detailed soil survey maps were generalized. Where detailed soil survey maps were not available, data on geology, topography, vegetation, and climate were assembled together with LANDSAT earth satellite images. Soils of like areas were classified and their extent determined. The map unit composition was determined by transecting or sampling areas on the more detailed maps and expanding the data statistically to characterize the whole map unit. Each soil polygon is attributed with a map unit identifier (MUID). The MUID is linked to other data tables that include the map unit name and the layers and components that define the map unit.

Groundwater

Another coverage which was considered in the GIS analysis of radon hazard was radon concentration in groundwater. As described earlier in the section on *Radon in Water,* radon can enter a home through the water supply system, especially if the domestic water supply is a private well. Because a groundwater radon concentration of 10,000 pCi/L is necessary to contribute 1 pCi/L of additional radon to indoor air, and because most groundwater radon concentrations measured in Nevada were well below that concentration (only seven exceeded 10,000 pCi/L, and of these, the highest value was only 16,000 pCi/L, as shown in appendix A), the radon in groundwater criterion was dropped from consideration as a major factor in GIS analysis of indoor radon hazard potential in Nevada.

DATA ANALYSIS

All coverages used in the analytical procedures were projected into the Lambert conformal projection, first standard parallel 33°00′00″N, second standard parallel 45°00′00″N, central meridian 117°00′00″W, units meters. These are the parameters of the 1:500,000-scale topographic map of Nevada published by the USGS (1984).

The first analytical procedure in creating the indoor radon hazard map of Nevada was relating point coverages (indoor radon and uranium) with polygon coverages (soils and geology) by intersecting the point coverages with the polygon coverages. The result is a point coverage where the points have the attributes of the underlying polygon. The following intersections were done: indoor radon with geology, indoor radon with soils, NURE uranium with geology, and NURE uranium with soils. The points were then selected according to similar soil or geologic attributes

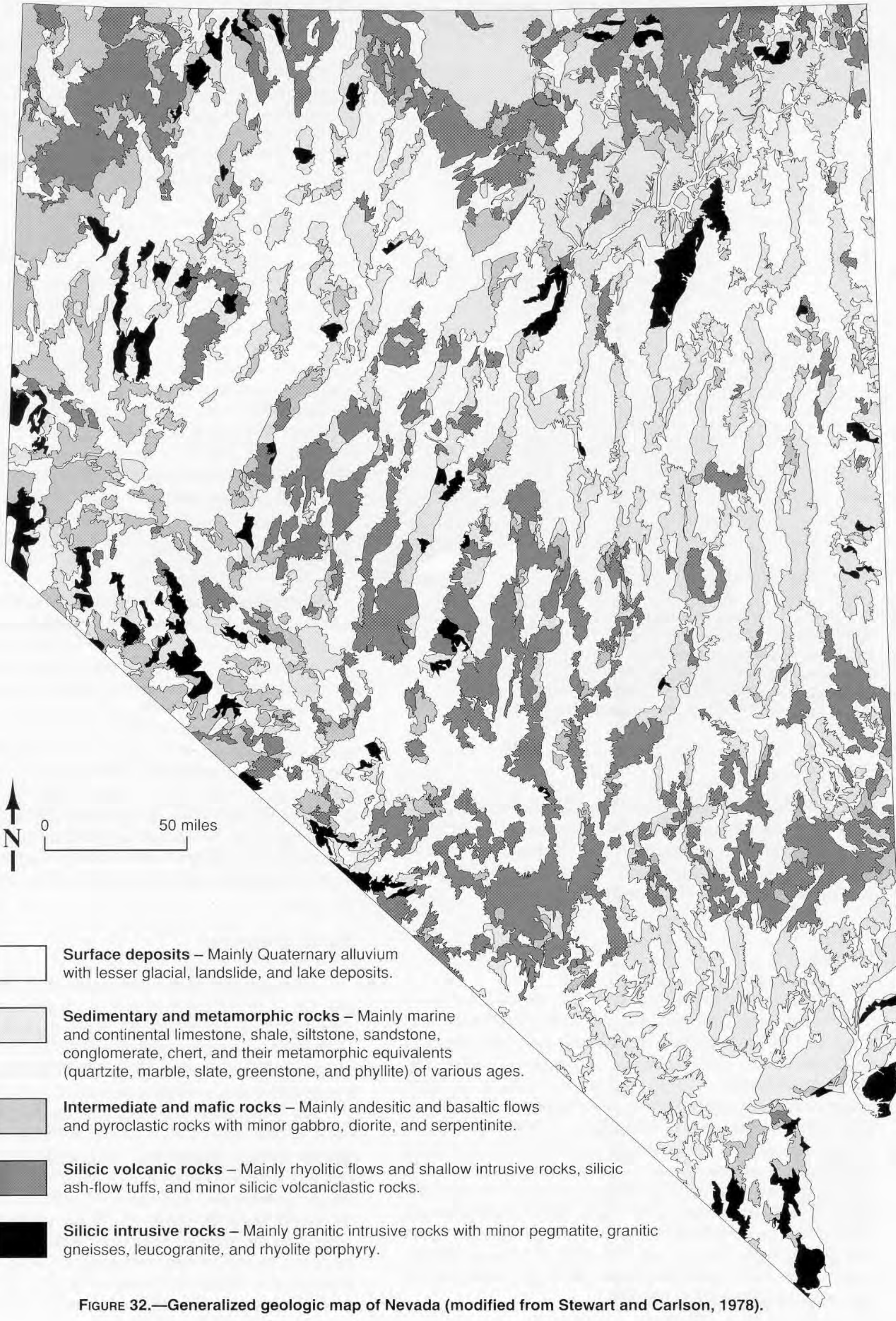


FIGURE 32.—Generalized geologic map of Nevada (modified from Stewart and Carlson, 1978).

and average uranium concentration or average indoor radon activity calculated. Averages were calculated both for all occurrences of geologic formations and soils units, and for individual geologic or soil polygons. The advantages and disadvantages for each method were considered after examining the results. The averages calculated over all occurrences of a unit were discarded because, while the occurrences are generally similar, there may be some specific differences affecting radon that could be lost in the generalities, for example, the statewide distribution of Tertiary rhyolitic flows and shallow intrusive rocks (geologic map symbol Tr3) is defined by age and general rock composition. However, within this general formation are rock units that have different source magmas with varying amounts of uranium. Treating each soil or geologic polygon as an individual unit overcomes this problem, but does not allow extrapolation to polygons with no data.

In order to prevent any confusion in the numerical analysis, each polygon in the soils and geology coverages was attributed with a unique number. The following statistics were compiled for each numbered polygon: average uranium content of geologic polygon, average uranium content of soil polygon, average indoor radon concentration for geologic polygon, average indoor radon concentration for soil polygon, percentage of indoor radon measurements greater than the EPA action level of 4.0 pCi/L geologic polygon, and percentage of indoor radon measurements greater than 4.0 pCi/L soil polygon. The last attribute determined was the highest indoor radon value for the soil or geologic polygon number.

To determine the relation between soils and geology the two polygon coverages were combined into one. The resulting coverage contained a total of 60,375 polygons, each having the following attributes: a unique number for the combined coverage, soil map unit, unique soil polygon number, geologic formation, and unique geology polygon number. The frequency of soil unit and geologic formation occurrences was determined and graphically examined. The correlation between specific soil units and geologic formations is only local, not statewide.

The results of the statistical and numerical analysis of the point coverages created by intersection with the polygon coverages were related to the combined geology and soils coverage by the unique soil or geologic polygon number used in the selection process. The combined geology soils coverage was queried on the various attributes to determine correlations and to construct the indoor radon hazard map of Nevada (plate 1).

HAZARD ZONE CRITERIA

Three indoor radon hazard zones were defined for Nevada on the basis of indoor radon data and data on likely uranium distribution in soil and near-surface rocks:

High, any one of the following conditions:

1. soil or geologic units with uranium content equal to or greater than 4.0 ppm eU,
2. any indoor radon measurement equal to or greater than 20.0 pCi/L,
3. average indoor measurement equal to or greater than 4.0 pCi/L, *or*
4. 25% of homes measured equal to or greater than 4.0 pCi/L.

Intermediate, any one of the following conditions:

1. soil or geologic units with uranium content equal to or greater than 2.0 ppm eU and less than 4.0 ppm eU,
2. any indoor radon measurement equal to or greater than 4.0 pCi/l and less than 20.0 pCi/L, *or*
3. average indoor measurement equal to or greater than 2.0 pCi/L and less than 4.0 pCi/L.

Low, all of the following conditions:

1. soil and geologic units with uranium content less than 2.0 ppm eU,
2. no indoor measurement greater than 4.0 pCi/L, *and*
3. average indoor measurement less than 2.0 pCi/L.

Each zone was selected individually and plotted. The resulting maps were overlaid on the computer, using GIS, to find areas of overlap. Areas of overlap were reconciled by checking the selection process and attribute calculating process and any errors were corrected. Plate 1 of this report is the resulting indoor radon potential hazard map at a scale of 1:1,000,000. Figure 33 is a simplified version at a scale of about 1:3,250,000. Excluding bodies of water, 19% of the state is in the High hazard zone, 71% is Intermediate, and 10% is Low.

Extensive unpopulated or sparsely populated areas of the state were classified on the basis of uranium content of soils and rocks alone because no indoor radon measurements were made. Most of these areas were classified Low or Intermediate radon hazard zones. The lack of indoor radon measurements introduces some statistical bias into the determination of the hazard of these areas because, if indoor radon data were available, high indoor radon measurements could increase the hazard rating but low measurements would not decrease the rating. Because of this bias, the reader is cautioned that direct comparisons should not be made between areas with indoor measurements and those without, and that it is especially important for those living in sparsely populated areas to measure the indoor radon of their homes because it may not have been measured in this study and the hazard rating as shown on plate 1 may be underestimated.

This bias is also responsible, to some extent, for the tendency for the High zones on plate 1 to be located in the valleys, where a large majority of Nevada homes are located.

CORRELATION OF INDOOR RADON POTENTIAL HAZARD MAP WITH GEOLOGY

A comparison of the hazard zones to the geology (Stewart and Carlson, 1976, 1977) and soils maps of the state shows that the zones are more closely related to geologic formations than to soil units. In Nevada, uranium concentration in surface soil is more closely linked to parent material (as indicated by geologic maps) than to the other soil factors

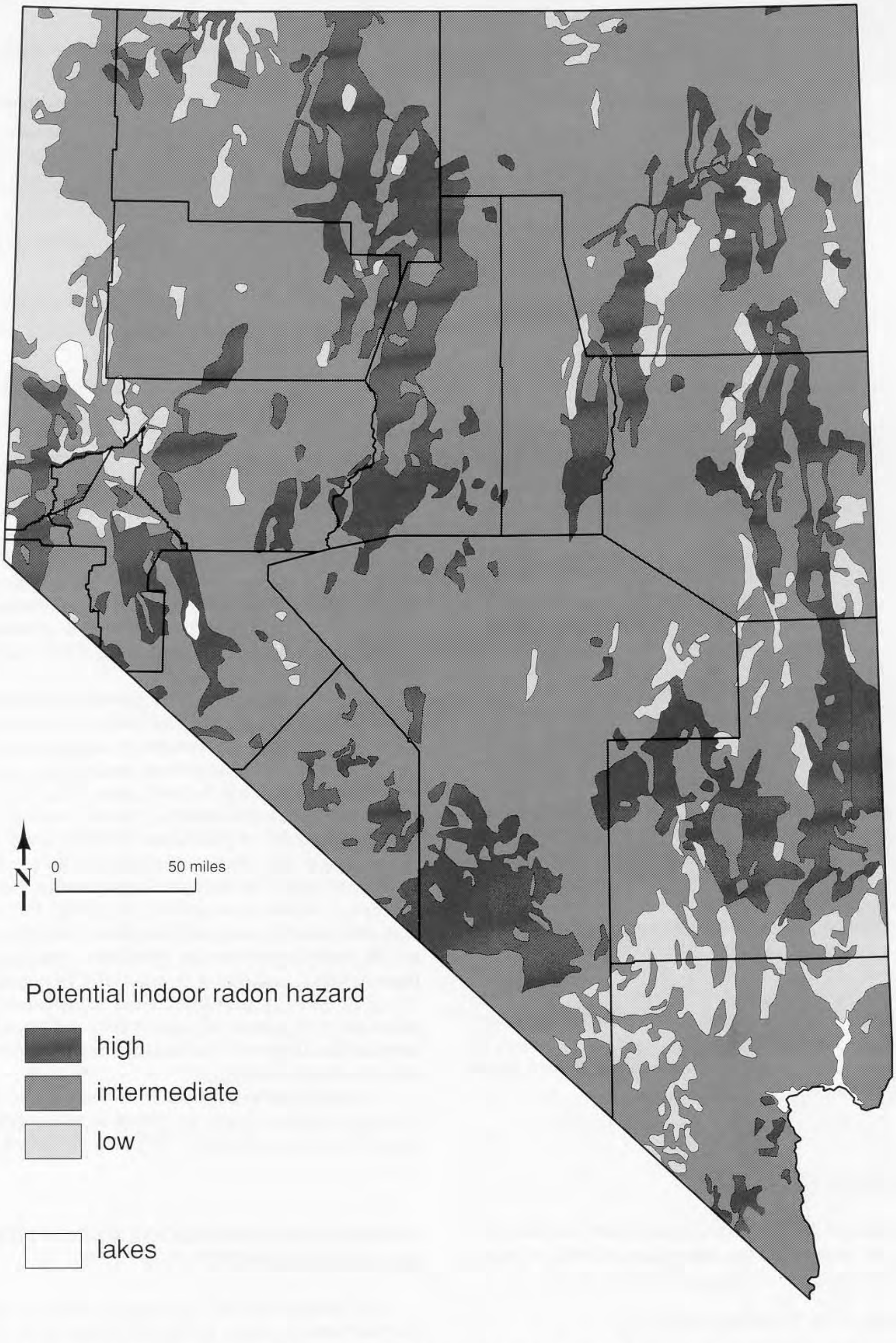


FIGURE 33.—Simplified indoor radon potential hazard map of Nevada (for more detail, see plate 1, a 1:1,000,000-scale version of the same map).

that are reflected in soil type maps. The NURE data effectively measure the bismuth-214 content of the upper several inches of the soils developed from underlying rocks.

Most of the following discussion will center on the occurrence of High indoor radon hazard zone shown on plate 1 due to the extreme potential for high radon concentrations in homes built in this zone. The following discussion will begin in the northeastern part of the state, in Elko County, and will progress in a general clockwise direction around the state, ending in the northwestern part of the state.

Plate 1 shows an occurrence of the High indoor radon potential hazard zone in Elko County, centered on the town of Wells and narrowing west of Wells to a strip that parallels U.S. Interstate 80 and the Humboldt River through the towns of Elko and Carlin. This zone extends southwest of Elko to include broad valleys extending into eastern Eureka County and northwestern White Pine County. Most of this High radon hazard zone lies within valleys filled by alluvial deposits derived from surrounding mountain ranges, and to a lesser degree from an area between Wells and Elko underlain by Cenozoic-age tuffaceous sedimentary rocks with minor amounts of tuff. The unusually uranium-rich rhyolite of the Toano Range, discussed in the section on *Radon in Outdoor Air*, shows up as a High zone between Wendover and Wells.

A long, dissected strip of High radon hazard zones about 200 miles long by up to 50 miles wide extends from the Elko-White Pine county line in the north almost to the Lincoln-Clark county line in the south, roughly paralleling the Nevada-Utah state line and occupying several major valleys. These High zones include the communities of Ely in White Pine County, and Pioche, Panaca, Caliente, Hiko, and Alamo in Lincoln County. Parts of these High zones extend through northwestern Lincoln County into adjacent eastern Nye County. Parts of the High zone in White Pine and Lincoln Counties correspond with upland and mountainous areas; these areas are underlain for the most part by Tertiary volcanic rocks composed of silicic ash-flow tuffs, rhyolitic flows and shallow intrusive rocks, andesite, and some tuffaceous sedimentary rocks. The area occupied by these rocks comprises the Tertiary Pioche-Marysvale volcanic field of southeastern Nevada and adjacent Utah. The valleys encompassed by this High radon zone are floored by alluvium derived from the bordering mountain ranges which are composed of the same silicic to intermediate volcanic and intrusive rocks described above.

In the extreme southern part of the state, in Clark County, only limited areas of High radon hazard zones occur. Several small areas of High zone surround Boulder City, extending to south of Boulder City roughly paralleling the Colorado River. A larger area of the High zone extends west from Searchlight to the state border, and a smaller area is located immediately north of Laughlin. Some of the areas of High hazard zone occur in valleys, while others occur in mountainous regions. In mountainous regions of Clark County, the High zones correlate with intermediate to silicic intrusive rocks, andesitic volcanic rocks, and basalt flows, all of Tertiary age. Geologic maps used in this analysis were not detailed enough to separate basalts, which are typically low in uranium, from silicic igneous rocks. Where High zones correspond to valleys, these valleys are generally flanked by mountainous areas composed of the above types of rocks. In addition, a few small areas defined as High hazard zones in Clark County may correlate with outcrops of Precambrian metamorphic and igneous rocks, such as the area of Precambrian granitic rock located a few miles north of Laughlin.

An extensive High radon hazard zone in southern Nye County extends roughly from Beatty on the south to near Goldfield on the north, and from the state line on the west to near the Lincoln-Clark county line on the east. Other areas in this part of Nevada defined as High radon hazard zones include an extensive area in eastern Esmeralda County south of Goldfield, and smaller areas scattered throughout Esmeralda County. Most of these areas of High radon hazard in southern Nye and Esmeralda Counties occur in upland and mountainous regions which are underlain primarily by volcanic rocks of the Tertiary Southwest Nevada volcanic field. These rocks consist predominantly of silicic ash-flow tuffs, rhyolitic flows and shallow intrusive rocks. The High radon zone of this region includes the major Tertiary volcanic centers of the Timber Mountain and Silent Canyon calderas. Northern Nye County contains a few small, scattered areas of High radon hazard zone. These areas are mostly underlain by Tertiary silicic to intermediate volcanic rocks.

A broad band of High radon hazard zone occupies the north-central part of the state, extending from the Nye-Lander county line on the south, north through Austin and western Lander County and adjoining eastern Pershing County to Battle Mountain, then northwest through Winnemucca and north from there through eastern Humboldt County to the state line at McDermitt. In this region, the High radon zones correspond both to valley areas and to upland and mountainous areas. The upland and mountainous areas with which the High zones correlate are mainly composed of Tertiary silicic ash-flow tuffs, and to a lesser degree of granitic rocks, such as at Austin where the High zone correlates with a granitic pluton of Jurassic-age. The valleys encompassed by these High radon zones are underlain by alluvium derived in part from the bordering mountain ranges. The High radon zone of Lander and eastern Humboldt Counties includes the major Tertiary volcanic center of the area, the Fish Creek Mountains caldera.

The northern part of the broad High radon hazard zone of eastern Humboldt County in the vicinity of Winnemucca, Orovada, and McDermitt encompasses valley areas, but it also includes some mountain areas such as the Santa Rosa Range east of Orovada. The rocks of the Santa Rosa Range and other nearby mountain ranges in the High radon zone are composed predominantly of Triassic and Jurassic clastic sedimentary rocks and some carbonate rocks which are locally metamorphosed and intruded by Mesozoic granitic rocks. As in other High radon potential zones of the state, this High zone, which mainly occupies valleys, results from a combination of alluvium derived from adjacent uraniferous silicic intrusive and volcanic rocks, and the sampling artifact due to usual location of tested homes in the valleys.

A few small, scattered High radon zones are located in both valleys and upland areas of northwest Humboldt County southwest and southeast of Denio. Some of the mountain ranges of these High zones are underlain by

Tertiary rhyolitic flows and shallow intrusive rocks, Tertiary silicic ash-flow tuffs, Mesozoic to Tertiary granitic rocks, and Tertiary basaltic and andesitic flows. The valley in which Denio is located is surrounded by uplands composed mostly of both granitic rocks and basaltic to andesitic volcanic rocks. Although most of the upland areas around Denio are not included in the High radon zone in this area, the alluvium of the valley is.

A northwest-trending band of High indoor radon hazard zones extends from south of Hawthorne in Mineral County, northward around Walker Lake into eastern Lyon County, where it joins another High zone that extends to the north and south of Yerington in central Lyon County. There are a few small, scattered High zones along the state border in southern Mineral, Lyon, and Douglas Counties. West and north of this area, a relatively broad High radon zone extends from the state border south of Minden and Gardnerville, northward through Carson City, and west to the eastern shore of Lake Tahoe. After narrowing considerably north of Washoe Lake, this High zone broadens to cover all of the valley occupied by Reno. Parts of this zone extend west to Verdi and the state border and northeast along State Route 445 to near Pyramid Lake in southern Washoe County. Most of the High radon zones in this region of Mineral, Lyon, Douglas, Carson City, and Washoe Counties correlate either with mountainous areas underlain in part by granitic rocks of Mesozoic to Tertiary age, or with valleys floored by alluvium derived from the adjacent ranges. An example of a granitic mountainous area is the Carson Range of the Sierra Nevada east of Lake Tahoe. Adjacent valleys to the east, filled in part with granitic detritus, are also included in the High radon zone. The High zone in Mineral County extending from Hawthorne northwest past Walker Lake corresponds to a valley floored by alluvium derived from mountains to the west and east, composed largely of granitic rocks. The mountains themselves, however, do not correlate with the High radon zone. A relatively small part of the High zones of this western Nevada area may correlate with some Tertiary andesitic to rhyolitic volcanic rocks, as at an upland area immediately north of Reno and perhaps in the mountains bordering the southwest side of Pyramid Lake.

Several High radon hazard zones occur in low-lying and partly marshy areas southwest and north of Fallon in western Churchill County, including Carson Sink. A similar High hazard zone occurs in western Pershing County in the broad valley along the Humboldt River north and south of Lovelock. The abundant organic-rich clays in the alluvium of the Humboldt River valley around Lovelock and in the marshes around Fallon may be partially responsible for the occurrence of the High radon hazard zones in these areas. As explained in the section on *Radon in Soil Gas*, the organic-rich clays can accumulate uranium, which produces radon as part of its radioactive decay series.

In summary, areas delineated on plate 1 as High indoor radon hazard zones in Nevada often correlate with silicic volcanic rocks, such as rhyolite and silicic ash-flow tuffs, and possibly with tuffaceous sedimentary rocks and andesitic and other intermediate volcanic rocks of Tertiary age, or with alluvium derived from such rocks. The next most prevalent rock type correlating with High radon zones is intrusive rock of granitic composition, usually Mesozoic or Tertiary in age. In some localized areas, High radon hazard zones may correlate with marshy areas, or alluvial areas underlain by organic-rich clays. Significantly, little or no correlation exists between High hazard zones and the various siliceous and carbonate sedimentary rocks of Precambrian to Paleozoic age (chert, shale, siltstone, sandstone, conglomerate, quartzite, limestone, dolomite, and others), or extensive areas underlain by mafic volcanic rocks such as basalt. The siliceous and carbonate sedimentary rocks and mafic volcanic rocks generally correlate with either Low or Intermediate hazard zones.

Other geologic factors not considered in the construction of the map of plate 1 may also affect the amount of radon emanating from rocks and soils, and thus, the amount of radon which may be available to migrate into a home built over those rocks and soils. These factors include faults, shear zones, and uranium mineralized zones in rocks, and grain size, porosity, permeability, and moisture content of surficial deposits and soils.

DISCUSSION

EPA in conjunction with the USGS has recently produced a report and map for Nevada (as well as the rest of the country) describing indoor radon potential (U.S. Environmental Protection Agency, 1993a). The map of Nevada contained in the EPA report depicts three radon hazard zones (Zones 1 through 3, with Zone 1 being the zone for highest indoor radon potential), similar to plate 1 of this report. However, there are obvious differences between the two maps, reflecting differences in the way the maps were constructed. The EPA radon zone map for Nevada depicts radon hazard zones on a county-by-county basis, that is, entire counties were assigned to either radon Zone 1, 2, or 3. The NBMG map, plate 1, disregards political boundaries, showing instead radon hazard zones cutting across county boundaries.

The EPA (1993a) map evolved from an earlier USGS Geologic Radon Province Map of the United States which evaluated radon potential based upon five criteria: indoor radon measurements, geology, aerial radioactivity (NURE), soil parameters (permeability, moisture content, topography, and drainage), and house foundation type (basement, no basement, or mixed). These five factors were applied to seven radon potential provinces across Nevada resulting in a ranking of all but one of the provinces in the moderate radon potential category, while the seventh ranked low. However, in the construction of their radon zone map of Nevada, EPA grouped the data from these seven provinces by county so that entire counties are depicted as being either Zone 1, 2, or 3.

NBMG used similar initial criteria in the construction of its radon hazard map of Nevada: indoor radon measurements, geology, soils data, and aerial radioactivity (NURE) data. However, the NBMG map differs greatly from the EPA map in that radon hazard zones shown on the NBMG map follow naturally occurring geologic provinces and boundaries which cut across political boundaries such as county lines.

We feel that the NBMG map is more useful at the state, county, or local level for assessing indoor radon hazard potential than is the EPA map. In a large state such as Nevada, some counties are as large as several eastern states (Nye County, Nevada's largest county, is larger than the states of Connecticut, Delaware, New Jersey, and Rhode Island combined). This fact, in combination with Nevada's scattered sparse population distribution (sometimes only one major population center in each county), and the fact that diverse geologic provinces cut across county boundaries (see fig. 32), makes the EPA county-by-county approach to mapping radon hazards of limited use in predicting potential radon hazard for a given region of a county.

The EPA map tends to minimize the radon hazards in certain counties. For example, all of Clark County is assigned to Zone 3 on the EPA map, that is, it has the lowest potential for elevated indoor radon hazards in Nevada. This assignment is based in large part on the fact that Las Vegas, the major population center of Clark County (and of Nevada), has very few NBMG indoor radon survey measurements exceeding the EPA action level for indoor radon of 4.0 pCi/L (about 3%). In addition, much of the county's rocks and soils have low to moderate potential for radon emanation due to relatively low uranium contents. However, the NURE data indicate that specific parts of Clark County outside the Las Vegas area contain rocks and soils with relatively high radioactivity due to uranium, and high potential for contributing to elevated indoor radon concentrations in homes built on these rocks. Examples of areas in Clark County underlain by bedrock containing elevated uranium levels are found around the communities of Searchlight, Laughlin, and Boulder City. Searchlight did not have any tested homes exceeding 4.0 pCi/L in NBMG surveys, but only four homes there were tested, and two of these were mobile homes. In Boulder City, about 10% of the homes tested exceeded 4.0 pCi/L, which is not an insignificant number. To date, no homes have been tested in Laughlin in NBMG indoor radon surveys.

In contrast to the EPA map, the NBMG indoor radon hazard potential map shows a large portion (76%) of Clark County included within High and Intermediate radon hazard zones, and only 24% of the county in the Low radon hazard zone. As the population of Clark County expands into as yet undeveloped geologic provinces which may have substantial potential for producing radon, residents should be aware that indoor radon testing should be done despite the low radon hazard potential indicated by the EPA map for Clark County.

In summary, although we understand the need by the EPA to delineate radon hazards by state and by county in order to assist in the targeting of resources, we believe that the approach used in the construction of plate 1 of this report, in which radon hazard zones were determined on the basis of geology, soils, and aerial radioactivity as well as indoor radon measurements, regardless of political boundaries, provides a more adequate and useful assessment of the indoor radon hazard potential of any specific area of the state. Furthermore, the NBMG radon hazard map (plate 1) is at a larger scale than the EPA map (1:1,000,000 versus about 1:6,000,000) which makes it possible to show more detail. Even so, the smallest radon hazard zones depicted on plate 1 represent areas on the ground which are about four square miles in area; any radon hazard zone smaller than this could not be depicted at the scale of the map. For this reason, plate 1 should only be used by state, county, and local organizations and agencies as a preliminary tool to assist in the targeting of resources and to implement radon-resistant building codes. Plate 1 should not be used to determine whether a particular home in a given hazard zone should be tested for radon. Homes with elevated radon have been found in all three zones and all homes should be tested for radon regardless of geographic location.

REDUCING RADON IN HOMES

EPA recommends that every home should be tested for radon concentration and, although there is no known "safe" concentration of radon, remedial action should be taken if the average annual radon concentration is not less than 4.0 pCi/L. Testing a home for radon concentration is easy and inexpensive using one of the passive radon detectors described in the section *Measurement of Radon*. EPA recommends the following steps:

Step 1. *Take a short-term test. If your result is 4 pCi/L (0.02 WL) or higher, take a follow-up test (Step 2) to be sure.*

Step 2. *Follow up with either a long-term test or a second short-term test:*

- *For a better understanding of your year-round average radon level, take a long-term test.*
- *If you need results quickly, take a second short-term test.*

Step 3.

- *If you followed up with a long-term test: Fix your home if your long-term result is 4 pCi/L or more.*
- *If you followed up with a second short-term test: The higher your short-term results, the more certain you can be that you should fix your home. Consider fixing your home if the average of your first and second tests is 4 pCi/L or higher.*

For more information on testing your home for radon, consult *A Citizen's Guide to Radon* (U.S. Environmental Protection Agency, 1992a), from which the above information was taken.

Radon Reduction Methods

There are two basic approaches to reducing radon concentrations in a house: 1) impede radon entry into the house, and 2) reduce radon concentration in the house once it gets there. EPA generally recommends systems that impede radon entry into the house. Figure 2 illustrates many potential radon entry routes into the home. EPA publication *Radon Reduction Techniques for Detached Houses — Technical Guidance* (U.S. Environmental Protection

Agency, 1987b) has a useful checklist that can be used to identify the source of radon in a home. Radon entry into a dwelling can be reduced by several different methods including ventilation, sealing, isolation, pressurization, and reducing negative pressure.

Table 12 summarizes various radon reduction techniques, their applicability to building foundation types and initial radon concentrations, effectiveness at reducing radon, relative installation costs, and additional factors for consideration. Any combination of radon reduction techniques should be tailored to the unique characteristics of the house such as foundation type, soil type, and daily activity patterns of inhabitants.

Types of foundation design common in Nevada include slab-on-grade, (concrete poured at ground level), crawlspace (stem wall), and basement. Slab-on-grade construction predominates in the southern part of the state where as many as 95% of the home foundations are of this type. In northern Nevada, about 85% of the homes (excluding mobile homes) have crawlspace foundations, and the rest are about equally divided between basements and slab-on-grade. As shown by the indoor radon survey data discussed earlier, mobile homes in Nevada generally have low radon concentrations, although some have been found to have indoor radon concentrations above 4.0 pCi/L. For radon reduction purposes, mobile homes are treated the same as houses with crawlspaces. Some homes have a combination of foundation styles and thus may require a combination of radon reduction techniques.

It is generally much easier and less expensive to install most radon reduction systems during the construction of a new home than it is to add them to an existing home. *Radon-resistant Construction Techniques for New Residential Construction — Technical Guidance* (U.S. Environmental Protection Agency, 1991) gives detailed information on radon reduction techniques used in new construction, and should be consulted before planning and building a home.

RADON REDUCTION METHODS APPLICABLE TO ALL FOUNDATION TYPES

Sealing

Sealing all accessible potential routes of radon entry into the house should be a part of any radon reduction system. Cracks, holes, joints, porous surfaces, open areas around plumbing and ductwork, open tops of block walls, and drains should all be sealed (refer to fig. 2). In homes with slab construction, poorly sealed sub-slab cold air return ductwork may be a source of radon entry into the home. A contractor can insert a seamless impermeable sleeve into such ductwork to prevent radon entry. Cold air return ductwork in basements and crawlspaces should be well sealed to prevent intake of radon-laden basement or crawlspace air into ductwork. For homes with only slightly elevated radon concentrations, sealing and increased ventilation may be enough to reduce radon to an acceptable level. Sealing alone is, however, not recommended as a solution to most radon problems because of the limitations in identifying, accessing, and permanently sealing all entry routes. Consult EPA publication *Radon Reduction Techniques for Detached Houses — Technical Guidance* (U.S. Environmental Protection Agency, 1987b) for details on what sealants to use.

Natural ventilation

Opening all windows in a house will reduce radon concentrations by mixing outside air with the radon-laden indoor air and by neutralizing the lower pressure in the house that draws radon into the home from the soil below (see section on *Radon Entry into a Home*). Windows should be opened equally on all sides of the house to avoid creating a pressure differential which could actually draw more radon into the home from the ground below. Although seasonally or temporarily effective, natural ventilation is impractical as a permanent, full-time radon reduction technique in Nevada due to the obvious disadvantages of having a house open all the time (heating and cooling costs, security concerns, and entry of dust and allergens).

For houses built over crawlspaces or uninhabited basements, simple ventilation of the crawlspace or basement can often dramatically reduce radon concentrations. All crawlspace vents should be opened year-round, or vents should be added where they are not present or insufficient. If this method is used in a part of Nevada with cold winters, pipe insulation, heat tape, and subfloor insulation should be installed to keep the water pipes in the crawlspace or basement from freezing, and to minimize heating costs due to increased ventilation.

Forced air ventilation

Forced air ventilation works the same way natural ventilation does to reduce radon concentrations, except that fans are used to control the air exchange rate. Existing heating or cooling ductwork may be used, but care must be taken not to use an exhaust fan to pull air out of the house because this depressurizes the house, increasing the influx of radon-laden air from the soil below. Forced air ventilation can also prevent the entry of radon gas by pressurizing the house. This method is subject to the same weather constraints as natural ventilation. Forced air ventilation of an uninhabited basement or crawlspace can be an effective method of reducing radon in living areas if the two areas are effectively sealed off from one another. Consult EPA publication *Radon Reduction Techniques for Detached Houses — Technical Guidance* (U.S. Environmental Protection Agency, 1987b) for guidance on size and location of fans for maximum effectiveness.

Heat recovery ventilation

A heat recovery ventilation system (air to air heat exchanger) increases ventilation from outside air while recovering heated air in the winter and cooler air in the

TABLE 12.—*Summary of radon reduction techniques.*

Method	Applicability	Effectiveness	Installation cost	Comments
Sealing of radon entry routes	All house types. All initial radon concentrations.	Extremely variable, up to 90% reduction of radon, dependent on accessibility, effectiveness of seal, and number of remaining entry routes.	low to high	Can be inexpensive for do-it-yourself sealing of major accessible entry routes. Contractor-installed coatings and sealants increase cost.
Natural ventilation	All house types. All initial radon concentrations. Limited by weather.	90% or more reduction of radon, depending on amount of outside air flow into house.	minimal	Easy, inexpensive short-term measure, but not a practical permanent solution to radon problems in most homes. Increased natural ventilation of a dirt-floored crawlspace may be an effective long-term solution in homes with crawlspaces.
Forced air ventilation (fans)	All house types. All initial radon concentrations. Limited by weather.	90% or more reduction of radon, depending on amount of outside air flow into house.	low to moderate	Installation costs can be reduced by using existing heating/cooling ductwork.
Forced air ventilation with heat recovery	All house types; best reductions in tight houses. Applicable when initial radon concentration is below 15 pCi/L. Works best in extreme climates (hot or cold).	Variable, but 50-75% reduction is typical, higher in tight house.	moderate to high	Installation cost may be less if existing ductwork can be used.
Reduction of house depressurization	All houses. All radon concentrations.	Variably effective, depending on amount of depressurization reduced.	low to moderate	Inexpensive for those measures easily implemented by the homeowner.
Air cleaning	All houses. All radon concentrations.	Up to 90% effective in removing the radon decay products attached to airborne dust but does not remove unattached radioactive particles.	high	Installation of air cleaners of sufficient capacity could be prohibitively expensive.
Pressurization	Houses with well-sealed basements or heated crawlspaces. All radon concentrations.	May be up to 90% effective, depending on how completely the basement or crawlspace is sealed from living area above.	moderate	Cost variable depending on type of fans installed and on heating/cooling penalty from increased ventilation.
Sub-slab suction	Houses with cement slab foundations or cement-floored basements and relatively good permeability below the slab. Moderate to high initial radon concentrations.	Up to 90% reduction of radon concentration depending on permeability of sub-slab soil.	high	One of the most effective and reliable methods of radon reduction for homes with slab foundations and significant initial radon concentration.
Drain tile suction	Houses with slab foundations and a relatively complete loop of existing drain tiles around the footings. Any initial radon concentration.	Up to 99% reduction of radon concentration depending on completeness of drain-tile loop and permeability of sub-slab soil.	moderate to high	Very effective method of radon reduction for homes with slab foundations and existing drain tiles around the footings.
Block wall suction	Houses with hollow block foundation walls where sub-slab suction is not sufficient. Moderate to high initial radon concentrations.	50 to 99% effective where walls can be effectively sealed.	high	Often used in combination with sub-slab suction.
Isolation and venting of source areas (sub-membrane suction)	Houses with dirt-floored crawlspaces where crawlspace ventilation is not the method of choice, or houses with badly cracked slabs or basement walls.	Variably effective.	moderate to high	Cost variable depending on type of liner installed.

NOTE: Be sure to retest your home for radon after performing any radon reduction work on your home to determine the amount of radon reduction and the need for additional measures.

summer. It reduces radon in a home in the same way that natural and forced air ventilation does, but it reduces the heating and cooling penalty that accompanies those methods. The energy savings of operating an HRV system over several years may outweigh its higher initial installation cost.

Reduction of house depressurization

Radon will enter a home if the air pressure inside the home is lower than that in the adjacent source of the radon, usually the ground surrounding the foundation. The lower pressure inside the home is caused by the thermal stack effect of warm air rising in the house, drawing radon-laden air into the home from the soil below. This effect is increased by the use of exhaust fans on indoor appliances such as clothes dryers and rangetop hoods, and by the lack of outside sources of makeup air for indoor combustion appliances such as furnaces, fireplaces, woodstoves, and gas water heaters and clothes dryers. Any measures that increase the air pressure in the home will reduce the entry of radon. Closing off thermal bypasses (openings between floors) can reduce the thermal stack effect of heated air rising and drawing radon-laden air into the home from the underlying soil. An outside makeup air supply should be available for combustion appliances. ***Before making alterations on the ductwork of combustion appliances, consult a professional contractor to avoid compromising the safety of such appliances or violating local building codes.***

Air cleaners

Air cleaners can remove cancer-causing radon decay products (see radon decay products in section *Occurrence of Radon*) attached to dust in the air of a home. EPA does not recommend air cleaning as a proven radon reduction method, however, because it does not remove radon itself or potentially dangerous unattached radon decay products from the air.

RADON REDUCTION METHODS APPLICABLE TO SPECIFIC SITUATIONS

Pressurization

In houses with well-sealed basements or heated crawlspaces, fans can be installed to pressurize the basement or crawlspace in contact with the soil, maintaining a high enough pressure to prevent the entry of radon. The basement or crawlspace must be effectively sealed off from living areas, and upstairs air is then blown into the basement or crawlspace to pressurize it. Care must be taken not to cause backdrafting of any combustion appliances located upstairs.

Suction systems

If a house is constructed on a cement slab or has a cement-floored basement, a sub-slab soil suction system may be the most effective method of preventing radon entry. Sub-slab suction or depressurization systems work by using a fan to suck soil gases out through pipes inserted into the soil or aggregate under the slab. The radon-laden air is then vented to the outside where it is quickly diluted and dissipated. Sub-slab suction is a common and generally reliable method of radon reduction when installed by a competent contractor. Variations of this type of system include sump hole suction, drain tile suction, and block wall suction. A sump located in a basement can be capped and used as the location of a radon suction pipe.

Existing drain tiles that direct water away from the foundation of a house can also be used to suck radon away from the foundation, especially if they form a complete loop around the foundation. If a home has basement block walls, a block wall suction system can be installed to suck radon from the hollow spaces in the concrete blocks through a pipe, duct, and fan system. A combination of these suction systems may be used depending on the specific characteristics of the foundation.

All of these suction systems must have exhaust pipes that vent above roof level and away from windows, doors, or air intakes to prevent reentry of the vented radon into the house. The exhaust fan for any such system should be located outside or in an uninhabited portion of the home, such as in a garage or attic. For the system to work efficiently, cracks and holes in slabs and foundation walls should be sealed with an appropriate non-shrinking, non-cracking sealant.

Isolation and venting of source areas

Sub-membrane suction or depressurization can be used to reduce radon in houses with dirt-floored crawlspaces where crawlspace ventilation is not the method of choice. The earthen floor of the crawlspace is covered with an impermeable liner of heavy plastic sheeting (usually 6 mil polyethylene or heavier) and tightly sealed against the edge of the foundation and support piers. Alternatively, a false floor may be installed. Perforated vent pipes in the enclosed space between the liner or false floor and soil may be connected to a fan to suck radon from below the membrane and vent it to the outside in a manner similar to that used in sub-slab suction.

DO IT YOURSELF OR HIRE A CONTRACTOR?

EPA operates a Radon Contractor Proficiency program to evaluate and train contractors in radon mitigation. A list of contractors trained by EPA in radon reduction methods may be obtained from the Radiological Health Division of the Nevada Division of Health. EPA does not recommend that average homeowners attempt radon mitigation techniques on their own. Some of these radon-reduction techniques could be accomplished with a reasonable amount of time and effort by a person untrained in radon mitigation, while others require the services of a professional contractor trained in radon mitigation techniques.

The decision to do it yourself or hire a trained contractor should be based on a careful risk to benefit analysis of the particular situation, weighing such criteria as these: radon concentration in the home; amount of time to be spent in the home; presence of children, elderly, or ill persons in the home; cost of mitigation; and availability of trained radon reduction contractors. Some of the more simple techniques such as sealing obvious routes of radon entry and increasing ventilation could first be implemented by the homeowner, followed by additional radon testing. This would indicate the need, if any, for installation of a more sophisticated radon reduction system by a professional contractor.

Whatever method of radon reduction used in a home, and whether a professional contractor is used or the system is homeowner-installed, it is imperative that follow-up radon testing be done to ensure that the system is doing what it was intended to do — reduce the concentration of radon in the house to less than 4.0 pCi/L. Follow-up testing should be done under conditions that are as close as possible to those that existed during the initial testing (equally accurate and reliable radon detection device, same house conditions, same room, and same time of year if a short-term detector is used). The testing results will indicate whether an acceptable radon concentration has been achieved or if additional measures need to be taken to reduce the amount of radon in the home.

For information in determining what radon reduction system best suits a particular set of circumstances or for technical guidance on installing radon reduction systems, consult the following EPA publications: *A Citizen's Guide To Radon* (second edition; U.S. Environmental Protection Agency, 1992a), and *Consumers Guide to Radon Reduction* (U.S. Environmental Protection Agency, 1992b).

Copies of EPA publications on radon may be obtained from the EPA regional office for Nevada:

EPA Region 9
Office of Radiation and Indoor Air (A-1-1)
75 Hawthorne Street
San Francisco, CA 94105
(415) 744-1045 or 744-1046

Addresses and telephone numbers of other agencies referred to in this section:

Radiological Health Section
Nevada Division of Health
505 East King Street
Carson City, Nevada 89710
(702) 687-5394

American Lung Association of Nevada
P.O. Box 7056
Reno, Nevada 89510
(702) 829-5864

Nevada Bureau of Mines and Geology
Mail Stop 178
University of Nevada
Reno, Nevada 89577-0088
(702) 784-6691

Examples of Mitigation Systems Installed in Nevada Homes

In order to establish the feasibility of installing effective radon reduction systems in northern Nevada, NBMG documented the installation of such systems in three homes of differing foundation type, all with initially high radon concentrations. These homes are described below as House A, House B, and House C.

House A is a 70-year-old, three-story frame home in southwest Reno with an occupied basement and a crawlspace/stem wall foundation under a more recent addition. A commercial house inspector reported to NBMG radon staff that he had obtained a charcoal canister radon measurement of 99 pCi/L in the occupied basement of House A and that the occupants wanted advice on mitigation. NBMG staff did confirmatory retesting of both the basement and ground-level (first) floor of the house in January 1993, using 7-day charcoal canister detectors provided and analyzed by the EPA radon laboratory in Las Vegas, obtaining radon measurements of 67 pCi/L in a basement hallway with slightly opened windows and 106 pCi/L in a closed basement storeroom that had no windows. Ground-level first floor measurements in two rooms during the same time period in January were 39 and 36 pCi/L.

Diagnostic testing was done by NBMG radon staff working in conjunction with a local contractor listed with the EPA Radon Contractor Proficiency (RCP) program, and a radon reduction system was installed in the home by this contractor in February 1993. Mitigation consisted of two separate sub-slab depressurization systems with RadonAway DynaVac GP500 fans installed near opposite ends of the house, which has a slab area of about 1,900 square feet. Mitigation efforts were complicated by poor sub-slab communication, pervasive cracks in the slab, buried footings, finished walls, and a multi-level slab floor. A passive system of perforated drain pipe vented to the outside was also installed under a polyethylene radon barrier sealed to the foundation walls of the crawlspace. All major visible and accessible cracks in the slab were sealed using a commercial radon sealant. Total cost of the system including materials and labor was about $1,700. Post-mitigation radon retests in March 1993 using 7-day charcoal canisters yielded radon measurements of 4 and 5 pCi/L in the basement and 1 pCi/L on the first floor under closed-house conditions.

House B is an 11-year-old, three-story frame house located about 15 miles north of Sparks. The occupied lowest level of the home has a concrete slab foundation with ground contact along walls consisting of soil and bedrock less than halfway up the walls and around less than half the perimeter of the house (similar to a daylight basement). An occupant of the house contacted NBMG radon staff with the information that he had obtained a commercial charcoal canister test result of about 130 pCi/L in the lowest level of the house, and requested retesting and mitigation advice. NBMG staff retested the house in late January 1993 using 7-day charcoal canisters provided and analyzed by the EPA radon laboratory in Las Vegas. Side-by-side canisters on the lowest level yielded measurements of 167 and 178 pCi/L. A charcoal canister measurement on the next highest floor was 80 pCi/L.

After diagnostic testing, the same contractor used at House A installed a single-point sub-slab depressurization mitigation system in March 1993 on the ground/basement level of House B, which has a slab area of about 2,220 square feet. The system uses a high-suction RadonAway DynaVac HS2000 fan installed in the garage of the house. All major visible and accessible cracks in the slab were sealed using a commercial radon sealant. Total cost of the system including materials and labor was about $1,350. Seven-day charcoal canister retests in March 1993 yielded measurements of 1.2 pCi/L on the ground/basement floor and 0.8 pCi/L on the second floor.

House C is a one-story, 8-year-old, three-bedroom, single-story frame house with a soil-floored crawlspace, about 1,900 square feet in area, located about 5 miles southwest of Gardnerville at the foot of the Sierra Nevada. A charcoal canister screening test required by a relocation company prior to sale of the home resulted in a radon measurement of 10.8 pCi/L in the living room of the ground-level first floor of the house in March 1993. The client contacted a local contractor listed with the EPA RCP program, who installed a sub-membrane depressurization radon reduction system in the crawlspace of the home in April 1993. The system consisted of a RadonAway DynaVac GP500 fan installed on the outside wall of the crawlspace, attached to a network of perforated drain pipe beneath a 4-mil polyethylene radon barrier sealed to the support piers and foundation walls of the crawlspace. Subsequent radon test results were 4.1 pCi/L on the ground floor of the house, after which the contractor contacted NBMG radon staff for assistance in identifying the source of the radon problem in the home and help in remediating it. NBMG radon staff conducted continuous radon monitoring in the house for a week using a Pylon Electronics Inc. model AB-5 scintillometer and took soil gas measurements at several locations around the foundation of the home. Soil-gas radon measurements at 1.0 meter depth ranged from 3,290 to 6,050 pCi/L in soil consisting of relatively permeable decomposed granite and numerous granite boulders. The contractor subsequently installed additional perforated pipe beneath the membrane attached to a second RadonAway DynaVac GP500 fan installed in the utility room off the garage at the opposite end of the house from the other fan system. NBMG staff retested the ground floor of the home using both a charcoal canister and continuous radon monitor and obtained an average radon concentration measurement of 3.5 pCi/L over a 1-week-long test period in June 1993. Total cost of the system including materials and labor was about $1,600.

RECOMMENDATIONS

Based on the studies conducted under the EPA radon project, much has been accomplished toward verification of the existence of a significant indoor radon hazard in the state, identification of source rocks and soils, and delineation of areas of the state having high potential for indoor radon. More work is necessary, however, specifically in communities identified as high hazard areas in previous surveys and on the Indoor Radon Potential Hazard Map of Nevada (plate 1). Additional dense coverage indoor radon surveys similar to the 1992 NBMG targeted community surveys should be conducted in more communities at high hazard for indoor radon to verify and delineate the radon hazard and to alert homeowners to the existence of the radon problem. More soil gas measurements should be made in these and other areas of the state to verify the potential indoor radon hazards as depicted on the Indoor Radon Potential Hazard Map, and to establish and quantify correlations between soil-gas radon and indoor radon.

Increased educational efforts are needed to raise public awareness of the potential health risks associated with high indoor radon concentrations possible in homes across the state. According to preliminary results of a 1992-1993 CRCPD (Conference of Radiation Control Program Directors, Inc.) national radon survey, 67% of people surveyed in Nevada claimed awareness of radon, although only 37% had a knowledgeable awareness of radon (defined as knowing radon's source and that it is a health hazard), and only 5% have tested their homes for radon (Louise Hill, 1993, personal commun.). Clearly, more work needs to be directed toward increasing public awareness of the radon problem and convincing the citizens of the state to test their homes for radon, especially in high-hazard areas and communities. To accomplish this goal, all state agencies involved in radon or public health should work with each other and EPA to raise the level of awareness and testing.

Based on the results of the studies in this report of NBMG and NDOH work on radon in Nevada, the following public recommendations are in order:

1. In order to determine the radon concentration and thus the potential health hazard, all Nevadans should test their homes for radon following EPA protocol, retesting if the result is over the EPA recommended action level of 4.0 pCi/L. Radon remediation efforts should be considered if the long-term retest (or average of two short-term tests) is 4.0 pCi/L or greater.

2. Retesting should be done every few years as homes tend to settle with age, causing cracks in the foundation which may allow the entry of radon into a home. Furthermore, retesting should be done if a room is added to the home, or if the home is remodeled such that a previously unused part of the house is now habitable, such as an unfinished basement to be used for living quarters. If a new or used home is purchased, it should be tested for radon either before or as soon after the purchase as possible.

3. Variations in indoor radon concentrations should be recognized. EPA's action level of 4.0 pCi/L and their conservative analysis of the health hazard posed by indoor radon is for average exposure over a lifetime. As shown in this report, summertime measurements are almost always lower than wintertime measurements. Likewise, measurements made when the weather is extremely cold and measurements made in the lowest floor of the home or building will almost always be the highest. Although charcoal canister

radon detectors can effectively measure radon in a home over the time period for which they are used, long-term (one year) ATD measurements will give the best measure of average annual radon concentration in the home.

4. In general, the indoor radon concentration of any home can be reduced to near the average Nevada outdoor air level as called for in the long-range goals of the Indoor Radon Abatement Act. This radon concentration in outdoor air in Nevada averages about 0.4 pCi/L, and it too, can vary from place to place and with time. There is no place in Nevada, except perhaps directly over a known uranium deposit, where we suggest that no homes should be built. As long as EPA guidelines for radon resistant construction are followed, homes with low indoor radon can be built nearly anywhere in the state.

5. As seen in the studies discussed in this report, underlying geology is, in fact, a major factor in radon concentration in the indoor air of a home or building. There is a tendency for homes in areas of uranium-rich rocks and soils to have relatively high indoor radon concentrations. Nonetheless, our statewide soil gas measurements suggest that there is sufficient radon source material for indoor radon to be a problem almost anywhere in the state. Therefore, as EPA recommends, every home should be tested for radon.

6. Although radon in water has not been shown to be a problem in Nevada, this is based on limited testing of Nevada's groundwaters and springs for radon. Nevada residents should consider testing their domestic water supply if the source is a private well or small local community water system and if they are concerned that waterborne radon may be a contributing factor to high indoor air radon concentrations in their homes.

ACKNOWLEDGMENTS

Thorough and thoughtful reviews by Barry J. Solomon of the Utah Geological Survey, James K. Otton and Douglass E. Owen of the U.S. Geological Survey in Denver, and Larry J. Garside of NBMG are gratefully acknowledged. Special thanks are in order also for editor Dick Meeuwig for his thoughtful and timely assistance, composing technician Raye Buckley for her assistance in layout of tables and typesetting, and cartographer Susan Tingley for advice and assistance in the development and layout of figures and plate 1.

We would like to acknowledge the help and support of NBMG staff members who provided technical assistance, quality control, and advice on the radon project: Keryl Fleming, Gary Johnson, and Dave Jones. We also acknowledge the help of many Mackay School of Mines students who assisted in digitizing maps, computer support, maintenance of technical equipment, and telephoning radon test volunteers: Rebecca Allen, Tracy Bowers, Tina Estrada, Ken Gibson, Hoang Hong, Dung Phan, Kathleen Ward, Jennifer Winzler, and Xiaoyi Zhang.

We thank Richard D. Hopper, Tammy Kluesner, and Edith Boyd of the U.S. Environmental Protection Agency radon laboratory in Las Vegas for their technical assistance in designing the stations for measuring radon in outdoor air, for providing laboratory analyses of radon, and for assistance in the calibration of NBMG radon measurement equipment.

We also thank all school district officials in the 17 Nevada counties who graciously cooperated in providing us with reports on radon testing and mitigation done in the schools. Finally, we would like to thank all the Nevada residents across the state who volunteered to test their homes for radon, thus providing us with the body of data on which many of the conclusions of this report are based.

REFERENCES

Agricola, G., 1556, De Re Metallica: New York, Dover Publications, English reprint (Hoover translation, 1950), p. 214.

Åkerblom, G., 1986, Investigation and mapping of radon risk areas: Lulea, Sweden, Swedish Geological Company Report IRAP 86036, 15 p.

Asher-Bolinder, S., Owen, D. E., and Schumann, R. R., 1991, A preliminary evaluation of environmental factors influencing day-to-day and seasonal soil-gas radon concentration, *in* Gundersen, L. C. S., and Wanty, R. B., eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 23-31.

Ball, T. K., Nicholson, R. A., and Peachey, D., 1983, Effects of meteorological variables on certain soil gases used to detect buried ore deposits: Transactions of the Institution of Mining and Metallurgy, v. 92, p. B183-B190.

Bonham, H. F., Jr., and Bingler, E.C., 1973, Geologic map of the Reno 7½′ Quadrangle: Nevada Bureau of Mines and Geology Map 4Ag, scale 1:24,000.

Bonham, H. F., Jr., and Burnett, J.L., 1976, Geologic map of the South Lake Tahoe 7½′ Quadrangle: Nevada Bureau of Mines and Geology Map 2Ag, scale 1:24,000.

Bonham, H. F., Jr., and Rogers, D. K., 1983, Geologic map of the Mt. Rose 7½′ Quadrangle: Nevada Bureau of Mines and Geology Map 4Bg, scale 1:24,000.

Brookins, D. G., 1991, Correlation of soil radon and uranium with indoor radon in the Albuquerque, New Mexico area: Environmental Geology Water Science, v. 17, no. 3, p. 209-217.

Bruno, R. C., 1983, Sources of indoor radon in houses: a review: Journal of Air Pollution Control Association, v. 33, p. 105-109.

Clements, W. E., and Wilkening, M. H., 1974, Atmospheric pressure effects on radon-222 transport across the earth-air interface: Journal of Geophysical Research, v. 79, p. 5025-5029.

Cohen, B. L., 1985, Survey of one-year average Rn levels in Pittsburgh area homes: Health Physics, v. 49, no. 6, p. 1053-1059.

Cohen, B. L., 1986, A National survey of ^{222}Rn in U.S. homes and correlating factors: Health Physics, v. 51, no. 2, p. 175-183.

Cohen, B.L., 1987, Surveys of radon levels in homes in the United States: a test of the linear-no-threshold dose-response relationship for radiation carcinogenesis, *in* Hopke, P.K., ed., Radon and its decay products: American Chemical Society Symposium Series 331, Washington, D.C., p. 462-474.

Cohen, B. L., 1991, Variation of radon levels in U.S. homes correlated with house characteristics, location, and socioeconomic factors: Health Physics, v. 60, no. 5, p. 631-642.

Cohen, B. L., and Cohen, E. S., 1983, Theory and practice of radon monitoring with charcoal adsorption: Health Physics, v. 45, no. 2, p. 501-508.

Cothern, C. R., and Lappenbusch, W. L., 1985, Radioactivity in drinking water: Health Physics, v. 48, no. 5, p. 529-716.

Damkjaer, A., and Korsbech, U., 1985, Measurement of the emanation of radon-222 from Danish soils: The Science of the Total Environment, v. 45, p. 343-350.

Duval, J. S., and Pitkin, J. A., 1988, Interpretation of aerial gamma-ray data for Nevada: U.S. Geological Survey Open-File Report 88-288, 11 p.

Environmental Systems Research Institute, Inc., 1990, Understanding GIS - The ARC/INFO method: ESRI, Redlands, Calif.

Eisenbud, M., 1987, Environmental radioactivity — from natural, industrial, and military sources (3rd ed.): San Diego, Calif., Academic Press, p. 15-19.

Fleischer, R. L., and Turner, L. G., 1983, Indoor radon measurements in the New York capital district, *in* EML Indoor Radon Workshop, U.S. Department of Energy, Environmental Measurements Laboratory Report EML-416, New York.

Garside, L. J., 1973, Radioactive mineral occurrences in Nevada: Nevada Bureau of Mines and Geology Bulletin 81, 121 p.

Garside, L. J., 1979, Radioactive mineral occurrences in Nevada - an update to NBMG Bulletin 81. Nevada Bureau of Mines and Geology Open-File Report 79-2, 28 p.

George, A. C., 1984, Passive, integrated measurement of indoor radon using activated carbon: Health Physics, v. 46, no. 4, p. 867-872.

Gesell, T. F., 1983, Background atmospheric ^{222}Rn concentrations outdoors and indoors — a review: Health Physics, v. 45, no. 2, p. 289-302.

Grose, T.L.T., 1985, Geologic map of the Glenbrook 7½′ Quadrangle: Nevada Bureau of Mines and Geology Map 2Bg.

Grose, T.L.T., 1986, Geologic map of the Marlette Lake 7½′ Quadrangle: Nevada Bureau of Mines and Geology Map 2Cg.

Gunby, J. A., Darby, S. C., Miles, J. C. H., Green, B. M. R., and Cox, D. R., 1993, Factors affecting indoor radon concentrations in the United Kingdom: Health Physics, v. 64, no. 1, p. 2-12.

Gundersen, L. C. S., 1991, Radon in sheared metamorphic and igneous rocks, *in* Gundersen, L. C. S., and Wanty, R. B., eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 39-50.

Gundersen, L. C. S., Reimer, G. M., and Agard, S. S., 1987, Geologic control of radon in Boyertown and Easton, Pa. [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 2, p 87.

Gundersen, L. C. S., Reimer, G. M., and Agard, S. S., 1988, The correlation between geology, radon in soil gas, and indoor radon in the Reading Prong, *in* Marikos, M., ed., Proceedings of GEORAD Conference, Geological Causes of Natural Radionuclide Anomalies: Missouri Department of Natural Resources Special Publication No. 4, p. 91-102.

Harley, J. H., 1978, Radon-222 measurement: U.S. Department of Energy Environmental Measurements Laboratory Report EML-347, New York, p. 30-65.

Harting, F. H., and Hesse, W., 1879, Der Lungenkrebs, die Bergkrankheit in den Schneeberger Gruben: Vierteljahrsschrift für Medizin und Offentliche Gesundheitswesen, v. 30, p. 296-309; v. 31, p. 102-132, 313-337.

Hess, C. T., Weiffenback, C. V., and Norton, S. A., 1983, Variations of airborne and waterborne radon-222 in houses in Maine, U.S.A.: International Symposium on Indoor Air Pollution, Health and Energy Conservation, 13-16 October 1981, Amherst, Maine.

Hess, C. T., Michel, J., Horton, T. R., Prichard, H. M., and Coniglio, W. A., 1985, The occurrence of radioactivity in public water supplies in the United States: Health Physics, v. 48, no. 5, p. 553-586.

Holaday, D. A., David, W. D., and Doyle, H. N., 1952, An interim report of a health study of the uranium mines and mills by the Federal Security Agency, Public Health Service, Division of Occupational Health, and the Colorado State Department of Public Health: Washington D.C., U.S. Public Health Service.

Hopper, R. D., Levy, R. A., Rankin, R. C., and Boyd, M. A., 1991, National ambient radon study: International Symposium on Radon and Radon Protection, Philadelphia, Pa., April 1991, 16 p.

Horton, T. R., 1985, Nationwide occurrence of radon and other natural radioactivity in public water supplies: U.S. Environmental Protection Agency report 520/5-85-008, 208 p.

Houghton, J. G., Sakamoto, C. M., and Gifford, R. O., 1975, Nevada's weather and climate: Nevada Bureau of Mines and Geology Special Publication 2, 78 p.

Ingersoll, J. G., 1983, A survey of radionuclide contents and radon emanation rates in building materials used in the U.S.: Health Physics, v. 45, no. 2, p. 363-368.

Jaacks, J. A., 1984, Meteorological influences upon mercury, radon and helium soil gas emissions [Ph.D. thesis]: Colorado School of Mines, Golden, 170 p.

Johnson, M. G., 1977, Geology and mineral deposits of Pershing County, Nevada: Nevada Bureau of Mines and Geology Bulletin 89, 121 p.

King, Chi-Yu, 1978, Radon emanation on San Andreas fault: Nature, v. 271, p. 516-519.

King, Chi-Yu, 1980, Episodic radon changes in subsurface soil gas along active faults and possible relation to earthquakes: Journal of Geophysical Research, v. 85, p. 3065-3078.

King, Chi-Yu, Walkingstick, C., and Basler, D., 1991, Radon in soil gas along active faults in central California, *in* Gundersen, L. C. S., and Wanty, R. B., eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 77-143.

Kochenov, A. V., Zinev'yev, V. V., and Lovaleva, S. A., 1965, Some features of the accumulation of uranium in peat bogs: Geochemistry International, v. 2, no. 1, p. 65-70.

Kotrappa, P., Dempsey, J. C., Hickey, J. R., and Stieff, L. R., 1988, An electret-passive environmental Rn monitor based on ionization measurement: Health Physics. v. 54, p. 47-56.

Kovach, E. M., 1945, Meteorological influences upon the radon content of soil gas: Transactions, American Geophysical Union, v. 26, p. 241-248.

Kraner, H. W., Schroeder, G. L., and Evans, R. D., 1964, Measurements of the effects of atmospheric variables on radon-222 flux and soil gas concentrations, *in* Adams, J. A. S., and Lowder, W. M., eds., The natural radiation environment: Chicago, Ill., University of Chicago Press, p. 191-215.

Lico, M. S., 1991, Data for radon-222 and other radionuclides in ground water, Nevada, 1986-89: U.S. Geological Survey Open-File Report 91-488, 17 p.

Lindmark, A., and Rosen, B., 1985, Radon in soil gas - exhalation tests and in situ measurements: The Science of the Total Environment, v. 45, p. 397-404.

Lowry, J. D., Brutsaert, W. F, McEnerney, T., and Molk, C., 1987, Point-of entry removal of radon from drinking water: Journal of American Water Works Association, v. 79, no. 4, p. 162-169.

Lowry, J. D., and Lowry, S. B., 1987, Modeling point-of-entry radon removal by GAC: Journal of American Water Works Association, v. 79, no. 10, p. 85-88.

Lucas, H. F., 1957, Improved low-level alpha-scintillation counter for radon: Review of Scientific Instruments, v. 28, p. 680-683.

Lundin, F. D., Jr., Wagoner, J. K., and Archer, V. E., 1971, Radon daughter exposure and respiratory cancer, quantitative and temporal aspects: U.S. Public Health Service Joint Monograph No. 1, Washington D.C., 193 p.

Mason, B., 1966, Principles of geochemistry (3rd ed.): New York, John Wiley & Sons, 329 p.

Matti, J.C., Castor, S.B., Bell, J.W., Rowland, S.M., and McAllister, J.A., 1993, Geologic map of the Las Vegas NE 7½′ Quadrangle: Nevada Bureau of Mines and Geology Map 3Cg, scale 1:24,000.

Milvy, P., and Cothern, C. R., 1990, Scientific background for the development of regulations for radionuclides in drinking water, *in* Cothern, C. R., and Rebers, P. A., eds., Radon, radium and uranium in drinking water: Chelsea, Mich., Lewis Publishers, p. 1-16.

Mineral Resources Data System, 1993 [computer database]: U.S. Geological Survey, Branch of Resource Analysis. [Available from USGS, BORA, MS 920, 12201 Sunrise Valley Drive, Reston, VA 22092.]

Moore, J. G., 1969, Geology and mineral deposits of Lyon, Douglas, and Ormsby Counties, Nevada: Nevada Bureau of Mines and Geology Bulletin 75, 45 p.

Morrison, R. B., 1964, Lake Lahontan: geology of the southern Carson Desert, Nevada: U.S. Geological Survey Professional Paper 401, 156 p.

Morrison, R. B., and Davis, J. O., 1984, Quaternary stratigraphy and archaeology of the Lake Lahontan area: a re-assessment: Desert Research Institute Social Sciences Center Technical Report No. 41, 50 p.

Nakahara, H., Kudo, H., Akiba, F., and Murakami, Y., 1980, Some basic studies on the absolute determination of radon concentration in the air by a cellulose nitrate detector: Nuclear Instruments and Methods, v. 171, no. 1, p. 171-179.

National Council on Radiation Protection and Measurements (NCRP), 1984, Evaluation of occupational and environmental exposures to radon and radon daughters in the United States: NCRP Report 78, Bethesda, Md., 204 p.

National Council on Radiation Protection and Measurements, 1988, Measurements of radon and radon daughters in air: NCRP Report 97b, Bethesda, Md., 174 p.

National Research Council, 1988, Health risks of radon and other internally deposited alpha-emitters [BIER IV]: Committee on the Biological Effects of Ionizing Radiation, Washington, D.C., National Academy Press, 602 p.

National Research Council, 1991, Comparative dosimetry of radon in mines and homes: Washington, D.C., National Academy Press, 244 p.

Nazaroff, W. W., 1988, Predicting the rate of ^{222}Rn entry from soil into the basement of a dwelling due to pressure-driven air flow, *in* Natural Radioactivity Proceedings of the Fourth International Symposium on the Natural Radiation Environment, Lisbon, Portugal, December 7-11, 1987: Radiation Protection Dosimetry, v. 24, no. 1-4, p. 199-202.

Nazaroff, W. W., 1992, Radon transport from soil to air: Reviews in Geophysics, v. 30, p. 137-160.

Nazaroff, W. W., Doyle, S. M., Nero, A. V., and Sextro, R. G., 1987, Potable water as a source of airborne Rn in U.S. dwellings: A review and assessment: Health Physics, v. 52, no. 3, p. 281-295.

Otton, J. K., Zielinski, R. A., and Been, J. M., 1989, Uranium in Holocene valley-fill sediments, and uranium, radon, and helium in waters, Lake Tahoe-Carson Range area, Nevada and California: Journal of Environmental Geology and Water Sciences, v. 13, no. 1, p. 15-28.

Pease, R.C., 1980, Geologic map of the Genoa 7½′ Quadrangle: Nevada Bureau of Mines and Geology Map 1Cg, scale 1:24,000.

Peller, S., 1939, Lung cancer among mine workers in Joachimsthal: Human Biology, v. 11, p. 130-143.

Price, J. G., Castor, S. B., and Miller, D. M., 1992, Highly radioactive topaz rhyolites of the Toano Range, northeastern Nevada: American Mineralogist, v. 77, p. 1063-1073.

Price, J. G., Rigby, J. G., Christensen, L., Hess, R., La Pointe, D. D., Ramelli, A. R., Desilets, M., Hopper, R. D., Kluesner, T., and Marshall, S. R., 1994, Radon in outdoor air in Nevada: Health Physics (in press).

Reimer, G. M., 1991, Simple techniques for soil-gas and water sampling for radon analysis, *in* Gundersen, L. C. S., and Wanty, R. B., eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 19-22.

Reimer, G. M., Gunderson, L. C. S., Szarzi, S. L., and Been, J. M., 1991, Reconnaissance approach to using geology and soil-gas radon concentrations for making rapid and preliminary estimates of indoor radon potential, *in* Gunderson, L. C. S., and Wanty, R. B., eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 177-181.

Rigby, J. G., 1991, Radon in Nevada: a natural hazard: Nevada Bureau of Mines and Geology Educational Series No. 18, 4 p.

Rigby, J. G., and La Pointe, D. D., 1993, Wind and barometric pressure effects on radon in two mitigated houses: The 1993 International Radon Conference Proceedings, Denver, Colo., p. VI 61-68.

Rundo, J., Markun, F., and Plondke, N. J., 1979, Observation of high concentrations of radon in certain houses: Health Physics, v. 36, no. 6, p. 729-730.

Samet, J. M., 1989, Radon and lung cancer: Journal of the National Cancer Institute, v. 81, p. 745-757.

Schery, S. D., Gaeddert, D. H., and Wilkening, M. H., 1984, Factors affecting exhalation of radon from a gravelly sandy loam: Journal of Geophysical Research, v. 89, p. 7299-7309.

Sinclair, A., 1986, Statistical interpretation of soil geochemical data, *in* Exploration geochemistry: design and interpretation of soil surveys: Reviews in Economic Geology, v. 3 p. 97-115.

Smith, R. C., II, Reilly, M. A., Rose, A. W., Barnes, J. H., and Berkheiser, S. W., 1987, Radon: a profound case: Pennsylvania Geology [newsletter], The Pennsylvania Geological Survey, v. 18, no. 2, p. 3-7.

Smyth, L. B., 1912, On the supply of radium emanation from the soil to the atmosphere: Philosophical Magazine and Journal of Science, October 1912, p. 632-637.

Stannard, J. N., 1988, Radon and radon decay products: the saga of the uranium miners, *in* Radioactivity and Health — a history: Batelle Memorial Institute, Richland, Wash., chapter 3, p. 119-194.

Stewart, J. H., and Carlson, J. E., 1976, Cenozoic rocks of Nevada - Four maps and brief description of distribution, lithology, age, and centers of vulcanism: Nevada Bureau of Mines and Geology Map 52, scale 1:1,000,000.

Stewart, J. H., and Carlson, J. E., 1977, Million-scale geologic map of Nevada: Nevada Bureau of Mines and Geology Map 57, scale 1:1,000,000.

Stewart, J. H., and Carlson, J. E., 1978, Geologic map of Nevada: U.S. Geological Survey, scale 1:500,000.

Stewart, J. H., McKee, E. H., and Stager, H.K., 1977, Million-scale Geologic map of Nevada: Nevada Bureau of Mines and Geology Bulletin 88, 114 p.

Szecsody, G. C., 1983, Earthquake hazards map of the Mt. Rose NE 7½′ Quadrangle: Nevada Bureau of Mines and Geology Map 4Bi, scale 1:24,000.

Thompson, G. A., and White, D. E., 1964, Regional geology of the Steamboat Springs area, Washoe County, Nevada: U.S. Geological Survey Professional Paper 458-A, 52 p.

Toohey, R., Essling, M., Morkun, F., and Rundo, J., 1985, Radon levels in single-family houses, *in* Environmental Radiation, 1985, Proceedings of the Midyear Symposium of the Health Physics Society, Laramie, Wyo.

Trexler, D.T., 1977, Geologic map of the Carson City 7½' Quadrangle: Nevada Bureau of Mines and Geology Map 1Ag, scale 1:24,000.

Tschanz, C. M., and Pampeyan, E. H., 1970, Geology and mineral deposits of Lincoln County, Nevada: Nevada Bureau of Mines and Geology Bulletin 73, 188 p.

Turner, R. M., and Bawiec, W. J., 1991, Geology of Nevada — A digital representation of the 1978 geologic map of Nevada: U.S. Geological Survey Digital Data Series DDS-2.

Tyson, J. L., Fairy, P. W., and Withers, C. R., 1993, Elevated radon levels in ambient air: Proceedings of the 6th International Conference on Indoor Air Quality and Climate, Helsinki, Finland, v. 4, p. 443-448.

U.S. Bureau of Census, 1990a, TIGER/Line precensus files, technical documentation: Washington D.C.

U.S. Bureau of Census, 1990b, TIGER/Line precensus files [machine readable data file]: Washington D.C.

U.S. Department of Agriculture, 1991, State Soil Geographic Data Base (STATSGO) Data users guide: Soil Conservation Service National Soil Survey Center, Lincoln, Nebr., 84 p.

U.S. Environmental Protection Agency, 1987a , Radon reference manual: U.S. Environmental Protection Agency booklet EPA/520/1-87-20.

U.S. Environmental Protection Agency, 1987b (revised 1988), Radon reduction techniques in detached houses — technical guidance (2nd ed.): U.S. Environmental Protection Agency booklet EPA/625/5-87/019, 192 p.

U.S. Environmental Protection Agency, 1991, Radon-resistant construction techniques for new residential construction — technical guidance: U.S. Environmental Protection Agency booklet EPA/625/2-91/032, 43 p.

U.S. Environmental Protection Agency, 1992a, A citizen's guide to radon (2nd ed.) — the guide to protecting yourself and your family from radon: U.S. Environmental Protection Agency pamphlet ANR-464, 15 p.

U.S. Environmental Protection Agency, 1992b, A consumer's guide to radon reduction — how to reduce radon levels in your home: U.S. Environmental Protection Agency pamphlet 402-K92-003, 17 p.

U.S. Environmental Protection Agency, 1993a, EPA's map of radon zones — Nevada: U.S. Environmental Protection Agency Air and Radiation Report 402-R-048.

U.S. Environmental Protection Agency, 1993b, EPA survey: Radon level too high in one out of five surveyed schools: Emanations, Newsletter of the Regional Radon Training Centers, v. 3, no. 1, p. 7.

U.S. Geological Survey, 1984, State of Nevada [topographic map]: U.S. Geological Survey, Reston, Va., scale 1:500,000.

White, S. B., Bergsten, J. W., Alexander, B. V., Rodman, N. F., and Phillips, J. L., 1992, Indoor ^{222}Rn concentrations in a probability sample of 43,000 houses across 30 states: Health Physics, v. 62, no. 1, p. 41-50.

Wilkening, M. H., 1959, Daily and annual courses of natural atmospheric radioactivity: Journal of Geophysical Research, v. 64, no. 5, p. 521-526.

Wilkening, M. H., 1982, Diurnal, seasonal, and geographical variation of outdoor radon concentrations: Health Physics Society Summer School, Las Vegas, Nev., 20-25 June 1982.

Wilkening, M., 1986, Seasonal variation of indoor Rn at a location in the southwestern United States: Health Physics, v. 51, no. 4, p. 427-436.

Wilkening, M., 1990, Radon in the Environment: Studies in Environmental Science 40: Amsterdam, Elsevier, 137 p.

Wrixon, A. D., Green, B. M. R., Lomas, P. R., Miles, J. C. H., Cliff, K. D., Francis, E. A., Driscoll, C. M. H., James, A. C., and O'Riordan, M. C., 1988, Natural radiation exposure in UK dwellings: NRPB R190, London, Her Majesty's Stationery Office, London.

APPENDIX A.—*Radon concentration and gross alpha and gross beta particle activity in well and and spring waters in Nevada.*

County	Site number	Latitude °N	Longitude °W	Radon (pCi/L)	Gross alpha (pCi/L)	Gross beta (pCi/L)
Carson City						
NDOH[1]	1	39.1715	119.7716	—	21	17
	2	39.1866	119.7865	—	3	4
	3	39.1667	119.8049	—	14	10
	4	39.1760	119.7726	—	10.5	8.5
	5	39.1175	119.7718	—	3	5
	6	39.1400	119.7671	—	3	3
	7	39.1171	119.7683	—	5.75	5
	8	39.1989	119.7716	—	10.1	3
	9	39.1888	119.7582	—	25.5	22
	10	39.1771	119.7339	—	5	7
	11	39.1772	119.7649	—	18	9
	12	39.1158	119.7725	—	5	—
	13	39.1602	119.8024	—	3	3
	14	39.2066	119.8034	—	15	14
	15	39.2050	119.8145	—	3.5	5.5
	16	39.0986	119.7464	—	3	5
	17	39.1695	119.7594	—	25	11
	18	39.2078	119.8119	—	57	46
	19	39.1830	119.7824	—	14	9
	20	39.1268	119.7704	—	19.8	12
	21	39.2096	119.7393	—	22	20
	22	39.1640	119.7581	—	12	10
	23	39.1785	119.7663	—	18.2	—
	24	39.1322	119.7626	—	3	3
	25	39.1588	119.7509	—	3	4
	26	39.1152	119.7782	—	10	—
	27	39.1779	119.8048	—	5	5
	28	39.1234	119.7649	—	3	3
	29	39.1988	119.8059	—	3	3
	30	39.1622	119.7483	—	9.5	11
	31	39.1877	119.8073	—	23	19
	32	39.1946	119.7736	—	12	7
	33	39.1897	119.7834	—	29	16
	34	39.1611	119.7136	—	4	4
	35	39.1642	119.7057	—	3	3
	36	39.1156	119.7515	—	5	6
	37	39.1818	119.7102	—	3	3
	38	39.1579	119.7051	—	3	3
	39	39.1766	119.7874	—	9.8	9
USGS[2]	58	39.1295	119.9428	10,000	—	—
	59	39.1289	119.9420	7,700	—	—
	141	39.1639	119.7042	360	—	—
	142	39.1550	119.7186	1,100	—	—
	143 s	39.1420	119.6486	970	—	—
	166	39.1872	119.8053	14,000	—	—
	167	39.1717	119.7986	4,300	—	—
	168	39.1767	119.7875	4,400	—	—
	169	39.1609	119.8000	3,600	—	—
	170	39.1464	119.8214	14,000	—	—
	171 s	39.1375	119.8433	80	—	—
	174	39.1859	119.7020	2,600	—	—
	175	39.1900	119.7314	1,900	—	—
	176	39.2014	119.7539	2,000	—	—
	177	39.1928	119.7714	2,400	—	—
	178	39.1892	119.7714	2,300	—	—
	179	39.1770	119.7833	3,100	—	—
	180	39.1772	119.7708	4,100	—	—
	181	39.1756	119.7731	2,500	—	—
	182	39.1689	119.7814	11,000	—	—
	183	39.1847	119.7633	2,800	—	—
	184	39.1778	119.7339	2,100	—	—
	185	39.1778	119.7417	1,100	—	—
	186	39.1831	119.7128	630	—	—
	187	39.1817	119.7236	660	—	—
	188	39.1684	119.7500	2,400	—	—
	189	39.1622	119.7500	1,500	—	—

County	Site number	Latitude °N	Longitude °W	Radon (pCi/L)	Gross alpha (pCi/L)	Gross beta (pCi/L)
Carson City *(continued)*						
USGS *(continued)*	190	39.1697	119.7511	1,500	—	—
	191	39.1709	119.7520	1,500	—	—
	192	39.1692	119.7517	3,200	—	—
	193	39.1692	119.7517	1,400	—	—
	194	39.1697	119.7558	5,100	—	—
	195	39.1706	119.7639	3,200	—	—
	196	39.1661	119.7633	2,700	—	—
	197	39.1661	119.7633	2,400	—	—
	198	39.1661	119.7633	2,700	—	—
	199	39.1661	119.7633	2,600	—	—
	200	39.1662	119.7606	1,800	—	—
	201	39.1642	119.7581	2,400	—	—
	202	39.1595	119.7517	1,700	—	—
	203	39.1684	119.7825	1,500	—	—
	204	39.1628	119.7745	6,800	—	—
	205	39.1545	119.7653	1,100	—	—
	206	39.1481	119.7628	1,300	—	—
	207	39.1489	119.7581	1,400	—	—
	208	39.1545	119.7461	1,000	—	—
	209	39.1495	119.7428	1,300	—	—
	211	39.1342	119.7714	830	—	—
	212	39.1345	119.7617	1,200	—	—
	216	39.2070	119.7892	2,500	—	—
	217	39.2097	119.7778	7,100	—	—
	270	39.1895	119.7078	240	—	—
Churchill						
NDOH	40	39.4013	118.7841	—	21.8	—
	41	39.5169	118.9276	—	6	10
	42	39.4653	118.7758	—	7.7	17
	43	39.4685	118.7623	—	20	20
	44	39.4901	118.8805	—	7.8	—
	45	39.4867	118.8356	—	33.3	33
	46	39.4619	118.7474	—	6.3	18
USGS	61	39.3670	118.7617	700	—	—
	62	39.3592	118.6861	1,300	—	—
	63	39.3592	118.6861	1,100	—	—
	64	39.3592	118.6861	1,100	—	—
	65	39.3578	118.6861	1,300	—	—
	66	39.3509	118.6861	1,000	—	—
	67	39.3578	118.6861	1,300	—	—
	68	39.3564	118.6861	1,100	—	—
	69	39.3564	118.6861	1,200	—	—
	70	39.3564	118.6861	1,100	—	—
	71	39.3550	118.6858	1,100	—	—
	72	39.3550	118.6858	840	—	—
	73	39.3550	118.6858	1,400	—	—
	74	39.3536	118.6858	1,100	—	—
	75	39.3536	118.6858	1,100	—	—
	76	39.4456	118.8647	760	—	—
	77	39.4395	118.8731	480	—	—
	78	39.4378	118.8286	560	—	—
	79	39.4453	118.7858	280	—	—
	80	39.4089	118.7831	280	—	—
	81	39.4072	118.7845	580	—	—
	82	39.3759	118.8142	320	—	—
	83	39.4586	118.6967	470	—	—
	84	39.4470	118.7611	80	—	—
	85	39.4500	118.7445	470	—	—
	86	39.4448	118.7675	1,300	—	—
	87	39.4303	118.7717	270	—	—
	88	39.4164	118.7467	250	—	—
	89	39.3911	118.7150	180	—	—
	90	39.3889	118.7272	340	—	—
	91	39.3978	118.7739	540	—	—

Appendix A.—*Radon concentration and gross alpha and gross beta particle activity in well and and spring waters in Nevada (continued).*

County	Site number	Latitude °N	Longitude °W	Radon (pCi/L)	Gross alpha (pCi/L)	Gross beta (pCi/L)
Churchill *(continued)*						
USGS *(continued)*	92	39.5053	118.9111	760	—	—
	93	39.4995	119.0050	680	—	—
	94	39.5006	118.9497	1,000	—	—
	95	39.5109	118.8561	370	—	—
	96	39.4909	118.8917	700	—	—
	97	39.5014	118.8536	890	—	—
	98	39.4917	118.8186	470	—	—
	99	39.4906	118.8056	690	—	—
	100	39.4834	118.7944	500	—	—
	101	39.4767	118.8181	720	—	—
	102	39.4845	118.8789	890	—	—
	103	39.4750	118.8667	560	—	—
	104	39.4636	118.8658	460	—	—
	105	39.4706	118.8314	840	—	—
	106	39.4628	118.8350	720	—	—
	107	39.5250	118.7628	360	—	—
	108	39.5042	118.6447	500	—	—
	109	39.5284	118.7531	440	—	—
	110	39.5145	118.7328	300	—	—
	111	39.5173	118.7550	520	—	—
	112	39.5078	118.7708	240	—	—
	113	39.5011	118.6722	450	—	—
	114	39.4875	118.6683	440	—	—
	115	39.4014	118.6703	410	—	—
	116	39.4786	118.7150	650	—	—
	117	39.4856	118.7603	110	—	—
	118	39.4800	118.7550	550	—	—
	119	39.4809	118.7761	210	—	—
	120	39.4772	118.7747	80	—	—
	121	39.4670	118.7422	120	—	—
	122	39.5148	118.5597	670	—	—
	123	39.4942	118.5814	650	—	—
	124	39.4842	118.5922	720	—	—
	125	39.4895	118.6667	660	—	—
	126	39.4731	118.6650	380	—	—
	127	39.5853	118.7228	490	—	—
	128	39.5617	118.7211	2,200	—	—
	129	39.6223	118.5092	490	—	—
	130	39.6070	118.4947	550	—	—
Clark						
NDOH	47	36.1761	115.0618	—	6	5
	48	35.9617	115.1664	—	6	12
	49	36.1231	115.1627	—	7.2	—
	50	36.7780	114.0879	—	8	9
	51	36.7691	114.0927	—	4	9
	52	36.7753	114.0510	—	14	17
	53	36.6079	114.4106	—	5.1	—
	54	35.6119	115.3847	—	7.6	—
Douglas						
NDOH	55	38.9765	119.9106	—	80.2	—
	56	38.9706	119.9411	—	28.3	20
USGS	35 s	39.0203	119.9033	109	—	—
	36	39.0106	119.9472	9,500	—	—
	37	39.0086	119.9464	1,200	—	—
	38	39.0072	119.9461	16,000	—	—
	39	39.0078	119.9472	3,900	—	—
	40	39.0064	119.9478	9,900	—	—
	41	38.9828	119.9450	4,630	—	—
	42	38.9764	119.9495	1,000	—	—
	43	38.9770	119.9500	780	—	—
	44	38.9778	119.9489	2,500	—	—
	45	38.9786	119.9461	2,500	—	—

APPENDIX A.—*Radon concentration and gross alpha and gross beta particle activity in well and and spring waters in Nevada (continued).*

County	Site number	Latitude °N	Longitude °W	Radon (pCi/L)	Gross alpha (pCi/L)	Gross beta (pCi/L)
Douglas *(continued)*						
USGS *(continued)*	46	38.9686	119.9456	2,200	—	—
	47	38.9714	119.9417	2,000	—	—
	48	38.9797	119.9345	1,400	—	—
	49 s	38.9736	119.9345	4,500	—	—
	50	38.9722	119.9334	9,100	—	—
	51	38.9658	119.9472	520	—	—
	52	38.9636	119.9450	11,000	—	—
	53	39.1122	119.9422	560	—	—
	54	39.0950	119.9403	660	—	—
	55	39.0945	119.9361	180	—	—
	56	39.0953	119.9392	100	—	—
	57	39.0634	119.9403	2,720	—	—
	164	39.0953	119.7889	460	—	—
	165	39.1067	119.7847	1,200	—	—
	172	39.1134	119.8347	2,300	—	—
	173 s	39.1225	119.8197	220	—	—
	210	39.1311	119.7483	690	—	—
	213	39.1289	119.7753	930	—	—
	214	39.1156	119.7753	2,300	—	—
	215	39.1261	119.7653	1,100	—	—
	218	38.8472	119.7792	3,200	—	—
	219	38.7795	119.5925	220	—	—
	220	38.9117	119.8320	7,100	—	—
	221	38.9231	119.8036	550	—	—
	222	38.9031	119.8292	3,600	—	—
	223	38.8822	119.8064	5,600	—	—
	224	38.8845	119.8006	700	—	—
	225	38.8564	119.7542	840	—	—
	226	38.9347	119.7322	940	—	—
	227	38.9395	119.7458	1,200	—	—
	228	38.9320	119.7706	1,300	—	—
	229	38.9297	119.7770	760	—	—
	230	38.9203	119.7467	1,100	—	—
	231	38.9195	119.6967	440	—	—
	232	38.9042	119.7150	1,400	—	—
	233	38.8961	119.7475	1,500	—	—
	234	38.8981	119.7650	800	—	—
	235	38.8953	119.7547	763	—	—
	236	38.8895	119.6806	100	—	—
	237	38.8572	119.7578	1,800	—	—
	238	38.9036	119.6706	601	—	—
	239	39.0197	119.8083	700	—	—
	240	39.0061	119.8453	704	—	—
	241	39.0045	119.8336	1,130	—	—
	242	39.0106	119.8020	1,400	—	—
	243	38.9906	119.8092	546	—	—
	244	38.9547	119.7983	690	—	—
	245	39.0186	119.7120	577	—	—
	246	39.0136	119.8261	560	—	—
	247	39.0128	119.7606	460	—	—
	248	39.0017	119.7697	500	—	—
	249	39.0050	119.7608	460	—	—
	250	39.0003	119.7614	500	—	—
	251	38.9903	119.7633	790	—	—
	252	38.9786	119.7822	80	—	—
	253	38.9731	119.7736	1,200	—	—
	254	38.9672	119.7042	674	—	—
	255	38.9625	119.7108	860	—	—
	256	38.9620	119.7606	480	—	—
	257	38.9556	119.7631	350	—	—
	258	38.9453	119.7792	710	—	—
	259	38.9486	119.7217	1,000	—	—
	260	38.9511	119.6370	530	—	—
	261	38.9408	119.6311	860	—	—
	262	39.0828	119.8203	790	—	—
	263	39.0550	119.7917	880	—	—

APPENDIX A.—*Radon concentration and gross alpha and gross beta particle activity in well and and spring waters in Nevada (continued).*

County	Site number	Latitude °N	Longitude °W	Radon (pCi/L)	Gross alpha (pCi/L)	Gross beta (pCi/L)
Douglas *(continued)*						
USGS *(continued)*	264	39.1120	119.7650	2,200	—	—
	265	39.0797	119.7539	310	—	—
	266	39.0845	119.7764	940	—	—
	267	39.0425	119.7422	200	—	—
	268	39.0278	119.7720	850	—	—
	269	39.0359	119.7256	460	—	—
	271	39.1150	119.1147	1,700	—	—
	272	38.7261	119.5047	339	—	—
	273	38.6992	119.5425	1,410	—	—
	274	38.6936	119.5442	836	—	—
USGS unpbl[3]	1	38.9344	119.7323	1,300	—	—
	2	38.9039	119.7150	1,200	—	—
	3	38.9553	119.7631	960	—	—
	4	39.0841	119.7764	1,100	—	—
	5	38.7259	119.5047	1,100	—	—
Elko						
NDOH	57	41.9869	114.6692	—	3	8
	58	41.9835	114.6716	—	6	—
	59	41.9898	114.6683	—	13	12
	60	40.9402	114.3657	—	4	8
	61	40.8331	114.3909	—	3	6
	62	40.9407	114.3735	—	3	8
	63	40.7367	114.0500	—	3	6
USGS	9 s	40.7114	116.1250	530	—	—
USGS unpbl	8	40.7239	116.1197	1,000	—	—
	9	40.7125	116.1039	770	—	—
	38	41.1136	114.9625	720	—	—
	39	41.1097	114.9708	1,300	—	—
	40	41.1106	114.9658	770	—	—
	41	40.9431	114.3642	760	—	—
	42	40.9394	114.3689	470	—	—
	43	40.9214	114.3447	420	—	—
	44	40.9119	114.3353	440	—	—
	45	40.7339	114.0450	400	—	—
Esmeralda						
NDOH	64	38.0722	117.2480	—	9.2	—
Eureka						
NDOH	13	39.5568	115.9940	940	—	—
	14	39.5067	115.9583	890	—	—
	15	39.5092	115.9602	570	—	—
Humboldt						
NDOH	65	40.9689	117.4760	—	12	6.5
	66	41.1576	117.6686	—	11.7	9
	67	39.0062	119.0487	—	3.75	4.5
USGS unpbl	24	41.5689	117.7861	1,400	—	—
	25	41.5567	117.7889	1,600	—	—
	26	41.5675	117.7847	1,000	—	—
	34	40.9767	117.7389	220	—	—
	35	40.9631	117.7436	400	—	—
	36	40.9644	117.7200	1,300	—	—
	37	40.9742	117.7342	260	—	—

APPENDIX A.—*Radon concentration and gross alpha and gross beta particle activity in well and and spring waters in Nevada (continued).*

County	Site number	Latitude °N	Longitude °W	Radon (pCi/L)	Gross alpha (pCi/L)	Gross beta (pCi/L)
Lander						
USGS unpbl	1	39.5067	117.1200	1,300	—	—
	2	39.4933	117.0708	1,100	—	—
Lincoln						
USGS unpbl	3	37.6164	114.5069	780	—	—
	4	37.6169	114.5058	910	—	—
	5	37.6136	114.5158	790	—	—
	6	37.6139	114.5167	680	—	—
	7	37.6128	114.5133	800	—	—
	27	38.1944	117.0783	1,200	—	—
	28	37.9528	114.4278	1,700	—	—
	29	37.9286	114.4517	1,500	—	—
Lyon						
NDOH	68	39.4108	119.2157	—	13.2	—
	69	39.0775	119.2116	—	4.3	7
USGS	10	39.6031	119.1678	80	—	—
	11	39.5856	119.1675	720	—	—
	12	39.6478	119.1689	80	—	—
	131	39.3742	119.2725	180	—	—
	132	39.3314	119.2111	580	—	—
	133	39.3134	119.1939	480	—	—
	134	39.3025	119.2020	390	—	—
	135	39.4220	119.2845	160	—	—
	136	39.4011	119.2308	890	—	—
	137	39.3920	119.2983	340	—	—
	138	39.3867	119.2958	460	—	—
	139	39.3892	119.2525	840	—	—
	140	39.4211	119.2103	1,000	—	—
	145	39.2697	119.5664	310	—	—
	146	39.2575	119.5883	1,200	—	—
	147	39.2450	119.6170	1,800	—	—
	148	39.2384	119.5883	1,000	—	—
	149	39.2192	119.5978	690	—	—
	150	39.2167	119.6450	970	—	—
	151	39.2745	119.5558	580	—	—
	152	39.2684	119.5261	190	—	—
	153	39.2609	119.5203	320	—	—
	155	39.3067	119.4928	750	—	—
	157	39.2900	119.5306	770	—	—
	158	39.3625	119.3761	750	—	—
	159	39.3545	119.3942	960	—	—
	160	39.3356	119.4264	480	—	—
	161	39.2997	119.3528	430	—	—
	162	39.2914	119.2683	810	—	—
	163	39.3767	119.3656	630	—	—
USGS unpbl	46	38.9867	119.1669	1,300	—	—
	47	38.9872	119.1544	1,100	—	—
	48	38.9850	119.1619	920	—	—
Mineral						
NDOH	70	38.5504	118.6608	—	13	13
	71	38.5325	118.6367	—	10.24	14
	72	38.5507	118.6657	—	3	5
	73	38.5515	118.6559	—	3	6
	74	38.5617	118.6881	—	12	—
	75	38.4814	118.6715	—	26	16
	76	38.5680	118.6815	—	15.5	13
	77	38.5652	118.6763	—	9	8
	16	38.3797	118.5508	2,200	—	—
	17	38.3847	118.5464	3,200	—	—
	18	38.5186	118.6311	1,100	—	—

Appendix A.—*Radon concentration and gross alpha and gross beta particle activity in well and and spring waters in Nevada (continued).*

County	Site number	Latitude °N	Longitude °W	Radon (pCi/L)	Gross alpha (pCi/L)	Gross beta (pCi/L)
MINERAL *(continued)*						
NDOH *(continued)*	19	38.5114	118.6347	1,000	—	—
	20	38.5258	118.6247	1,000	—	—
Nye						
NDOH	78	36.2117	115.9943	—	5.5	4
	79	38.6974	117.1575	—	3.5	3
	80	38.5353	117.0654	—	20.3	10
	81	38.7114	117.0676	—	5	—
USGS	275	36.7711	116.6900	430	—	—
	276	36.7661	116.6883	320	—	—
	277	36.7661	116.6917	410	—	—
	278	36.7658	116.6931	460	—	—
USGS unpbl	30	38.1944	117.0783	1,600	—	—
	31	38.2106	117.0736	1,400	—	—
	32	38.2117	117.0742	1,100	—	—
	33	38.0686	117.2292	680	—	—
Pershing						
USGS unpbl	21	40.3325	118.2853	1,600	—	—
	22	40.3364	118.2767	2,000	—	—
	23	40.2133	118.3878	1,600	—	—
Storey						
USGS	144 s	39.2836	119.6825	250	—	—
	154	39.3270	119.5308	620	—	—
	156	39.3106	119.5514	750	—	—
Washoe						
NDOH	82	40.6511	119.3573	—	43	—
	83	40.7634	119.4654	—	189	93
	84	40.7537	119.4437	—	77	51
	85	40.7431	119.4367	—	77	41
	86	39.3963	119.7954	—	21	16
	87	39.6314	119.7251	—	7	6
	88	39.5339	119.7931	—	3	7
	89	39.4443	119.7789	—	3	6
	90	39.5309	119.7872	—	3	5
	91	39.5152	119.7557	—	3	5
	92	39.4815	119.7741	—	3	5
	93	39.4842	119.7795	—	3	6
	94	39.3463	119.7797	—	3	5
	95	39.4635	119.7813	—	23	5
	96	39.5289	119.7625	—	3	5
	97	39.5281	119.7627	—	3	5
	98	39.5159	119.8510	—	7	10
USGS	1	40.2820	119.7836	250	—	—
	2	40.4875	119.8070	740	—	—
	3	40.5803	119.7297	690	—	—
	4 s	40.7520	119.6983	450	—	—
	5 s	40.7062	119.7292	80	—	—
	6	40.7212	119.4825	1,700	—	—
	7 s	40.8117	119.8742	260	—	—
	8	40.8392	119.5458	980	—	—
	13	39.5870	119.7375	420	—	—
	14	39.6339	119.6753	880	—	—
	15	39.6378	119.7033	790	—	—
	16	39.4131	119.7958	820	—	—
	17	39.3992	119.8125	630	—	—
	18	39.3756	119.8386	660	—	—
	19	39.4553	119.7761	880	—	—
	20	39.4436	119.7789	870	—	—

APPENDIX A.—*Radon concentration and gross alpha and gross beta particle activity in well and and spring waters in Nevada (continued).*

County	Site number	Latitude °N	Longitude °W	Radon (pCi/L)	Gross alpha (pCi/L)	Gross beta (pCi/L)
Washoe *(continued)*						
USGS *(continued)*	21	39.4186	119.7728	1,200	—	—
	22	39.4014	119.7292	650	—	—
	23	39.3953	119.7878	1,000	—	—
	24	39.3770	119.7395	830	—	—
	25	39.5345	119.7911	560	—	—
	26	39.5389	119.7636	570	—	—
	27	39.5245	119.7870	680	—	—
	28 s	39.3228	119.9334	800	—	—
	29	39.3334	119.8928	4,100	—	—
	30	39.3481	119.7867	2,900	—	—
	31	39.2767	119.7900	500	—	—
	32 s	39.2867	119.8678	2,600	—	—
	33	39.2603	119.8222	910	—	—
	34	39.3047	119.8303	12,000	—	—
	60	39.6017	119.8742	640	—	—
Westpac[4]	1	39.4434	119.7795	570	—	—
	2	39.4619	119.7795	506	—	—
	3	39.4688	119.7826	535	—	—
	4	39.4703	119.8078	570	—	—
	5	39.4806	119.7680	520	—	—
	6	39.5108	119.7771	423	—	—
	7	39.5148	119.7573	462	—	—
	8	39.5229	119.7566	644	—	—
	9	39.5281	119.7630	575	—	—
	10	39.5287	119.7629	655	—	—
	11	39.5200	119.7843	773	—	—
	12	39.5366	119.7763	877	—	—
	13	39.5349	119.7855	678	—	—
	14	39.5328	119.7852	353	—	—
	15	39.5308	119.8017	495	—	—
	16	39.5268	119.8044	930	—	—
	17	39.5324	119.7602	887	—	—
White Pine						
USGS unpbl	10	39.2544	114.8769	1,500	—	—
	11	39.2481	114.8656	1,100	—	—
	12	39.2469	114.8944	1,500	—	—

[1]NDOH = Nevada Division of Health, Water Systems Engineers
[2]USGS = Lico, 1991
[3]USGS unpbl = USGS unpublished data (Michael Lico, personal commun., 1992)
[4]Westpac = Westpac Utilities data (Ron McHenry, personal commun., 1992)
s = spring, all the remaining sites are wells
— = no data

The Nevada Bureau of Mines and Geology (NBMG) is a research and public service unit of the University of Nevada and is the state geological survey. NBMG is part of the Mackay School of Mines at the University of Nevada, Reno. NBMG scientists conduct research and publish reports on mineral resources, engineering geology, environmental geology, hydrogeology, and geologic mapping. Individuals interested in Nevada geology are encouraged to visit, call, or write NBMG or visit our homepage at **www.nbmg.unr.edu.**

When visiting NBMG by car, please stop at the information booth just inside the Center Street entrance on the south end of the Reno campus of the University of Nevada. Ask for the Mackay School of Mines map and directions to parking areas and the NBMG offices in the west wing of the Scrugham Engineering-Mines building. Free parking for Publication Sales Office customers is located on the southwest corner of Palmer Engineering building.

Information Office (room 311)
Publication Sales Office (room 310)

Store hours: 7:30 a.m. to 3:00 p.m., Monday through Friday
(open until 5:00 p.m. on Tuesdays)

NBMG publications and maps, U.S. Geological Survey maps, and related publications can be purchased at the Publication Sales Office or ordered over the Internet at **www.nbmg.unr.edu/sales.htm.**

Orders for publications or requests for information may also be made by telephone, fax, e-mail, or U.S. Mail.

Orders:	(775) 784-6691 x2
Information:	(775) 784-6691 x133
Phone hours:	7:30 a.m. to 4:15 p.m., Monday through Friday
Fax:	(775) 784-1709
e-mail: (orders)	nbmgsales@unr.edu
(information)	nbmginfo@unr.edu
U.S. Mail:	Nevada Bureau of Mines and Geology Mail Stop 178 University of Nevada Reno, NV 89557-0088

HIGH HAZARD — Any one of the following:

1. soil or geologic unit with uranium content equal to or greater than 4.0 parts per million equivalent uranium (ppm eU),
2. any indoor radon measurement equal to or greater than 20.0 picocuries per liter (pCi/L),
3. average indoor measurement equal to or greater than 4.0 pCi/L, or
4. 25% of homes measured equal to or greater than 4.0 pCi/L.

INTERMEDIATE HAZARD — Any one of the following:

1. soil or geologic unit with uranium content equal to or greater than 2.0 ppm and less than 4.0 ppm eU,
2. any indoor radon measurement equal to or greater than 4.0 pCi/L and less than 20.0 pCi/L, or
3. average indoor measurement equal to or greater than 2.0 pCi/L and less than 4.0 pCi/L.

LOW HAZARD — Any one of the following:

1. soil or geologic unit with uranium content less than 2.0 ppm eU,
2. no indoor radon measurement greater than 4.0 pCi/L, and
3. average indoor measurement less than 2.0 pCi/L.

The purpose of this map is to assist state, county, and local agencies and organizations in the targeting of resources and in the implementation of radon-resistant building codes. This map should not be used to determine whether a particular home in a given hazard zone should be tested for radon. Homes with elevated radon have been found in all three hazard zones and all homes should be tested for radon regardless of geographic location.

Scale 1:1,000,000

0 10 20 30 40 50 60 70 80 kilometers

0 10 20 30 40 50 miles

CONTOUR INTERVAL 1000 FEET

INDOOR RADON POTENTIAL HAZARD MAP OF NEVADA

Base map: Nevada Bureau of Mines and Geology Map 43, 1972