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SURVEY OF RESIDENTIAL INDOOR AND OUTDOOR RADON CONCENTRATIONS IN CALIFORNIA

FINAL REPORT

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Kai-Shen Liu, Ph.D., M.P.H., Steven B. Hayward, Ph.D., John R. Girman, M.S.[*], Barbara A. Moed, M.S.[**], and Fan-Yen Huang, M.S.

California Indoor Air Quality Program
Air & Industrial Hygiene Laboratory
California Department of Health Services
2151 Berkeley Way
Berkeley, CA 94704

* Geo-Radon Services
P.O. Box 15
Guerneville, CA 95446

** California Public Health Foundation
2001 Addison Street, Suite 210
Berkeley, CA 94704

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ABSTRACT

A study was conducted to determine the annual average radon concentrations in and near California residences, to determine the approximate fraction of the California population regularly exposed to residential radon concentrations exceeding 4 pCi/l and 8 pCi/l, and to the extent possible, to identify factors (such as geologic region or building type) which may be useful in predicting high risk areas or groups in California. Annual average indoor radon concentrations were measured with passive (alpha track) samplers sent by mail and deployed by home occupants, who also completed questionnaires on building and occupant characteristics. One quarter of the households also deployed an outdoor sampler. The geographic areas sampled included the Salinas/Santa Cruz area (pretest area - 38 residences), the entire state (310 residences), and portions of the southern Sierra Nevada foothills (37 residences). A subset of the residences was studied in detail to determine factors affecting indoor radon concentrations.

Results of pretest indoor measurements ranged from 0.2 pCi/l to 5.9 pCi/l, with geometric means of 0.85 pCi/l in bedrooms, and 0.93 pCi/l in living rooms. For the statewide main survey, indoor radon concentrations ranged from 0.1 pCi/l to 16 pCi/l, with a geometric mean of 0.83 pCi/l in bedrooms and 0.85 pCi/l in living rooms. When the whole-house value was calculated by averaging the concentrations in the bedroom and living room, the geometric mean was 0.85 pCi/l and the geometric standard deviation was 1.91. The geometric mean of the concentrations in the 27 basements measured was 2.17 pCi/l, which was significantly higher than that of whole-house concentrations. Whole-house, annual average indoor measurements in the Sierra foothills area ranged from 0.4 pCi/l to 8.8 pCi/l with a geometric mean of 1.28 pCi/l. The geometric mean of annual average outdoor radon concentrations was 0.55 pCi/l for the pretest area, 0.42 pCi/l for the statewide survey, and 0.66 pCi/l for the southern Sierra foothill area. The estimated fractions of California residents exposed to radon concentrations exceeding 4 pCi/l and 8 pCi/l are 0.8% and 0.03% respectively. The estimated number of residents exposed to concentrations exceeding 4 pCi/l is 240,000, and the expected number of residents exposed to concentrations exceeding 8 pCi/l is 8,900.

The best single predictor of indoor radon concentrations found in this study was the emanation rate of radon from soil. Other variables found to be associated with indoor concentrations were geographic region, ventilation, type of substructure, type and age of residence. In addition to the Sierra foothills, Ventura County was identified as an area with elevated radon concentrations. Residences with rarely-opened windows and doors, dwellings with a concrete slab, single-family houses, and new structures were found in general to have higher radon concentrations.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SECTION 1. INTRODUCTION

1.1. Statement of the Problem

1.1.1. Legal Mandate

This research was conducted to develop the data necessary to assist the California Air Resources Board (ARB) in assessing residential indoor and outdoor radon concentrations in California. As required by the California Health and Safety Code (HSC) Chapter 3.5, the ARB, in consultation with the California Department of Health Services (DHS), evaluates the public health risk of substances which are being considered for possible identification as toxic air contaminants (TACs). HSC Section 39660.5 requires the ARB to consider indoor exposures as well as outdoor exposures in conducting risk assessments for the TACs Program. Under HSC Sec. 39655, the ARB is specifically required to identify as toxic air pollutants those substances which have been designated as hazardous air pollutants under Section 7412 of Title 42 of the United States Code. Radionuclides, which include radon, have been so designated under the federal program. Because indoor exposure to radon progeny may result in a cancer risk many times higher than that from outdoor exposure to all radionuclides combined, it is important that the ARB obtain additional data regarding indoor radon concentrations in California prior to including radionuclides in the TACs Program.

1.1.2. Health Effects and EPA Guidelines

Radon itself poses a relatively insignificant health risk even though it is radioactive, since it is a noble gas, and therefore has a short residence time in the lung. However, radon decays into a series of other short-lived elements, all of which are are solids, and are also radioactive. These elements, or radon progeny, include two isotopes of polonium, both of which emit high energy alpha radiation. These isotopes have short half-lives relative to the time it takes for the body's clearance mechanism to remove them from the lung, so that when atoms of polonium are inhaled, they can decay and emit alpha particles in the lung. These alpha particles can damage the lining of the respiratory tract and subsequently cause lung cancer.

According to an estimation by the U. S. Environmental Protection Agency (U.S.EPA), approximately 5,000-20,000 deaths per year may be attributed to average concentrations of indoor radon (1). Indoor concentrations have been shown to vary by several orders of magnitude within each of several study areas throughout the United States and Europe (2). At average concentrations (1-1.5 pCi/l), the individual lifetime risk is usually estimated to be approximately 0.2%, or 2,000 cases per million population. A substantial fraction of this aggregate risk (10-30%) is borne by those who have resided for many years in residences which have concentrations exceeding 8 pCi/l. This is estimated to occur in 1-3% of the U.S. stock of single-family houses (3).

The U.S.EPA has recommended that residences with annual average radon concentrations exceeding 4 pCi/l be modified within a reasonable time to reduce those concentrations, that homes with concentrations greater than 20 pCi/l be modified quickly, and that homes with concentrations greater than 200 pCi/l be modified immediately (1). Reduction of annual average radon concentrations to just below 4 pCi/l can be relatively simple and inexpensive, but reducing radon concentrations much further becomes difficult and expensive. However, mitigation to concentrations lower than 4 pCi/l may become more viable in the future since mitigation of elevated radon concentrations is still an area of active research. Recently the U.S. Congress mandated that the U.S.EPA set a national goal of reducing radon concentrations in buildings to the ambient level.

1.1.3. Prior Studies in California

Prior to this study, no statewide survey of radon concentrations in residences had been carried out in California. The average concentrations measured in several smaller, regional, annual studies conducted in California are approximately equal to or less than that for the country as a whole. The average radon concentration measured by the Lawrence Berkeley Laboratory in 55 residences from Alameda, Merced, San Joaquin and Stanislaus Counties was 1.18 pCi/l (4). The median value of the 86 residences measured by Los Angles County using their employees living in the counties of Los Angeles and Orange was 0.6 pCi/l (5). The arithmetic mean and geometric mean radon concentration measured in the residences of 436 *Los Angeles Times'* employees living in the Counties of Los Angeles, Orange, Riverside, San Bernardino and Ventura were 0.90 and 0.67 pCi/l respectively (6). Since none of these studies covered the entire State, which is geologically and climatically diverse, these results cannot be generalized to the entire State. Thus, while radon exposures are expected to pose significant health risk to the general public, appropriate exposure data are lacking for risk assessment to demonstrate this. This ARB-funded study is the first study in which a distribution of statewide radon concentrations has been obtained.

1.1.4. Factors Influencing Indoor Radon Concentrations

Soil is the source of most radon to which people are exposed. In fact, soil is the ultimate origin of radon even when other immediate sources are of significance. These other sources include building materials that originate from the earth's crustal materials, water, natural gas, and outdoor air. However, in most cases these sources contribute little to indoor concentrations (7).

A schematic representation of the key elements of soil as a source of indoor radon is presented in Figure 1-1. Two main determinants of indoor radon concentrations are presented in this figure: radon generation or availability, which is the amount of radon gas available within the soil; and radon transport, which is the movement of the radon in the soil and from the soil into the building structure. The boxes represent the major stages, from the generation of radon in soil to its entry into a building. Labels on horizontal arrows indicate a characteristic of the soil that is a measure of how readily radon moves from one stage to the next, while labels on vertical arrows indicate parameters and processes that significantly influence the rate of transition from one stage to another. Finally, labels on diagonal arrows indicate paths by which radon generated in soil may fail to enter a building.

As this figure illustrates, many factors influence indoor radon concentrations for which soil is the source. At this time, predicting whether a specific residence is likely to have high radon levels is not feasible. However, since the principal cause of high radon concentrations indoors appears to be pressure-driven flow of soil gas with high radon content (7), residences built on soil with high radium content and/or high permeability to air are expected to have the highest potential for high levels of radon (8).

As also shown in Figure 1-1, meteorology and substructure type influence the amount of radon-containing soil gas that enters a residence. Soil gas flow is enhanced when the pressure in the lower portion of the residence is lower than the pressure in the soil (9). This pressure difference can be caused by several factors, including the stack effect (caused by the rising of heated air), which occurs when the building interior is warmer than the outdoor environment, the operation of exhaust fans, the operation of combustion appliances without outdoor sources of combustion air, and the action of wind on the structure. Residences with basements, with slabs-on-grade containing cracks in the concrete interfaced with the soil, or with unventilated crawl spaces are likely to have higher soil gas entry rates than are residences with ventilated crawl spaces or foundations without cracks.

1.2. Project Objectives

The objectives of this study are listed below in the order of priority:

1. To determine the annual average radon concentrations in and near California residences.

2. To determine the approximate fraction of the California population regularly exposed to residential radon concentrations greater than 4 pCi/l and 8 pCi/l.

3. To the extent possible, to identify factors (such as geologic regions or building types) which may be useful in predicting high risk areas or groups in California for focusing future investigations.

Three specific hypotheses were also tested in this study:

1. The geometric mean of radon concentrations measured in California residences is not higher than that estimated by Nero *et al.* (3) to apply to residences throughout the United States.

2. The fractions of California residences with radon concentrations exceeding 4 pCi/l and 8 pCi/l are not larger than 7% and 1.3%, respectively, which are those estimated by Nero *et al.* (3) for the United States.

3. Radon concentration distributions are not the same for different geologic regions and various types of buildings.

SECTION 2. STUDY METHODOLOGY

2.1. Study Design

This study of residential indoor and outdoor radon concentrations had several major components, which included (1) a pretest, (2) a main survey of statewide, randomly-selected residences, (3) a focused survey of residences within or near the southern Sierra foothills, and (4) field work on a subset of the residences (Fig. 2-1). A search for a sampling frame for selecting a state-wide sample of dwellings found no single, central registry in which the addresses of all California residences are available. However, since nearly all households have at least one motor vehicle, the vehicle registration records maintained by the California Department of Motor Vehicle (DMV) contains almost all addresses of California residences. Currently, approximately 20 million private vehicles are registered with the DMV. Approximately 400,000 annual renewal notices are mailed weekly from the DMV to car owners to collect registration fees. Neither the location nor the type of owner's residence is likely to be related to the due date of their auto registration fee. The weekly mailing addresses of car owners is an ideal sampling frame for this state-wide survey. Therefore ten computer tapes which contained one week's mailing addresses were acquired from the Data Processing Unit of the DMV.

The pretest was designed to monitor 40 residences in Santa Cruz and Monterey Counties prior to the main survey. This area was chosen because of its proximity to Berkeley, and because geologic considerations suggested that it may be an area of elevated radon concentrations. The results of the pretest were used to determine the response rate to the recruiting letter, to improve instructions about sampler placement, and to modify the self-administered questionnaire for the main survey.

The main survey was designed to monitor 360 homes which were selected from the entire state. The annual radon concentrations measured in this sample of residences were used to determine the central tendency of the statewide distribution of radon concentrations and to estimate the fraction of California residences having radon concentrations exceeding 4 pCi/l and 8 pCi/l.

In addition to the 360 residences selected statewide, 40 residences were chosen from Fresno, Tulare, Mono and Inyo Counties. The towns from which the residences were chosen were within or near the western and eastern foothills of the southern Sierra Nevada. Geological and geochemical considerations, as discussed in the next paragraph, led to the selection of the towns included in this focused study. The sample size of 40 residences yields a statistical power of over 60% to detect an average increase of 0.3 pCi/l. In other words, if the increase were exactly 0.3 pCi/l, the likelihood that it would be detected with a sample of this size is 6 out of 10.

High risk radon areas are related to geology, which influences the radon generation rate and the characteristic migration distance for radon in the soil surrounding a building, as indicated in Figure 1-1. The primary factors controlling the concentration of radon in soil gas are the radium concentration, the radon emanation rate, and the porosity of the soil. Either the expected or the remotely-measured radium concentrations were used in this study to select several areas suspected to have higher than average radon generating rates. For the expected radium concentrations, we used the mean radium contents of the predominant rock types as found in the literature (generally as the uranium concentration, which can be related to radium by a constant). For the remotely measured radium concentrations, we used the National Airborne Radiometric Reconnaissance (NARR) data. This database contains continuous aerial measurements of bismuth-214 (Bi^{214}), a rapid decay product of radon-222 (Ra^{222}) along more than one million flight miles throughout the U.S., and is described in Moed, *et al.*, 1984 (10). Bi^{214} emits gamma radiation, which is ionizing, electromagnetic radiation of energies between 10 thousand electron volts (keV) and 9 million electron volts (MeV) produced by the nuclei as they decay. The bismuth-214 measurements were used to compute uranium-238 concentrations during the NARR program. The unit area of investigation for data acquisition during that program was the national topographic map series of one degree (of latitude) by two degrees (of longitude) quadrangles. The aerial gamma-spectrometric data reported by the NARR program involved grouping those measurements performed above each geologic map unit within each quadrangle, and reporting the arithmetic mean and standard deviations for uranium-238.

We used either the uranium statistical tables from NARR as remotely measured radium or the expected radium contents from the literature, one degree by two degree geologic maps (1:250,000), the U.S. Postal Service's 1987 National Zip Code and Post Office Directory, and county and city street maps to select zip codes for sampling areas that were likely to have higher-than-average radon generating rates. Permeability of soil to air, an important characteristic that influences the distance radon may move from where it is produced in soil, was not used as a predictor for site selection in this study due to the limited funds available. Rather, permeability to air was examined as a variable in the data analysis of the study.

Of all the residences monitored, 60 were visited by our team members. Among the 60 residences, 10 were in the pretest area, 25 were in the foothills of the Sierra Nevada Mountains, and 25 were distributed statewide. These visits included checking the placement of samplers, validating the questionnaire, measuring the permeability to air and radon concentration of soils near the residence, collecting soil samples, and gathering water samples if the water supply was from a private well.

2.2. Pretest

The objectives of the pretest were discussed above in Section 2.1. The pretest was conducted in an area selected for three reasons: diversity with respect to factors believed to be determinants of radon concentrations; proximity to our location (to minimize travel costs and to maximize support); and diversity with respect to socio-economic factors. The geologic setting selected for the pretest was also believed to be among those with high potential for elevated indoor radon concentrations relative to the rest of California. The existence of outcrops of granitic rocks, which in general have higher radium concentrations than other types of rocks, of Mesozoic age

(65 - 225 million years ago) in the mountains of this area suggested that local soils may contain relatively more radium than other parts of northern California. Mesozoic granites occur at Ben Lomond and Bald Mountains north of Santa Cruz, Pacific Grove, Carmel Highlands, and the northern end of the Gabilan Range, which is east of Salinas. This speculation was also supported by NARR remotely measured radium contents as reported in Moed, *et al.*, 1984 (10), which show slightly elevated radon north of Santa Cruz and in the Gabilan Range. The cities and towns from which the zip codes were chosen for the pretest were Salinas, Carmel, Carmel Valley, Ben Lomond, Pacific Grove, Santa Cruz, and Boulder Creek. The numerical aspects of the selection process are described in the following paragraph.

A total of 2124 addresses in the specified zipcode zones were selected from the DMV's list. Among them, addresses of 802 residences were randomly selected to recruit volunteers. A recruiting letter and a mini-questionnaire were sent to these residences in mid-September, 1987. Sixteen letters were returned because of invalid addresses. Of the 786 recipients, 168 responded by returning the mini-questionnaires within a month. Eighteen of the respondents indicated in the mini-questionnaires that they were not interested in participating in this survey. One hundred and fifty were willing to be part of the study. The final number of residences included in the pretest was 43, of which 40 were randomly selected and 3 were selected from the low-income-stratum (Table 2-1).

Indoor radon samplers, along with a cover letter, instruction sheet, survey questionnaire, and return envelope, were mailed to each of the 43 residences in mid-October, 1987 (see Appendix A). Since the master bedroom and the living room (or main activity room) were to be monitored for radon, each participant received at least two samplers. In addition, four residences had a basement. Therefore extra samplers were sent to those homes to be placed in the basement. Duplicate samplers were placed in four of the 43 living rooms, one of the four basements, and 20 of the 43 master bedrooms. All of the indoor radon samplers were to be exposed for one year, except for the extra sampler in the master bedroom. Occupants were asked to return these after two months. Information obtained on the returning of the two-month samplers was used to improve the main survey. Outdoor radon samplers were sent to ten residences by the end of November, 1987, with half receiving one and the other half receiving two outdoor samplers. These outdoor samplers were also to be in place for one full year. All duplicates of indoor and outdoor samplers were to be installed side by side.

Among the 43 residences selected, ten were visited for intensive study. Two clusters in the pretest area were visited to increase the range of both geologic settings and building construction types sampled. Five houses in Santa Cruz and Boulder Creek were visited; another five in Salinas, Carmel, and Pacific Grove were visited.

2.3. Statewide Survey

Approximately 5,500 addresses were randomly selected from the ten computer tapes with the constraint that only 20 addresses were chosen from each of the 274 of the 287 "zip code areas" which had more than 20 records. For the 13 zip code areas which had less than 20 records in our database, all addresses were chosen. Here a zip code area was defined by the first four digits of the five digit zip code, creating a contiguous geographic cluster. This way of selecting addresses would guarantee a sample of residences that had a wide coverage of areas and was still population-related. A recruiting letter and a mini-questionnaire were sent to the addressees in early February 1988, asking for response within two weeks. At the end of February, over 1,000 letters had been returned. Three hundred thirty-two were undeliverable, 176 residents were not interested, and 846 were interested in participating in the radon survey. At this point, there were some zipcode areas without a positive response. For each of the zip code areas without a volunteer, 25 new addresses were selected for a second mailing, so that in early March, a total of 500 additional recruiting letters were mailed in an attempt to obtain at least one volunteer from each of the 20 zipcode areas without a volunteer.

By mid-March, 961 recipients had responded positively to our request (Table 2-2). Only one zip code area (9005X) had no positive response. For each zip code area, one volunteer was randomly chosen, based on the probabilities assigned to each household according to the reciprocal of the number of registered motor vehicles (e.g., households whose mini-questionnaire indicated that there were two registered vehicles had only half of the chance to be chosen as a household with only one registered vehicle). Seventy-three volunteers were chosen randomly, again from the 287 zip code areas based on the assigned probabilities, to complete the selection of 360 residences. At the end of March, a cover letter, instructions, radon samplers, a survey questionnaire and a return envelope were mailed to each of the 360 volunteers selected. All participants received at least two indoor radon samplers, one to be placed in the master bedroom and the other in the main activity room. Duplicates were placed in 10% of the main activity rooms. All residences having a basement received an additional indoor sampler to be placed in the basement. Duplicates were also placed in 25% of the basements. Outdoor radon samplers were sent to 25% of the 360 residences, with 10% of these residences receiving duplicate outdoor samplers. The participants were instructed to deploy the radon samplers in early April, 1988.

2.4. Sierra Foothills

The areas selected for denser sampling during the focused survey were chosen based on expected or remotely measured radium content of rocks. Several towns were selected from the eastern San Joaquin Valley (Orange Cove, Woodlake, Dinuba, Reedley, and Sanger), the western foothills of the southern Sierra Nevada Mountains (Three Rivers, Auberry, Shaver Lake, Hume, Dunlap, Badger, Miramonte, Tollhouse, and Squaw Valley) within Fresno and Tulare Counties, and from the Owens Valley (Big Pine, Independence, Lone Pine, Bishop) and Mammoth Lakes east of the Sierra Nevada in Mono and Inyo Counties. Mesozoic granites and granodiorites, which are some of the more radioactive rocks in California, as reported by Wollenberg and Smith, 1972 (11), are ubiquitous to the north, northeast and east of the group of towns in the San Joaquin Valley as stated in the California Division of Mines and Geology, 1965 (12). This group of towns is located on Recent alluvial fan deposits and Pleistocene channel deposits that are probably weathered from Mesozoic granites. These types of deposits tend to be coarse-grained, which implies moderate to high permeability. Soils of granitic origin and moderate permeability suggest elevated indoor radon concentrations. The group of towns located in the western Sierra foothills are located on Mesozoic granites. The group of towns east of the Sierra Nevada in Mono and Inyo Counties are surrounded by Mesozoic metavolcanic rocks and Pleistocene rhyolite and pyroclastic rocks. Rhyolite has a high expected radium content. The NARR data show measured radium contents to be high over these rocks. The zip codes corresponding to the geologically-selected towns were obtained and used for selecting residences for site visits.

A total of 487 addresses were selected from the specified areas in the Counties of Fresno, Tulare, Mono and Inyo for volunteer recruitment. In mid-March, sixty of the recipients of our recruiting letter responded positively. Forty were chosen randomly from the 60 volunteers to be included in this survey (Table 2-3). The procedures for the placement of indoor and outdoor radon samplers were the same as the main, statewide survey.

2.5. Survey Questionnaires

As stated earlier, two questionnaires were used in this study. A mini-questionnaire was sent with the recruiting letter, and then later a long questionnaire was mailed with the radon samplers to the participants. Copies of the mini-questionnaire and long questionnaire are shown in Appendix B. Questions included in the mini-questionnaire concerned residents' knowledge about the radon problem, their willingness to be participants of this study, whether they planned to move within a year, the type of residence and its substructure, the market value of their residence, the annual household income, and the number of registered motor vehicles. This information was collected to aid in selection of residences and to allow comparison of the characteristics of the participants with the general public. Only respondents who did not plan to move within a year were selected to be included in this survey.

The main questionnaire was designed to obtain information on housing characteristics and household activities potentially associated with indoor radon concentrations. Information solicited included the type and age of the residence, detailed information on the substructure, the source of drinking water, the number and use of exhaust fans, opening of windows and doors, cooling and heating of indoor air, the number of permanent residents, and the number of tobacco smokers. The instructions requested that the questionnaire be answered by the head of the household and sent back after the radon samplers had been placed.

2.6. Site Visits

The staff made site visits for three purposes: (1) to determine the extent to which the instructions for sampler placement had been followed; (2) to determine the extent to which questionnaires had been answered correctly; and (3) to measure the permeability to air and the radon content of soil gas, and to take soil and water samples. Activities toward the first two purposes were quality assurance and quality control exercises related to the three objectives of this project. Measurements and sampling carried out toward the third purpose resulted in the collection of data on possible determinants of indoor radon concentrations, thereby addressing the third objective of this project: to identify factors which may be useful in predicting high risk areas in California. Site visits were conducted during both the pretest and the main surveys.

During the pretest, ten residences were visited: five in Santa Cruz and Boulder Creek; and five in Salinas, Carmel, and Pacific Grove. During the main survey, 50 were selected for intensive on-site study. Half of the residences visited were drawn from the Fresno, Tulare, Mono, and Inyo County sample, and half were drawn state-wide, but from the remaining counties.

2.7. Measurement Methods

Methods of field measurements and sampling are discussed in this section. These include measurements performed using a mailout approach at all houses, measurements made and sampling procedures used during site visits to the 60 intensively studied houses, and the measurement methods used in the laboratory. Table 2-4 lists the instrumentation used during this project.

2.7.1. Air Measurements

In this study, the EPA's "follow-up measurement" of radon (13) was adapted. This measurement is made over a long period of time, in this case a year. Annual measurements integrate diurnal and seasonal variations in indoor radon concentrations. EPA recommends that the residence be operated normally to measure the concentrations that people would actually be exposed to over that period. This is clearly consistent with the objectives of this study, *i.e.*, determining annual average radon concentrations in and near residences for use in exposure assessments.

The only type of sampler recommended by the EPA for annual average measurements at the time the study was initiated was the alpha-track detector. The supplier of the alpha-track sampler employed in this study (the Rad-Trak) is Tech/Ops Landauer. This company is a leader in alpha track technology, and has participated successfully in the EPA's Radon/Radon Progeny Measurement Proficiency Program (14). Its samplers consist of a piece of CR-39 plastic inside a small, filtered plastic box shaped like a cylindrical pill box. Radon atoms diffuse through the filter and decay through a chain of four short-lived products. Alpha particles emitted by radon-222, polonium-218, and polonium-214 upon decay produce defects in the CR-39 plastic. In the laboratory, the exposed CR-39 is etched in acid and the number of tracks per unit area are determined. Conversion factors determined using radon chambers at federal laboratories are used together with the sampling duration to convert track densities to radon concentrations. The uncertainty of the measurement depends on the number of tracks in the area of the CR-39 plastic that is counted.

Instructions for placing indoor samplers were consistent with EPA's suggested guidelines, at least to the extent that sufficient samplers were available for each residence. Residents were instructed to place samplers in the living room/main activity room that is occupied the most, and in the master bedroom. The instructions are shown in Appendix A. The placement of samplers was chosen to obtain measurements in the main activity room and a bedroom as recommended by EPA, to obtain outdoor measurements at one quarter of the residences, to obtain measurements in the basement of any residences that had one, and to follow EPA guidelines for quality assurance and quality control.

The type F alpha track sampler used for measuring outdoor radon is composed of a CR-39 chip taped to the interior bottom of a filtered plastic cup of approximately the same dimensions as a 10-oz. drinking cup. The larger dimensions of this cup improve the sensitivity of the type F over the type SF by a factor of three. With advice from Tech/Ops Landauer, we selected the type F for outdoor measurements for this reason, since outdoor radon concentrations are usually much lower than indoor radon concentrations.

At the 60 residences visited, our objectives were to check the deployment of the radon samplers, to check the questionnaires, to measure air permeability of soil and radon concentrations of soil gas, and collect soil and water samples. A team of two scientists visited each residence. Blank questionnaires were completed by our staff through observation and questions posed to the occupant(s). Appendix C shows the form used while checking sampler deployment.

2.7.2. Soil Measurements

Forty-six of the 60 residences were visited by the radiation geologist. The radiation geologist or another staff member visually assessed variations in surficial, native soil texture (grain-size), and structure (or macroporosity) within 4 meters of the residence. At the same time, possible variations between backfill and native soil were also assessed. The on-site assessments of surficial variability were used, along with consideration of the location of utility pipes and cables, to select four measurement sites for permeability to air. This procedure can be very difficult in certain types of soil, and the number of soil probes installed was dependent upon the time it took to do each one. Consistent with the constraint that no more than one day could be spent at a house, the team attempted to install four soil probes at each house. A surface soil sample was collected near at least two soil probe sites at each house. A soil gas sample was drawn from a soil probe to measure the radon concentration at a depth of 1 m. This soil gas sample was obtained from a site 4.6 m from the house foundation to minimize the influence of the presence and the operation of the house on the radon concentration. The sampling procedure is described in Appendix D, as is the procedure for analysis of soil samples for radium content and radon emanation rate. Appendix E includes specific protocols used for obtaining soil gas samples with flow-through (Lucas) cells and for counting those cells.

Soil probes fabricated by a machine shop expressly for this study were driven into the ground to a depth of 1 m for soil gas sampling and measurements of permeability to air. The air permeameter was also fabricated in-house expressly for this study. The permeameter and its use is described in Appendix D. Typically, air flow rates were measured twice at each of two operating pressures. Logforms were used to record flow rates and pressures, which were then converted to permabilities as described in Appendix D.

2.7.3. Water Measurements

Water samples were collected at residences where private well water was domestically used. Seventeen of the 60 houses had private wells. The sampling and analysis protocols for radon in water are shown in Appendix F. Most houses with private wells had a storage tank near the house. The distance to the well head varied considerably. Samples were collected at or as close as possible to the tank. During sampling the most important considerations were to purge the pipes for 10 minutes so that a sample of water representative of that in the storage tank was collected, and to ensure that the sample was not aerated by the sampling. The procedure described in Appendix F worked well except when air could not be eliminated from the outgoing water stream. Analysis was accomplished by liquid scintillation techniques, using an organic phosphor dispersed in oil. The solubility of radon in oil is so much greater than in water that essentially all the radon is extracted by the oil. The gross alpha counting rate in the oil phase of the sample vial is related to the radon concentration in the water sample.

SECTION 3. RESULTS

3.1. Quality Assurance

To assure that the samplers were not contaminated, 27 samplers were selected randomly from the more than 1,000 samplers purchased for use as field blanks and were kept unopened with original sealed packing. After the exposed samplers had been received, the field blanks were opened and sealed immediately with the seal provided by Tech/Ops Landauer Company. The blanks were then sent back with the exposed samplers to Tech/Ops Landauer for laboratory analyses. The results of the laboratory analysis of the blanks are shown in Table 3-1. The reported concentrations ranged from 0.1 to 0.3 pCi/l. This positive bias could have been due to a small exposure of the blank samplers or to spontaneous defects arising in the CR-39 chip, either of which would have occurred during handling or storage, or it could have been introduced during the analysis. In any case, the bias was small. Furthermore, investigation of the true cause of the bias, and hence determination of whether or not it would be appropriate to correct the experimental results based on the blank results, was beyond the scope of the study.

Forty-three duplicates from the pretest and main survey were deployed side-by-side in 35 living rooms and 8 basements. The radon concentrations of the paired samplers showed good agreement (Table 3-2). A correlation coefficient of 0.92 suggested that the precision of the samplers was good.

To further insure the quality of the analysis of samplers, 27 additional samplers were sent to the EPA laboratory in Montgomery, AL for exposure to known concentrations in a radon chamber. Fourteen of the samplers were exposed at a concentration of 370 $\pm$ 8.3 pCi/l for a period of 5 days, and 13 were exposed at a concentration of 367 $\pm$ 9.2 pCi/l for a period of 10 days. These track densities correspond to those that would result from exposure of field samplers for one year at approximately 5 and 10 pCi/l, respectively. These samplers were also returned to Tech/Ops Landauer with the other samplers, and were given identification numbers that would not allow the company to know that they were spiked samples.

The results of this first analysis of these spiked samples are shown in Table 3-3. As shown in the table, the results of the analysis showed a significant positive bias and poor precision. Discussions with personnel from Tech/Ops Landauer revealed that they have three possible analytical methods from which to choose: a conventional, computer-controlled image analysis system (CON method), a new fiber optic image analysis system (FO method), and a manual counting system (manual method). It was further learned that most samplers used in this study were analyzed by the FO method or, when the track densities were very high, by the manual method. The FO method enlarges the images of alpha tracks, so that a large area of the chip can be automatically counted in a short period of time using a lower magnification, while still maintaining good detectability. However, most detectors analyzed by Tech/Ops Landauer for other field studies have lower track densities than those in this study, since the samplers are not often deployed for more than a few months. The result is that, at moderate concentrations (*i.e.*, above 2 pCi/l) for samplers exposed for a full year, individual tracks can appear to overlap when analysis is done by the FO method. It was therefore postulated that the poor accuracy for recounting spiked samples was due to the use of the FO method.

Because of the poor accuracy and precision shown in the counting of the spiked samples (which all had fairly high track densities), Tech/Ops Landauer was requested to recount all spiked samples using the CON method. In order to again prevent them from knowing that they were recounting spiked samples, and to obtain information on the precision of counting non-spiked (real) samples, Tech/Ops Landauer was actually requested to recount 52 samplers. These included 26 of the 27 spikes, the 10 real samplers that had the highest values, 10 real samplers chosen at random, and 6 blanks. Table 3-4 shows the result of the recount. It is clear from this table that the CON method resulted in far greater accuracy in counting the spiked samples than either the manual or FO methods. It also shows that samples with low exposures appeared to be counted equally well by either the FO or CON methods.

The recount, for which results are displayed in Table 3-4, raised the possibility of inaccuracy of results for samplers which had been found to have been exposed to concentrations between 2 pCi/l and 5 pCi/l, which would have been analyzed initially by the FO method. Tech/Ops Landauer was therefore requested to recount all samplers whose initial value was greater than or equal to 2 pCi/l (a total of 103 samplers), as well as the one spiked sampler not recounted in the first recount. The results are shown in Table 3-5. Of the 104 samplers subject to the second recount, 14 were found to differ by an amount greater than the expected precision based purely on the counting statistics. Of these, one was the spiked sampler, and the others were all well above 2 pCi/l in both the initial count and the recount, with the exception of one.

The following procedure was therefore carried out to correct the data to remove counting bias due to the initial use of the FO (or even manual) count method at high track densities. All results of the first analysis which were not recounted (all of which were below 2 pCi/l) were left unchanged. For all samplers recounted at least once, and whose value changed in the recount by more than the expected count precision, the concentration from the initial count was replaced by the recount value. In cases where samplers had been recounted twice, the average of the two recount values was used. All together, 13 of the original counts were corrected.

After correction it was estimated that the inaccuracy (defined as the percentage deviation of the spiked sample values from the exposed concentration) ranged from 1% to 26% with a mean of 10%. For the duplicates, the coefficient of variation ranged from 0% to 39%, with a mean of 5% for values above 2 pCi/l. For values under 2 pCi/l, the coefficient of variation ranged from 0% to 54%, with a mean of 9%.

3.2. Pretest

The characteristics of the 192 volunteers and 38 participants who completed the pretest were similar (Table 3-6). Eighty-seven percent of the volunteers and 89.5% of the participants lived in a single-family house. The most common type of substructure was a crawl space (51.5% and 44.7% respectively). Approximately one third of the participants were not aware of radon prior to the study. The mode and median of their annual household income were in the category ranging from $35,000 to $49,999. More than one-third of them owned two vehicles.

The results of indoor and outdoor radon measurements are shown in Table 3-7. Seventeen of the 20 duplicates in bedrooms were returned after two months. The radon concentrations of the 17 samplers ranged from 0.6 to 2.9 pCi/l with a geometric mean of 1.65 pCi/l and a geometric standard deviation of 1.5. The 37 samplers retrieved from the bedrooms after one year varied from 0.2 pCi/l to 1.9 pCi/l with a geometric mean of 0.85 pCi/l. The mean of the bedroom radon concentrations measured during the winter months was significantly higher than that of the annual readings ($p<0.01$). The ratios of the paired readings (winter vs. annual) ranged from 1.1 to 5.5 with a mean of 2.8.

The 36 annual samplers retrieved from the living rooms had radon concentrations from 0.3 to 5.9 pCi/l with a geometric mean of 0.93 pCi/l. The radon concentrations measured in the living rooms were not significantly different from those measured for the full year in the bedrooms (0.85 pCi/l) by the paired t-test ($p=0.07$). The radon concentrations measured in the bedroom and living room of each individual residence were therefore averaged to represent the whole-house value. For the residences from which only one sampler was retrieved, the result of this sampler was used as the whole-house value. The frequency distribution of the 38 whole-house values is presented in Fig.3-1. The result of the test of normality on the logarithm-transformed data indicated that the distribution of the radon concentrations was not significantly different from log-normal.

Annual average outdoor radon concentrations were determined from 10 residences. The lowest radon concentration measured outdoors was 0.3 pCi/l, a value that is within the range of the results of blank samplers. The highest value measured outdoors was 1.1 pCi/l. The arithmetic mean of outdoor samplers was 0.59 pCi/l and the geometric mean was 0.55 pCi/l.

3.3. Statewide Survey

A total of 6,228 letters were sent to recruit volunteers for the statewide radon survey. Three hundred and fifty-nine letters were returned because of invalid addresses. Among the 5,869 recipients, 1,210 volunteered their residences for the radon survey. The positive response rate of 20.61% was slightly lower than that of the pretest (24.42%). However, this response rate was higher than those of the surveys carried out by Lawrence Berkeley Laboratory (approx. 10%) and the *Los Angeles Times* (approx. 5%). Survey materials were sent to 360 randomly selected residences. Of these, 332 (92.%) returned their completed questionnaires, log-forms and consent forms for home visits. Approximately 8% of the original 360 participants never returned anything even after attempts at phone contact by our staff. A year later, at least one sampler had been received from each of 310 residences. The completion rate over the one-year period was 93%.

As can be seen from Table 3-8, the characteristics of all volunteers (1,210) were very similar to those of the volunteers who responded early enough to be included into the selection process (961). More than 80% of the volunteers lived in single-family houses and approximately 45% of the substructures of their residences were crawl spaces. The mode and median of their annual household income fell into the category of $35,000-$49,999. Approximately 40% of the households owned two registered motor vehicles. The effects of adjusting for the number of registered vehicles was reflected in the characteristics of the participants. Both the average annual household income and the fraction of single family houses were lowered consequently. More households from lower socio-economic levels were included in the 310 participants than those within the original volunteers.

The summary statistics of the indoor and outdoor radon concentrations are given in Table 3-9. The radon concentrations measured in the 308 bedrooms ranged from 0.1 to 11 pCi/l, with a geometric mean of 0.83 pCi/l and a geometric standard deviation of 1.96. The radon concentrations measured in the 300 living rooms varied from 0.2 to 16 pCi/l, with a geometric mean of 0.85 pCi/l and geometric standard deviation of 1.94. As in the pretest, the paired t-test showed no significant difference in average radon concentration was found between the bedroom and living room. When the whole-house value was calculated by averaging the radon concentrations in the bedroom and living room, the geometric mean was 0.85 pCi/l and the geometric standard deviation was 1.91, with a range from 0.15 to 13 pCi/l. The frequency distribution of the 310 whole-house values is shown in Fig. 3-2. However, as expected, the radon concentrations measured in the 27 basements, with a geometric mean of 2.17 pCi/l, were significantly higher than the whole-house values, while the outdoor radon concentrations, with a geometric mean of 0.42 pCi/l, were significantly lower than the indoor concentrations.

3.4. Sierra Foothills

Thirty-seven of the 40 original participants in this portion of the study returned their completed questionnaires after the placement of radon samplers. All 37 participants completed the one year monitoring. The housing characteristics of the volunteers and participants are shown in Table 3-10. Since the major purpose of this part of the study was to recruit households from potential problem areas, no efforts were made to adjust the bias due to the difference in the number of registered motor vehicles. After the selection, the fraction of single-family houses (83.8%) was higher than that of the original volunteers (75.6%). However, the median annual household income of the 37 participants ($20,000-24,999) was lower than that of the original volunteers ($25,000-34,999). The substructures of 20 residences were crawl spaces (54.1%). Approximately 40% of the 37 participants and 36% of the 88 volunteers owned two registered motor vehicles.

The radon concentrations measured in the 36 bedrooms (one bedroom sampler was not retrieved) ranged from 0.4 to 2.5 pCi/l, with a geometric mean of 1.16 pCi/l and a geometric standard deviation of 1.61 (Table 3-11). The radon concentrations measured in the 37 living rooms varied from 0.4 to 16 pCi/l, with a geometric mean of 1.37 pCi/l and a geometric standard deviation of 1.80. After averaging the concentrations in the bedroom and living room, the whole-house values ranged from 0.4 pCi/l to 8.8 pCi/l, with a geometric mean of 1.28 pCi/l and a geometric standard deviation of 1.70. The frequency distribution of the 37 whole-house values is shown in Fig. 3-3. As can be seen from this figure, the mode is higher than that of the statewide data. Of the 37 residences, radon measurements were available from only two basements. The radon concentration of one basement was 1.6 pCi/l and the other was 2.9 pCi/l. The geometric mean of outdoor radon concentrations was 0.66 pCi/l, which was slightly higher than the results of the pretest and the statewide survey.

3.5. Geographic Variations

In this study, two geographic areas were selected to determine whether elevated indoor radon concentrations would be found in these two areas. Thirty-eight residences were monitored in the Counties of Santa Cruz and Monterey during the pre-test period and 37 residences were measured in the Counties of Fresno, Tulare, Mono and Inyo (Sierra foothills) at the same time as the statewide survey. The geometric mean of indoor whole-house concentrations in the pre-test area was 0.89 pCi/l, similar to that of the statewide average. The geometric mean of the Sierra foothills was 1.28 pCi/l, which was significantly higher than the statewide average.

The *Los Angeles Times'* radon survey found the County of Ventura and the northwestern region of Los Angeles to be an area with elevated indoor radon concentrations (6). To compare our results with the *LA Times'* study, 15 residences were identified from the same area. With a geometric mean of 1.88 pCi/l and a geometric standard deviation of 1.87, our measurements were even higher than those of the the LA Times' survey (G.M.=1.56 pCi/l, G.S.D.=2.44). This result confirms the LA Times' study conclusion that this region had elevated radon concentrations. When a t-test was carried out to determine if the geometric mean of this area was higher than that of the remainder of the state after excluding the 15 measurements from the 310 statewide measurements, the result was highly significant ($p = 0.0001$).

3.6. Estimated Fraction of High Values

The indoor concentration data from all three portions of the study closely matched a log-normal distribution (see Figures 3-1, 3-2, and 3-3). Therefore, expected fractions of residences having radon concentrations exceeding 4 pCi/l and 8 pCi/l were calculated based on the log-normal model. Data were first transformed by taking the logarithm of the original concentrations, and probabilities of values exceeding ln(4) and ln(8) were determined from a normal table based on the mean and the standard deviation of the transformed data. Confidence limits of the 95% confidence interval were subsequently calculated based on the mean and the standard error of the transformed data. The results of the estimated fraction of residences having indoor radon concentrations exceeding 4 pCi/l and 8 pCi/l are shown in Table 3-12.

The estimated fraction of residences in the State of California having radon concentrations exceeding 4 pCi/l is 0.8%. The lower bound of the 95% confidence interval is 0.6% and the higher bound is 1.1%. Currently, there are approximately 11 million housing units in California, according to the Population Research Unit of the California Department of Finance. Therefore, the expected number of residences exceeding 4 pCi/l is 88,000, but this number may vary from 66,000 to 121,000. The estimated fraction of residences having radon concentrations exceeding 8 pCi/l is 0.03%, with 95% confidence limits of 0.02% and 0.04%. Translating this figure into the number of residences, the expected number of housing units exceeding 8 pCi/l is 3,300, with a lower bond of 2,200 and a higher bond of 4,400. Because these results are based on the statewide distribution of radon concentrations, the approximate fraction of residents exposed to concentrations exceeding 4 and 8 pCi/l can be found by multiplying these numbers by 2.7, the average number of residents per household, based on data obtained from the California Department of Finance. This yields an approximate number of California residents exposed to concentrations exceeding 4 and 8 pCi/l of 240,000 and 8,900, respectively.

Due to the homogeneity of the radon concentrations measured in the pretest area compared with the data of the statewide survey, the estimated fractions of high values in the pretest area are lower than the estimates for the entire state even though their geometric means are identical. The estimated fraction of values exceeding 4 pCi/l in the areas of Sierra foothills is larger than the corresponding fraction of the state data. However, because of the small sample size, the confidence interval is wider.

The highest proportion of residences expected to have radon concentrations exceeding 4 pCi/l is again found in Ventura County and the northwestern portion of Los Angeles County. In this survey, the estimated fraction of housing units exceeding 4 pCi/l is 11.5%, which is in reasonably good agreement with the corresponding estimate of 14.6% from the *Los Angeles Times'* independently conducted survey (6).

3.7. Factors Affecting Indoor Radon Concentrations

3.7.1. All Participating Households

To test if housing characteristics and household activities were related to indoor radon concentrations, F-tests were carried out on relevant variables of the main questionnaire for all participating households. The significant findings are presented in Table 3-13. The four variables in the table are those with significant F-values to indicate that the mean concentrations of different categories (*e.g.*, single house, townhouse, mobile home, *etc.*) of a variable (*e.g.*, type of residence) are not equal. The "*" sign indicates that the pair-wise contrast (Bonferoni) test is statistically significant. Indoor radon concentrations varied with type and age of residence, type of substructure and frequency of window/door opening. Single family houses, new residences, residences with full concrete slab or whose windows/doors were rarely opened were found in general to have higher radon concentrations.

To evaluate the joint effect of all significant variables mentioned above, including also geographic region, a multilinear model was assumed. The results of the stepwise procedure of the multilinear regression are presented in Table 3-14. Geographic region was the first variable entered into the regression model, with the Sierra foothills and Ventura areas at higher risk than other areas. The second variable entered into the model was ventilation, in which the frequency of opening window/door related negatively with radon concentrations. Type of substructure, type of residence and age of dwelling were entered as the third, fourth and fifth variables. The contribution of each entered variable to R^2, the square of the multiple correlation coefficient, decreased as more variables were entered, and the cumulative R^2 reached 0.268 at the fifth variable. The final model with the five determinants is listed at the bottom of Table 3-14.

3.7.2. Site-visited Households

The most complete data sets collected for possible determinants of indoor radon concentrations during site visits were the radionuclide content of soil samples (n = 118) and *in situ* permeability data (n = 178), collected at 59 houses. The radionuclide content controls the radon source strength of the soils. The permeability of the soil controls the distance that radon atoms in soil pores can move, under a given pressure, from their generation sites via soil gas flow.

The results of the analyses of radionuclides in soils are summarized in Table 3-15. When a radium atom decays in soil, the resulting radon atom may, after recoil, come to rest either in a grain of soil or in a pore. The emanating Ra^{226} is only the Ra^{226} that produces radon that is available for migration through soil pores. The difference between the total Ra^{226} and the emanating Ra^{226} is the fixed radium, or that which produces radon atoms which do not escape soil grains. The emanating percentage is simply the ratio of emanating to total radium multiplied by one hundred. Of these variables, the emanating Ra^{226} is physically most indicative of a soil's ability to act as a source of indoor radon. Radium-228 (Ra^{228}), a member of the Th^{232} decay chain, decays to Rn^{220}, called thoron. Thoron's 55-second halflife severely limits its migration distance; it is virtually always unimportant as a radon isotope indoors. Potassium-40 (K^{40}) is usually present in soils and generally contributes roughly one quarter of the γ-radiation from soils. The exposure rate from these radionuclides is a measure of the rate of ionization produced in air by x- or γ-radiation. This value was computed from the measured U^{238}, Th^{232}, and K^{40} concentrations as reported by Beck and DePlanque, 1968 (15).

The 118-sample distributions for Ra^{226}, Ra^{228}, and K^{40} were first tested for normality and lognormality. The distributions of the radium isotopes were both lognormal. The distribution of K^{40} was normal. The geometric means of emanating and total Ra^{226} from the soil samples were 0.16 and 0.85 pCi/g, respectively; the geometric standard deviations were 1.71 and 1.55, respectively. The range of emanating Ra^{226} from the soil samples is approximately an order of magnitude. The radionuclide contents of the two soil samples analyzed from each house were tested for statistically significant differences. None were found.

The permeability measurements at each house were divided into two groups based on the differences from the foundations: (1) either less than or equal to 1.9 m or (2) more than 1.9 m. A t-test was applied to look for differences in permeability between these two groups at a depth of 1 m, *e.g.*, perhaps related to soil disturbance caused by the building process. No statistically significant differences were found. The arithmetic mean permeability was calculated for each of the 58 houses for which the data were complete. The distribution of means has an arithmetic mean of 1.0×10^{-7} cm^2 and an arithmetic standard deviation of 2.2×10^{-7} cm^2. However, the distribution of the measured permeabilities, as shown in Figure 3-4, is neither normal nor lognormal. After taking the square root of the measured permeabilities and averaging all transformed measurements for each house, the distribution approached normality. When the fourth root of the permeabilities was taken and the transformed values were averaged for each house, the distribution of the 58 values was normal.

The mean of our measurements, 1.0×10^{-7} cm^2, corresponds to a soil with a uniform particle size of a fine sand (approx. 500 μm uniform diameter). For perspective, a clean gravel (approx. 1000 μm) has a permeability of 10^{-4} cm^2. Permeabilities below 10^{-11} cm^2, the lower limit of detection of our permeameter, are soils with silty clays (2-50 μm), clays (<2 μm), and water-saturated soil of coarser median grain size (16, 17). Of the 178 measurements of air permeability performed in situ in the 59 hones, 20 were below 10^{-11} cm^2. These values were set to zero, except when the logarithms were taken, in which case a very small number was added to all values.

To examine the relationship between indoor radon concentrations and the soil variables, two correlation matrices were constructed. The first tested correlations between the natural logarithm (ln) of the indoor radon concentration and the following variables constructed from soil variables: the natural logorithm of the emanating Ra^{226} (Ra_{em}) content of the soil, the natural logarithm of the total Ra^{226} (Ra_{tot}) content of the soil, the square root of the permeability, and the products of the square root of the permeability with the emanating Ra^{226} and with the total Ra^{226} content. The second matrix tested the correlations between the natural logarithm of the indoor radon concentration and the following other variables constructed from soil variables: the natural logarithm of the emanating Ra^{226} content of the soil, the fourth root of the permeability, and the products of the fourth root of the permeability with the emanating Ra^{226} and the total Ra^{226} content of the soil. Those variables that were significantly correlated with the ln (indoor radon concentration) with 95% confidence, along with their correlation coefficient and level of significance, are listed in Table 3-16.

No combinations of these three variables was found to correlate as well with the ln (indoor radon concentrations) as did the ln ($Ra_{\epsilon\mu}$).

The results of the analysis of water samples obtained at seventeen residences are shown in Table 3-17. The contribution of radon from domestically-used water in this particular sample of homes was apparently negligable for two reasons. The first reason is that the correlation between the water concentrations and the air concentrations was not significantly different from zero. The second is that the highest concentration measured in water was less than 5000 pCi/l. This is orders of magnitude below the highest concentrations found in California well water by the Public Water Supply Branch of the California Department of Health Services. Furthermore, if one applies the rule of thumb that 10,000 pCi/l of water is generally responsible for approximately 1 pCi/l of air in the residence, all of the values listed in Table 3-17 would result in less than 1 pCi/l from the water, and most would result in less than 0.1 pCi/l.

SECTION 4. DISCUSSION

4.1. Potential Bias in the Results

4.1.1. Sampling Bias

The use of zip code area as a sampling unit has the advantage of spreading the monitored residences widely and evenly across the entire state. But the disadvantage is that the sample of selected residences is biased toward rural areas and hence biased toward less populated areas. For instance, over half of all households (53.9%) are in southern California, while only 40.3% of the monitored residences were from this area. Efforts were made to adjust for population bias by dividing the State of California into six homogeneous regions based on geologic information and radon concentrations. After the adjustment, the percentage of residences having radon concentrations exceeding 4 pCi/l changed from 0.84% to 0.76%. Since the 95% confidence interval of the first estimate was between 0.6% to 1.1%, this bias was considered to be negligible.

There were also other sources of bias which might have affected the estimate of the number of residences over 4 pCi/l. In the main survey, the response rates to the recruiting letter were approximately 25%. Even though higher than those of the radon survey carried out by the *Los Angeles Times*, this response rate was still too low to be considered representative. Since recipients from middle/high socioeconomic classes were more willing to volunteer than were those from low socioeconomic class, proportionally more single family houses (75%) were included than the true fraction in the state (55%, according to the California Department of Finance). And it has been shown by this study as well as the *Los Angeles Times'* survey that the type of residence is related with indoor radon concentrations.

Other determinants of radon concentrations which are also likely to cause bias due to unequal distribution among the monitored residences compared with California residences are the type of substructure and the age of the residence. But there was neither enough detailed information available on all major determinants for residences statewide for bias correction nor a large enough sample size for simultaneous adjustment of several variables. The only adjustment that was tried was on geographic regions, the most important determinant of indoor radon concentrations, as stated above, and the bias was negligible (0.76% vs. 0.84%). Comparing this with the U.S.EPA's estimate of 10% of U.S. residences having annual average radon concentrations exceeding 4 pCi/l, and even assuming 50% bias at either end (1.26% and 0.42%), this bias correction would not affect the general picture of the extent of the radon problem in California very much. A more accurate estimate can only be obtained by increasing the sample size drastically.

4.1.2. Analytical Errors

Results of analyses of duplicates demonstrated that analytical precision was acceptable relative to the goals of the study. However, a low level of contamination was evident in the results of the analysis of the field blanks. As noted in Section 3.1, determining the cause of the field blank contamination would have been beyond the scope of this study. Based on our conversation with the personnel from Tech/Ops Landauer, we were assured that there were in-house blanks taken from each batch of plastic chips to control for potential contamination and to adjust for baseline values. Without clear evidence that the field blank contamination was additive to the results obtained by field samples, it appeared premature to simply subtract the average value from all results. However, the small bias that was apparent from the field blank analysis is an issue that should be investigated in the future by companies which provide alpha track samplers, in light of EPA's new charge to reduce indoor radon concentrations to ambient levels.

Analysis of spiked samplers showed marked inaccuracies at high concentrations. These inaccuracies would probably not have been detected if spiked samplers had not been submitted blindly to Tech/Ops Landauer along with the other samplers. It should be noted that Tech/Ops Landauer cooperated fully in resolving these inaccuracies once they were notified of the problem. However, our experience illustrates graphically the importance of a full QA/QC program including the analysis of field blank and spiked samplers in any radon survey.

The analysis of heavily exposed samplers would probably have been more accurate if the samplers had not been exposed for a full year. This is likely to be the reason that Tech/Ops Landauer had not discovered such problems in the past, since most users of alpha track samplers do not expose them for a full year. Unfortunately, shorter measurements (typically for one to three month periods) can give a very misleading impression of the average annual concentration, as evidenced by the two-month results in the pre-test area, for which the geometric mean was 1.6 pCi/l, as opposed to 0.8 pCi/l for an annual average in the same area.

4.2. Discussion of Results

4.2.1. Outdoor Air Concentrations

The outdoor radon concentrations measured in this study, whose geometric mean was 0.55 pCi/l for the pretest area; 0.42 pCi/l for the statewide survey; and 0.66 pCi/l for the Sierra foothills, are reasonable considering the predominant geochemistry in the areas studied. Although the outdoor concentrations are significantly lower than the indoor concentrations, the range of the values found in this study is greater than those measured in ambient air by other researchers. These results may be due to the fact that the participants were instructed to place the outdoor samplers at the side of the house under the eaves, a covered patio, a carport, or a porch to minimize exposure to wind, rainfall or direct sunlight. The outdoor samples may therefore have been influenced by radon-rich air exfiltrating from the adjacent houses so that the outdoor radon concentrations measured were elevated relative to concentrations in open areas near but not adjacent to the houses sampled. Therefore, the outdoor radon concentrations measured in this study are probably between ambient and indoor levels. The correlation coefficient of 0.36 between the indoor and outdoor concentrations indicated that, although indoor radon concentrations are related to outdoor concentrations, the predictability of indoor concentrations from outdoor ones is subject to considerable uncertainty.

4.2.2. Soils

The distribution of total radium content of soil from this study (see Table 3-15) agrees reasonably well with the results of 350 γ-spectrometric analyses of surficial soils collected nationally: arithmetic mean of 1.1 pCi Ra^{226}/g soil; range 0.3 - 5.4 pCi/g (19). The NARR database, a more extensive national sampling of radium contents of soils, has a geometric mean of 0.7 pCi/g and a geometric standard deviation of 1.7 (20).

Since soils are derived from rocks, the form of the distributions of Ra^{226}, Ra^{228}, and K^{40} in a large sampling of soils is expected to reflect that of the distributions of these radionuclides in a large sampling of rocks. The distributions of these three radionuclides measured in ten geochemical categories of 2500 rocks were all lognormal (24). Our results from 118 soils also showed Ra^{226} and Ra^{228} to be lognormally distributed, while K^{40} was normally distributed.

The air permeabilities of soil measured during this study (arithmetic mean of 1.0×10^{-7} cm^2, arithmetic standard deviation of 2.2×10^{-7} cm^2) fall within the range of those reported in the literature, 10^{-12} to 10^{-4} cm^2 (17). Most measurements reported in the literature, however, use water as the fluid, rather than air, particularly for in situ measurements. Kunz *et al.* (21) reported air permeabilities of 4×10^{-7} cm^2 for sands and 10^{-6} to 10^{-5} cm^2 for gravels measured *in situ*. Sextro, *et al.* (20) reported air permeabilities of 6×10^{-7} cm^2 in a sandy gravel in Washington. Sextro, *et al.* (22) reported permeabilities of 10^{-8} to 10^{-6} cm^2 in soils of unreported grain-size distribution surrounding four houses containing elevated indoor radon levels in New Jersey.

The mean of permeability measurements reported here seems somewhat high for California, which contains clay soils in many areas. However, the choice of site visits in areas dominated by soils of granitic origin within the pretest and the Sierra foothills study areas probably created a bias toward coarser, more permeable soils compared with a random sampling of soils within California. Air permeability tends to increase as the degree of water saturation of a soil decreases. Our protocol promoted field work in drier soils, since we requested that residents refrain from watering several days prior to our visit, and since we avoided rainy months for the site visits. Average air permeabilities would probably be lower at the same locations.

4.2.3. Determinants of Indoor Concentrations

Analysis of data from our field work at 60 houses, 25 of which were within one region with elevated indoor radon concentrations identified by this survey, shows a statistically-significant correlation between two measures of radon generation rate, emanating and total radium, and indoor radon concentration. The radium concentrations in soil and indoor radon concentrations measured in this study both vary by one to two orders of magnitude. However, the air permeabilities measured in this study vary by more than five orders of magnitude. Therefore, when seeking statistical correlations, the data on air permeability in soil were transformed and normalized to a comparable scale. Two simple mathematical transformations which compressed the range of the measured permeabilities and made the transformed data approach a normal distribution were arbitrarily chosen: the square root and fourth root. It is possible that other empirical transformations not attempted could have improved results. Three of nine variables that combine a measure of radon generation rate with pressure-induced transport distances also showed statistically-significant correlations with indoor radon concentration. These findings support the assumption that geographic variations in radon source strength of soils are important controlling factors for regions with elevated indoor radon. Our results, though not exhaustive, show that variations in radon generation rates correlate better with indoor radon data than with soil permeability, or a variable that combines the two. Similar results were obtained in New Jersey (23).

The statistically modeled determinants of indoor radon concentrations for the statewide results show that "region" alone explained half (13%) of the variation in the indoor radon concentration accounted for by the stepwise regression model using five variables. This is shown by the R^2 column in Table 3-14. Adding "natural ventilation" to the model improved the R^2 by another 6%. Adding "substructure" to the model improved the R^2 by another 3%. Several physical processes are involved between the formation of a radon atom in soil and the accumulation of radon gas in indoor environments: radon generation and transport in soil, the entry of soil gas into the indoor space, and the degree of dilution of radon-rich soil gas with radon-poor outdoor air within the indoor space. The variable "region", as used here, is simply occurrence or non-occurrence within a hot spot found by this survey. We hypothesize that indoor radon concentrations vary more with radon generation rates in soil, which vary with location in California, than with substructure type, which influences the rate of soil gas entry into a house, or use of natural ventilation, which affects dilution within the indoor space. Surveys in New Jersey, for example, have found source strength variations to be the most important factor controlling the occurrence of radon hot spots, while type of substructure and meteorology influence small scale variations in indoor radon (23).

Some problems in sampling techniques were found during site visits. The data on radon in soil gas was severely compromised by a change in sampling technique during the middle of the work. When flow-through Lucas cells and a pump were in use, we apparently depleted the radon source most of the time. This was realized when background or very low (less than 20 pCi/l) concentrations of radon were found in the Lucas cells, but only after many samples had been taken. During the study, we experimented with reducing the volume of gas flushed from the soil probe before sampling, with reducing the volume of soil gas flushed through the Lucas cell during sampling, and with reducing the flow rate to prevent de-pressurizing the source volume. However, we continued to deplete the source, suggesting that the maximum volume of gas that should be flushed from the probe sampling system is one internal volume of the soil probe and the sample train.

Measurements using the soil probes fabricated for this survey were difficult to carry out because of the need to find probe locations that were free of underground utilities, and because even then, underground rocks or very dense layers of clay above more permeable soils made it necessary to drive some probes repeatedly at slightly different locations. Many probes were damaged by attempts to drive them through rocks, which were often indistinguishable in effect from dense clay until the probe was removed and the damage assessed. Because of these problems and the need to have year-long time-dependent data for ease of data interpretation, soil probe sampling is not recommended as a routine method for evaluating the potential for radon problems in a large geographic area.

The waterborne radon data must be considered to be lower limits, due to either the persistent existence of bubbles in the sampling stream from shallow wells, or degassing of oxygen as the temperature of the water sample increased between the times of sampling and analysis. Chilling of field samples before collection of aliquots for liquid scintillation analyses would probably have improved the technique.

SECTION 5. CONCLUSIONS

This radon survey is the first to cover the entire State of California. Using the list of DMV's registered motor vehicles as the sampling frame allowed every household with a registered vehicle to have a chance to be selected. The scheme of recruiting and selecting participants based on zipcode zones maximized the probability of including wide geographic coverage, yet was still partially population-based. Year-long monitoring of radon using alpha track samplers provided a measurement of annual average radon concentrations, which is important for evaluating long-term exposure, and therefore assessing risk. The low drop-out rate enabled us to retrieve deployed samplers and acquire radon data from most of the selected residences.

All three study objectives were met, as follows:

1. The annual geometric mean radon concentration in California residences was determined to be approximately 0.9 pCi/l. The geometric mean radon concentration near residences was found to be 0.4 pCi/l.

2. The approximate fraction of the California population regularly exposed to residential radon concentrations greater than 4 pCi/l and 8 pCi/l is 0.8% and 0.03%, respectively.

3. Factors were identified which may be useful in predicting high risk areas or groups in California for focusing future investigations. In this survey, indoor radon concentrations were found to be associated with geographic location, ventilation, type and age of residences, and type of substructure. The Sierra foothills and the Ventura County area had higher concentrations than other areas in California. Residences whose windows/doors were rarely opened by occupants, structures with a full concrete slab, single family houses, and new residences were found in general to have higher radon concentrations.

The three specific hypotheses were also successfully tested in this study:

1. The results of this study indicated that outdoor radon concentrations are as high or higher than outdoor values measured elsewhere in the U.S.. The geometric mean of 0.9 pCi/l is about the same as the national geometric mean estimated by Nero (3) after excluding the radon data from the Reading Prong.

2. The smaller geometric standard deviation (1.9) compared with Nero's estimate (2.8) yields smaller percentages of residences estimated to have radon concentrations exceeding 4 pCi/l or 8 pCi/l than are likely to occur nationally. The approximately one percent of housing units expected to have radon concentrations over 4 pCi/l is lower than estimates from any radon survey carried out in other states. However, since many of these surveys were

carried out using the EPA screening protocol, it is doubtful that they are as indicative of long-term radon exposure as are the results of this survey.

3. Radon concentration distributions are not the same for different geologic regions and various types of buildings. (The effect of these factors is discussed under Objective 3 above.)

The fact that only a small percentage of California residences are expected to have annual average concentrations over 4 pCi/l does not imply that there is no radon problem in this state. Actually, the findings of elevated radon concentrations in the areas of the Sierra Foothills and Ventura/Los Angeles Counties indicate that there are some problem areas which need further investigation. Finding these areas of elevated indoor radon was possibly fortuitous given the limited scope of the sampling (which was due in turn to the funding limitations), the geologic and climatic diversity of California, and the large variations in population density. In general, a survey of this size using a simple population-based sampling scheme would not have been expected to identify even a moderately-sized region of elevated indoor radon unless it also had a sufficiently high population to increase the probability of extensively sampling it. However, the study design employed, which combined the influences of population and geographic area, provided greater sensitivity, and was the major reason for the success in reaching the study objectives.

SECTION 6. RECOMMENDATIONS

Following are recommendations for further studies based on the results of this work:

1. A detailed study should be undertaken to identify more areas with elevated indoor concentrations throughout the state.

2. Detailed studies in any areas identified now or in the future as having elevated radon concentrations (such as the Ventura County area and the southern Sierra Nevada foothill area) should be carried out to determine the extent of the problem area. (Such a study is already being undertaken in Ventura County by the Department of Health Services.)

3. A study should be undertaken to determine seasonal variations in indoor radon concentrations, and how these vary with climate. It would be desirable to integrate such a study with a more detailed study to identify more areas with elevated indoor concentrations, and to obtain further information on the relationship between the distance from the house and the outdoor concentration. Until such time as such a study can be conducted, it is recommended that any outdoor measurements be made some distance from any structure, unless they are specifically being made to determine the concentrations in, e.g., an enclosed patio.

4. A study should be undertaken to extend the results beyond residences. Buildings with high priority should include office buildings and schools. (Note: the Department of Health Services has already carried out a survey in 29 schools with two-day measurements. However, it would be desirable to have measurements averaged over the entire school year.)

5. It is highly recommended that quality assurance/quality control (QA/QC) be a strong component of any further radon survey, both in California and elsewhere. Such a program should include duplicate samplers, spiked samplers, and field blanks, all analyzed blind by the vendor laboratory. It is also recommended that prior to any such survey, the source of the non-zero field blank measurements be determined, so that a rational decision can be made as to whether blank values should be subtracted from all measured values.

6. Before more field measurements are made of soil parameters, it is recommended that more development be carried out on the measurement methods.

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Table 2-1

Summary of residence selection process for the California radon survey study - pretest

Sample description	Number of residences
Letters mailed requesting participation (16 letters returned for incorrect/ insufficient address)	802
Maximum number of households contacted about willingness to participate (802-16)	786
Volunteered to participate (42 responses received too late to be included in the study)	192
Not interested	23
Randomly selected	40
Added low-income residences	3
Samplers mailed	43
Main questionnaires returned	41
At least one sampler returned	38

Table 2-2

Summary of residence selection process for the California radon survey study - statewide

Sample description	Number of residences
Letters mailed requesting participation (359 letters returned for incorrect/ insufficient address)	6,228
Maximum number of households contacted about willingness to participate (6,228-359)	5,869
Volunteered to participate (249 responses received too late to be included in the study)	1,210
Not interested	240
Randomly selected	360
Samplers mailed	360
Main questionnaires returned	332
At least one sampler returned	310

Table 2-3

Summary of residence selection process for the California radon survey study - Fresno, Mono, Inyo and Tulare Counties

Sample description	Number of residences
Letters mailed requesting participation (15 letters returned for incorrect/ insufficient address)	487
Maximum number of households contacted about willingness to participate (487-15)	472
Volunteered to participate (28 responses received too late to be included in the study)	88
Not interested	20
Randomly selected	40
Samplers mailed	40
Main questionnaires returned	37
At least one sampler returned	37

Table 2-4

Lists of the instrumentation used during this project

Equipment	Use	Availability
Alpha track-etch radon sampler:	Measure annual average radon concentration:	Commercially available, Tech/Ops Landauer,/Inc.
Rad Trak	indoor	
Type F	outdoor	
Permeameter	Measure air permeability of soil in the field	Fabricated by commercial machine prior to intensive field work
Lucas Cells, photo-multiplier and counting electronics, Randem and Pylon Electronics	Measure radon in soil air grab samples	Sanitation & Radiation Laboratory and Air & Industrial Hygiene Lab
Liquid Scintillation Counter, Beckman Instruments	Measure radon in water samples	Sanitation & Radiation Laboratory, Dept. of Health Services
Gamma Spectrometer: 8"x4" NaI(Tl) detector/ Scipp 1600 multichannel analyzer	High sensitivity measurements of Bi-214, and Tl-208, radon and thoron decay products, respectively, in soil	Lawrence Berkeley Laboratory
	Measure radon emanation rates of soils	

Table 3-1

Radon Concentrations of Blank Samplers

Sampler ID	Radon Concentration (pCi/L)
648488	0.3
648504	0.3
648609	0.1
668576	0.2
668886	0.3
668891	0.3
669317	0.2
669334	0.3
670173	0.3
670434	0.3
670460	0.2
670513	0.1
670546	0.3
670604	0.2
670628	0.3
670629	0.2
670665	0.2
670701	0.2
670727	0.2
670835	0.3
670938	0.2
671486	0.3
671539	0.2
671606	0.3
671645	0.3
671658	0.2
671681	0.2

Table 3-2

Results of Duplicate Samplers by Location

Location	Radon Concentration (pCi/L) Pretest	Statewide	Fresno, Mono, Inyo & Tulare
Living room	1.7, 1.4	0.5, 0.6	20.0, 11.5
	1.5, 1.6	7.1, 7.0	1.5, 1.5
	2.0, 2.0	0.5, 0.4	1.5, 1.7
	1.1, 1.0	0.2, 0.3	0.8, 1.2
	1.4, 1.3	1.2, 1.1	
		0.6, 0.4	
		0.3, 0.3	
		3.5, 3.1	
		0.9, 0.9	
		0.6, 0.7	
		0.5, 0.4	
		0.3, 1.0	
		0.6, 0.4	
		1.2, 1.4	
		0.6, 0.6	
		0.7, 0.7	
		1.4, 1.4	
		1.4, 1.2	
		0.7, 0.7	
		0.8, 0.8	
		0.4, 0.4	
		0.5, 0.6	
		1.2, 1.3	
		0.6, 0.7	
		0.6, 0.6	
		0.3, 0.4	
Basement		1.0, 1.2	2.8, 2.9
		4.8, 5.9	
		3.4, 3.8	
		2.4, 5.5	
		5.8, 3.0	
		3.0, 3.1	
		0.9, 2.3	

Table 3-3

Results of First Analysis of Spiked Samples

Equivalent Exposure (pCi/l)	Result of Analysis (pCi/l)
5.0	5.7
5.0	7.7
5.0	7.5
5.0	11.8
5.0	9.2
5.0	6.8
5.0	9.4
5.0	5.7
5.0	7.8
5.0	8.7
5.0	11.9
5.0	11.0
5.0	10.5
5.0	9.4
10.0	15.8
10.0	11.5
10.0	16.8
10.0	11.6
10.0	15.8
10.0	16.0
10.0	15.8
10.0	11.6
10.0	10.2
10.0	11.9
10.0	17.4
10.0	14.5
10.0	17.9

Table 3-4

Comparison of Original Results and Reanalysis for 52 Alpha Track Detectors

Sample Type	Original (pCi/l)	Method	Recount (pCi/l) - CON Method
Spikes (5 pCi/l)	5.7	FO	5.5
	7.7	FO	5.1
	9.4	manual	5.3
	7.5	manual	5.2
	11.8	manual	5.4
	9.2	manual	5.5
	6.8	manual	5.7
	9.4	manual	5.8
	5.7	manual	5.3
	7.8	manual	5.5
	8.7	manual	5.8
	11.9	manual	5.9
	11.0	manual	6.3
	10.5	manual	6.0
Spikes (10 pCi/l)	15.8	FO	9.3
	11.5	FO	9.4
	16.8	FO	9.4
	11.6	manual	9.0
	15.8	manual	9.6
	16.0	manual	9.0
	15.8	manual	9.4
	11.6	manual	9.4
	10.2	manual	9.9
	11.9	manual	11.9
	17.4	manual	9.2
	14.5	manual	9.8
	17.9	manual	9.3
10 Highest	19.4	FO	18.0
	18.0	FO	17.8
	9.2	FO	6.9
	6.9	FO	7.1
	7.0	FO	6.6
	11.0	FO	7.9
	10.5	manual	10.9
	9.9	manual	3.6
10 Random	0.75	FO	0.74
	2.0	FO	1.0
	0.94	FO	1.2
	1.0	FO	1.3
	0.52	FO	0.49
	0.29	FO	0.31
	0.84	FO	0.85
	1.06	FO	1.14
	1.62	FO	1.48
	0.68	FO	0.73
Blanks	0.28	FO	0.25
	0.34	FO	0.28
	0.25	FO	0.22
	0.34	FO	0.30
	0.32	FO	0.29
	0.26	FO	0.20

Table 3-5

Results of Second Reanalysis of Radon Samplers

First Analysis	First Recount	Second Recount	First Analysis	First Recount	Second Recount	First Analysis	First Recount	Second Recount
2.2		2.1	2.4		2.3	3.7		3.6
2.5		2.5	2.0		2.1	2.3		2.2
3.3		3.4	10.4		10.5	2.5		2.6
2.7		2.4	2.8		2.7	**9.2**	**6.9**	**6.6**
2.6		2.5	3.3		3.4	2.5		2.7
2.1		2.0	3.1		2.9	2.9		2.6
2.5		2.3	4.2		3.9	2.8		2.8
2.2		2.2	3.5		3.5	**6.3**		**5.0**
2.0		1.9	2.0		1.8	**10.5**	**7.3**	**6.8**
2.0		1.9	2.7		2.5	2.0		1.9
4.1		3.9	5.4		5.2	2.2		2.2
2.3		2.4	2.4		2.1	2.1		1.9
2.1		2.0	2.4		2.3	2.5		2.3
2.0	**1.0**	**1.1**	2.5		2.3	19.4		22.0
3.9		3.7	3.0		2.8	2.6		2.5
18.0	**17.8**	**14.0**	2.0		2.0	3.0		2.9
2.1		2.0	2.4		2.4	2.1		2.0
3.5		3.4	6.8		6.8	2.1		2.0
3.1		3.0	2.2		2.0	3.0		2.8
2.4		2.3	4.3		4.2	2.0		1.8
2.2		2.1	**9.9**	**3.6**	**3.9**	2.0		2.2
3.1		2.9	2.0		1.9	**6.9**		**5.2**
2.2		2.1	2.1		2.1	7.0		6.8
3.5		3.4	3.4		2.8	3.9		3.5
2.7		2.5	2.5		2.2	2.0		1.7
2.9		2.9	2.6		2.6	**8.8**		**7.0**
15.9	**11.7**	**11.3**	3.1		3.0	5.8		4.8
6.1		**4.8**	3.0		2.6	3.4		3.1
2.4		2.0	3.9		3.6	4.2		4.3
2.6		2.4	3.7		3.9	2.1		1.9
2.1		2.1	2.7		2.8	3.4		3.6
4.2		3.9	2.8		2.8	**11.0**	7.9	**7.5**
7.0		**5.5**	3.8		3.7	**7.0**		**5.9**
3.1		2.8	2.9		2.8	3.0		3.0
2.3		2.0						

Note: numbers in boldface were changed from the original values.

Table 3-6

Summary of Housing Characteristics Data* for Pretest Study

Parameter	38 Participant Homes No. of homes (%)	150 Volunteer Homes No. of homes (%)	192 Respondent Homes No. of homes (%)
Aware of radon:			
No	12 (31.6)	52 (34.7)	66 (34.4)
Yes	26 (68.4)	98 (65.3)	126 (65.6)
Building type:			
Single-family house	34 (89.5)	131 (87.3)	167 (87.0)
Duplex	0 (0.0)	5 (3.3)	5 (2.6)
Townhouse	0 (0.0)	2 (1.3)	4 (2.1)
Condo ≤ 3 floors	2 (5.3)	8 (5.3)	12 (6.3)
Mobile home	2 (5.3)	3 (2.0)	3 (1.6)
Other	0 (0.0)	1 (0.7)	1 (0.5)
Substructure:			
Basement	1 (2.6)	5 (3.3)	7 (3.6)
Crawl space	17 (44.7)	76 (50.7)	99 (51.5)
Concrete slab	7 (18.4)	27 (18.0)	37 (19.3)
Other	1 (2.6)	1 (0.7)	2 (1.0)
Don't know	1 (2.6)	2 (1.3)	2 (1.0)
Combinations	11 (28.9)	39 (26.0)	45 (23.3)
Annual income:			
$5,000-$7,499	1 (2.6)	1 (0.7)	1 (0.5)
$7,500-$9,999	1 (2.6)	2 (1.4)	2 (1.1)
$10,000-$14,999	3 (7.9)	7 (4.9)	7 (3.8)
$15,000-$19,999	1 (2.6)	3 (2.1)	5 (2.7)
$20,000-$24,999	3 (7.9)	11 (7.7)	14 (7.7)
$25,000-$34,999	9 (23.7)	34 (23.9)	41 (22.5)
$35,000-$49,999	8 (21.1)	27 (19.0)	40 (22.0)
$50,000-$69,999	6 (15.8)	31 (21.8)	39 (21.4)
≥ $70,000	6 (15.8)	26 (18.3)	33 (18.1)
Number of automobiles:			
1	4 (10.5)	16 (10.8)	18 (9.5)
2	15 (39.5)	54 (36.5)	69 (36.3)
3	4 (10.5)	29 (19.6)	44 (23.2)
4	6 (15.8)	24 (16.2)	31 (16.3)
≥ 5	9 (23.7)	25 (16.9)	28 (14.7)

*Missing data are not included.

Table 3-7

Summary Statistics for Annual Radon Concentrations Measured in Pretest Study

Location	Radon Concentration (pCi/L)				
	Mean	S.D.	Min	Max	N
Bedroom	0.95[a] (0.85)[b]	0.41[c] (1.62)[d]	0.2	1.9	37
Living room	1.18 (0.93)	1.03 (1.97)	0.3	5.9	36
Whole house[e]	1.05 (0.89)	0.65 (1.77)	0.2	3.8	38
Basement	1.50 (1.50)	0.14 (1.10)	1.4	1.6	2
Outdoors	0.59 (0.55)	0.24 (1.47)	0.3	1.0	10

[a]Arithmetic mean

[b]Geometric mean

[c]Arithmetic standard deviation

[d]Geometric standard deviation

[e]Average of bedroom and living room concentration

Table 3-8

Summary of Housing Characteristics Data* for Main Study - Statewide

Parameter	310 Participant Homes No. of homes (%)	961 Volunteer Homes No. of homes (%)	1210 Respondent Homes No. of homes (%)
Aware of radon:			
No	121 (39.2)	407 (42.5)	533 (44.3)
Yes	188 (60.8)	551 (57.5)	671 (55.7)
Building type:			
Single-family house	236 (76.1)	793 (82.5)	980 (81.1)
Duplex	7 (2.3)	22 (2.3)	29 (2.4)
Townhouse	8 (2.6)	22 (2.3)	29 (2.4)
Condo ≤ 3 floors	27 (8.7)	55 (5.7)	85 (7.0)
Condo > 3 floors	4 (1.3)	5 (0.5)	7 (0.6)
Mobile home	27 (8.7)	58 (6.0)	70 (5.8)
Other	1 (0.3)	6 (0.6)	8 (0.7)
Substructure:			
Basement	10 (3.2)	22 (2.3)	31 (2.6)
Crawl space	133 (42.9)	435 (45.4)	553 (45.9)
Concrete slab	116 (37.4)	351 (36.6)	437 (36.3)
Other	7 (2.3)	17 (1.8)	23 (1.9)
Don't know	5 (1.6)	16 (1.7)	24 (2.0)
Combinations	39 (12.5)	117 (12.1)	137 (11.4)
Annual income:			
< $5,000	4 (1.4)	6 (0.7)	9 (0.8)
$5,000-$7,499	3 (1.0)	7 (0.8)	11 (1.0)
$7,500-$9,999	5 (1.7)	6 (0.7)	15 (1.3)
$10,000-$14,999	16 (5.5)	38 (4.2)	54 (4.7)
$15,000-$19,999	23 (7.8)	49 (5.4)	62 (5.4)
$20,000-$24,999	26 (8.9)	78 (8.6)	95 (8.3)
$25,000-$34,999	60 (20.5)	160 (17.6)	214 (18.8)
$35,000-$49,999	70 (23.9)	208 (22.9)	248 (21.8)
$50,000-$69,999	40 (13.7)	188 (20.7)	220 (19.3)
≥$70,000	46 (15.7)	167 (18.4)	212 (18.6)
Number of automobiles:			
1	93 (30.1)	136 (14.2)	173 (14.4)
2	130 (42.1)	386 (40.4)	494 (41.0)
3	50 (16.2)	226 (23.6)	281 (23.3)
4	22 (7.1)	109 (11.4)	143 (11.9)
≥ 5	14 (4.5)	99 (10.4)	114 (9.5)

*Missing data are not included.

Table 3-9

Summary Statistics for Annual Radon Concentrations Measured in Main Study - Statewide

Location	Radon Concentration (pCi/L) Mean	S.D.	Min	Max	N
Bedroom	1.08[a] (0.83)[b]	1.07[c] (1.96)[d]	0.1	11	308
Living room	1.10 (0.85)	1.24 (1.94)	0.2	16	300
Whole house[e]	1.09 (0.85)	1.12 (1.91)	0.2	13	310
Basement	2.65 (2.17)	1.68 (1.95)	0.6	7.7	27
Outdoors	0.49 (0.42)	0.30 (1.75)	0.1	1.5	68

[a] Arithmetic mean

[b] Geometric mean

[c] Arithmetic standard deviation

[d] Geometric standard deviation

[e] Average of bedroom and living room concentration

Table 3-10

Summary of Housing Characteristics Data* for Main Study - Fresno, Mono, Inyo, Tulare Counties

Parameter	37 Participant Homes No. of homes (%)	60 Volunteer Homes No. of homes (%)	88 Respondent Homes No. of homes (%)
Aware of radon:			
No	11 (29.7)	21 (35.0)	37 (43.0)
Yes	26 (70.3)	39 (65.0)	49 (57.0)
Building type:			
Single-family house	31 (83.8)	46 (76.7)	65 (75.6)
Duplex	0 (0.0)	1 (1.7)	2 (2.3)
Mobile home	6 (16.2)	13 (21.7)	17 (19.8)
Other	0 (0.0)	0 (0.0)	2 (2.3)
Substructure:			
Crawl space	20 (54.1)	35 (58.3)	49 (57.0)
Concrete slab	14 (37.8)	19 (31.7)	25 (29.1)
Other	0 (0.0)	0 (0.0)	2 (2.3)
Combinations	3 (8.1)	6 (10.0)	10 (11.7)
Annual income:			
< $5,000	1 (2.9)	1 (1.8)	2 (2.4)
$5,000-$7,499	1 (2.9)	2 (3.6)	4 (4.8)
$7,500-$9,999	1 (2.9)	1 (1.8)	3 (3.6)
$10,000-$14,999	3 (8.8)	7 (12.5)	8 (9.6)
$15,000-$19,999	7 (20.6)	11 (19.6)	12 (14.5)
$20,000-$24,999	7 (20.6)	9 (16.1)	10 (12.0)
$25,000-$34,999	4 (11.8)	8 (14.3)	17 (20.5)
$35,000-$49,999	7 (20.6)	11 (19.6)	18 (21.7)
$50,000-$69,999	3 (8.8)	4 (7.1)	6 (7.2)
≥ $70,000		2 (3.6)	3 (3.6)
Number of automobiles:			
1	6 (16.2)	10 (16.7)	14 (15.9)
2	15 (40.5)	23 (38.3)	32 (36.4)
3	10 (27.0)	15 (25.0)	24 (27.3)
4	1 (2.7)	4 (6.7)	8 (9.1)
≥ 5	5 (13.5)	8 (13.3)	10 (11.4)

*Missing data are not included.

Table 3-11

Summary Statistics for Annual Radon Concentrations Measured in Main Study - Fresno, Mono, Inyo, Tulare Counties

Location	Radon Concentration (pCi/L) Mean	S.D.	Min	Max	N
Bedroom	1.28[a] (1.16)[b]	0.54[c] (1.61)[d]	0.4	2.5	36
Living room	1.77 (1.37)	2.42 (1.80)	0.4	16	37
Whole house[e]	1.52 (1.28)	1.33 (1.70)	0.4	8.8	37
Basement	2.23 (2.14)	0.88 (1.50)	1.6	2.8	2
Outdoors	0.71 (0.66)	0.26 (1.51)	0.3	1.1	10

[a]Arithmetic mean

[b]Geometric mean

[c]Arithmetic standard deviation

[d]Geometric standard deviation

[e]Average of bedroom and living room concentration

Table 3-12

Estimated Percentage of California Residences Having Indoor Radon Concentrations Exceeding 4 and 8 pCi/L

	Percentage (95% Confidence interval) >4 pCi/L	>8 pCi/L
Pretest	0.44 (0.17-1.08)	0.01 (0.00-0.02)
Statewide	0.84 (0.61-1.13)	0.03 (0.02-0.04)
Fresno	1.57 (0.67-3.37)	0.03 (0.01-0.09)
Ventura	11.51 (4.40-24.40)	1.06 (0.25-3.61)

Table 3-13

Variables Related with Indoor Radon Concentration

Housing variable	Sample size	Geometric MEAN	Geometric (S.D.)	Arithmetic MEAN	Arithmetic (S.D.)
Building Type:					
Single-family house	236	0.90	(1.91)	1.17	(1.23)
Townhouse, Condo & Apartment	43	0.76	(1.90)	0.94	(0.70)
Mobile home	27	0.67	(1.71)	0.76	(0.42)
Other	4	0.41	(1.43)	0.43	(0.15)
Substructure:					
Full slab	112	--1.04	(1.87)	1.29	(1.07)
Full basement	7	* 0.85	(3.81)	2.44	(4.84)
Full crawl space	102	--0.68	(1.70)-- *	0.79	(0.53)
Other	86	0.88	(1.90)--	1.10	(0.86)
Home Age:					
0-9 years	68	--1.02	(2.12)	1.44	(1.78)
10-25 years	109	* 0.84	(1.73)	0.97	(0.54)
26-50 years	111	0.81	(1.92)	1.06	(1.06)
> 50 years	22	--0.65	(1.89)	0.80	(0.58)
Ventilation (Windows/doors open):					
Rarely	50	*--1.11	(2.12)--	1.59	(2.07)
Occasional	183	--0.84	(1.86) *	1.04	(0.75)
Often	63	0.73	(1.80)--	0.91	(0.90)

* : Significant at 0.05 level by Bonferoni t-test

Table 3-14

Stepwise Regression Model for the Dependence of ln(radon concentration) on Selected Variables

Variable	Order entered	Coefficent	S.E. of Coefficent	F	P > F	R^2
Intercept		0.082				
Region[a]	1	0.719	0.108	44.50	0.0001	0.128
Ventilation[b]	2	-0.049	0.011	20.81	0.0001	0.189
Substructure[c]	3	0.230	0.069	10.98	0.0010	0.223
Building type[d]	4	0.271	0.077	12.23	0.0005	0.246
Home age[e]	5	0.237	0.081	8.56	0.0037	0.268

Regression Model:

ln(radon concentration) = 0.082 + 0.719 * (Region) - 0.049 * (Ventilation) + 0.230 * (Substructure) + 0.271 * (Building type) + 0.237 * (Home age)

[a]Region: Fresno area and Ventura area = 1, Else = 0

[b]Ventilation: Window/Door open all 4 seasons

[c]Substructure: Full concrete slab = 1, Else = 0

[d]Type of residence: Single house = 1, Else = 0

[e]Home age: 0-9 years = 1, Else = 0

Table 3-15

Radioactivity of Soils

Variable	Mean	S.D.	MIN	MAX
Emanating Ra^{226}(pCi/g)	0.16[a](0.18)[b]	1.71[c](0.10)[d]	0.05	0.53
Total Ra^{226}(pCi/g)	0.85 (0.93)	1.55 (0.40)	0.40	2.08
Emanating Percentage	18.7 (19.7)	1.4 (6.0)	7.5	32.6
Total Rn^{228}(pCi/g)	0.74 (0.85)	1.70 (0.44)	0.23	2.18
K^{40}(ppm)	1.82 (2.00)	1.58 (0.73)	0.41	3.55
Exposure Rate (ρ^*/hr)	7.28 (7.91)	1.53 (3.07)	2.17	15.69

[a]Geometric Mean

[b]Arithmetic Mean

[c]Geometric S.D.

[d]Arithmetic S.D.

*ρ (Roentgen) = 5.43 x 10^7 MeV/g air

Table 3-16

Variables Significantly Correlated with ln(Indoor Radon Concentrations)

Variable	Pearson Correlation Coefficient	Significance
$\ln(Ra_{\epsilon\mu})$	0.4275	0.0008
$\ln(Ra_{\tau\sqrt{\tau}})$	0.3424	0.0085
$(Ra_{\tau\sqrt{\tau}})(K^{1/4})$	0.3015	0.0226

Table 3-17

Radon in Water

ID	City	Location	Water Rn (pCi/L)	Indoor Rn (pCi/L)
1	Kerman	faucet at well	792	1.85
2	Tollhouse	faucet at well	906	1.40
3	Tollhouse	faucet 46 m from well	1506	0.55
4	Auberry	well head	3425	1.05
5	Squaw Valley	faucet at house	586	2.40
6	Lone Pine	faucet nearest well 0.4 km away	2043	2.45
7	Lone Pine	well head	2363	1.55
8	Independence	faucet at house 0.4 km from well	4575	1.20
9	Bishop	private well	2699	1.40
10	Mammoth Lakes	house faucet	bd*	1.30
"	"	outdoor faucet	31	1.30
11	Auberry	kitchen faucet	670	1.20
12	Reedley	faucet between tower and house	198	1.05
13	Dinuba	pressure storage tank	353	1.55
14	Three Rivers	private well, river water	47	0.95
15	Three Rivers	faucet near well	367	1.25
16	Newman	well head tap	602	1.00
17	Angels Camp	garden faucet 0.4 km from well	169	0.68

*below detection limit

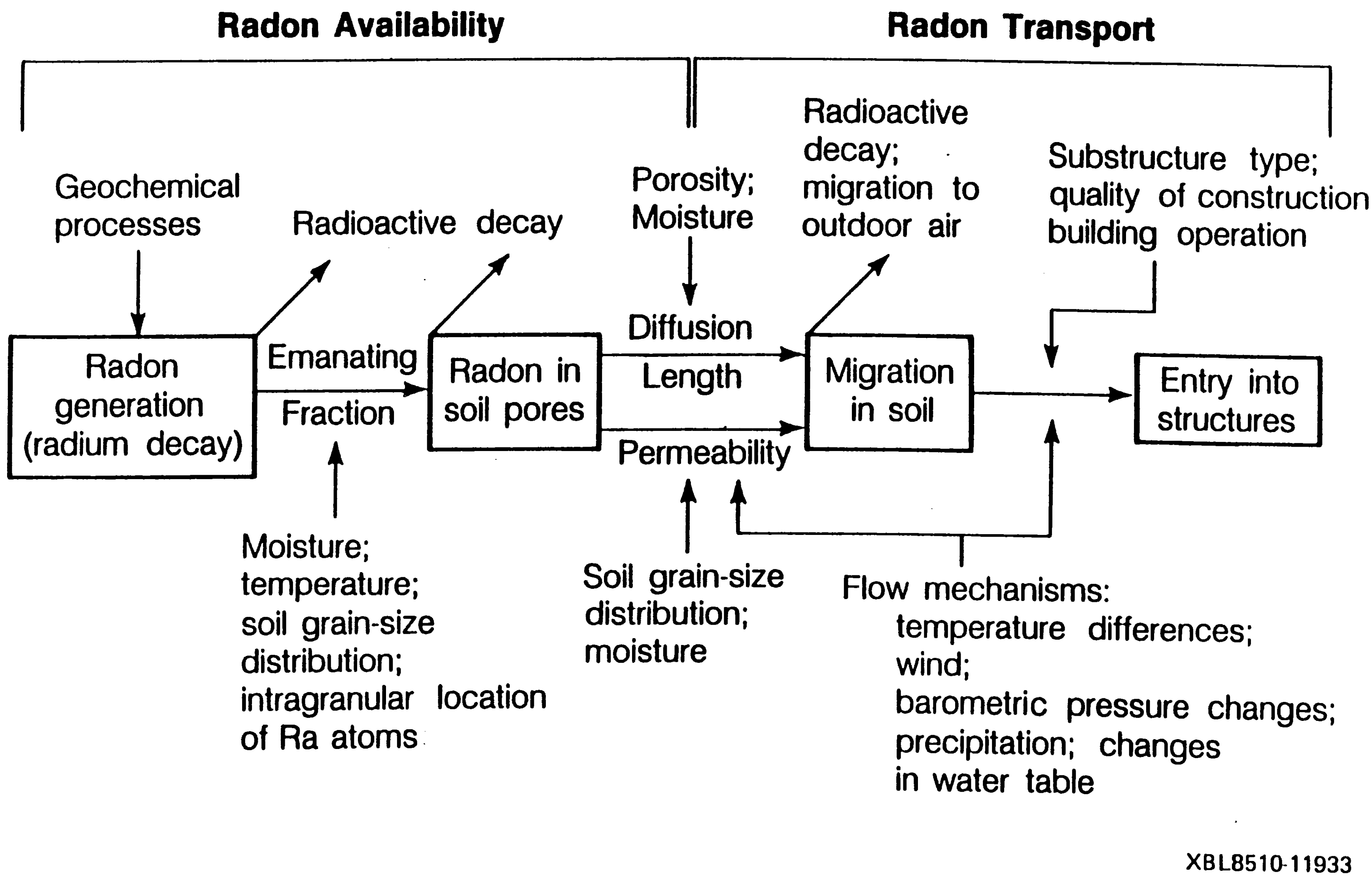

Figure 1-1. Schematic representation of the stages of radon in soil.

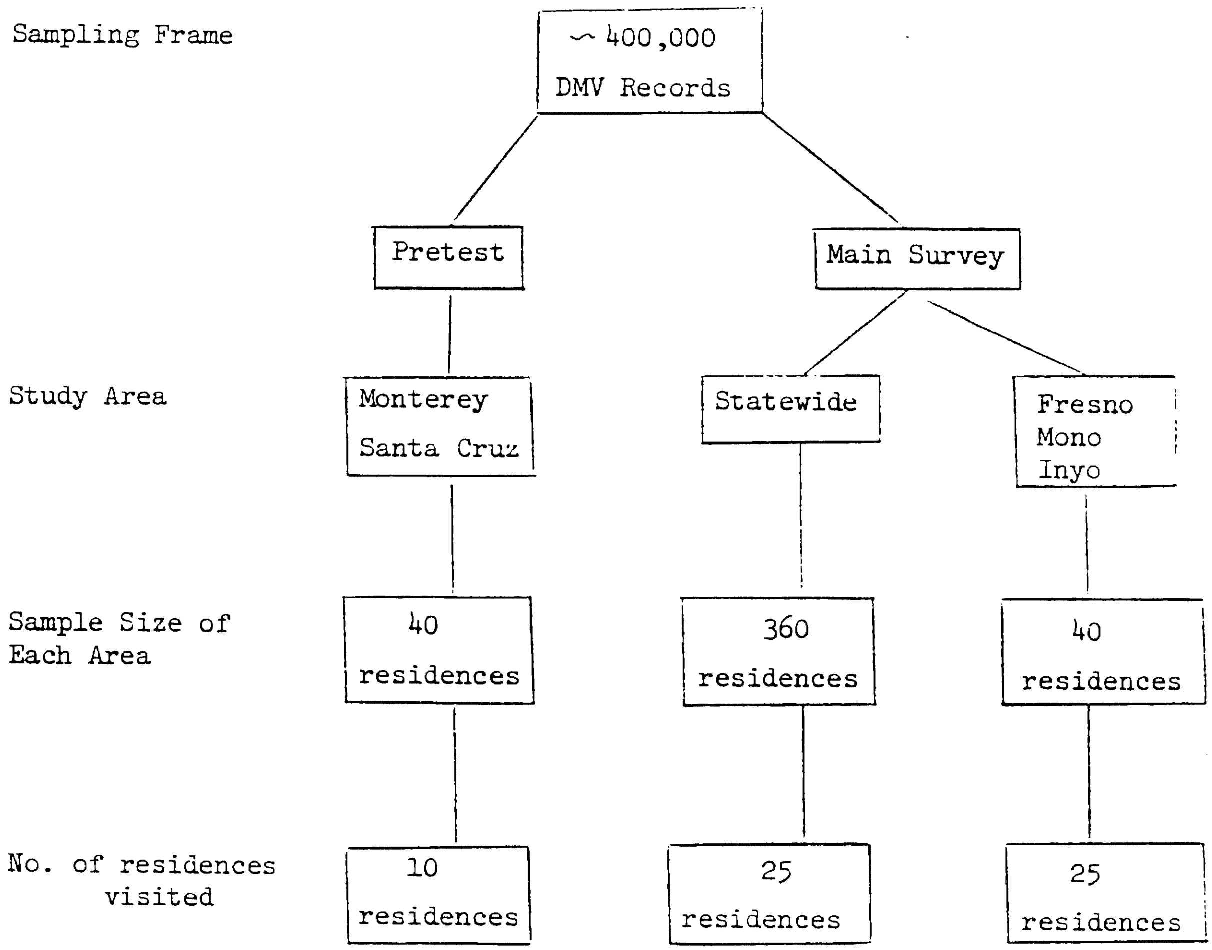

Fig. 2-1 Study Design

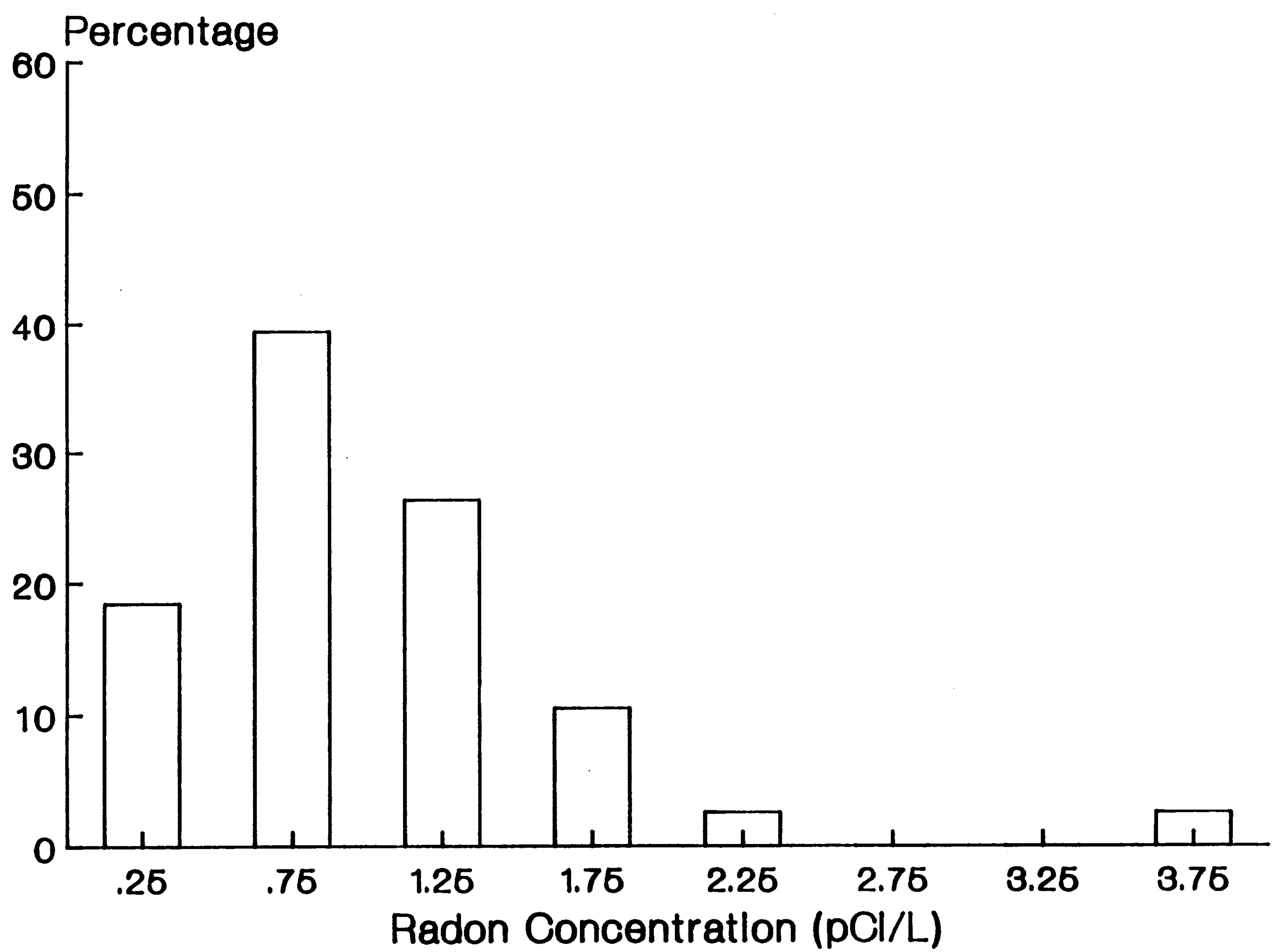

Figure 3-1. Radon Distribution-Pretest

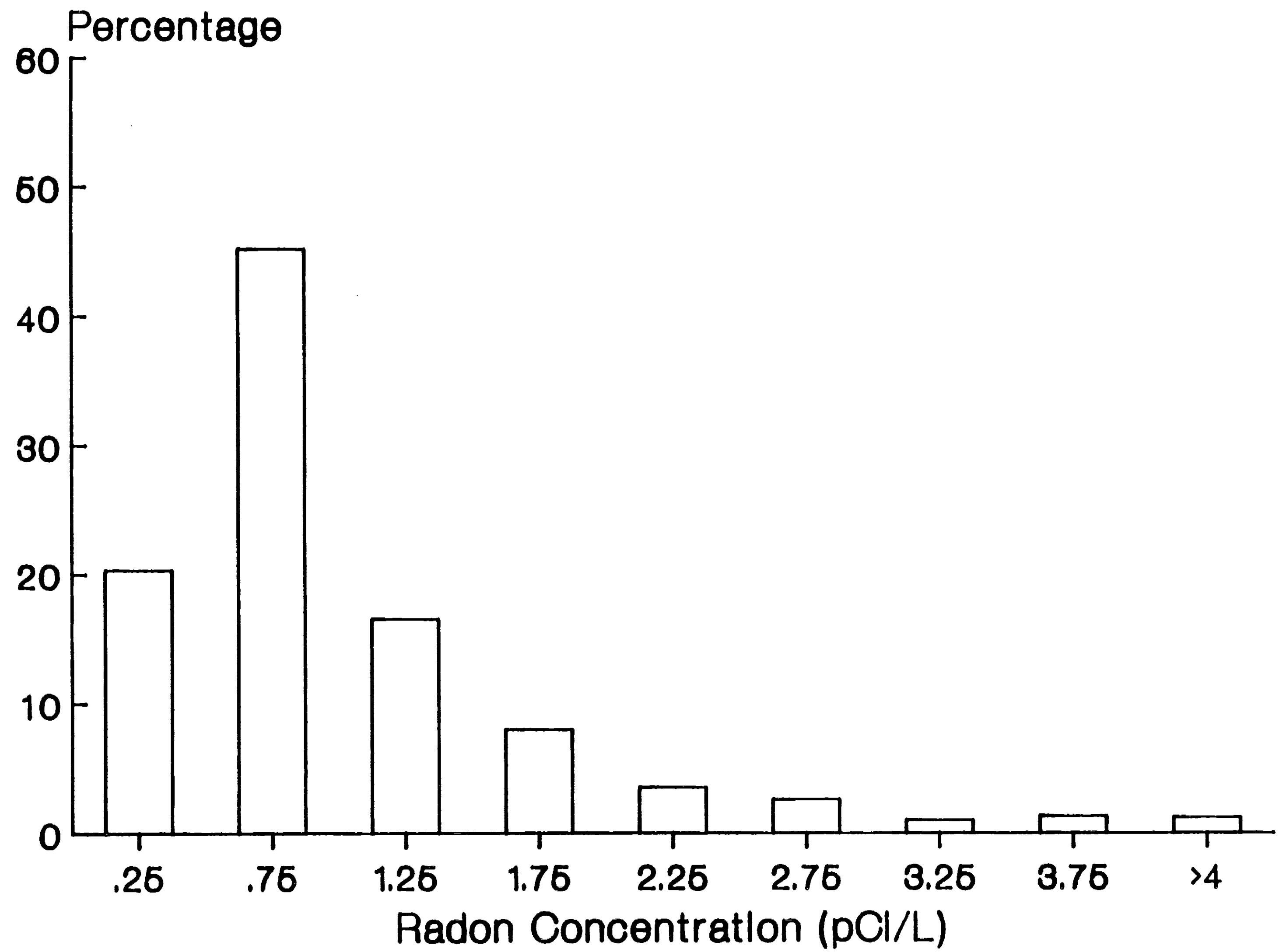

Figure 3-2. Radon Distribution-Statewide

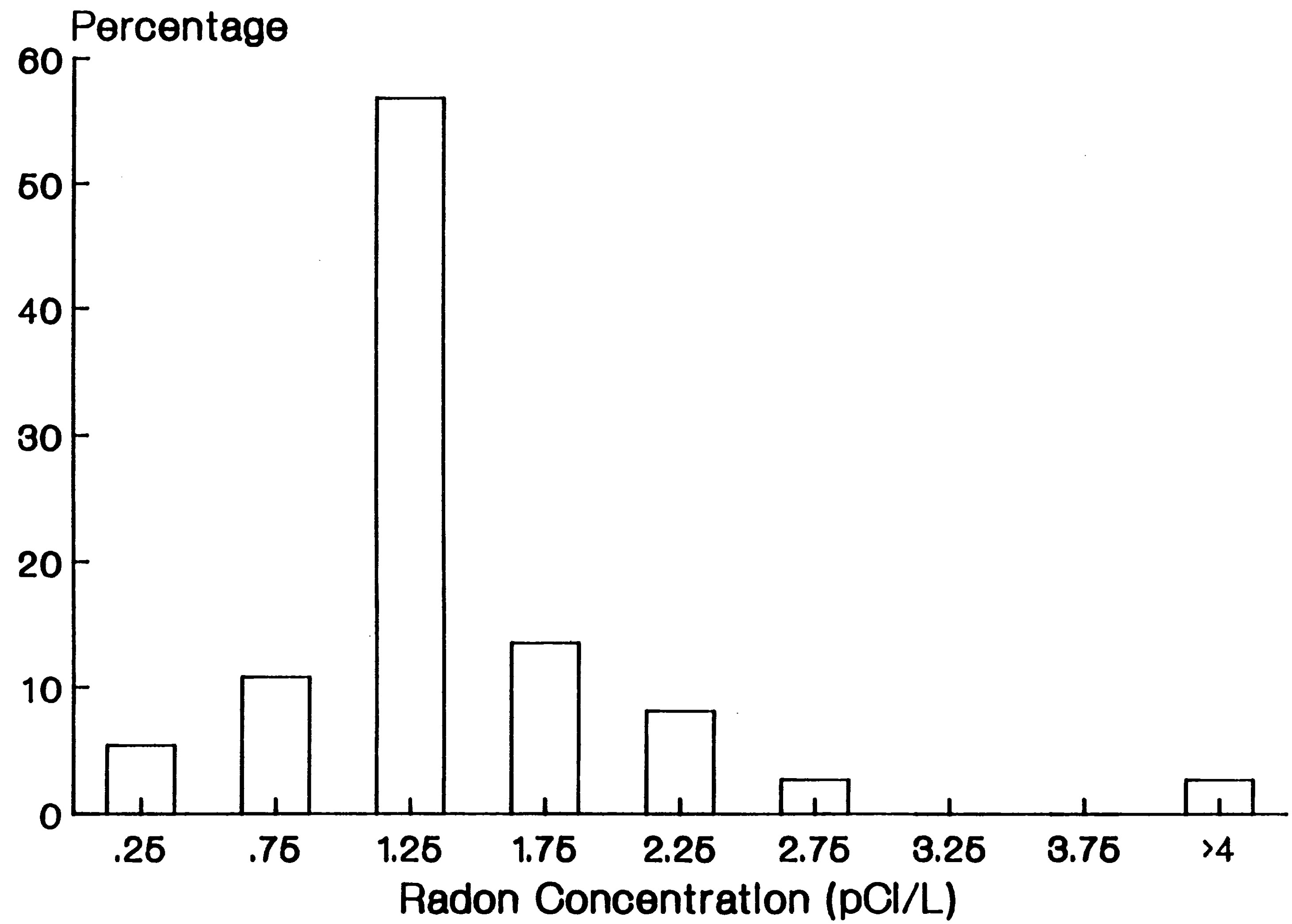

Figure 3-3. Radon Distribution-Sierra

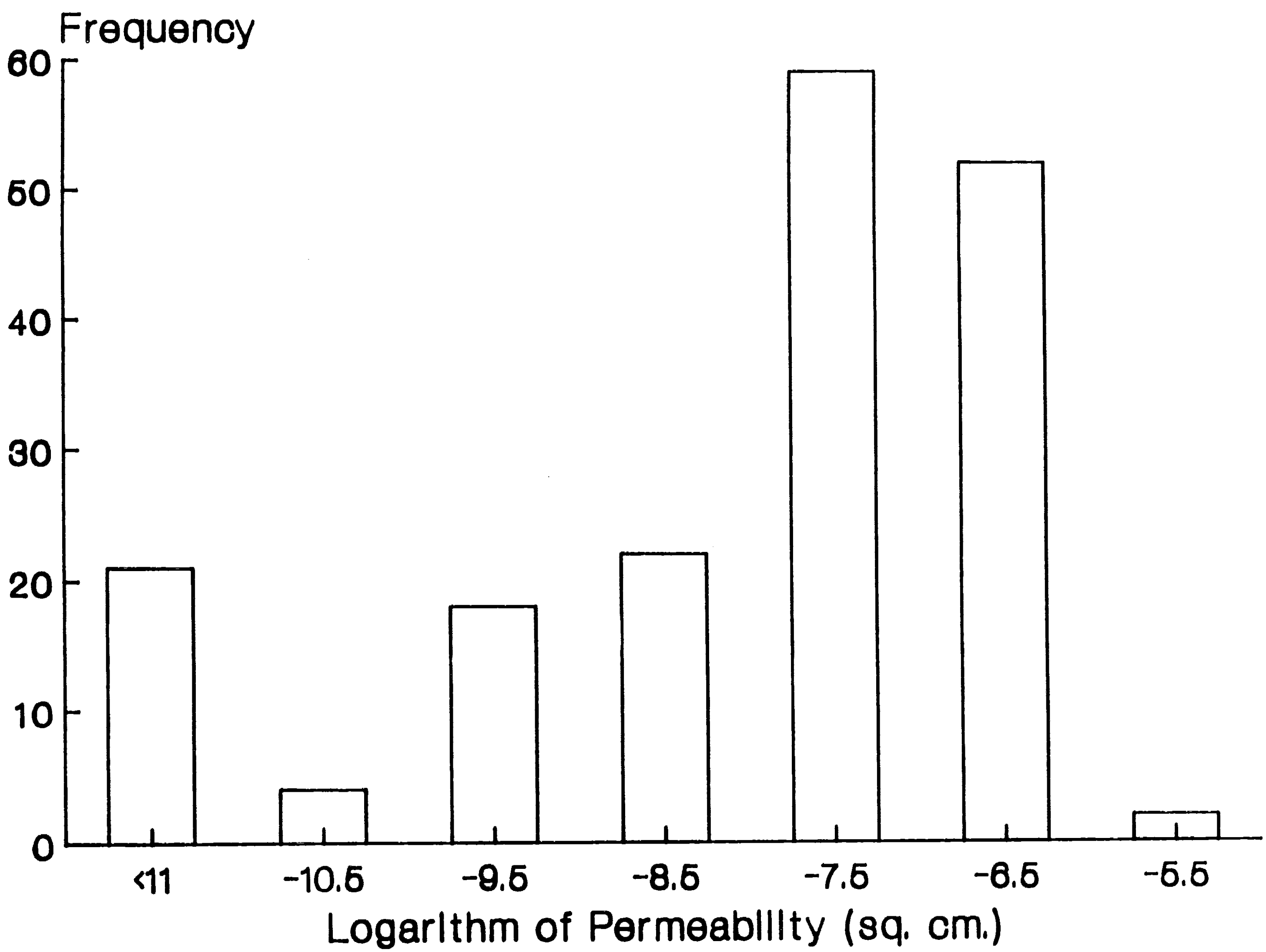

Figure 3-4. Soil Permeabilities

APPENDIX A

Cover Letters and Instructions

STATE OF CALIFORNIA—HEALTH AND WELFARE AGENCY

GEORGE DEUKMEJIAN, *Governor*

DEPARTMENT OF HEALTH SERVICES
2151 BERKELEY WAY
BERKELEY, CA 94704
(415) 540-2469

February 8, 1988

Dear Resident:

The California Department of Health Services and the Air Resources Board will be conducting a one-year study in California during 1988-89 to measure radon levels within and near homes. Radon is a naturally occurring substance which at high levels may cause health problems.

Your home has been randomly selected for possible inclusion in this study of 440 homes throughout the State. We hope you will be interested in participating in the study. Your participation will benefit both your family and all Californians. You will learn what level of radon is present in your home, and we will be able to estimate the extent of the radon problem in this State. This project is funded by the California Air Resources Board and will cost you nothing. Similar measurements made by a private firm would cost anywhere from $40 - $500. As you will see from reading the enclosed material, there will be very little inconvenience for those who volunteer.

Before you make up your mind whether or not you wish to participate, we recommend that you do the following: First, read the enclosed fact sheet which will answer most of your questions about the study, and about radon in general. Second, have the head of your household fill out the brief questionnaire that is enclosed. **Please fill out the questionnaire whether or not you wish to participate in the study. Please return the questionnaire within two weeks in the postage-paid envelope.**

Thank you for taking the time to read these materials. If you volunteer your home and it is selected for inclusion in the study, you will be assisting us in investigating an important public health issue affecting the people of the State of California. If you have further questions after reading the enclosed materials, please call me collect at (415) 540-2469.

Sincerely,

Kai-Shen Liu, Ph.D., M.P.H.
Epidemiologist
Indoor Air Quality Program
Air and Industrial Hygiene Laboratory

Enclosures

QUESTIONS AND ANSWERS ABOUT RADON AND THE STATE'S SURVEY

Q What is radon, and how does it get into houses?

A Radon is a radioactive gas that is formed by the decay of radium, an element that occurs naturally in all soil and rock. Since radon does not react chemically with other materials, it can move through the ground more readily than most other chemicals or substances and reach air or water to which people have access. The main source of radon gas in the air inside U.S. homes is the soil and rock beneath the house. Radon can migrate through cracks and openings in floors, concrete slabs, or basement walls. Less often, the main source of radon in indoor air is well water that is used for showering or other household purposes. Recent research indicates that indoor radon levels vary with both soil and house characteristics.

Q Why is radon a health concern?

A Exposure to radon gas increases the risk of developing lung cancer, even in non-smokers. Here's how: The products of the radioactive decay of radon are also radioactive. Once they are produced, they tend to stick to dust particles which are present even in clean air. When these dust particles are inhaled, they carry these radioactive atoms deep into the lungs, where they can remain until they decay. In so doing, they emit radiation that can cause lung cancer. It is estimated that between 5,000 and 20,000 people die every year in the U.S. as a result of exposure to radon gas in their homes.

Q Is radon gas a problem in homes in California?

A We know of a few homes in which radon levels have been found to be above the level at which the EPA recommends immediate action to lower the levels. However, very few homes have been measured in California, and none of these measurements have been part of a systematic survey of radon in the State. Therefore we know very little at this time about the prevalence of homes with levels that are high enough to be of concern. This is the reason that we are conducting this study.

Q If I agree to participate, will my home be part of the study for certain?

A Not necessarily. We have had to request participation from more than 440 homes because we know that not everyone will be able to participate. If more than 440 agree to participate, we will have to select 440 homes from that group. You will be notified within 1 - 2 months of your reply if you have been selected (see next question).

Q What will I have to do if I agree to participate, and my home is chosen?

A If you agree to participate, you will receive another letter in 1 - 2 months. This letter will let you know whether or not your home has been selected for the study. Following the letter, you will receive a package containing from 2 - 6 radon samplers, instructions for installing them, a record sheet, a questionnaire about your home, and a postage-paid envelope in which to send back the questionnaire.

Q What is the sampler like? How does it work?

A The samplers are about the size of a small pillbox, require no electricity, and make no noise. You put it in place (according to the instruction) and leave it alone until it's time to send it back to us. There is no danger associated with their use. They actually just contain a special plastic that is sensitive to radon.

Q How much will this disrupt my activities?

A Most of the homes will receive from two to four samplers. Unwrapping and setting out the samplers should take no more than a half-hour of your time. Completing the questionnaire will require an additional half-hour of your time.

Q How long will the radon measurement take?

A The samplers should be left in place for a full year. Near the end of that time, we will mail you a package containing a postage-paid mailer and instructions for packing up the samplers in it.

Q Will anyone come to my home to make measurements?

A Not for most homes. However, we wish to perform soil measurements at about 15% of the homes. If your home is selected for this part of the study, we would visit your yard at a time agreeable to you, and collect a small sample of soil. We would also perform some soil measurements in your yard and collect a water sample if you use well water.

Q Can I participate if I live in an apartment?

A Yes, we assume that some of the participants will live in apartments, condominiums, townhouses or mobile homes.

Q Will I be notified of the results of radon testing in my home?

A You will be given the choice of being notified of the results or not.

Q Will the results be confidential?

A Yes, your name and address will be held in strictest confidence. The information collected will only be used to make a statistical report.

STATE OF CALIFORNIA—HEALTH AND WELFARE AGENCY

GEORGE DEUKMEJIAN, *Governor*

DEPARTMENT OF HEALTH SERVICES
2151 BERKELEY WAY
BERKELEY, CA 94704
(415) 540-2469

March 21, 1988

Dear Participant:

Thank you very much for agreeing to participate in the radon survey by the California Department of Health Services and the Air Resources Board. Enclosed you will find a set of radon monitors, instructions for their placement, a survey questionnaire, and a postage-paid return envelope. Please read the instructions carefully before beginning to place the monitors. To help you carry out the radon sampling successfully, a procedure is provided below for you to follow:

1. On Saturday, April 2, 1988, place one radon monitor in the master bedroom and one monitor in the living room (or main activity room). If you are not able to place the monitors on April 2, choose a date that is close to April 2, and convenient to you. Follow the enclosed "Instructions for Indoor Radon Measurements" step by step and make sure you have the correct side (with holes) of the monitor facing the open air.

2. Please have the head of your household fill out the radon survey questionnaire. The last part of the questionnaire is actually a log form and a form requesting permission to visit your home and to take water and soil samples from your house. Please fill out this part also.

3. After the questionnaire and the forms have been completed, please put them into the postage-paid envelope and send them back to us at your earliest convenience.

The monitors should be left undisturbed for about one year. You will receive instructions for returning radon monitors at the appropriate time. If you have any questions or plan to move in the near future, please call me collect at (415)-540-2469.

Sincerely

Kai-Shen Liu, Ph.D., M.P.H.
Epidemiologist
Indoor Air Quality Program
Air & Industrial Hygiene Laboratory

KSL(BL)

Enclosures

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Sincerely

Kai-Shen Liu

Kai-Shen Liu, Ph.D., M.P.H.
Epidemiologist
Indoor Air Quality Program
Air & Industrial Hygiene Laboratory

KSL(BL2)

Enclosures

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2151 BERKELEY WAY
BERKELEY, CA 94704
(415) 540-2469

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1. On Saturday, April 2, 1988, place one radon monitor in the master bedroom, one monitor in the living room (or main activity room) and one monitor in the basement. If you are not able to place the monitors on April 2, choose a date that is close to April 2, and convenient to you. Follow the enclosed "Instructions for Indoor Radon Measurements" step by step and make sure you have the correct side (with holes) of the monitor facing the open air.

2. Please have the head of your household fill out the radon survey questionnaire. The last part of the questionnaire is actually a log form and a form requesting permission to visit your home and to take water and soil samples from your house. Please fill out this part also.

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Enclosures

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March 21, 1988

Dear Participant:

Thank you very much for agreeing to participate in the radon survey by the California Department of Health Services and the Air Resources Board. Enclosed you will find a set of radon monitors, instructions for their placement, a survey questionnaire, and a postage-paid return envelope. Please read the instructions carefully before beginning to place the monitors. To help you carry out the radon sampling successfully, a procedure is provided below for you to follow:

1. On Saturday, April 2, 1988, place one radon monitor in the master bedroom, one monitor in the living room (or main activity room) and two monitors in the basement. If you are not able to place the monitors on April 2, choose a date that is close to April 2, and convenient to you. Follow the enclosed "Instructions for Indoor Radon Measurements" step by step and make sure you have the correct side (with holes) of the monitor facing the open air.

2. Please have the head of your household fill out the radon survey questionnaire. The last part of the questionnaire is actually a log form and a form requesting permission to visit your home and to take water and soil samples from your house. Please fill out this part also.

3. After the questionnaire and the forms have been completed, please put them into the postage-paid envelope and send them back to us at your earliest convenience.

The monitors should be left undisturbed for about one year. You will receive instructions for returning radon monitors at the appropriate time. If you have any questions or plan to move in the near future, please call me collect at (415)-540-2469.

Sincerely

Kai-Shen Liu, Ph.D., M.P.H.
Epidemiologist
Indoor Air Quality Program
Air & Industrial Hygiene Laboratory

KSL(BLA2)

Enclosures

INSTRUCTIONS FOR INDOOR RADON MEASUREMENTS

The enclosed box(es) contain(s) radon monitors which are wrapped in sealed bags. Sampling begins when the bag is opened and the monitor is removed. Please place the monitors in locations specified on the back of the bags. Placement should begin on Saturday, April 2, 1988 or a date close to it. Read all instructions carefully before proceeding. Please follow the five steps.

STEP 1. Tear or cut open the bag and remove the Radtrak monitor. This begins the monitoring period. Please record the starting date on the label on the monitor.

STEP 2. Please write down the identification number and starting date on page 6 of the survey questionnaire.

STEP 3. In the specified room (as indicated on the back of the bag), select a site following the guidelines as closely as possible:

a. Keep the monitor away from possible drafts from windows, heating vents, fans, air conditioners, or portable heaters. If it is possible, please keep it also away from exterior walls.

b. Avoid sites such as closed spaces (closet, drawer, or cabinet), or places reachable by small children or pets.

c. If you are asked to put the monitor in your basement (only when you have a basement), it should be at least two feet from the floor, walls, and ceiling.

STEP 4. Please place the monitor upright (holes pointing up) on a shelf, table or other flat surface. Alternately, you may hang it from the ceiling, the wall, or the frame of a mirror or a picture. In any case, be sure that the side with holes is facing the open air. If two monitors are to be placed in the same room, keep them no more than one foot from each other, and preferably closer.

STEP 5. Please leave the monitor undisturbed until you receive the instructions to return them.

Based on past experience with other surveys, during the one-year exposure period, some of the monitors have been mistakenly thrown away or covered up by other members of the surveyed households. Therefore it is important to let everyone in your household be aware of the placement of the radon monitors. If you have any questions about the instructions, please call me collect at (415)-540-2469.

STATE OF CALIFORNIA—HEALTH AND WELFARE AGENCY GEORGE DE

DEPARTMENT OF HEALTH SERVICES
2151 BERKELEY WAY
BERKELEY, CA 94704
(415) 540-2469

March 21, 1988

Dear Participant:

Thank you for agreeing to participate in the radon survey. The indoor radon monitors have been sent to you in a separate package. In order to gain a better understanding of the relationship between outdoor and indoor radon concentrations, 25% of the surveyed residences were selected for outdoor radon measurements. Your home has been selected.

The package you received contains one outdoor radon monitor. You may wonder about the size and weight compared with the indoor radon monitor. Actually, the outdoor radon monitor is very light and only about the size of a small cup. The monitor is held in a big, strong housing that protects it from rain, wind, sun, extreme temperatures and other potential damage. Please take the following steps to install it on Saturday, April 2, 1988 or on a date that is convenient to you and close to April 2.

Step 1. Tear or cut open the aluminum bag to remove the outdoor radon monitoring device.

Step 2. Follow these guidelines to find a good site for the outdoor radon monitor:

- The monitor should be 5 to 6 feet above the ground.
- Try to minimize exposure of the monitoring device to direct sunlight or rainfall.
- An ideal place would be a covered patio, a carport, a porch, or the side of the house under the eaves.
- Place the monitor in a location where it can stay for a full year.

Step 3. Fasten the monitor to a post or wall using the hook on the top of the device. Make sure it is held firmly so that it cannot be blown down by a strong wind. The side with the white filter should be facing toward the ground.

Step 4. Fill out the log form, place it into the postage paid envelope, and mail it back to us as soon as possible.

The outdoor monitor should be left undisturbed for one year. You will receive instructions for returning it at the appropriate time. If you have any questions, please call me collect at (415)-540-2469.

Sincerely,

Kai-Shen Liu, Ph.D., M.P.H.
Epidemiologist
Indoor Air Quality Program
Air & Industrial Hygiene Laboratory

KL(01)

Enclosure

LOG FORM

Please describe briefly where you put the outdoor monitor and fill in the starting date. Cut off the form and mail it back to us as soon as possible.

ID NUMBER	LOCATION OF OUTDOOR MONITOR	STARTING DATE MONTH	DAY	YEAR
________	______________________________	_____	_____	_____
	______________________________			

APPENDIX B

Mini- and Main Questionnaire

California Department of Health Services
Air and Industrial Hygiene Laboratory
California Indoor Air Quality Program
2151 Berkeley Way, Room 334
Berkeley, CA 94704

Radon Survey Mini-questionnaire

Please take a few minutes to fill out this mini-questionnaire. Answer every question to the best of your knowledge. This information is essential for us to select a representative sample of typical California homes. Your responses will be kept completely confidential.

1. Were you previously aware of radon as a problem in indoor environments?

   No ____ Yes ____

2. Do you think that you have a radon problem inside your residence?

   No ____ Don't know ______

   Yes ____ If yes, please give the reason ________________________________

   ____

3. Do you plan to move within a year? No ____ Yes ____

4. In what type of building do you live?

   Single family house ____
   Duplex ____
   Townhouse ____
   Condominium or apartment not over 3 stories high ____
   Condominium or apartment over 3 stories high ____
   Mobile home ____

   Other, please specify ________________________________

5. What is the type of substructure underneath your building. (You may check more than one)

   Basement ____
   Crawl space ____
   Concrete slab ____

   Other, please specify ________________________________

   ____

   Don't know ____

(over)

6. What is the approximate value of your residence at today's market value?

less than $10,000	_____	100,000-149,999	_____
10,000-19,999	_____	150,000-199,999	_____
20,000-29,999	_____	200,000-249,999	_____
30,000-49,999	_____	250,000-299,999	_____
50,000-99,999	_____	300,000 or more	_____
		Don't know	_____

7. How many registered motor vehicles are there in your household (please specify the number of each)?

auto	_____	motorscooter	_____
pickup	_____	motorcycle	_____
van	_____	RV or motorhome	_____

other (please specify) ______________________________

8. What is the approximate total income of your household?

less than $5,000	_____	20,000-24,999	_____
5,000- 7,499	_____	25,000-34,999	_____
7,500- 9,999	_____	35,000-49,999	_____
10,000-14,999	_____	50,000-69,999	_____
15,000-19,999	_____	70,000 or more	_____

(Note: This question is optional but your answer would assist us greatly in selecting a representative sample of homes. As with other answers, this will be kept strictly confidential.)

9. Please indicate your willingness to participate in the radon survey by checking the appropriate space and write down your name, current address, and telephone numbers for future contact.

Willing _____ Not interested _____

Why not? ______________________________

NAME: ______________________________ (please print)
Last First

Address: ______________________________
Street

____
City Zip

Home phone number ( )-______________

Work phone number ( )-______________

Best time to call ______________________________

PRIVACY NOTIFICATION

The authority for maintaining the requested information by the Indoor Air Quality Program, Air and Industrial Hygiene Laboratory, Division of Laboratories, State Department of Health Services is the Health and Safety code, Article 9.5, Section 426. The information will be used to select residences for a statewide radon survey. Because the mailing list was provided by the Department of Motor vehicles, information on motor vehicles was collected for the correction of potential bias of home selection. Information on dwelling types, house values and household incomes will allow us to include reasonable number of residences in each category so that the results of this survey can be generalized to all California residences. Personal data collected from this survey will be kept strictly confidential. Results of the study will be presented only in statistical summaries. It is voluntary to answer any of the questions and there are no consequences of not providing all or part of the requested information. Summaries of data acquired through this survey will be shared with the funding agency, California Air Resources Board.

For more information or access to your records, please contact Kai-Shen Liu, Air & Industrial Hygiene Laboratory, 2151 Berkeley Way, Berkeley, CA 94704, (415) 540-2469.

To be completed by
California Department of
Health Services
ID ________
Date ________________

Indoor Air Quality Program
Air & Industrial Hygiene Laboratory
California Department of Health Services
Radon Survey Questionnaire

1. What type of residence do you live in ?
   ___ a single family house
   ___ a townhouse
   ___ a condominium
   ___ an apartment
   ___ a mobile home
   ___ other, please specify ______________________________

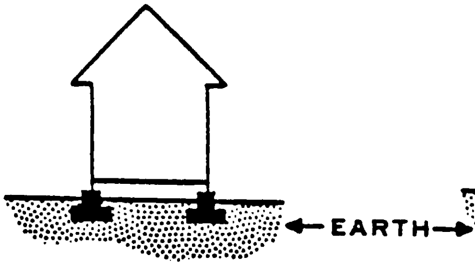
2. Do you live in an attached housing unit (shares at least one common wall with another housing unit)?
   ___ yes ___ no (If no, please go to question 3)
   a. What is the total number of units in the building to which your housing unit is attached?
      ___ 2- 4 units (such as duplex, triplex, quadruplex)
      ___ 5-10
      ___11-30
      ___31-50
      ___50+
   b. What is the total number of floors in this building ? _____
   c. Which floor or floors do you live on ? ______

3. What is the main type of building material used for the outside walls of your residence :
   ___ brick
   ___ concrete
   ___ cinderblock
   ___ wood
   ___ stucco
   ___ other, please specify__________________________
   ___ don't know

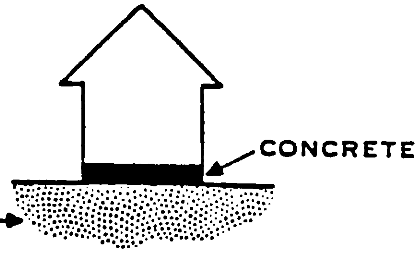
4. What is your best guess about the age of your residence ?
   ___ 0- 4 years old
   ___ 5- 9 years old
   ___ 10-25 years old
   ___ 26-50 years old
   ___ more than 50 years old

5. On the next page, there are figures of different types of house substructures. Please **check the one that best matches your house**. If none of the figures matches your house, please modify the one most similar to your residence. You may also draw a picture using the space at the bottom of that page.

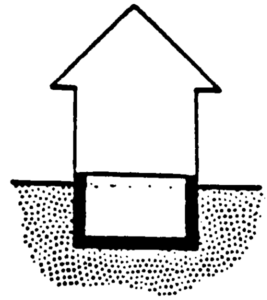
Here a basement is defined as a space or a room whose exterior walls are at least 50% below ground level.



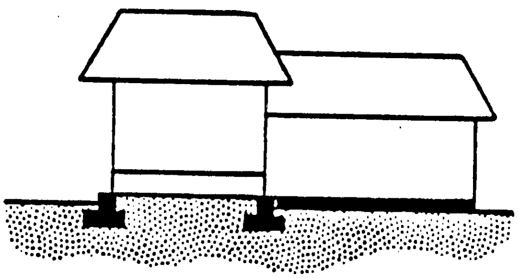
☐ FULL CRAWL SPACE



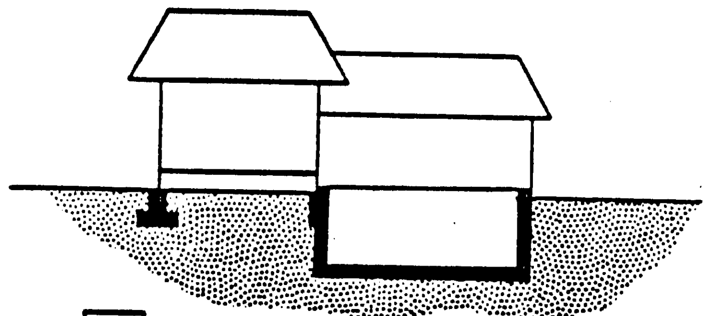
☐ FULL SLAB ON GRADE



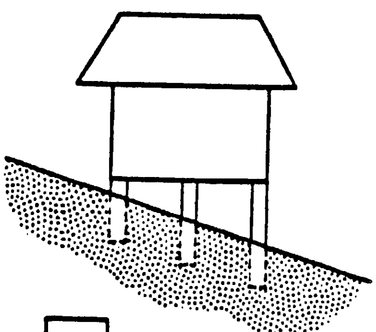
☐ FULL BASEMENT



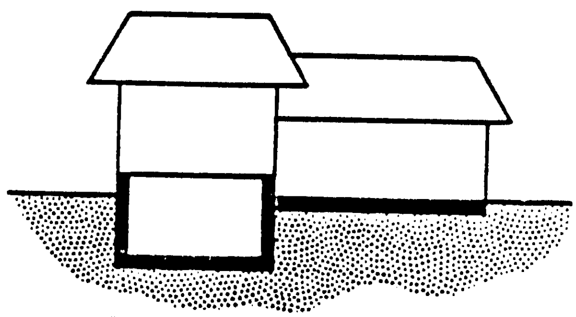
☐ CRAWL SPACE AND SLAB



☐ CRAWL SPACE AND BASEMENT



☐ PIERS



☐ SLAB AND BASEMENT

☐ DON'T KNOW

☐ OTHER *(please draw a picture and describe briefly)*

6. Does your residence have a crawl space?
___ yes ___ no (If no, please go to question 7)

a. What is the floor material of the crawl space?
   - ___ exposed earth
   - ___ paved
   - ___ plastic sheet
   - ___ other, please explain: ______________________

b. Is the crawl space vented or not ? (vents may be screened or shuttered window-like openings, or a series of holes in the lower exterior wall of building)
   - ___ yes, vented
   - ___ no, not vented

c. Approximately how much of the living area on the ground floor of your residence is above the crawl space? (check the value closest to your estimate)
   - ___ a quarter
   - ___ one half
   - ___ three quarters
   - ___ whole house

d. Is the floor over the crawl space insulated ?
   - ___ yes, insulated
   - ___ no, not insulated
   - ___ partially insulated

7. Does your residence have a basement ?(a basement is here defined as a space or room whose exterior walls are at least 50% below ground level)
___ yes ___ no (If no, please go to question 8)

a. Approximately how much of the living area on the ground floor of your residence is over the basement? (Check the value closest to your estimate)
   - ___ a quarter
   - ___ one half
   - ___ three quarters
   - ___ whole house

b. Is the basement used as living space (such as bedroom, living room, family room etc.)? ___ yes ___ no

8. Does your residence have a slab-on-grade foundation? ___ yes ___ no
If yes, approximately how much of the living area on the ground floor of your residence is over the slab? (Check the value closest to your estimate.)

- ___ a quarter
- ___ one half
- ___ three quarters
- ___ whole house

9. Is your residence built on piers ? ___ yes ___ no
If yes, approximately how much of the living area on the ground floor of your residence is on the piers ? (Check the value closest to your estimate.)

- ___ a quarter
- ___ one half
- ___ three quarters
- ___ whole house

10. Where does your drinking water come from?

- ___ private well
- ___ small community supply
- ___ large community supply

11. Is your residence on :

- ___ a hill top
- ___ a hill side
- ___ flat land (less then 10% grade)
- ___ other, please specify ______________________________

12. Do you have a kitchen fan vented to the outside ?
___ yes, ___ no. If yes, approximately how many times is it used during a normal week ?
___ 0, ___ 1, ___ 2, ___ 3, ___ 4, ___ 5-7
for how long each time ? ______ minutes.

13. Do you have a bathroom exhaust fan(s) in your residence ?
___ yes, ___ no
If yes, how many ? _____
Please write down also the total amount of time (by adding up the times from each) they are used during a typical day: _____ minutes.

14. Do you have a whole house fan ? (a whole house fan is a large electric fan which moves indoor air to the attic or outdoors and which is usually mounted in the attic)
___ yes, ___ no
If yes, on average, how many hours is it on during each season ?

Spring	_____	hrs. per day
Summer	_____	hrs. per day
Fall	_____	hrs. per day
Winter	_____	hrs. per day

15. How often do you leave the windows and/or outside doors open regularly during each season ? Please check the appropriate spaces.

	Never	rarely	occasionally	often	always
Spring	___	___	___	___	___
Summer	___	___	___	___	___
Fall	___	___	___	___	___
Winter	___	___	___	___	___

16. What type of air cooling is used in your home ?

___ central air conditioner
___ room air conditioner
___ evaporative (swamp) cooler
___ other, please specify ___
___ none

Please circle the month(s) the air cooling is regularly used.

Jan. Feb. Mar. Apr. May Jun.

Jul. Aug. Sept. Oct. Nov. Dec.

17. What type of heating is used in your home ? (Check all that apply)

___ Central heating(ducts carry warm air or pipes carry steam or hot water to all rooms) fueled by :
- ___ gas
- ___ oil
- ___ electricity
- ___ other, please specify ___

___ Fixed or immovable space heaters of the following type(s):
- ___ electric (baseboard or wall)
- ___ gas (floor or wall)
- ___ fireplace
- ___ woodstove
- ___ other, please specify ___

___ Portable space heaters of the following type(s):
- ___ electric
- ___ kerosene
- ___ gas
- ___ other, please specify ___

18. If your furnace, boiler, or space heater is fueled by gas, oil, coal, wood, or kerosene, does it have an outdoor combustion air supply vent ?

___ doesn't apply
___ yes
___ no
___ don't know

19. How many people live in your home on a permanent basis (include yourself) ? ___

20. Is this residence owned or rented ?

___ owned
___ rented
___ Other, please specify ____________________

21. Do people normally smoke in your home?

___ yes ___ no

If yes, about how many of each of the following:

	number per day
___ cigarettes	______
___ cigars	______
___ pipe	______
___ other	______

22. Please write down any additional comments you think are important.

____

____

LOG FORM

Please write down the identification number and starting date for each monitor. The identification number is the number on the monitor and the starting date is the date that you install the monitor. Since not every house has a basement and only a small portion of the homes receive two monitors for the bedroom and/or living room, you will probably not have to fill in all the spaces below. For locations which are not applicable or for which you receive no additional monitor, just leave those spaces blank.

LOCATION	ID NUMBER	STARTING DATE MONTH	DAY	YEAR
BEDROOM	______	___	___	___
LIVING ROOM OR MAIN ACTIVITY ROOM	______	___	___	___
LIVING ROOM OR MAIN ACTIVITY ROOM	______	___	___	___
BASEMENT	______	___	___	___
BASEMENT	______	___	___	___

REQUEST FOR PERMISSION TO VISIT YOUR HOME

As indicated in the fact sheet of our previous mailing, we plan to visit 15% of the surveyed residences to do some soil measurements and take soil samples. Water samples will also be taken from homes using well water. We would like your permission for this work. Please indicate your willingness to let us visit your house and take soil and water samples by checking the appropriate space.

_____ Yes, I will allow personnel from California Department of Health Services to visit my home and to sample soil and water from my house at a prearranged time.

_____ No, I will not allow personnel from California Department of Health Services to visit my home.

TEMP 1097A (3/88)

PRIVACY NOTIFICATION

The authority for maintaining the requested information by the Indoor Air Quality Program, Air and Industrial Hygiene Laboratory, Division of Laboratories, State Department of Health Services is the Health and Safety code, Article 9.5, Section 426. The information collected from this survey will be used to assess radon concentrations in and near California residences, to estimate radon exposure to the general public and to study factors related to elevated radon levels.

Personal data collected from this survey will be kept strictly confidential. Results of the study will be presented only in statistical summaries. It is voluntary to answer any of the questions and there are no consequences of not providing all or part of the requested information. Summaries of data acquired through this survey will be shared with the funding agency, California Air Resources Board.

For more information or access to your records, please contact Kai-Shen Liu, Air & Industrial Hygiene Laboratory, 2151 Berkeley Way, Berkeley, CA 94704, (415) 540-2469.

APPENDIX C

Field Inspection Form

INSPECTION FORM FOR RADON MONITORS

Home ID: ____________

Address: ____

Inspector's initial: ________ Date inspected: ____________

INDOOR MONITOR

MONITOR ID	LOCATION (bedroom, living room, basement etc)	STARTING DATE FILLED IN? (yes or no)	OPENING FACING THE AIR? (yes or no)	APPROPRIATELY PLACED? (*see footnote)
______	________	____	____	______________
______	________	____	____	______________
______	________	____	____	______________
______	________	____	____	______________
______	________	____	____	______________
______	________	____	____	______________

* Please comment on things such as avoiding drafts, closed spaces, keeping appropriate distance from the floor and within one foot from paired monitor etc.

OUTDOOR MONITOR

ID	LOCATION (describe briefly)	OPENING FACING THE GROUND? (yes or no)	APPROPRIATELY INSTALLED? (*see footnote)
________	______________	____	______________
________	______________	____	______________

* Please comment on things such as 5-6 feet above the ground, avoiding direct sunlight, rainfall and within one foot from the paired monitor etc.

APPENDIX D

Detailed Soil Measurement Methods

All sampling and measurement sites were documented. All samples were labeled on-site using a systematic method that incorporated a unique house I.D. number. The probe site identification number consisted of the house I.D., the compass direction to which the side of the house faced, and the distance in feet from the foundation. Soil samples were identified using the same method when collected within a 3-ft. radius of the probe, or without the distance from the foundation when collected over a larger area. Soil gas samples consisted of the probe I.D. number plus a scintillation cell I.D. number.

Soil probes were driven into the ground to a depth of 1 m for soil gas sampling and measurements of permeability to air. Because the degree of water saturation of the soil greatly influences these procedures and results, participants were asked to refrain from watering their yards for the 48 hours preceding our arrival. Figure D-1 is a schematic of the probe used. The probe's internal volume is approximately 500 cm^3. The sum of the area of the 20 sampling holes near the probe tip is 1.58 cm^2., which is equivalent to the surface area of a sphere of radius 0.71 cm.

The air permeameter fabricated for this study is shown schematically in Figure D-2. Air from a cylinder is passed serially, via 3/8-inch tubing, through a metering valve and one of an array of four rotameters, to the probe. A pressure tap at the top of the probe allows the differential pressure to be measured by one of three magnehelic gauges. Typically, operating pressures of 50 and 250 Pascals (Pa) were used, and the flow rate at each pressure was measured twice. After the first measurement at an operating pressure, the flow was stopped and then restarted. If no flow occurred at these pressures, pressure was increased to 400, 1000, and 4000 Pa sequentially until flow was observed. The dynamic range of the permeameter used is 10^{-11} to 10^{-5} cm^2. In very tight soils, no flow could be measured at 4000 Pa.

Figures D-3 and D-4 are logforms used for measurements of permeability. At the time this work was carried out, there was no protocol for measuring permeability of soils to air *in situ*. We chose low operating pressures to approximate the pressures produced in the soil surrounding a house under typical conditions.

The permeability to air is defined as the coefficient k (cm^2) in the air flux equation:

$$v = -(k/\eta)\ \nabla (p + \rho g h) \qquad \text{where}$$

v = volume flux density per unit area, or velocity (cm s^{-1})
η = viscosity of air (1.83 x 10^{-4} dyne-s cm^{-2})
p = pressure of air (dyne cm^{-2})
ρ = density of air (g cm^{-3})
g = gravitational acceleration (cm s^{-2}) and
h = elevation change between pressure tap and tip of soil probe (cm).

Because ρ is small, the flux equation, Darcy's Law, is usually written:

$$v = -(k/\eta) \nabla p$$

The equation is solved by analogy with electrical resistance between a spherical electrode of radius r buried at depth D in a conductor with resistivity ρ and a surface electrode. The air flow rate measured through the soil probe, q, divided by the surface area of a sphere of radius r surrounding the probe tip, is equivalent to the air velocity at a distance r from the tip. Therefore, :

$$q = \frac{4\Pi rk}{\eta} \frac{p}{1 + (r/2D)}$$ which, for D >> r, reduces to:

$$k = \frac{\eta q}{4\Pi rp} .$$

In terms of field measurement units, which are pascals for pressure (p) and cm^3 min^{-1} for flow rate (q),

$$k = 4.1 \times 10^{-8} (q/p) \text{ in } cm^2.$$

As stated above, one soil gas sample was collected per house at a depth of 1 m and a distance of 4.6 m from the foundation. The measurement method employed alpha scintillation flasks (Lucas cells). These cells are generally cylindrical 100 - 160 ml air sampling vessels with one or two sampling ports at the top and a quartz window on the bottom. The interior of the cell is coated with silver-activated zinc sulfide, which scintillates, or emits a weak flash of light, when struck by an alpha particle. After sampling for soil gas, at least three hours must elapse to allow radon decay products to come to radioactive equilibrium with the radon. The quartz window of the Lucas cell is placed on a photomultiplier tube (PMT), which amplifies the light pulses produced by the scintillator. The electrical pulses of the PMT are then counted by a scaler. The net counts, corrected for decay between sampling and counting, are related to the radon concentration in the gas sample, as follows:

$$\text{pCi Rn/l} = \frac{\left(\frac{GC}{TC} - BGR\right) e^{\lambda(TD)}}{(3)(2.22)(0.76)(0.163)}$$

BGR = background counting rate
GC = Gross counts
TC = Counting duration (min)
TD = Delay time (min)
λ = radon decay constant, 1.24×10^{-4}/min

The numbers in the denominator are the number of alpha emitters in the cell, the number of decays per minute per picocurie, the cell efficiency, and the cell volume, respectively.

Two sampling methods were used for soil gas during the site visits. Both methods involved flushing the internal volume of the soil/probe with a pump after the probe was installed in the soil at the proper depth but before sampling. The flow rate of the pump was set each day with an electronic bubble flowmeter. Flushing was timed so that the probe was flushed with an approximately known volume of gas. Soil gas was passed through a filter to exclude soil particles and through a drying column prior to entry into the Lucas cell so that moisture would not be introduced into the cell. During the pretest, a vacuum pump was carried to the field to evacuate the cells just prior to use. The evacuated cell was clamped off from the probe-sampling tubes during flushing and then opened for sampling. After sampling, the date, time and house I.D. were noted and these cells were returned to the Sanitation and Radiation Laboratory of DHS for analysis and data reduction. During the main survey and southern Sierra Foothills study, a different sampling procedure was used. Newly-purchased Lucas cells had two sampling ports for flowing air through the cells. The Lucas cell was removed from the probe sampling tube assembly during flushing. After flushing, the Lucas cell was inserted between the drying column and the pump. In the early part of the study, five Lucas cell volumes were pumped through the cell during sampling and the sampling time was recorded. Lucas cells were counted the same day. Later, to minimize possible soil gas depletion, the volume of gas flushed through the probe was reduced from 3.0 to 2.25 l, and through the cell from 0.8 to 0.5 l. The sampling and counting protocol follows as Appendix E.

Two soil samples from each house visited were analyzed for radioactivity at the Low Background Facility at Lawrence Berkeley Laboratory. This facility is described by Wollenberg and Smith (11). Radium contents and radon emanation rates were determined at an approximately constant soil moisture content, since emanation rate is a function of moisture content. The radium content and radon emanation rate of soils were measured using sodium-iodide gamma-spectrometry, by counting for a few hours for radium concentrations and for about an hour for radon emanation rates. Because the low resolution of the NaI(Tl) detector creates broad peaks for the several isotopes present, the tails of these peaks overlap when soils are counted. Therefore data from several prominent photopeaks must be collected and unfolded. For radium-226 determinations, the 1.76 MeV photopeak from bismuth-214, a radon-222 product, was used, as well as the 2.62 MeV photopeak from thallium-208, a thoron product in the thorium-232 decay chain, and the 1.46 MeV photopeak from potassium-40, another commonly occurring radionuclide in soil. The method employed is conventionally used when measuring the natural radioactivity of soils by NaI(Tl)-based gamma spectrometry (15). Figure D-5 is a typical gamma spectrum of soils collected during this study. The prominent photopeaks are labeled. The net counting rates within the energy intervals containing the 1.46, the 1.76, and the 2.62 MeV photopeaks are linear combinations of the radionuclide contents as follows:

$$\begin{bmatrix} NCR_{2.62} \\ NCR_{1.76} \\ NCR_{1.46} \end{bmatrix} = \begin{bmatrix} A_{11}A_{12}A_{13} \\ A_{21}A_{22}A_{23} \\ A_{31}A_{32}A_{33} \end{bmatrix} \begin{bmatrix} \text{ppm Th} \\ \text{ppm U} \\ \text{\% K} \end{bmatrix}$$

Here NCR = net counting rate
A_{ij} = sensitivity constants
ppm = parts per million

Uranium and thorium ore standards from the Atomic Energy Commission's New Brunswick Laboratory and chemically pure potassium chloride of the same geometry as soil sample boxes were used for working standards. The three standards were counted separately and data were recorded from each of the three photopeaks of interest during each standard run. The 3 x 3 matrix of sensitivity constants was used, along with the measured net counting rates in the 1.46, 1.76, and 2.62 MeV photopeaks, and the sample weight to compute the uranium (U), thorium (Th), and potassium (K) concentrations in the soil samples. The radium-226 and radium-228 concentrations were related to the uranium-238 and thorium-232 concentrations, respectively, by constants that are specific activity ratios. The exposure rate from external gamma radiation due to an infinite plane of soil containing the measured U, Th, and K contents was also reported. Exposure is a measure of the ionization produced in air by x- or gamma radiation. One Roentgen (R), the unit of exposure, equals 1.61 x 10^{12} ion pairs/g air (or 5.43 x 10^{7} MeV/g air).

For radon emanation rate measurements, a soil sample was placed in a tightly sealed container with an activated charcoal canister. Radon emanating from the sample was adsorbed by the charcoal. After the system had equilibrated for about a week, the charcoal was removed and tightly sealed in a box. After waiting 3 hours for equilibrium of radon decay products, gamma spectrometry was performed. The net counting rate within the energy interval 0.130 to 2.00 MeV was recorded and used to determine the radon activity on the charcoal. Figure D-6 is a typical gamma spectrum resulting from radon and its short-lived products on charcoal. The major photopeaks from radon products within this interval are 0.242, <u>0.295,</u> and <u>0.352</u> MeV from Pb^{214}, and <u>0.609,</u> 0.666, 0.768, 0.806, 0.934, <u>1.12</u>, 1.15, 1.24, 1.28, 1.38, 1.40, 1.41, 1.51, 1.66, 1.73, <u>1.76</u>, and 1.85 MeV from Bi^{214}. The underlined photopeaks are the most abundant. The calibration standard used was a known quantity of uranium ore in equilibrium with its decay products disseminated in a charcoal canister. The calibration constant was 1.3 counts per minute per picocurie of radon. The periods of exposure and decay between exposure and counting, the radon halflife, and the sample weight were used to determine the radon emanation rate of the soil sample:

$$DCR = \left(\frac{C}{TC} - BG\right) e^{\lambda(TD)}$$

$$ECR = \frac{DCR}{1 - e^{-\lambda(TI)}}$$

$$\text{pCi Ra/g soil} = \frac{ECR}{(1.3)G}$$

TI = integration time
TC = counting time
λ = radon decay constant
BG = background counting rate
GCR = gross counting rate
NCR = net counting rate
DCR = decay-corrected counting rate
ECR = equilibrium-corrected counting rate
G = weight of soil sample
C = counts

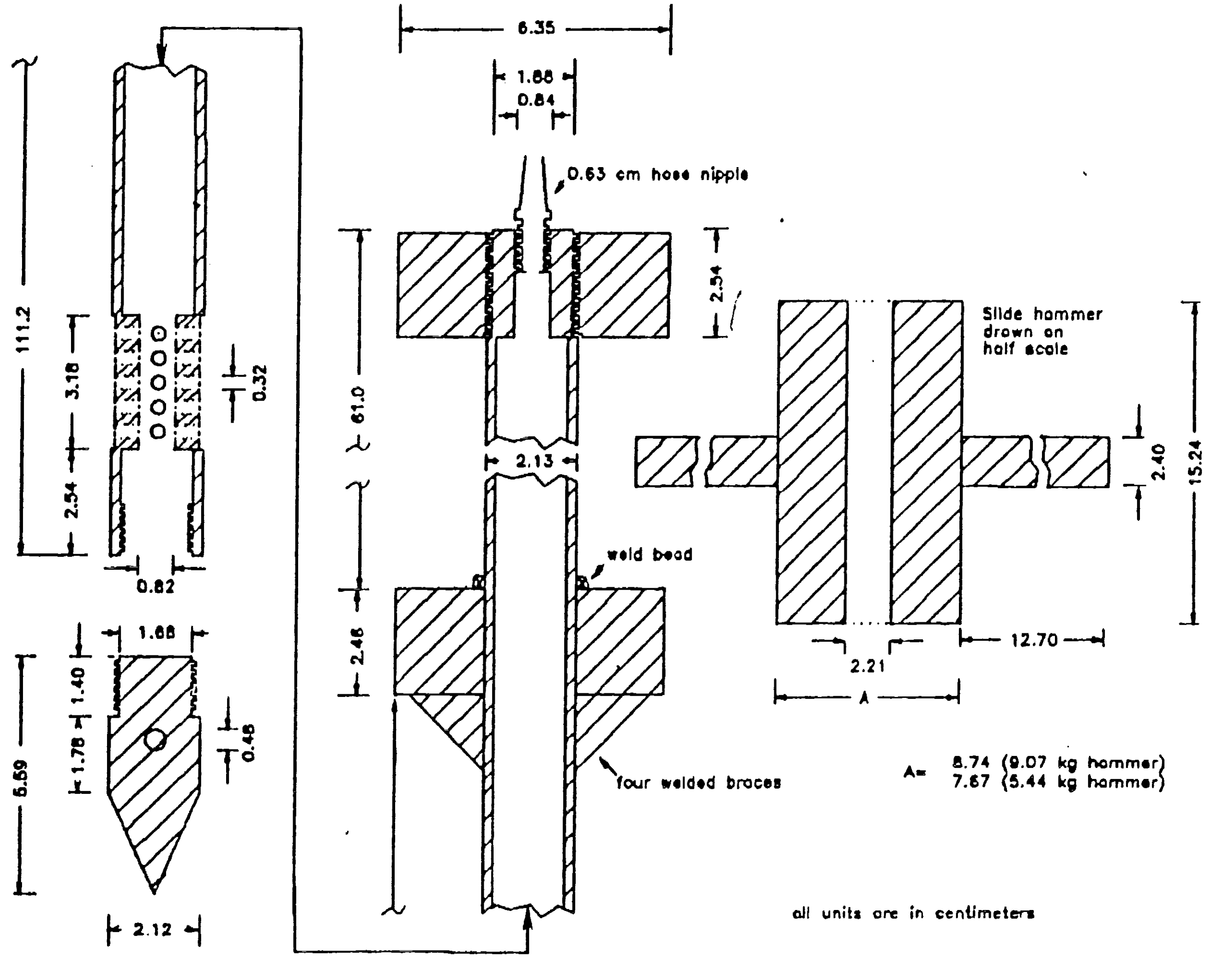


Figure D-1. Schematic drawing of the soil probe used in this study.

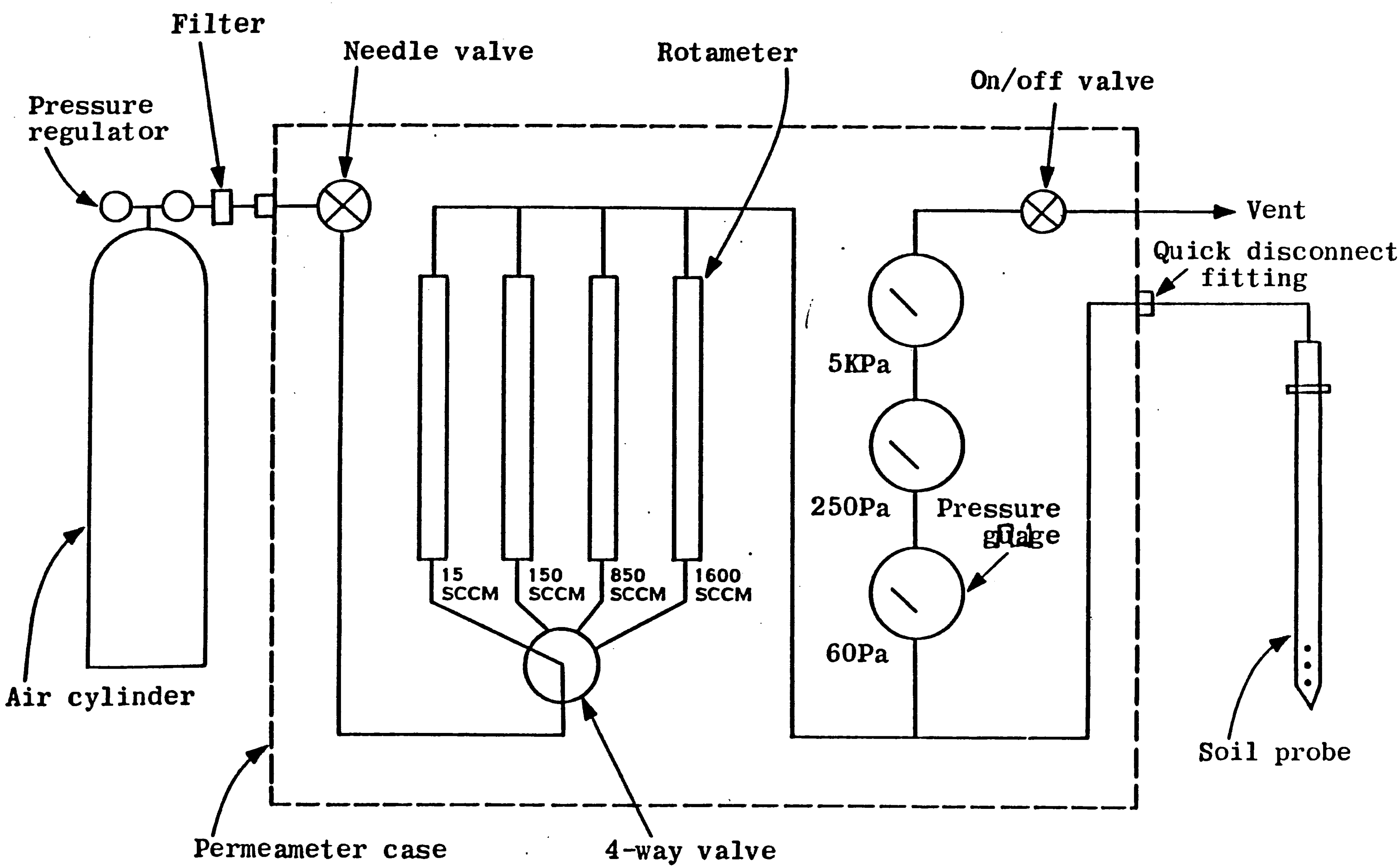


Figure D-2. Schematic of the permeameter used in this study.

California Department of Health Services

Air and Industrial Hygiene Laboratory

SOIL GAS SAMPLING LOGSHEET

House I.D.__________________ Soil Gas Sample I.D.____________
(Probe I.D. plus Lucas cell I.D.)

Address ____________________________

City ____________________________ State _______ Zip Code _______

Flush pump I.D.____________________

Pump flow rate______________________sccm

Duration of probe flushing__________min

Sampling start date_________________ Time_________ am pm

Duration of soil gas sampling_______min

Comments ____
____
____

* * * * * * * * *

SOIL GAS COUNTING LOGSHEET

Soil Gas Sample I.D. ______________

Detector ________________________ Counted by __________

Check source counts _______________ in 5 minutes

Date counted ______________________ Start time_________ am pm

Gross counts _______________________ Counting duration ______min

Midpoint of count interval ________ am pm

Delay time _____________________min
(from sampling to counting midpoints)

Lucas cell background _____________ Net counts_____________

Decay corrected net counts ________

Radon concentration __________pCi/l

Figure D-3. Logform for measurements of permeability.

SOIL PROBE DATA SHEET

Name ______________________ House I.D. ______________________
Address ______________________ Scientist ______________________
______________________ Date ______________________

DESCRIPTION	FIELD DATA	FIELD DATA
Probe I.D.	______________________	______________________
Probe Description	Bearing ________ Reference ________ Distance from ref. ______ m	Bearing ________ Reference ________ Distance from ref. ______ m
Soil Description	Moisture: __ Dry, __ Moist, __ Wet Texture: __ Clayey, __ Silty, __ Sandy, __ Loamy, __ Gravelly Munsell Color ________	Moisture: __ Dry, __ Moist, __ Wet Texture: __ Clayey, __ Silty, __ Sandy, __ Loamy, __ Gravelly Munsell Color ________
Radon in Soil Gas	Sample I.D. ________ Collect date ________ Collect time ________	Sample I.D. ________ Collect date ________ Collect time ________
Air Permeability Temperature (T) Pressure (P) Flowmeter I.D. Flowmeter Readings	__ C / __ Pa / LL L M H / 1. ____ 2. ____ 3. ____ X ____ __ C / __ Pa / LL L M H / 1. ____ 2. ____ 3. ____ X ____	__ C / __ Pa / LL L M H / 1. ____ 2. ____ 3. ____ X ____ __ C / __ Pa / LL L M H / 1. ____ 2. ____ 3. ____ X ____
Comments	______________________ ______________________ ______________________	______________________ ______________________ ______________________
COMPUTATIONS Flowrate (Q) Q(sccm)/P(Pa) Air Permeability	____ sccm ____ sccm ____ sq cm ____ sq cm	____ sccm ____ sccm ____ sq cm ____ sq cm

Figure D-4. Logform for measurements of permeability.

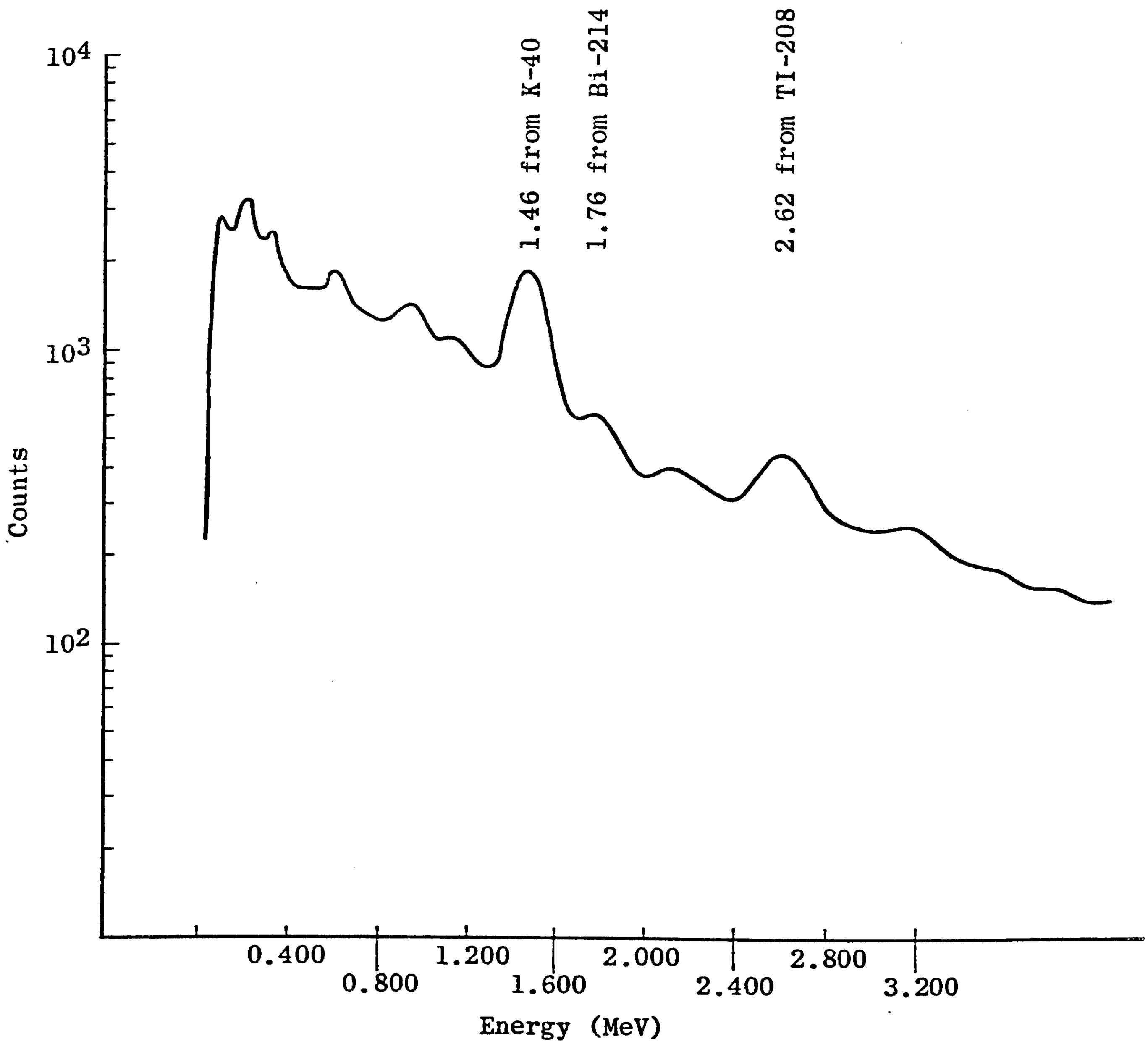


Figure D-5. Typical gamma spectrum of a soil sample.

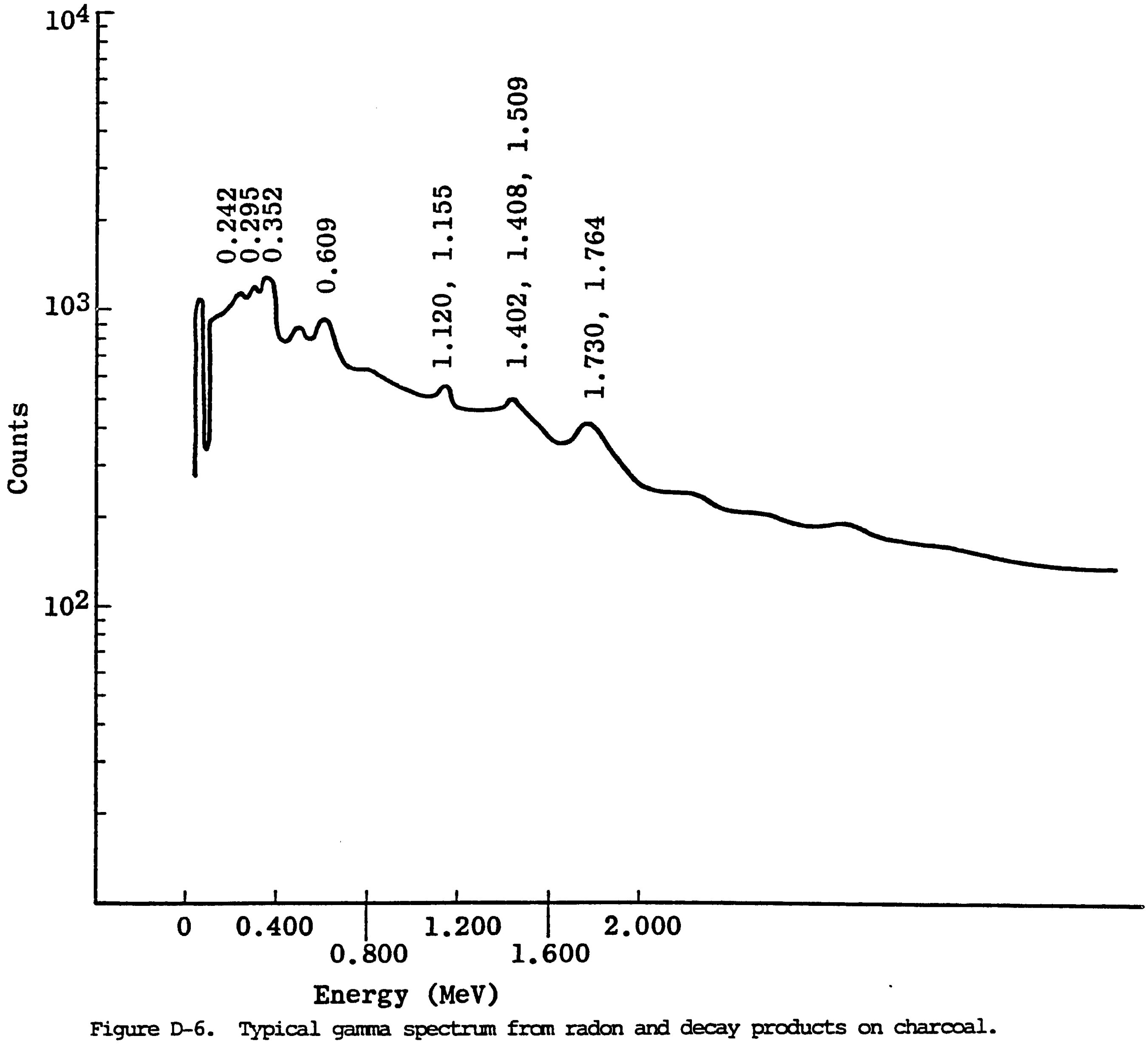


Figure D-6. Typical gamma spectrum from radon and decay products on charcoal.

APPENDIX E

Soil Gas Sampling Protocol

SOIL GAS SAMPLING PROTOCOL USING FLOW-THROUGH CELLS

Probe site should be 4.5 m (13 - 14 ft.) from foundation and poured concrete, if possible. Depth should be 1 m. If neither of these conditions are met, note in comments section of logsheet.

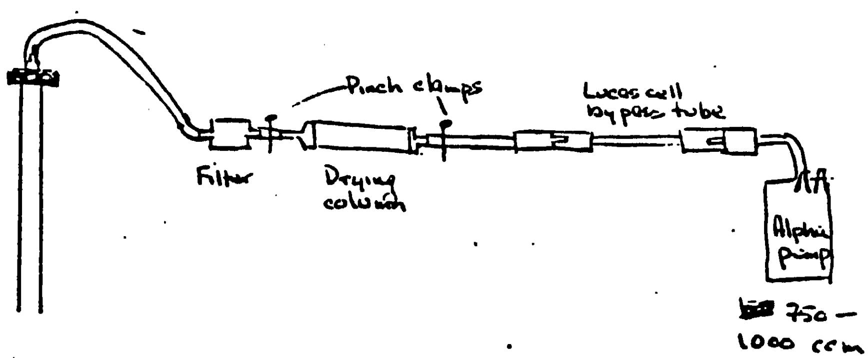
Probe should be capped during insertion to prevent venting.

Fill out soil gas sampling logsheet.

Select a Lucas cell that has not been used for at least four days for soil gas sampling.

Collect soil gas sample before measuring permeability.

Probe flushing: pump a total of 2.25 liters (revised from 3.0 liters.

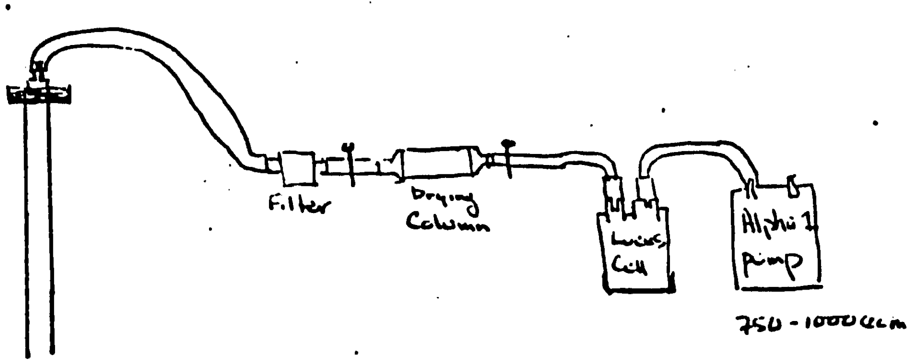


Pinch off tubing between drying column and bypass tubing before substituting the Lucas cell for the bypass tube.

Gas sampling: Open pinch clamp and pump 0.5 liter (revised from 1.0 liter) through the Lucas cell.

Record start time and duration of flow.
Tturn the pump off. Disconnect Lucas cell from sampling line.

Close pinch clamps surrounding the drying tube.



PROTOCOL FOR COUNTING LUCAS CELLS ON THE PYLON AB-5 DETECTOR

Since it takes three hours for radioactive equilibrium to be established after collecting a gas sample, use the Pylon AB-5 photomultiplier in the hotel during the evening.

Don't use cells more frequently than every four days so that cell backgrounds will be low enough to be neglected.

NEVER HAVE THE AB-5 ON WHILE UNCOVERING THE PHOTOMULTIPLIER TUBE.

Before counting samples, ensure that the discriminator and high voltage potentiometer settings are those listed on the label on the AB-5. Obtain a five minute counting of the check source. Record your data and compare it with counts predicted by counting rate attached to the side of the check source.
You will have to program a 30 minute counting interval for samples (except the check source, which will be counted for five minutes).

After putting a Lucas cell in the AB-5 and closing the cover, turn the power on. Wait five minutes so that the photomultiplier can warm up and any spurious counts that might arise from light saturation can dissipate.

Fill out the soil gas counting logsheet, which is below the soil gas sampling logsheet, and shown on the following page.

Flush Lucas cells immediately after counting. Outdoor air is preferable to indoor air as a flushing gas. Exchange 1.5 liters, or about 9 cell volumes.

APPENDIX F

Sampling Protocol for Radon in Water

SAMPLING PROTOCOL FOR RADON (Rn) IN WATER

Sampling Kit:

1. Small plastic bucket
2. Tygon tubing with sampling adapter(s)
3. 4 oz. glass prescription sample bottles and caps
4. SRL Radiological Analysis Forms and Labels - one for each duplicate sample set. A duplicate sample set consists of two (2) prescription bottles (A,B) taken from the same sampling bucket.

Sampling Procedure:

1. Purge ~~well~~ well or ~~local~~ resident's supply pipe or the ~~main~~ municipal's pipe for 15 minutes to ensure collection of a water sample representative of the aquifer. ~~This protocol is consistent with that for VOCs (AB 1803) and for SEB's proposed Monitoring Regulations.~~

2. At sampling point attach Tygon tubing to port, faucet, tap, etc. using appropriate adapter as necessary. Direct delivery end to the bottom of the bucket and slowly run the water into the bucket for approximately 5 minutes. Discard the water in the bucket at least once and allow the water to overflow during the remainder of the sampling.

3. Remove the prescription bottle cap and by hand, with the bottle in an upright position, carefully submerge the bottle and cap. Avoid agitating the water and minimize creation of bubbles. With the bottle underwater, insert the end of the tubing into the bottle and allow the water to exchange to assure a fresh sample. Remove the tubing and cap the bottle tightly while cap and bottle are both under water.

4. After removing the capped bottle from the bucket, invert the bottle and check to see if any bubbles are present. If bubbles are present, empty the bottle and re-sample beginning with Step 3. Collect at least two separate samples (duplicates) from the same sampling bucket.

5. Wipe bottles thoroughly and attach an identification label to each dry bottle. Fill in the SRL Radiological Analysis Form completely. Note carefully that, because of the short half-life of radon (3.8 days), it is essential that date and time of collection be exact.

6. Return the samples to the laboratory by overnight carrier.

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S015015

QA Protocol for Sampling and Analysis of Radon (Rn) in Drinking Water

Sampling (S):

1. A sample, taken in accordance with "Sampling Protocol for Radon (Rn) in Water" is defined to be the water in a four ounce (4 oz.) glass prescription bottle taken from a sampling bucket. Samples always shall be taken at least in duplicate. Each duplicate sample set shall be collected from the same sampling bucket.

2. A batch of samples shall be interpreted as a group of samples taken by the same collector (SEB) and which arrives at the SRL/DHS Mailroom at the same time. SEB will arrange the sampling schedule and minimize the number of collectors to keep the sampling variable as low as possible.

3. Samples shall be sent directly to the Sanitation & Radiation Laboratory, c/o DHS Mailroom, 2151 Berkeley Way, Berkeley, CA, 94704, by overnight carrier. Sampling shall take place preferably on Monday but never later than on Tuesday of any week. This minimizes the loss in analytical sensitivity for Rn-222 which has a half-life of only 3.8 days.

Analysis (A)

1. Samples shall be analyzed by SRL for Rn-222 using a liquid scintillation method with an oil-based scintillator.

2. Contents of each 4 oz. sample bottle shall be apportioned in duplicate into 20 mL scintillation vials for subsequent alpha counting by liquid scintillation (LS). Ordinarily, only water from one (1) sample bottle from each duplicate sample set shall be separated into two (2) vials.

3. Quality Assurance (QA) requires that for every tenth duplicate sample set which is apportioned as per (A2), the contents of the second sample bottle of the sample set also shall be apportioned identically into two (2) other scintillation vials as per the first sample bottle of the same duplicate sample set. Further, this QA protocol for analyzing duplicates shall be followed if a batch of samples consists of fewer than ten (10) samples.

4. Each of the 2 vials from the first sample bottle of a duplicate sample set shall be counted once for alpha emissions by LS with at least one background and one standard count to be made per set of ten (10) samples or batch of samples. Further, one of the 2 vials also shall be counted at some appropriate later time to ensure that the alpha emissions originally counted

were from Rn-222, i.e., an accounting for matrix alpha emissions. Should the analyst then determine that a second LS count of the second vial of a given sample also is to be made, it shall be done at this time. For QA, when (A3) holds, the scintillation vials from both duplicate sample bottles shall be apportioned as per (A2) and alpha counted by LS as per (A4).

Reporting of Data:

1. It shall be assumed that, when data is reported on sample slips, background and standard alpha emission counts shall have been made as per (A4) and shall be available to SEB or other appropriate personnel upon request. Further, any matrix effects of alpha emissions other than those due to Rn-222 shall be assumed to be negligible unless such digressions are specifically noted on the sample slip.

2. For each 4 oz. sample bottle, two (2) separate alpha counts shall appear on the sample slip. Each count shown shall be the LS count of each vial derived from one (1) sample bottle, i.e., a minimum of two (2) LS counting activities. Proceeding, whenever a given duplicate sample set is to be analyzed as a replicate as per (A3), four (4) separate alpha counts shall appear on the individual sample slip. These four (4) counts denote the measurements of alpha emissions (one (1) count per vial) from each of 2 vials derived from each of 2 sample bottles (i.e., a minimum of four (4) LS counting activities) taken from the same sampling bucket (see S1).

SRL/SEB (7/08/87)

Radon-222 in Water by Liquid Scintillation

Procedure:

1. For each sample set (sample set = 2 bottles from the same bucket). label and tare two glass scintillation vials containing 10 ml of an oil-based scintillation cocktail.

2. From one bottle of each sample set carefully decant without agitation approximately 10 ml of sample into each of the two pre-weighed vials containing liquid scintillation cocktail.

3. Cap the vials tightly and shake immediately.

4. Weigh each of the filled vials and record the net weight of sample in each of the vials.

5. Place the vials in a liquid scintillation counter and count for 100 minutes each. For each batch of samples include a standard, a background, and a duplicate analysis (4 vials - 2 from each sample bottle in a sample set).

6. Recount all the vials two more times to check for proper decay of the radon.

Calculation:

$$\text{Rn-222 pCi/L} = \frac{(\text{Net CPM})(\text{Decay Factor})}{(\text{Sample Wt.(g)})(\text{Rn-222 CPM/pCi})} \times (1000\ \text{g/L})$$

$$2\sigma\ \text{Error} = \frac{1.96\sqrt{CPM_S/T_S + CPM_B/T_B}\ (\text{Decay Factor})}{(\text{Sample Wt.(g)})(\text{Rn-222 CPM/pCi})} \times (1000\ \text{g/L})$$