**IDENTIFYING AREAS WITH POTENTIAL FOR HIGH INDOOR RADON LEVELS:
ANALYSIS OF THE NATIONAL AIRBORNE RADIOMETRIC RECONNAISSANCE
DATA FOR CALIFORNIA AND THE PACIFIC NORTHWEST**

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Abstract

Radon-222 is an important indoor air pollutant which, through the inhalation of its radioactive decay products, accounts for nearly half of the effective dose equivalent to the public from natural ionizing radiation. Indoor radon concentrations vary widely, largely because of local and regional differences in the rate of entry from sources. The major sources of indoor radon are soil and rock near building foundations, earth-based building materials, and domestic water; of these, soil and rock are thought to be predominant in many buildings with higher-than-average concentrations. Thus, one key factor in determining radon source potential is the concentration of radium, the progenitor of radon, in surficial rocks and soils.

We have analyzed aerial radiometric data, collected for the National Uranium Resource Evaluation Program, for seven Western states with a view towards 1) providing information on the spatial distribution of radium contents in surficial geologic materials for those states, and 2) investigating approaches for using the aerial data, which have been collected throughout the contiguous United States and Alaska, to identify areas where high indoor radon levels may be common.

The results showed a range of mean radium concentrations averaged over geologic map units of $0.1 - 3.6 \text{ pCi g}^{-1}$, with an overall mean for the study area of 0.7 pCi g^{-1} . Radium concentrations were found to be relatively low in central and western portions of Washington, Oregon, and northern California; they were found to be relatively high in central and southern California.

A field validation study, conducted along two flight-line segments near Spokane, Washington, showed close correspondence between the aerial data, in situ measurements of both radium content and radon flux from soil, and laboratory measurements of both radium content of and radon emanation rate from soil samples.

Keywords: indoor air pollution, ionizing radiation, natural radiation, pollutant sources, radium, radon, soil, aerial radiometric surveys

1. Introduction

Radon-222 is a naturally occurring radioactive gas that is ubiquitous in our environment. An elevated occurrence of lung cancer in underground uranium miners is widely attributed to their exposure to high concentrations of radon progeny (Archer and Lundin, 1967). Radon-progeny exposures of the lung are now believed to contribute approximately half of the effective dose equivalent that is received by the general population from natural radioactivity (UNSCEAR, 1982). Most of the public's exposure to radon progeny occurs indoors, and concern over the health risks that may result has recently increased. This increase of concern is reflected by an increase in the occurrence of symposia and workshops that are exclusively devoted to radon and its progeny (e.g., Colle and McNall, 1980; Clemente, et al., 1982; USEPA, 1983; NEA, 1983; George, et al., 1983).

The frequency distribution of radon-progeny levels in the housing stock in the United States is not yet well known. However, existing measurements in this and other countries indicate a very broad distribution such that radon-progeny levels in a small fraction of houses exceed the mean by as much as two orders of magnitude (see, for example, Cliff, 1978; Stranden, et al., 1979; Hildingsson, 1982; McGregor et al., 1980; Nero et al., 1983; George and Eng, 1983). Consequently, a small fraction of the population receives exposures that are greater than the current limit for uranium miners, and which, in some cases, exceed cumulative exposures at which biological effects have been observed. Furthermore, there appears to be a tendency for geographic clustering of houses with unusually high radon concentrations (Moschandreas and Rector, 1982; Cliff, et al., 1983; Akerblom, 1983; Gross and Sachs, 1982; Doyle, et al., 1983). Identification of these areas in the United States has thus far been haphazard. Development of a cost-effective, systematic approach for identifying such areas is desirable from a public health standpoint.

The data that were acquired during the National Airborne Radiometric Reconnaissance (NARR) Program may be useful for this purpose. The database contains continuous aerial measurements of a prompt decay product (bismuth-214) of radon-222 along more than one million flight miles that were roughly uniformly distributed throughout the United States (Mitchell, 1981). These data indicate the quantity of radium-226, the progenitor of radon-222, in the soil or rock near the surface of the ground.

The authors of a few recent articles have emphasized the probable importance of radon-rich soil gas as a source of indoor radon for houses containing concentrations that are greater than the average (Nero and Nazaroff, 1983; Bruno, 1983; Akerblom et al., 1983). Though the concentration of radon in soil gas is not determined solely by the radium concentration of the soil (see section 2.5, "Sources of Indoor Radon"), the radium concentration is an important factor, being an indicator of the potential radon source strength of geologic materials.

The possibility of locating areas characterized by inherently high radon source strengths by means of the NARR measurements of radium should be investigated for three reasons: 1) the spatial coverage of the NARR data is extensive; 2) the NARR data are currently available in useful formats; and 3) a survey of

indoor radon levels in a substantial fraction of homes in the United States would have an enormous cost.

This report describes a study of the aerial measurements of radium within the states of Washington, Oregon, Idaho, and California, and portions of Montana, Nevada, and Utah. We first provide background information on radon. We then describe the objectives and design of the NARR Program, and the contents of the resultant reports. The next section discusses the approach we have taken to assess the variability of radium concentrations, as measured in the NARR Program, on both local and regional scales. We discuss the general findings of a survey of aerial measurements of radium within the Pacific Northwest and the state of California. The results of a limited ground-based investigation of aerial radium anomalies are also presented and discussed.

2. Background

2.1 Components of the Natural Radiation Environment

The natural environment is the major source of radiation to which people are exposed. Both external and internal sources contribute to the absorbed dose. The three types of emissions that arise from radionuclides have significantly different ranges in air: a few centimeters for alpha particles; roughly a meter for beta particles; several hundred meters for gamma radiation.

The primary sources of external radiation are cosmic rays and primordial terrestrial radionuclides along with their decay products. The latter are ubiquitous in rocks and soils and are present in the atmosphere due primarily to the exhalation of gaseous radionuclides from the ground. At elevations between sea level and 1000 m, where most of the U.S. population lives, terrestrial radionuclides account for between fifty and eighty percent of the external radiation field (Vohra, 1980). External terrestrial radiation arises almost entirely from potassium-40, and from members of the uranium and thorium decay chains. These chains begin with uranium-238 and thorium-232, respectively, and proceed through numerous intermediate radionuclides due to spontaneous alpha and beta emissions before terminating in stable isotopes of lead. Each decay chain contains an isotope of radon (radon-222, referred to as radon, and radon-220, sometimes referred to as thoron, respectively) which can migrate into the atmosphere. Table 1 shows the concentrations in rocks of uranium-238, thorium-232, and the isotopes of radium that directly produce radon within each chain (radium-226 and radium-224, respectively).

Terrestrial radionuclides can become internal sources through ingestion and inhalation. The food chain transfers some radionuclides from soils to people. People inhale airborne radon, thoron, and their short-lived progeny.

2.2 The Radium-226 Decay Chain

The uranium decay chain is shown, excluding infrequent decay branches, in Figure 1. In addition to the specific radioisotopes that comprise the decay series, the half lives and modes of nuclear decay for the isotopes are relevant to our discussion. All radionuclides of the series are trace elements that are present in rocks, soils, and earth-based building materials.

The radium-226 decay subchain, which is the focus of our interest, is enclosed by the box in Figure 1. The relatively long half life of radium-226, the progenitor of radon-222 (radon) ensures that rocks, soils, and building materials produce radon at an effectively constant rate. The decay of radium-226 by emission of an alpha particle yields a recoiling gaseous radon atom, which is chemically inert and has a half life of 3.82 days. Some recoiling radon atoms stop in defects in host grains, in pore spaces, or in fissures or fractures in geologic sources. Migration of radon through and from the source material is then possible. Radon produces four short-lived progeny before the relatively long half life of lead-210 effectively terminates the radium-226 decay subchain. The prompt radon progeny are chemically reactive. Therefore, they are unlikely to escape from a geologic source material in which they are

generated. However, the reactivity of radon progeny that are produced by atmospheric radon is important from a health risk viewpoint.

2.3 Health Risks

Prior to the establishment of radiation protection guidelines for uranium miners, miners suffered an elevated incidence of lung cancer in comparison with the general population. The cause of this epidemiological observation is commonly attributed to the inhalation of the alpha-emitting radon progeny, polonium-218 and polonium-214. Progeny atoms, whether attached to particles or unattached, if inhaled, may be deposited on the mucous membranes of the tracheobronchial or pulmonary regions of the lung. The tracheobronchial region of the lung is generally considered to receive most of the dose arising from this irradiating process (NEA, 1983; UNSCEAR, 1982).

Radiological risk assessments often incorporate the linear hypothesis for dose-response, i.e., that the probability of the occurrence of biological effects is directly proportional to cumulative dose. It is still not clear whether the application of the linear hypothesis to the doses and dose rates that are typically received by the public from radon progeny indoors accurately estimates or overestimates the risk (UNSCEAR, 1982). Though the miner data can be only equivocally analyzed and applied to the general population, (Nero, 1983; UNSCEAR, 1982; NEA, 1983), several studies of this sort have been published (USRPC, 1980; NRC, 1980; Guimond, et al., 1979). The major sources of uncertainty that are inherent in these extrapolations arise from differences in the physical conditions of the exposure to radon progeny, and from differences in individual biological factors. The activity median diameter of the attached progeny, the fraction of unattached progeny, and the age and breathing rate of the person all affect the bronchial dose (NEA, 1983). In addition, the inhalation of other carcinogens and synergistic effects probably influence the sensitivity of lung tissue for the development of cancer; these factors may have contributed to the elevated risk of lung cancer that has been observed among uranium miners. We compare the cumulative exposures of miners and the general population after reviewing typical indoor concentrations in section 2.4, "Radon and Progeny: Concentrations and Radiation Protection Guidelines". UNSCEAR (1982), NEA (1983), and NAS (1981) are review articles which address dose and risk assessments of exposure to the airborne progeny of radon and thoron.

The International Commission on Radiation Protection has recently recommended the use of a new unit, "effective dose equivalent", which normalizes the risks of developing somatic effects due to partial or whole-body irradiation by external or internal sources of alpha, beta, and gamma radiation (ICRP, 1977; as cited in NEA, 1983). The use of this unit has led to a consensus regarding the relative importance of the modes of irradiation for the general population; the order, in decreasing importance, is considered to be inhalation, external irradiation, and ingestion (UNSCEAR, 1982). Indoor exposure to the short-lived progeny of radon and thoron contributes approximately one-half of the annual effective dose equivalent per person of 2.0 mSv (0.2 rem) due to natural sources in regions of typical background radioactivity, according to population-weighted global estimates (UNSCEAR, 1982).

The distribution of average indoor radon concentrations, which ranges over two orders of magnitude (UNSCEAR, 1977), and is discussed in section 2.4, "Radon and Progeny: Concentrations and Radiation Protection Guidelines", strongly suggests that a small fraction of the general population receives annual effective dose equivalents due to radon progeny indoors that are much greater than the average value of 1 mSv. This fraction of the population sustains an elevated risk for development of lung cancer relative to the non-smoking population.

2.4 Radon and Progeny: Concentrations and Radiation Protection Guidelines

World-wide measurements of radon and radon-progeny concentrations were reviewed in UNSCEAR (1982). Measurements in the contiguous United States were reviewed in Gesell (1983). The following discussion is based primarily on these two sources.

The outdoor concentrations of radon and progeny are much lower in oceanic and arctic air than in continental air. Mean annual radon concentrations range from 0.003 to 0.3 pCi l⁻¹, with typical continental concentrations probably between 0.08 (UNSCEAR, 1982) and 0.25 (Gesell, 1983) pCi l⁻¹. Concentrations of radon progeny in outdoor air are typically 0.08 pCi l⁻¹ (UNSCEAR, 1982).

Mean annual concentrations of radon in indoor air are generally higher than local outdoor concentrations, and typically range from 0.2 to 4 pCi l⁻¹ (Nero, 1983). Concentrations of radon progeny in indoor air are typically 0.5 pCi l⁻¹ (UNSCEAR, 1982). The distribution of indoor radon concentrations appears to be lognormal (UNSCEAR, 1982; Doyle, et al., 1983), and concentrations of tens of picocuries per liter have been measured in some areas (Nero, 1983; Akerblom et al., 1983; UNSCEAR, 1982; Hess, et al., 1983).

A special unit of concentration, the working level, has been defined for the purpose of radiation protection from radon progeny. The working level (WL) is a measure of the concentration of potential alpha energy arising from radon progeny; one WL is defined as any combination of radon progeny in one liter of air that will yield 1.3×10^5 MeV of alpha energy by decay to lead-210. (This definition is based on the alpha energy released by radon progeny that are in equilibrium with 100 picocuries of radon in one liter of air.) A related unit of cumulative exposure is the working level month (WLM), defined as follows: "inhalation of air containing a radon-daughter concentration of 1 WL for 170 working hours results in an exposure of 1 WLM" (Rock et al., 1970 and 1971).

The current limit for average annual occupational exposure to radon progeny is 4 WLM per year. The average concentrations of radon and progeny that are currently found in ventilated areas of underground uranium mines are generally less than 30 pCi l⁻¹, in accordance with this limit of exposure rate (UNSCEAR, 1982).

The cumulative exposures of miners who suffered an elevated incidence of lung cancer relative to the general population are estimated to range from 120 to 5500 WLM (Archer and Lundin, 1967). Miners exposed to the current annual occupational limit for twenty years would receive cumulative exposures of 80 WLM. If the public spends 80% of its time indoors for 75 years, then the typical range of indoor radon concentrations, $0.2 - 4 \text{ pCi l}^{-1}$, would result in 3 - 60 WLM of cumulative exposure. A fraction of the population living in areas of high radon source strengths probably receives cumulative exposures to radon progeny that exceed the lower limit of the range cited for miners with an elevated incidence of cancer.

Guidelines for remedial action to reduce exposures to radon progeny have been established for a few areas exhibiting elevated radon source strengths. For Grand Junction, Colorado, the U.S. Surgeon General recommended a threshold of 0.05 WL for remedial action, and suggested that remedial action be considered when concentrations between 0.01 and 0.05 WL are found (U.S. Government, 1972). The Florida Dept. of Health and Rehabilitative Services (FDHRS) recommended remedial action when concentrations exceed 0.029 WL in houses of the phosphatic areas in Florida (FDHRS, 1978, as cited in Roessler et al., 1980)). The U.S. EPA proposed that remedial action be undertaken when radon concentrations exceeded 3 pCi l^{-1} in houses that were built on inactive uranium-processing sites (USEPA, 1980). In Sweden, which contains several regions characterized by elevated radon source strengths, the government established the following limits for annual mean concentrations of radon progeny: 0.11 WL in existing residences; 0.054 WL in rebuilt residences; and 0.019 WL in new residences (Hildingsson, 1982).

2.5 Sources of Indoor Radon

The major sources of indoor radon are the soil and rock adjacent to the foundation, the building materials, and the water supply. In this section, we discuss the characterization of the radon source strength of porous media (i.e., soil, and rock, and buildings materials that are derived from them), and then consider the probable relative importance of the major sources of indoor radon for explaining the observed distribution of indoor radon concentrations and entry rates. Much of this discussion is based on Nero and Nazaroff (1983). It is useful to divide the discussion of the radon source strength of porous media into two parts: factors that influence the production of migratory radon atoms (those atoms that are physically available for migration from their site of formation), and the processes that transport radon through the porous media.

The total rate of generation of radon activity within a source is simply the product of the radon decay constant ($2.1 \times 10^{-6} \text{ s}^{-1}$ for radon, and $1.3 \times 10^{-2} \text{ s}^{-1}$ for thoron) and the radium activity at the point of interest. Since only some of the radon produced becomes available for migration through the source, the emanation rate (or effective radon-generation rate) is a better measure than the total radon-generation rate of the radon source strength at the point of interest. The radon-emanation rate is the product of an "emanation ratio" (or emanation fraction) and the total generation rate. Historically, radon source strengths of soils have been cited as concentrations of "emanating radium-226", which is the product of the emanation ratio and the radium-226

activity per unit mass of soil.

Tanner (1964, 1980) has reviewed the mechanisms which generate radon that is available for migration through the source material. Parent radium atoms are typically located within mineral grains, and sometimes within coatings on the surface of grains. The alpha decay of radium imparts a significant recoil energy to the resulting radon atom, which may, upon expending this energy, stop in the fluid in the intergranular or pore space. Such radon atoms are then free to migrate through the porous medium. Since pore diameters are less than the recoil path length in air, and since recoil path lengths are shorter in water than air (1×10^{-4} um in water, and 60 um in air, as cited in Andrews and Wood (1972), and Jost (1960), respectively), most of the mobile radon atoms are probably generated close to pores that contain some water. However, any process that increases the surface-to-volume ratio of radium-containing grains may promote an increase in the radon-emanation ratio. Examples of such effects include the following: chemical alteration of grains by fluids; crystal dislocations that may result from recoil damage or stress; and micro-fractures that may result from mechanical weathering.

The transport of radon from its site of formation through a porous source material may occur through several mechanisms: molecular diffusion and the flow of pore gas through interconnected pores result in local migration; water-borne transport, and airborne transport through fractures, fissures, and cracks result in the migration of radon over greater distances. The movement of radon by molecular diffusion and by pressure-induced flow of interstitial gas through homogeneous porous media have been rigorously treated elsewhere. Currie's articles (1960a, 1960b, 1961) contain equations which describe transient and steady-state molecular diffusion in porous media. These papers also discuss experiments on gaseous diffusion in both dry and wet granular materials. Review papers by Tanner (1964 and 1980) and Wilkening (1980) discuss gaseous diffusion and flow in the ground; the review paper by Nero and Nazarov (1983) discusses diffusion and flow through both the ground and concrete; and the review paper by Colle, et al. (1981) discusses the diffusion of radon through concrete. Bulashevich and Kharitdinov (1959) derived equations describing migration due to diffusion and convection. Clements and Wilkening (1974) discusses a steady-state transport equation for radon migration in soils due to diffusion and pressure-induced flow of interstitial gas.

Gaseous diffusion is described by Fick's Law, which states that the flux is proportional to the concentration gradient, with the proportionality constant being called the diffusion coefficient. The diffusive migration of radon is described by the diffusion equation with decay and production terms.

Pressure-induced flow of interstitial gas through porous media is described by Darcy's Law, which states that the fluid flow per unit cross-sectional area is proportional to the pressure gradient, the proportionality constant being the product of the permeability of the medium and the inverse of the viscosity of the interstitial fluid.

The bulk radon source strength of a porous medium is frequently measured and reported in terms of the exhalation rate (or flux) of radon from the surface of the source. The flux is dependent upon the macroscopic physical properties

of the source (i.e., density, porosity, and permeability), and environmental conditions (i.e., moisture content of the source, pressure, and temperature) in addition to the radon-emanation rate of the source. The techniques that are commonly used to measure the flux of radon (see, for example, Countess (1976) and Wilkening (1977)), are influenced by both the radon-emanation rate and the diffusive transport properties of the source. The flux of radon varies over time due to the changes in environmental conditions.

The variability of radium concentrations and radon-emanation rates of source materials is considerable. Table 1 shows the variability of the concentration of radium-226 in rocks: while the averages of the classes of rocks show a sixteenfold variation, the ranges indicate a five-hundred-fold variation for individual samples which had detectable (equal to or greater than 0.1 pCi g^{-1}) quantities of radium. While the samples at the high ends of the ranges certainly contain unusually high radium concentrations, none approaches the concentrations found in deposits that are currently mined (1000 ppm of uranium-238 is often cited as the average for those deposits). While knowledge of both rock type and corresponding mean radium-226 content is indicative of statistically-probable radium content, means can not confidently be used as priori indicators of site-specific radium contents. UNSCEAR (1982) cited 0.7 pCi g^{-1} of radium-226 as the average concentration in soil and $0.3 - 1.4 \text{ pCi g}^{-1}$ as the typical range. Myrick et al. (1983) reported an average of 1.1 pCi g^{-1} and a range of $0.2 - 4.2 \text{ pCi g}^{-1}$ for 330 soil samples which were collected in 33 states in the U.S. This broader range seems more appropriate when compared to the radium content of rocks. The range of radium concentrations in typical concretes, as cited in Nero and Nazaroff (1983), is $0.2 - 2.0 \text{ pCi g}^{-1}$. The incorporation of either natural earth materials that contain elevated concentrations of radium (e.g., Swedish alum shale) or industrial by-products that contain elevated radium levels (e.g., wastes from bauxite or phosphate processing) has produced concretes which contain 35 and $7-20 \text{ pCi g}^{-1}$ of radium-226, respectively. Measurements of emanation rates or ratios are rarely reported in the literature. Austin and Drouillard (1978) reported radon-emanation ratios for 800 samples of uranium ores collected in the U.S. The range of the means of samples that were grouped by location was 5-57%. Barretto, et al. (1972) reported radon-emanation rates (and ratios) for fifty rock and nineteen soil samples; the ranges of the measurements were $0.05 - 8 \text{ pCi kg}^{-1} \text{ h}^{-1}$ ($0.5 - 26\%$) for rocks, and $0.2 - 9.5 \text{ pCi kg}^{-1} \text{ h}^{-1}$ ($10 - 55\%$) for soils. Pearson and Jones (1966) found that emanation rates from 70 soil samples ranged from 1.3 to $6.0 \text{ pCi kg}^{-1} \text{ h}^{-1}$, with a mean of $4.3 \text{ pCi kg}^{-1} \text{ h}^{-1}$. Sisigina (1974) reported emanation ratios for 38 soil samples from the U.S.S.R.; she measured values from 6 to 40%, and found that sandy soils clustered in the lower half of this range, while clayey soils clustered in the higher half. Measurements of radon-emanation rates of ordinary concretes were summarized in Nero and Nazaroff (1983). They report the range of emanation ratios as 3-28%, and the corresponding range of emanation rates as $0.3-1.2 \text{ pCi kg}^{-1} \text{ h}^{-1}$.

The flux, or radon-exhalation rate, from sources also varies substantially. Nero and Nazaroff (1983) computed an expected range of diffusive flux from concrete walls to be $0.02 - 0.06 \text{ pCi m}^{-2} \text{ s}^{-1}$, based on the emanation rates from 106 concrete samples from the U.S., and standard assumptions for the thickness and diffusion coefficient of the wall. Wilkening et al. (1974) reviewed measurements of the flux of radon from uncovered soil. They estimated a world-wide

average flux of $0.42 \text{ pCi m}^{-2} \text{ s}^{-1}$, and reported a range of $0.005 - 1.4 \text{ pCi m}^{-2} \text{ s}^{-1}$. (Measurements reported in section 7, "Field Study of Two Aerial Bismuth-214 Anomalies" of this report indicate that the upper limit of this range should be increased). The flux of radon from uranium tailings may be two orders of magnitude greater than values cited for typical soils.

Nero and Nazaroff (1983) compared the potential strengths of various sources of indoor radon with the observed distribution of indoor radon concentrations and entry rates. They also summarized the mechanisms by which radon may enter buildings, and the results of experiments performed in several houses to determine the source-transport mechanisms of indoor radon. These authors tentatively concluded that while the contribution of radon from concrete can account for low radon-entry rates, soil is probably the predominant source in most cases where the radon-entry rates are high. The domestic water supply can also be the predominant source of high indoor radon concentrations if it is derived from aquifers that occur in unusual geologic settings (see, for example, Hess et al., 1982). The conclusions of an experimental investigation of the relationship between radium and radon concentrations in the ground and indoor radon concentration in Sweden (Akerblom et al., 1983) support Nero and Nazaroff's contention that soil gas is the predominant source of indoor radon in houses which contain elevated radon-progeny concentrations. An important conclusion of these studies in Sweden is that soils are likely to have high radon source strengths when characterized by either high radium contents and typical permeabilities, or high permeabilities and typical radium contents.

2.6 Brief Description of the Natural Airborne Radiometric Reconnaissance Program

Beginning in 1974, the U.S. Department of Energy sponsored the National Airborne Radiometric Reconnaissance (NARR) Program as a major component of the National Uranium Resource Evaluation (NURE) Program. The principal objectives of the NURE Program were to refine the estimates of potential uranium resources in the U.S., and to select areas deemed favorable for future exploration. The objective of the NARR Program was to supply for the United States a semi-quantitative evaluation of the distribution of naturally occurring radionuclides, that could be used for detecting areas containing anomalously high radioactivity, which might delineate uraniferous geochemical provinces.

Gamma spectrometry from aircraft was used to measure the radioactivity of the near-surface soil. Since numerous radionuclides in the soil and the atmosphere produce gamma radiation that may interact with the detectors, and since their relative contributions vary spatially and temporally, it is necessary to measure the intensity of radiation from cosmic sources, from atmospheric terrestrial sources, from potassium-40, and from the thorium-232 decay series in the soil to derive a quantitative measurement of the concentration of the uranium series in the soil. (Kogan et al. (1971) is an excellent reference on gamma spectrometry of natural environments.) All of these measurements are made simultaneously through discrimination of energies of the gamma rays that interact with the thallium-activated sodium iodide detectors. The determination of the uranium concentration in the soil is based on the intensity of the 1.76 MeV photopeak of bismuth-214, which is one of the short-lived progeny of

radon-222 (see Figure 1). Therefore, the aerial uranium-238 data are actually a more direct measure of the radon-222 and radium-226 in the ground than of uranium-238. Gamma rays generated within the soil to a depth of 0.5 m can be detected by airborne measurement systems.

The NARR Program measured gamma radiation from the earth along primary flight lines that were oriented east-west and separated, typically, by either three or six miles. Tie lines were flown normal to the primary flight lines and were separated by twelve to eighteen miles. In all, data have been acquired along more than 1.1 million miles of flight lines within the contiguous U.S. and Alaska. The unit area of investigation for data acquisition and publication was the National Topographic Map Series of $1^{\circ} \times 2^{\circ}$ quadrangles, covering areas delineated by one degree of latitude (approximately 69 miles) and two degrees of longitude (this distance is proportional to the cosine of latitude, and ranges roughly from 90 to 125 miles for the U.S.). The contiguous United States comprises 474 such quadrangles. The primary contractor for the NURE Program was the Bendix Field Engineering Corporation in Grand Junction, Colorado. Seven independent subcontractors performed the aerial radiometric reconnaissance in accordance with specifications by Bendix so that this enormous program could be completed in a timely manner. The results of the aerial radiometric reconnaissance of the contiguous United States are presently available, by quadrangle, from Bendix Field Engineering Corporation (see Appendix).

3. Previous Work

3.1 Aerial Radiometric Surveys

Airborne radiometric measurement systems were developed during the late 1950's and the 1960's as an aid to geological mapping (see, for example, Pitkin, 1968, and Moxham, 1970) and uranium exploration (IAEA, 1973 and 1976) and for monitoring the gamma exposure rates surrounding nuclear facilities (Burson et al., 1972). The earlier systems measured the intensity of the total gamma radiation field, including a significant contribution that arose from atmospheric testing of nuclear weapons.

In the United States, the Aerial Radiological Measurements Surveys (ARMS), conducted for the U.S. Atomic Energy Commission by the U.S. Geological Survey and EG & G from 1958 to 1963, measured the gamma intensity and derived exposure rates for areas containing 30% of the population. Exposures from natural radiation within the United States were estimated from the ARMS data by Oakley (1972).

Aerial gamma spectrometer systems of enhanced sensitivity were developed during the late 1960's. These systems could distinguish variations of 0.25% K, 1.0 ppm U, and 2.0 ppm Th in the ground (Grasty et al., 1983), and thus were suitable for distinguishing variations in background radioactivity. The NARR Program used similar airborne gamma spectrometer systems. Canada has conducted a Federal-Provincial Uranium Reconnaissance Program based on aerial gamma spectrometry (Darnley et al., 1969; Darnley, 1976). This measurement technique was also used in regional surveys of Canada to estimate annual dose equivalents received by the public due to external gamma radiation indoors (Grasty et al., 1983). Regional variations of background radiation were documented via aerial gamma spectrometric surveys in Sweden (Wilson, 1983).

3.2 Ground-Based Verification of Aerial Gamma Spectrometric Measurements

Since aerial gamma spectrometry has been used extensively by geologists as a tool for mapping and uranium exploration, some ground-based investigations of aerial measurements have been reported at conferences pertaining to uranium (IAEA, 1969 and 1976). We will focus our discussion on studies that specifically investigated the correlation between aerial gamma spectrometric measurements of bismuth-214 and ground-based measurements of either bismuth-214 contents or radon source strengths of geologic materials.

Investigations of aerial bismuth-214 anomalies in Sweden indicated a high correlation between aerial and ground-based measurements in geologic materials; a high correlation was also seen between the aerial anomalies and elevated concentrations of radon in either soil gas or groundwater (Wilson, 1983).

The results of a ground-based investigation of an aerial bismuth-214 anomaly located northwest of Richmond, Virginia are reported in Baillieu and Dexter (1982). Measurements of total gamma intensity, of bismuth-214 concentrations, and of radon concentrations in groundwater substantiated this

anomaly.

Aerial reconnaissance over three adjacent quadrangles in central Alaska indicated that the Sischu Creek area, located at the corner that is common to the three quadrangles, contained elevated concentrations of bismuth-214 (Western Geophysical Company of America, 1980a, 1980b, and 1980c, as cited in Girdley et al., 1982). These results were reinforced by an ensuing detailed aerial gamma spectrometric survey (Western Geophysical Company of America, 1980d). The results of ground-based study of the Sischu Creek area are reported in Girdley, et al. (1982). In situ and laboratory gamma spectrometric measurements also indicated elevated concentrations of bismuth-214 in the rhyolitic rocks of the area.

The existence of elevated concentrations of bismuth-214 within Oconto and Forest Counties in northeastern Wisconsin was suggested by aerial anomalies (Geometrics, 1978, as cited in Blackburn and Mathews, 1982). Ground-based radiometric surveys substantiated elevated concentrations (14 ppm U or 4.7 pCi g⁻¹ Ra) in the Hagar Rhyolite (Blackburn and Mathew, 1982).

3.3 Investigations of the Correlation between Aerial Measurements of Bismuth-214 and Indoor Radon Concentrations

Very little work of this nature has thus far been undertaken. The most extensive studies have been supported by the Swedish government (Wilson, 1983). The Canadian government has recently begun supporting this type of work (Wagner, 1983).

In Sweden, surficial radium-226 activities, as determined from aerial measurements of bismuth-214, exhibited substantial regional variability. These measurements were used as the basis for selecting several towns in which indoor concentrations of radon were studied, with the expectation that the indoor radon concentrations would display considerable regional variability. The results of measurements of annual average indoor radon concentrations in 253 houses from four towns are reported and discussed in Akerblom et al. (1983). Most of the houses studied were wooden, and none contained contaminated concrete, so that contributions of radon from building materials were probably insignificant. Detailed studies of the radon source strengths of surrounding geologic materials were conducted at 105 houses. The risk of high indoor radon concentrations was found to be related to the radium concentrations in the ground, regardless of the type of foundation. When the radon source strengths of geologic materials were similar, houses with full or partial basements were more prone to indoor radon problems than were houses with crawl spaces or slab-on-grade foundations. The potential importance of permeabilities and porosities of soils as factors that influence both the radon source strengths of soils and the rates at which soil gas enters houses was suggested.

Indoor progeny concentrations in thirteen communities in Northern Saskatchewan were compared with aerial measurements of bismuth-214 (Wagner, 1983). The distribution of progeny concentrations, based on grab-samples, in 300 buildings, compared favorably with the spatial distribution of contours of

radium concentrations computed for the region.

Indoor radon concentrations for thirty-six houses in eastern Pennsylvania were compared with the spatially corresponding National Airborne Radiometric Reconnaissance data in van Assendelft and Sachs (1982). The radon concentration of each house was compared to the bismuth-214 counting rate along a short segment of the NARR flight line that was closest to the house of interest. The aerial data was not a good indicator for this set of houses.

Kothari and Han (1983) compared the annual average indoor radon concentrations for houses in nine locations in the U.S. with the geometric mean of equivalent uranium concentrations, as determined from bismuth-214 data acquired along segments of NARR flight lines that were near the location of interest. A positive correlation was found between the mean equivalent uranium concentration for each location and the percentage of houses containing radon concentrations that exceeded a threshold value.

4. Detailed Description of the National Airborne Radiometric Reconnaissance Program

4.1 Spatial Coverage

Though this program provided aerial radiometric data throughout the United States, the density of the measurements was variable. The distance which separated the primary flight lines, varied from 0.25 miles to 6 miles. Consistent with the objective of estimating potential uranium resources, measurements were most dense in sparsely populated areas that were either known to contain highly elevated uranium concentrations, or were considered to be good prospects, based on geologic analogy. In densely populated areas, the flight lines were at least three miles apart. It also appears that a priori knowledge of the uranium content of prevalent rocks in a quadrangle or large region in some cases influenced the choice of the density of measurements. (For example, in regions of the western United States where ultrabasic and basic extrusive rocks prevail, e.g. the Columbia Plateau, flight lines are further apart than in adjacent regions). In general, the primary flight lines for the western half of the contiguous U.S. were separated by three miles, while those for the eastern half of the U.S. were separated by six miles.

4.2 Data Collection

Each aircraft that was used for radiometric reconnaissance contained two gamma spectrometers, a proton precession magnetometer, a position-tracking camera, exterior probes for measuring temperature and barometric pressure, a tape deck for storing data, standard aerial navigational instrumentation, a clock, and a computer that controlled data acquisition and storage.

Locations were noted during the flight by placing fiducial marks on tape while above prominent topographic or man-made features. Photographs that were taken every three seconds during flight, topographic maps, and records of data from the navigational instruments were subsequently used to finalize the locations of measurements. Ten miles was the maximum distance allowed between precisely determined measurement sites, and all intersections of flight lines were precisely located.

One gamma spectrometer measured radiation produced only by atmospheric sources, while the other measured radiation from all sources. The measurements of temperature and of altitude above the ground were used to normalize all gamma spectrometric data. The measurements of the total magnetic field intensity, which were made with the proton precession magnetometer, can be used to determine the depth of igneous or metamorphic rocks, and to delineate contacts, or boundaries, between adjacent rock types. Reford and Sumner (1964) present an excellent review article on aeromagnetism.

The data acquisition system recorded measurements of gamma radiation, total magnetic field intensity, temperature, and barometric pressure every second, averaged the terrain clearance every second, and triggered the position-tracking camera every three seconds. The computer transferred these data, as well as navigational data, time, and fiducials to magnetic tape.

4.3 Gamma Spectrometric Data

In this section we discuss principles of the measurement technique, primary and background data, calibration of airborne systems, normalization of data, and sources of error.

Large thallium-activated sodium iodide gamma detectors were arranged in arrays above and below the aircraft while the NARR data were collected. Gamma rays interacting with these detectors induce light pulses whose intensities are proportional to the energies of the incident photons. Photomultiplier tubes detect these light pulses and convert them to an analog signal which is linearly amplified, converted to a digital signal, and fed to a multichannel pulse-height analyzer. The pulse-height analyzer linearly assigns photons with energies between 0 and 3 MeV to 255 energy bands or channels, while photons with energies between 3 and 6 MeV are summed and stored in channel 256. The gamma spectrometric data of primary interest when measuring radiation produced within the ground are the following: the 1.46 MeV photopeak from potassium-40; the 1.76 MeV photopeak from bismuth-214 of the uranium decay chain; the 2.62 MeV photopeak from thallium-208 of the thorium decay chain; and the sum of events with energies below 3 MeV, which is referred to as the gross gamma activity.

These data are superimposed upon a variable background continuum that arises from three sources: the aircraft and the detection system; cosmic rays; and atmospheric radon progeny. The first component is constant. The latter two vary spatially and temporally and must, therefore, be continuously monitored during data acquisition. The cosmic component of the background can be monitored by the same gamma spectrometer that measures the radiation from the ground. The sum of events with energies between 3 and 6 MeV is used to make the correction for background arising from cosmic rays. Since the measurement of the component of background arising from atmospheric radon progeny is based on the 1.76 MeV photopeak from bismuth-214, as is the measurement of radium in the ground, a second gamma spectrometer whose detectors are shielded from bismuth-214 produced within the ground is used to distinguish the two sources.

Two types of constants are needed to calibrate gamma spectrometers: sensitivity constants and stripping coefficients. The stripping coefficients are needed to account for both Compton scattering of gamma rays within solid sources and contributions by photopeaks produced by other radionuclides in the uranium and thorium chains to the channel intervals for the 1.46, 1.76, and 2.62 MeV photopeaks. A good discussion of spectral stripping and its influence on the calibration of gamma spectrometers can be found in Kogan et al. (1971). Since the calibration constants for a detection system are strongly dependent on detector-source geometry, the calibration of an airborne system must include determinations of the dependence of all calibration constants on altitude above the ground.

All gamma spectrometers used in the aerial reconnaissance program were calibrated at Walker Field in Grand Junction, Colorado. This facility was specifically built for calibrating airborne spectrometers and consists of five large (9.1 m by 12.2 m) concrete pads that contain known concentrations of the radionuclides of interest. Ward (1978) described the calibration facility at Walker Field. Grasty (1976) describes the procedure by which airborne gamma

spectrometers are calibrated. Basically, the system's responses are determined above three pads that are each enriched with a known concentration of potassium, uranium, or thorium, and above a fourth pad that is enriched with known concentrations of all of these radionuclides. These responses are used in a set of simultaneous equations that is solved for sensitivity constants for potassium-40, uranium-238, and thorium-232, and for nine stripping coefficients. The dependence of these constants on altitude above the pads was also determined at Walker Field.

Calibration data acquired at the Lake Mead test range were used to derive constants that are necessary to correct for background arising from atmospheric bismuth-214. Geodata International, Inc. (1977) describes the use of this calibration facility. Basically, the responses of the shielded and unshielded detectors in the bismuth-214 photopeak over land and over water were used to derive the ratio of atmospheric bismuth-214 that was detected by the shielded detectors relative to the unshielded detectors. The fact that a deep body of water absorbs virtually all gamma radiation and exhales no radon to the atmosphere makes this possible. The dependence of this fraction on altitude was also determined.

The constant gamma background that arises from the aircraft and its instrumentation was determined during flights at high altitudes above water.

After subtracting background counting rates due to the aircraft, cosmic rays, and atmospheric bismuth-214, it was assumed that the net counting rates measured by the unshielded detectors arise solely from radionuclides in the ground. While this assumption is valid for potassium and the thorium chain, it may not always be valid for the uranium chain due to the diffusion of radon-222 from the ground and the subsequent vertical distribution of radon and progeny in the atmosphere. As mentioned earlier, the technique used to measure the contribution of atmospheric bismuth-214 to the background assumes that, at a given altitude, the ratio of the bismuth-214 counting rate measured by the shielded (or "upward-looking") detectors relative to the counting rate measured by the unshielded (or "downward-looking") detectors is constant.

However, two meteorological factors that influence the vertical distribution of radon and progeny in the atmosphere, and thus influence the validity of this assumption regarding corrections for background, are precipitation and the degree of atmospheric mixing (Jacobi and Andre, 1963; Gogolak and Beck, 1980). Precipitation removes radioactive aerosols from the atmosphere and deposits them on the ground (Finck and Persson, 1980); this alters the vertical concentration profile of bismuth-214, and therefore, the ratio of bismuth-214 counting rates described above. The degree of vertical atmospheric mixing is frequently inferred from vertical temperature gradients (Gogolak and Beck, 1980). Atmospheric mixing exhibits a characteristic diurnal pattern such that normal or strong mixing typically prevails during the daytime between the early morning and the middle of the afternoon, while very weak mixing prevails during the nocturnal temperature inversion. It is therefore highly probable that normal or strong mixing occurred during the determination of the ratio of bismuth-214 counting rates that served to correct the aerial data. When temperature inversions persist throughout the day, and atmospheric mixing is very weak, the actual ratio of bismuth-214 counting rates measured by the two gamma spec-

trometers will be significantly different from the value used during data reduction. Therefore, precipitation and temperature inversions both introduce significant random error for aerial determinations of radium concentrations. Therefore, Bendix specified suspension of data acquisition during periods of temperature inversions and precipitation (Bendix Field Engineering Corp., 1979).

Other sources of error for aerial gamma spectrometric measurements generally produce variations in the attenuation and angular distribution of the gamma flux from the ground. Variations in soil moisture influence the gamma flux from the ground because rain and surface water contain very little radium or radon and attenuate gamma rays very effectively in comparison with soil gas. Kirkegaard and Lovborg (1980) discuss the dependence of exposure rate on soil moisture. The exposure rate above a soil containing 50% water by weight, which is a practical upper limit, is 36% lower than the exposure rate above the same soil when dry. This is a "worst case" estimate of the errors that may arise due to variations in soil moisture, however, since the calibration pads at Walker Field contain 20 - 30% moisture (Dodd, 1982) as do many soils. Bendix Field Engineering Corp. (1979) also specified suspension of data acquisition when the moisture content of the soil was high. The water content of snow produces similar effects. Variation in vegetative cover is another source of error for aerial radiometric measurements. Vegetation can cause errors in two ways: by attenuating the gamma flux from the ground; and by reflecting the radio waves from the radar altimeter system, thereby causing an underestimate of the altitude for the measurements, which influences the calculation of the radionuclide concentrations in the ground. Rubin et al. (1980) contains a detailed treatment of the effects of vegetation on the aerial measurement of radium concentrations.

Another potential source of error may result from geochemical and physical differences between surficial soil and slightly deeper geologic material. While aerial gamma spectrometric measurements are sensitive to gamma rays produced within 0.5 meters of the surface, radon may be transported from depths of 1 to 2 meters. These potential differences may be especially relevant in previously glaciated areas and in floodplains.

4.4 Treatment of Aerial Data

After the raw gamma spectra were corrected for background, stripping was performed and the data were normalized to an altitude of 130 m at standard temperature and pressure. Lists of reduced individual measurements, or records, are included in the reports for each quadrangle.

A check for statistical adequacy was performed on the net counting rates in the potassium-40, bismuth-214, and thallium-208 photopeaks. The net counting rates in each of these peaks was required to be at least equal to the sum of the background corrections that were applied to it for the measurement to be deemed statistically adequate. Measurements which failed this test were assigned values of zero and were omitted from statistical analyses.

Base maps of flight lines and locations of measurements were superimposed on geologic maps so that a geologic map unit could be assigned to each measure-

ment record. The map supplement (contained in the rear pocket of this report), which shows the flight lines, geology, and locations of statistically-significant bismuth-214 anomalies for the Dillon quadrangle, Montana, illustrates the way in which this was done. Data were smoothed by computing either five- or seven-point running averages for K, U, Th, U/K, U/Th, Th/K, gross gamma, atmospheric bismuth-214, and cosmic counting rates, terrain clearance, temperature, barometric pressure, and residual magnetic field intensity. Lists of these averaged records are included in the reports for each quadrangle.

The smoothed radiometric data for each flight line are also plotted in a figure referred to as a "stacked profile". The stacked profiles contain the most site-specific graphic presentation of absolute radiometric data presented in the NARR narrative reports. Most of the NARR reports published in 1980 or later also contain "printer plot contour maps" for each radiometric variable, which depict the absolute data throughout the quadrangle. These maps were derived from the smoothed data and interpolations among the flight lines.

The remaining analyses of the aerial radiometric data that are included in the NARR reports are based on grouping the measurements by geologic map unit. The frequency distributions of the measurements of K, U, and Th and of the computed ratios of U/K, U/Th, and Th/K for each geologic map unit in a quadrangle are shown in figures referred to as "geologic histograms". The arithmetic means and the standard deviations were computed for the distributions of these six radiometric variables for each map unit. A table of these statistical values is included in each report. Maps of the quadrangle, referred to as either "standard deviation maps" or "significance factor profile maps", were produced for each of the six radiometric variables. On these maps, the mean value for the geologic map unit at a site is represented by the flight line. The degree of deviation of the measurement at each site from the mean for the geologic map unit is shown by the length of lines or the number of dots which appear above a primary flight line or to the right of a tie line, for measurements that were greater than the mean.

The report for each quadrangle also describes the occurrences of "statistically-significant uranium anomalies". These anomalies were designated through comparisons of smoothed bismuth-214 counting rates with the bismuth-214 counting rates corresponding to one, two, and three standard deviations above the mean for the geologic map unit at the location of interest. A statistically-significant uranium (or radium-226) anomaly was designated when one of the following occurred: one record had a bismuth-214 counting rate that was greater than the counting rate at three standard deviations above the mean; two successive records had bismuth-214 counting rates that were between those at two and three standard deviations above the mean; two of three successive records had bismuth-214 counting rates that were greater than that at one standard deviation above the mean, and a third record had a bismuth-214 counting rate that was between those at two and three standard deviations above the mean; or four successive records had bismuth-214 counting rates that were between those at one and two standard deviations above the mean.

Each NARR report also contains an interpretive map showing the locations of uranium (or radium-226) anomalies. These maps depict a geologist's interpretation of the uranium standard deviation map in the context of all other relevant

data. This map may be referred to as "interpretation map", "uranium anomaly map", or "preferred uranium anomaly map".

Each NARR report contains summaries of the physiography and geology of the quadrangle. Documented occurrences of uranium mineralization are also summarized.

5. Examination of NARR Data by LBL: Cursory Approach

5.1 The Database

There are numerous ways in which the aerial data can be analyzed. As a preliminary to actual analysis, the reports of the results of the airborne radiometric measurements within the ninety-two quadrangles of interest were used to construct a summary database, which we refer to here as the primary database. The primary database is organized according to quadrangle and geologic map unit, following the summary strategy that was used by the NARR Program (see section 4.4, "Treatment of Aerial Data"). This database was established as an indexed file comprising records for each geologic map unit within each quadrangle.

The following data for each geologic map unit were extracted from each of the ninety-two NARR reports and entered into the primary database: the number of aerial measurements performed above the geologic map unit; the number of uranium (actually bismuth-214) anomalies that occurred within the geologic map unit; the arithmetic means and standard deviations of the measurements of U, Th, and K above the map unit, and of the U/Th, U/K, and Th/K ratios that were computed for the geologic map unit. Though the primary database contains thorium and potassium data, we are primarily interested in, and have restricted our analyses to, the equivalent uranium data.

A secondary file was created that contained only the data that were relevant for investigations of the frequency distributions of radium concentrations within individual quadrangles and among geographic regions. We refer to this file as the radium master file. Records were defined as in the primary database.

Two data fields were transferred without change from the primary database to the radium master file: the number of measurements performed above each geologic map unit, and the number of bismuth-214 anomalies that occurred within each map unit.

Several calculations, based on data that were either contained in, or derived from, the primary database were performed. Since our interest is radon source strengths, the bismuth-214 data that were reported as means and standard deviations of equivalent uranium-238 concentrations within each geologic map unit were converted to radium activity concentrations using the fact that one ppm of equivalent uranium-238 equals 0.336 pCi g^{-1} of radium-226. (The bismuth-214 data are a more direct measure of radium than of uranium because radium-226 is the closest preceding long-lived radionuclide to bismuth-214 (see Figure 1)). The coefficient of variation, which is a measure of relative dispersion and is simply equal to the standard deviation divided by the mean, was calculated for the radium concentrations in each geologic map unit. The fraction of the area of a quadrangle that was occupied by each geologic map unit was estimated as the ratio of the number of aerial measurements performed above each geologic map unit to the total number of aerial measurements performed within the quadrangle of interest.

Two data fields were added to each record in this file. The first allowed the geologic map units within individual quadrangles to be ranked by ascending

mean radium concentrations. The second was a code representing the state in which each quadrangle was located. When the location of a quadrangle crossed state boundaries, the quadrangle was assigned to the state that contained the greatest fraction of the quadrangle's area.

5.2 Regional Radium Calculations

To study the regional variability of radium concentrations as measured by aerial reconnaissance, a mean and standard deviation were calculated for all measurements of radium concentrations within each quadrangle. We refer to these quadrangle-wide statistics as regional radium statistics. The bases of these computations were the radium mean, the radium standard deviation, and the fraction of the quadrangle's area in which each geologic map unit outcrops. Standard statistical formulas for weighted calculations of these statistics from grouped data were employed (Arkin and Colton, 1972). When variables are defined as follows:

- x_{ij} = j^{th} measurement in the i^{th} map unit;
- n_i = number of measurements above the i^{th} map unit;
- $\bar{x}_i$ = mean content of the i^{th} map unit;
- s_i = standard deviation of measurements above the i^{th} map unit;
- $\bar{X}$ = mean content within the quadrangle;
- S = standard deviation of measurements within the quadrangle;

the standard statistical formula for the mean of grouped data ($\bar{X}$) is equivalent to the computational formula used here:

$$\bar{X} = \frac{\sum_i \left(n_i \bar{x}_i \right)}{\sum_i n_i} \quad (1)$$

Similarly the standard statistical formula for the standard deviation of grouped data (S) is equivalent to the computational formula used here:

$$S = \sqrt{\frac{\sum_i (n_i - 1) s_i^2 + \sum_i n_i (\bar{x}_i - \bar{X})^2}{\sum_i n_i}} \quad (2)$$

Data that were acquired above water were omitted from the regional statistical calculations, as were data for map units when none of their associated bismuth-214 measurements passed the statistical adequacy test (as described in section 4.4, "Treatment of Aerial Data"). This latter situation only occurred if the spatial extent of the geologic map unit was very limited.

For comparative purposes, the average radium content was computed for the whole area studied. An estimate of the land area within each quadrangle was computed to adjust for both the influence of varying latitude on a quadrangle's area, and the smaller land area present in coastal quadrangles. Quadrangle-wide mean (or regional) radium-226 contents were weighted by area during this computation.

5.3 Presentation of Radium Data Within Individual Quadrangles

We have found three formats to be useful for presenting a synthesis of radium data within individual quadrangles. As we discuss each format we present an example for either the Butte or Dillon quadrangles, Montana and Idaho. The city of Butte, which is situated on the boundary between these quadrangles, has endemic indoor radon problems (Lloyd, 1981). The aerial measurements of bismuth-214 in this area are also discussed in section 6, "Examination of NARR Data by LBL: Detailed Approach".

Tables summarizing the radium data within each quadrangle were generated from the radium master file. The types of data that are included in these tables are illustrated by Table 2, for the Dillon quadrangle. These tables are particularly useful in conjunction with a geologic map of the quadrangle. The map supplement of this report shows the geology of the Dillon quadrangle. The alphabetical list of geologic map units allows the user to readily locate information for a particular map unit. For example, the geologic map of the Dillon quadrangle indicates that the city of Butte is underlain by the following map units: QAL (Quaternary alluvium), TU (Tertiary coarse-grained valley fill), and KG (Cretaceous granodioritic Boulder batholith). These map units, when found alphabetically in Table 2, are seen, by means of their rank, to have mean radium concentrations (0.67, 0.72, and 0.73 pCi g⁻¹, respectively) that lie near the center of the distribution of means for map units within the quadrangle. Neither are the standard deviations for radium within KG and QAL noteworthy. The coefficient of variation for TU, however, appears to be atypically high. High coefficients of variation may indicate map units of high potential radon source strengths, particularly when the mean radium content of the rock unit is moderate or high. The numbers of radium anomalies that occur within KG and QAL in Dillon are high, and suggest that KG and QAL outcrop at some sites that contain elevated radium contents. However, the high number of anomalies may merely reflect the comparatively large areas occupied by these two map units, as is seen by scanning the column labelled "fraction of quad area". The extreme variation in the area occupied by map units within the Dillon quadrangle suggests that a ratio of the number of radium anomalies to area occupied may be a more useful indicator.

The "radium rank numbers" allow the user to readily learn which map units have comparatively high mean concentrations of radium. The spatial distribution of outcrops of these map units could then be discerned on the geologic map, and superposition with population centers could be checked. For example, the radium summary data for the one hundred and fifteen map units that outcrop within the Butte quadrangle (Texas Instruments, 1979; indicate that two map units containing elevated radium concentrations outcrop within the city of Butte. Within this quadrangle, map unit KG occupies fourteen percent of the area and was found to have a bimodal radium distribution: KG1 contains an average of 0.68 pCi g^{-1} (ranked 56 of 115), while KG2 contains an average of 1.21 pCi g^{-1} (ranked 109 of 115). Map unit A (alaskite and pegmatite dikes and sills), which outcrops predominantly near the city of Butte, contains an average of 1.40 pCi g^{-1} (ranked 113 of 115). Therefore the elevated radon source strengths observed within the city of Butte are more clearly indicated by the summary radium data within the Butte quadrangle than by the summary data for the Dillon quadrangle.

While the tables described above contain much information, assessments of the radium data for a moderate number of quadrangles could be very time-consuming. We found that a visual representation of the distribution of radium concentrations within each quadrangle was useful. Histograms were constructed that display the percentages of a quadrangle's area that are occupied by map units whose mean radium concentrations lie within eight intervals.

Figure 2 displays the format that was chosen and the frequency histograms for the Butte, Dillon, Spokane, and Vancouver quadrangles. The regional radium statistics are also presented in the caption under the histogram for each quadrangle. The distribution of mean radium-226 concentrations for the map units within the Vancouver quadrangle lies within the lower portion of the distribution observed within the entire area of study (the observed range is $0.07 - 3.57 \text{ pCi g}^{-1}$). The regional radium-226 concentrations for both the Spokane and Dillon quadrangles are representative of the average radium content (0.73 pCi g^{-1}) of the area studied. The deviations from the mean, as seen by the values of the regional standard deviations, for Spokane and Butte are slightly greater than typical, while the deviation from the mean for the Dillon quadrangle is unusually high. The coefficient of variation for the Dillon quadrangle is the highest observed. The regional radium-226 content within the Butte quadrangle is slightly greater than the average for the area studied. The presence of several rock units within the Butte quadrangle that contain elevated average concentrations of radium-226 is clearly indicated by its histogram, while the values of its regional radium mean and standard deviation do not highlight this fact. The great dispersion about the mean of the distribution of radium concentrations within the Dillon quadrangle does not appear to arise from the presence of rock units that contain elevated average concentrations of radium-226 as seen in Figure 2 and Table 2. This suggests that the dispersion for the Dillon quadrangle may be due to greater-than-average dispersion about the average radium-226 contents for individual rock units. The standard deviations of the distributions of radium contents for individual geologic map units that occur throughout the entire study area infrequently exceed 0.5 pCi g^{-1} ; therefore the magnitude of the standard deviations for the distributions of radium contents within TU, DG, and PEA (1.0, 1.5, and 2.5, respectively, as seen in Table 2) probably account for the great regional dispersion within the Dillon

quadrangle.

It is important to note that these histograms are statistically-biased with respect to dispersion, since the observed spread is dependent upon the number of map units present within a quadrangle. This is clearly seen by comparing the spread in the histograms for Spokane and Butte, which displayed equal regional standard deviations (statistically-unbiased estimators of dispersion about the regional mean). Butte contains one hundred and fifteen map units, while Spokane contains a total of twenty-nine units. Therefore, comparisons among these histograms may yield misleading assessments unless they are previously divided into groups of quadrangles containing total numbers of map units that are roughly comparable. The average number of map units per quadrangle is forty-eight, and the observed range is eight to one hundred and forty-nine. The number of map units within each quadrangle is provided as a portion of the titles of the tables that summarize the radium data by map unit.

Statistically-unbiased histograms of radium contents can be most confidently obtained from complete sets of bismuth-214 measurements within each quadrangle.

The third format that we have found useful for presenting a synthesis of radium data within individual quadrangles is a map included in the reports of the results of the NARR surveys within each quadrangle. This map may be referred to as the "uranium anomaly", the "preferred uranium anomaly", or the "interpretation" map. Generally, these maps show the locations of spatial associations of statistically-significant uranium anomalies, which are defined in section 4.4, "Treatment of Aerial Data". Our review of NARR reports suggests that the preceding statement is true for quadrangles in which a low to moderate number (less than about 200) of statistically-significant uranium anomalies were found. When larger numbers of anomalies were encountered, however, it seems that the uranium anomaly maps often depict the results of a more rigorous interpretation of the statistically-significant radiometric anomalies.

This duality of interpretation of anomalies is illustrated in Figure 3 which is an example, from the Butte quadrangle, Montana, of these uranium anomaly maps. Approximately nine hundred statistically-significant uranium anomalies were defined from the bismuth-214 measurements. Their locations are indicated in Figure 3 by the presence of a heavy dot on the flight line. These anomalies occur throughout the quadrangle, such that choosing distinct spatial associations is difficult. The sites of statistically-significant U/Th and U/K anomalies are also shown on this map by heavy dots above and below the primary flight lines, respectively. The eighty-five boxes along the flight lines show the locations of "preferred uranium anomalies", which, by definition, occur where statistically-significant anomalies of U, U/Th, and U/K coincide, thus representing a more rigorous interpretation of the radiometric data than was generally used. The virtue of the uranium anomaly maps lies in their display of specific geographic sites within a quadrangle that have a higher probability of elevated radium concentrations in the ground.

5.4 Presentation of Regional Radium Data

Table 3 summarizes the regional data. The following information is included for each quadrangle: the mean, standard deviation, and coefficient of variation for the frequency distribution of radium measurements; the range of the average concentrations of radium within the geologic map units that occur in the quadrangle; the number of uranium anomalies that were reported; and the average separation between flight lines during the collection of the aerial radiometric data. When the distance indicated is not an integer number, portions of the quadrangle were flown at different spacings.

To assess whether distributions of radium concentrations in soils and rocks exhibit regional variability, we have displayed four statistical characteristics of the regional distributions of radium contents on a base map of the $1^{\circ} \times 2^{\circ}$ quadrangles within the study area. The regional means and standard deviations of the distributions of measurements of radium within each drangle were divided into six classes; their geographical distributions are shown in Figures 4 and 5, respectively. A non-standard shading scheme was used in these figures, due to the number of classes. Lines represent the classes with higher values.

The mode of the distributions of regional radium means and standard deviations occurs in the third class, ranked by increasing values. As an additional basis for comparison, the area-weighted average radium content was computed for the entire area studied, and is 0.73 pCi g^{-1} , with a standard error of the mean of 0.32 pCi g^{-1} . The preponderance of low regional radium means and standard deviations north of 41° latitude and west of 120° longitude is striking. This region, characterized by low radium concentrations, includes the Cascade Range and areas to its west, and the Coast Range in northern California. Similarly, a preponderance of moderate to comparatively high regional radium means and standard deviations generally characterizes a region south of 38° latitude and east of 122° longitude, which includes most of central and southern California and southwestern areas of Nevada that are adjacent to its boundary with California. The distributions of radium concentrations within the remaining quadrangles in the study area are not readily characterized on a regional basis.

Some additional information about the regional variability of radium contents is shown in Figures 6 and 7. The percentage of a quadrangle's area that is occupied by geologic map units whose average radium-226 contents exceed a threshold are shown. Note that these results are subject to the same statistical bias as the frequency histograms for individual quadrangles (as discussed in section 5.3, "Presentation of Radium Data Within Individual Quadrangles"). The threshold used in Figure 6, 1.0 pCi g^{-1} , approximates the average concentration of radium in the continental crust (see Table 1). A threshold of 1.4 pCi g^{-1} is applied in Figure 7.

6. Examination of NARR Data by LBL: Detailed Approach

The NARR narrative reports pertaining to the following four quadrangles were studied in greater detail: Vancouver, Oregon and Washington; Spokane, Washington, Idaho, and Montana; Dillon, Montana and Idaho; and Butte, Montana. This work was conducted prior to the completion of the primary database, and had two objectives: 1) to ascertain whether the distributions of aerial measurements of radium varied significantly among major physiographic and geologic provinces; and 2) to assess the degree to which the variable-threshold approach to defining anomalous areas, as employed during processing of NARR data, reflects spatial variations in the absolute bismuth-214 counting rates within a quadrangle.

Significant variations in radium data among major physiographic provinces are generally suggested by the information contained in Table 3, and in Figures 4 and 5, as discussed in section 5.4.

The Dillon quadrangle in Montana and Idaho is used to illustrate the degree of correlation between anomalous areas delineated on the bases of deviations from the mean radium contents of map units (or variable threshold) versus deviations from a constant threshold. The map supplement, contained in the rear pocket of this report, shows the geology of the Dillon quadrangle, and the locations of both the NARR flight lines and the bismuth-214 anomalies, as interpreted in High Life Helicopters and Geodata International, Inc. (1979). The dots above the primary flight lines (ML) and to the left of the tie lines (TL) indicate the positive dispersion of the smoothed bismuth-214 records from the mean value (i.e., counting rates that exceed the mean) for the frequency distribution of records acquired above the appropriate map unit, in multiples of the standard deviation. Negative dispersion about the mean (i.e., counting rates that are less than the mean) is indicated by dots below primary flight lines and to the right of tie lines. The numbers along the flight lines are record numbers; the locations of every fiftieth averaged record is shown with an open circle along the flight lines.

A few examples, based on the map supplement and radium data in Table 2, are given to clarify the variable-threshold approach to delineating radium anomalies. A cluster of bismuth-214 anomalies occurs surrounding the intersection of ML 23 and TL 8 on the map. The number of dots above ML 23 in this vicinity indicates radium contents at least two standard deviations, and sometimes more than three standard deviations above the mean for the local map unit, Kg. The distribution of radium contents within Kg (the Boulder granitic batholith of Cretaceous age) has a mean of 0.73 and a standard deviation of 0.34 pCi g^{-1} , as seen in Table 2. Therefore, radium contents of at least 1.4 pCi g^{-1} , and occasionally exceeding 1.8 pCi g^{-1} are deduced for this vicinity. An association of scattered radium anomalies occurs in the lower left corner of the map, primarily along ML 2, ML 3, and ML 4, to the left of TL 3. Several anomalies occur along ML 2, to the right of its intersection with TL 1, between records 14480 and 14550. The corresponding map unit, Tcv (Tertiary Challis Volcanics), has a mean radium content of 1.04 pCi g^{-1} and a standard deviation of 0.43 pCi g^{-1} , according to Table 2. We would therefore expect radium contents between 1.5 and 1.9 pCi g^{-1} in this vicinity. A final example is located on ML3, between its intersections with TL6 and TL7, and between records 3500 and 3600.

The distribution of radium within the corresponding map unit, Qal (Quaternary alluvium), is characterized by a mean of 0.67 and a standard deviation of 0.28 pCi g⁻¹. Since the strength of the anomaly exceeds 3 standard deviations above the mean, as seen in the map, radium contents exceeding 1.5 pCi g⁻¹ are indicated for this vicinity.

To reiterate, the variable-threshold approach to delineating areas containing anomalous levels of radium leads to the following expectations for the cases in point: concentrations exceeding 1.8 pCi g⁻¹ where ML 23 and TL 8 intersect; concentrations between 1.5 and 1.9 pCi g⁻¹ on ML 2, between records 14480 and 14550; and concentrations exceeding 1.5 pCi g⁻¹ on ML 3, between records 3560 and 3600.

Figure 8 displays the radium activities along the primary flight lines within the Dillon quadrangle. This figure is a composite of the net bismuth-214 counting rates, as traced from radiometric "stacked profiles" contained in Geodata International, Inc., (1979). The accuracy of this figure is limited by parallax due to enlarging from microfiche. However, the accuracy is adequate for comparative purposes. Figure 8 indicates the following radium concentrations for the vicinities previously discussed: 2.0-2.5 pCi g⁻¹ on ML 23; 1.5-2.5 pCi g⁻¹ on ML 2 (excluding the largest peak in this vicinity, since that data was acquired at an unacceptable altitude); and 7 pCi g⁻¹ on ML 3.

Clearly, more specific assessments of local variations in radium contents can be more quickly ascertained when absolute values are presented, as in Figure 8. Though a specification (Bendix Field Engineering Corp., 1979) for the NARR Program, dated 2/1/79, indicates that "printer plot contour maps" of the six radiometric variables are one of the required formats for graphic presentation of data, these contour maps were unfortunately not included in roughly half of the ninety-two reports surveyed during this work. However, examination of the radium data for the Vancouver, Spokane, Butte, and Dillon quadrangles indicated that local sites that exhibited significantly elevated radium concentrations relative to their surroundings were generally distinguished as anomalous by the variable-threshold technique. An important class of exceptions to this generalization includes map units that contain substantially elevated mean radium concentrations. This type of map unit frequently occurs within quadrangles characterized by relatively high regional radium contents. Another class of map units that may be overlooked by the variable-threshold technique for defining anomalous areas comprises those with slightly elevated mean radium contents and high standard deviations. Therefore, when locating areas within a quadrangle that have high potential for elevated radon source strengths, it is important to use the table of radium data for the quadrangle in addition to the uranium anomaly map. The spatial distribution of all map units containing mean radium contents exceeding some threshold (for example, a multiple of either the average crustal abundance of radium, or the regional average radium content) can be discerned from the geologic map of the quadrangle. Subsequent work can then be focussed on these general areas and the specific locations indicated by the uranium anomaly map.

7. Field Study of Two Aerial Bismuth-214 Anomalies

The objective of the field study was to investigate the degree of correlation between aerial measurements of the radium contents of soils and ground-based field measurements and laboratory measurements of the radon source strengths of soils. It was prompted by recognition of two facts: 1) other soil and environmental characteristics, in addition to radium content, influence radon source strengths of soils; 2) random sources of error are inherent to aerial gamma spectrometric measurements of environmental levels of radium. A more ambitious study was planned than was completed, due to early winter storms.

The following criteria were used to choose a study area: proximity to a population center; mild to moderate winters; local occurrence of several rock types that exhibited significantly different mean radium contents; and the occurrence of a five-fold range of aerial bismuth-214 counting rates along segments of flight lines traversing each of several local rock types. The Spokane quadrangle was selected. It is located in parts of Washington, Idaho, and Montana between latitudes 47° and 48° N and longitudes 116° and 118° W. Extensive outcrops of granites, basalts, metamorphic rocks, and alluvial deposits occur near the city of Spokane.

Fifty-two occurrences of uranium mineralization have been reported in the Spokane quadrangle (LKB Resources, Inc., 1978; Fleshman, 1982). Most of them occur either in the area of Mt. Spokane, located less than 30 miles roughly NNE of Spokane, or within an area in Idaho and western Montana that extends eastward from Coeur d'Alene Lake to the Coeur d'Alene mining district (Fleshman, 1982).

Two short segments of flight lines that traversed granitic outcrops were investigated. The smoothed aerial net bismuth-214 counting rates exhibited threefold and eightfold increases above local background counting rates along the two segments investigated. The segment exhibiting a threefold increase was a portion of flight line 77 (LKB Resources, Inc., 1978), whose length was one mile, located near Deer Park in Spokane County, Washington (more precisely within township 28N, range 42E, section 29). The other segment was a portion of flight line 73 (LKB Resources, Inc., 1978) located near Mt. Spokane State Park in Spokane County, Washington (township 28N, range 44E, section 1).

When possible the following in situ measurements were performed: total gamma counting rate; radium-226 concentration; radon-222 flux from the soil surface. Soil and rock samples were collected for analysis of emanating and total radium-226 concentrations.

A portable gamma scintillometer that combines a multirange linear ratemeter with a 7.6 cm x 7.6 cm cylindrical NaI(Tl) detector was used for initial radio-metric reconnaissance and for measurements of the total gamma counting rates at a height of 0.6 m above the ground surface. The scintillometer was built at Lawrence Berkeley Laboratory; its use in field studies of environmental radio-activity is described in Wollenberg and Smith (1964). The counting rates detected by this instrument were converted to units of gamma exposure rate.

A portable four-channel gamma ray spectrometer, manufactured by Geometrics, that utilizes a 7.6 cm x 7.6 cm cylindrical NaI(Tl) detector was used to measure the radium content of near-surface geologic materials. The detector was deployed on a tripod 1.5 m above the ground while gamma spectra were acquired. The gamma spectrometer, which is able to measure the quantities of specific radionuclides contributing to the gamma radiation field, has a much slower response-time than the portable gamma scintillometer. Therefore, the gamma scintillometer was used to quickly locate sites along the traverse where the intensity of the gamma field changed, while the gamma spectrometer was used to measure radium concentrations along the traverse. The portable gamma spectrometer was calibrated at the Walker Field facility in Grand Junction.

The technique used to measure the flux of radon-222 from the ground is based upon the collection of exhaling radon-222 on activated charcoal. This technique combines elements of two documented techniques for measuring the flux of radon: the "accumulation technique" (Wilkening, 1977) and the "charcoal canister technique" (Countess, 1976). A canister containing 35-45 grams of activated charcoal is placed near the middle of the volume of an inverted can whose edge is pressed into the soil. Radon entering the can from the soil is adsorbed by the activated charcoal. The duration of deployments of these assemblies has typically been 1-3 days. Upon completing the exposure, the charcoal canister is put into a metal box, which is then sealed with mylar tape to prevent the loss of radon. The flux of radon (or its exhalation rate) from the soil surface is computed from the counting rate, as determined by gamma spectrometry at LBL, arising from radon progeny on the charcoal, after adjusting for radioactive decay and varying lengths of deployment. Since recent experimental evidence suggests a time-dependence for flux measurement techniques involving the accumulation of radon exhaling from a source within a closed volume (Rogers and Associates, Inc., 1981), these computations of flux are considered to be estimates. However, since this technique was used to measure radon flux concurrently at a series of sites, and deployments were of uniform duration, the relative fluxes indicated for the sites should be valid. A relative measure of the flux of radon from the soil was considered adequate for the comparative purpose of this field study.

All measurements of radon and radium that were performed at Lawrence Berkeley Laboratory were made in the Low Background Facility, which is described in Wollenberg and Smith (1966). The measurement system incorporates a large (20 cm diameter by 10 cm thick) cylindrical NaI(Tl) scintillation detector, linear amplification and signal-conversion components, and a 1600-channel pulse-height analyzer. A digital gain stabilizer is also included to prevent spectral shifts that may arise due to variations in the response of the photomultiplier tube. Gamma events of energies from 0.1 to 4.1 MeV are linearly assigned and stored in a block of 400 channels. This facility was used for determining the emanating and total radium-226 concentrations in soil samples, and the radon-progeny activities adsorbed by the canisters of charcoal during radon flux measurements.

The spectral regions of interest depend on the measurement being performed. When the activity of radon progeny on a charcoal canister is being determined, the net counting rate within the spectral interval representing gamma rays of energies from 0.2 to 2 MeV is used to compute the number of pCi of radon on the charcoal. This energy interval includes several prominent gamma emissions from

lead-214 (0.242, 0.295, and 0.352 MeV) and bismuth-214 (0.609, 0.768, 1.238, 1.378, 1.764 MeV). When the activity of radium in a soil or rock sample is being determined, the net counting rates in the 1.46 MeV photopeak from potassium-40, the 1.76 MeV photopeak from bismuth-214, and the 2.62 MeV photopeak from thallium-208 are used to compute the activity of radium in the sample, analogous to the aerial gamma spectrometric measurements acquired during the NARR.

The protocol we have used for measuring emanating and total radium activities of geologic materials includes two distinct measurements. The sample is first spread into a thin layer and aerated long enough to allow emanating radon atoms to diffuse from pore spaces, then packed and immediately counted; the resultant radium-226 concentration represents the radium atoms that generate fixed, or nonmigratory, radon atoms. The measurement of emanating radium-226, i.e. the concentration that produces migratory radon, is based on adsorption of mobile radon-222 by a canister containing activated charcoal. The sample is aerated as described above, then put in a tight 2.2 liter can. A charcoal canister is placed in the center of the volume of air above the sample on a tripod, the lid of the can is emplaced, and the exterior joint is sealed with mylar tape. The duration of the exposure is typically several days so that acceptable counting statistics are achieved. Upon ending the exposure, the charcoal canister is sealed in a metal box. The activity of radon progeny on the charcoal is determined by gamma spectrometry after a delay of one day, which allows potentially-interfering thoron progeny to decay, and equilibrium between radon-222 and its short-lived progeny to be achieved. The net counting rate within the energy interval between 0.2 and 2.0 MeV, corrected for decay, and accounting for the duration of exposure, can then be used to compute either an equilibrium radon-emanation rate, or the equilibrium concentration of emanating radium-226 for the sample. The total concentration of radium-226 in the sample is the sum of the concentrations of radium-226 that produce fixed and migratory radon atoms.

Calibration standards used at the Low Background Facility are secondary standards derived from primary standards distributed by the New Brunswick Laboratory of the U.S. Department of Energy. The primary standards are either U or Th ores mixed in dunite. The standard for K is chemically pure KCl. The shape, volume, and density of the secondary standards used approximate these characteristics for the samples as closely as possible.

Figure 9 shows the smoothed aerial determinations of radium concentrations along the segment of flight line 77 that we studied. Each aerial data point shown represents the average of five measurements. The positions of our measurement and sampling sites are shown at the bottom of the figure. The results of laboratory measurements of the concentrations of emanating and total radium-226 in the soil samples that we collected are also shown in Figure 9. The sharpness of the profiles of our measurements relative to the profile of the aerial measurements probably reflects the extreme differences in detector-source geometry (and thereby the volume of sample from which radiation is measured) of the two measurement techniques. Aerial detectors respond to radiation produced within a cylindrical volume of soil that has a large diameter (tens to hundreds of meters) and small height (0.5 m). This geometry has a homogenizing effect when the radium concentrations in the soil vary locally. We therefore believe

the comparison between the shapes of the profiles is reasonably good. It is also expected that measurements of radium concentrations in the laboratory should be somewhat higher than field measurements since the sample preparation in the lab contains the emanating radon-222, while these atoms are mobile in the field. The moisture content of in situ soils can also produce underestimates of radium concentrations relative to laboratory measurements of drier samples.

Figure 10 shows the results of our in situ measurements along the same flight-line segment. During in situ measurements, the gamma-detector responds to radiation produced by a volume of soil that is intermediate between laboratory and aerial detectors. The aerial measurement technique therefore produces spatially-homogenized radium contents relative to our ground-based field measurements. This is reflected when the shapes and magnitudes of these two profiles are compared. The shape of the gamma exposure rate profile compares favorably with the profile for aerial measurements of radium contents. The results of measurements of the flux of radon from the soil during two distinct time periods are shown. The profile exhibiting higher values of flux was acquired during the period of decreasing barometric pressure, while the flux measurements represented by the second profile were acquired during a period of constant barometric pressure. The shape of the former flux profile conforms reasonably well with the shape of the profile of aerial radium measurements. The shape of the latter profile of radon-222 fluxes, however, does not reflect the aerial determinations of radium nearly as well. The complete lack of correspondence observed at sampling site 6 was subsequently found to be due to the presence of a large boulder at a depth of five or six inches below the surface of the soil. The measurement of radon flux at sampling site 6 on the other profile was consequently made at a site located ten feet west of the former sampling site. It may be important to note that seven of the radon flux measurements reported here exceed the upper limit ($1.4 \text{ pCi m}^{-2} \text{ s}^{-1}$) of the range reported in a review of flux measurements (Wilkening, et. al., 1972), suggesting that the actual range of values of radon flux from soil is not yet well characterized, if areas of uranium mining and processing are excluded.

Figure 11 compares our measurements of radium concentrations performed in situ and in the laboratory with the average aerial determinations of radium concentrations along the segment of flight line 73 that we studied. The correlation between our in situ gamma spectrometric determinations of radium contents and the aerial determinations are quite good. The shape of the profiles representing laboratory measurements of total and emanating radium-226 contents also indicates that the soils associated with the peak displayed by the NARR radium data do have radium contents and radon source strengths that are elevated relative to surrounding soils.

This limited study indicates that two locations associated with threefold and eightfold increases in NARR bismuth-214 data do have higher radon source strengths than adjacent areas. This was directly indicated by both the flux of radon from the soil surface and the concentrations of emanating radium-226 from soil samples. The general validity of the relative magnitudes of radium contents as exhibited by aerial measurements of bismuth-214 was substantiated, though the suppression of very local variations in radium contents by aerial measurement techniques was also seen.

8. Summary and Conclusions

A survey of aerial measurements of radium-226 performed within ninety-two quadrangles located in seven western states was conducted. A thorough study of the variation of radium-226 contents within and among four quadrangles served as the basis for devising approaches to assessing local and regional variations of radium contents that minimized front-end costs. Two aerial bismuth-214 anomalies were investigated during a field study.

The field study confirmed that two sites locally characterized by threefold and eightfold increases of radium content during the NARR do have significantly higher radon source strengths and radium contents than adjacent areas.

Regional variability of radium concentrations was primarily assessed by comparisons of regional radium statistics, which were computed for the frequency distributions of radium concentrations measured within each quadrangle. For a basis of comparison, these regional mean radium concentrations were used to compute an area-weighted mean for the whole area included in this survey; a mean of 0.73 pCi g^{-1} and a standard error of the mean of 0.32 pCi g^{-1} resulted. The regional radium concentrations computed for the ninety-two quadrangles ranged from 0.18 to 1.52 pCi g^{-1} , thus displaying eightfold variation. Within quadrangles, deviations from the regional means ranged from 0.07 to 0.88 pCi g^{-1} , and thus display twelvefold variation. Relative dispersion about the regional means, measured by the coefficient of variation, ranged from 0.25 to 0.84 , thus displaying threefold variation. The spatial distribution of regional mean radium concentrations, as seen in Figure 4, suggests that significant regional differences occur. The spatial variation of values of the regional radium standard deviations as seen in Figure 5, lends further support for the existence of regional differences in radium concentrations. The central and western portions of Washington and Oregon, and California north of 39° latitude appear to contain low concentrations of radium. A region including central and southern California appears to contain moderate to high concentrations of radium, relative to the average for the area studied.

The mean radium contents of the geologic map units throughout the entire study area ranged from 0.07 to 3.57 pCi g^{-1} , thus displaying fiftyfold variation. Of course, the variability of individual measurements of radium is expected to be substantially greater than the range exhibited by the map unit averages.

This study indicated that the NARR radium data show significant variations on both local and regional scales. The regional radium data presented in Table 3 and Figures 4 through 7 may be used in a few ways to rank quadrangles by potential radon source strengths. Areas within specific quadrangles that have high potential for elevated radon source strengths may be delineated by means of uranium anomaly maps and the spatial distribution of geologic map units characterized by elevated mean radium concentrations. While the results of our field investigation are encouraging, the degree of correlation that may be expected between the actual radon source strengths of soils and their potential radon source strengths, based on NARR data, is uncertain.

The work begun here applying the NARR Program data to the regional assessment of radon source potential could be usefully extended in several directions. One topic requiring further study is the correspondence between aerial bismuth-214 data and indoor radon concentrations. The work of Kothari and Han (1983) has shown that such a correspondence may exist; further studies should be conducted on a broader scale. One approach is to design a survey for the Western U.S. incorporating data accumulated during the current study of aerial survey results. Such a survey, particularly if it included measurements of radium content in soils along with indoor radon concentrations, could constitute a valuable test of the utility of the aerial data.

A second important research topic is to develop an approach for combining the aerial data on radium contents with a comparable indicator of transport characteristics of soil to generate an index for radon source potential (see, for example, DSMA Atcon Ltd., 1983) that is more comprehensive than the approach reported here. The utility of such an index presupposes readily available data on, for example, the permeability of soils; such data may exist in usable form in soil conservation reports. It also presupposes a clear understanding of transport mechanisms and pathways by which radon enters houses; such an understanding appears to be evolving out of the recent work of many researchers.

There are two shortcomings to the approach taken in this report to analyze the NARR data: 1) the scale of investigation is effectively limited to $1^{\circ} \times 2^{\circ}$ quadrangles; finer resolution is not easily achieved; and 2) population distribution is ignored in evaluating the radon source potential of a region. One approach to overcoming these limitations is to utilize the aerial data, currently available on magnetic tape, to generate a map of radium concentrations in soil for the United States. The finer scale of measurements, on the order of 0.04 km^2 , would offer substantial improvements in resolving the geographic variations in radium concentration. Furthermore, such data could be coupled with demographic information to more readily identify areas in which attention to indoor radon levels should be focussed.

In sum, we consider the following to be persuasive reasons to continue to investigate the utility of the large radiometric data base as an indicator of the geographic variability of radon source potential: the broad distribution of indoor radon concentrations, which indicates that a significant fraction of the population receives exposures comparable to or greater than those permitted occupationally in mines; the relatively high risk of lung cancer estimated to result from exposure to radon progeny, relative to other risks due to exposure to environmental contaminants; the predominance of soil as a source of indoor radon; and the significant local and regional variability of radium contents, based on NARR measurements of bismuth-214, reported here.

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Appendix: Inspecting and Ordering NARR Data

A1. Inspecting NARR Reports

The U.S. Department of Energy has distributed the NARR narrative reports to twenty repositories so that reports may be inspected by the public. The sites are scattered about the contiguous United States. The repositories and their locations, as listed in Mitchell (1981), are provided below.

California

U.S. Geological Survey Library
345 Middlefield Road
Menlo Park, CA 94025

U.S. Department of Energy
Energy Resources Center
1333 Broadway
Oakland, CA 94612

Colorado

Colorado State Library
1362 Lincoln Street, Room 100
Denver, CO 80203

U.S. Geological Survey Library
Federal Center
P.O. Box 25046
Denver, CO 80225

Bendix Technical Library
U.S. Department of Energy
P.O. Box 1569
Grand Junction, CO 81502-1569

Kansas

Kansas Geological Survey
1930 Avenue A, Campus West
University of Kansas
Lawrence, KS 66044

Massachusetts

Massachusetts Institute of Technology
Lindgren Library, 14E-210
Cambridge, MA 02139

Appendix A1 Continued

New Mexico

Government Publications Section
Zimmerman Library
University of New Mexico
Albuquerque, NM 87106

Nevada

Nevada Bureau of Mines and Geology
Mackay School of Mines
University of Nevada
Reno, NV 89507

Oklahoma

Oklahoma Geological Survey
University of Oklahoma
830 Van Vleet Oval, Room 163
Norman, OK 73069

Oregon

Department of Geology and Mineral Industries
1069 State Office Building
Portland, OR 97201

Pennsylvania

U.S. Department of Energy
9 Parkway Center, Suite 221
875 Greentree Road
Pittsburgh, PA 15220

Texas

Bureau of Economic Geology
Geology Building
University of Texas
Austin, TX 78712

Corpus Christi State University
P.O. Box 6010
6300 Ocean Drive
Corpus Christi, TX 78411

Utah

Documents Division, Marriott Library
University of Utah
Salt Lake City, UT 84112

Utah Geological Survey Library
606 Blackhawk Way
Salt Lake City, UT 84108

Appendix A1 Continued

Virginia

U.S. Geological Survey Library
Gifts and Exchange Unit, National Center
12201 Sunrise Valley Drive
Reston, VA 22092

Washington

U.S. Geological Survey Library
U.S. Courthouse, Room 678
920 West Riverside Avenue
Spokane, WA 99201

Wyoming

Natrona County Public Library
Casper, WY 82601

Wyoming Geological Survey
P.O. Box 3008
University Station
Laramie, WY 82071

A2. Purchasing NARR Data

The first step in this process is learning the names of the $1^{\circ} \times 2^{\circ}$ quadrangles that encompass the area of interest. This is most easily accomplished with a map referred to as a "index to topographic maps of the Geological Survey, 1:250,000-scale series." This index map shows the names and latitudinal and longitudinal extents of the four hundred seventy-four $1^{\circ} \times 2^{\circ}$ quadrangles comprising the contiguous U.S., superimposed on a base map of the U.S. that includes state and county, or parish, boundaries. This index map is commonly available for inspection at large public and institutional libraries that contain map reference facilities. A free copy of the map be obtained from the following address:

Branch of Distribution
U.S. Geological Survey
Federal Center
Denver, Colorado 80225

The next step is deciding the preferred format of presentation of the NARR data. Basically, two options exist: the narrative reports, whose contents are summarized in section 4.4, "Treatment of Aerial Data," and which are available on microfiche or on paper; and IBM-compatible magnetic tapes. Each option is available only on a quadrangle-by-quadrangle basis. The costs of these format options per quadrangle vary significantly.

The primary source of information regarding NARR data is:

Bendix Field Engineering Corporation
Technical Library
P.O. Box 1569
Grand Junction, Colorado 81502-1569

This section summarizes our current understanding of data format options; the Bendix library should be contacted for confirmation and current prices.

The narrative reports are available on microfiche from the Bendix Technical Library. These reports are also available on paper from the specific subcontractor who performed the NARR measurements in the quadrangle of interest. The address of the appropriate subcontractor may be obtained through the Bendix Technical Library. Table A1 contains the Bendix report numbers and identifies the subcontractors for the narrative reports used during this study.

Processed radiometric data for each quadrangle may also be purchased on magnetic tape from the Bendix Technical Library. Two types of tapes that are available may be of interest for potential radon source strengths: reduced single-record data tapes, and statistical-analysis data tapes. The former tapes basically provide data summed during one-second sampling intervals, corrected and normalized as described in sections 4.2 through 4.4 of this report. The

latter tapes contain averaged, or smoothed, data and the results of the application of the variable-threshold approach to delineating locations of radiometric anomalies. The statistical-analysis tapes were used to generate the stacked profiles and the standard deviation maps which are included in the narrative reports.

Table A1. Index to NARR Reports¹

<u>Quadrangle</u>	<u>State</u>	<u>Bendix Report Number</u>	<u>Author Code</u> ²
Adel	OR	GJBX-104(80)	GI
Alturas	CA	GJBX-406(81)	WGC
Ashton	WY,ID,MT	GJBX-106(79)	WGC
Baker	ID,OR	GJBX-101(78)	GI-HLH
Bakersfield	CA	GJBX-231(80)	HLH
Bend	OR	GJBX-240(81)	QEB-HLH
Boise	ID,OR	GJBX-10(80)	EGG
Bozeman	MT	GJBX-81(79)	GI-HLH
Brigham City	UT	GJBX-124(79)	GI-HLH
Burns	OR	GJBX-240(81)	QEB-HLH
Butte	MT	GJBX-126(79)	TI
Canyon City	OR	GJBX-240(81)	QEB-HLH
Cape Flattery	WA	GJBX-135(81)	QEB-HLH
Challis	ID	GJBX-156(79)	GI-HLH
Chico	CA	GJBX-4C7(81)	WGC
Cnoteau	MT	GJBX-126(79)	TI
Cody	WY	GJBX-105(79)	WGC
Concrete	WA	GJBX-136(81)	QEB-HLH
Coos Bay	OR	GJBX-408(81)	WGC
Copalis Beach	WA,OR	GJBX-135(81)	QEB-HLH
Crescent	OR	GJBX-240(81)	QEB-HLH
Crescent City	CA	GJBX-409(81)	WGC
Cut Bank	MT	GJBX-126(79)	TI
Death Valley	CA,NV	GJBX-164(79)	GI-HLH
Dillon	MT,ID	GJBX-107(79)	GI-HLH
Driggs	WY,ID	GJBX-93(81)	GI
Dubois	ID,MT	GJBX-155(79)	WGC
El Centro	CA,AZ	GJBX-12(80)	LKB
Elk City	ID,MT	GJBX-10(80)	EGG
Elko	NV,UT	GJBX-159(79)	GI-HLH
Eureka	CA	GJBX-409(81)	WGC
Fresno	CA	GJBX-231(80)	QEB-HLH
Goldfield	CA,NV	GJBX-66(79)	GI-HLH
Grangeville	OR,ID	GJBX-98(81)	GI
Great Falls	MT	GJBX-126(79)	TI
Hailey	ID	GJBX-10(80)	EGG
Hamilton	ID,MT	GJBX-119(79)	GI-HLH
Hoquiam	WA,OR	GJBX-291(81)	QEB-HLH
Idaho Falls	ID	GJBX-10(80)	EGG
Jordan Valley	OR,ID	GJBX-95(80)	GI
Kalispell	MT	GJBX-76(81)	GI
Kingman	CA,NV,AZ	GJBX-59(79)	WGC
Klamath Falls	OR	GJBX-20(80)	GI-HLH
Lander	WY	GJBX-62(80)	GI
Los Angeles	CA	GJBX-214(80)	QEB-HLH
Lovelock	NV	GJBX-125(78)	GI-HLH
Mariposa	CA,NV	GJBX-231(80)	QEB-HLH
McDermitt	NV	GJBX-168(79)	GI-HLH
Medford	OR	GJBX-384(81)	WGC

Table A1. (continued)

<u>Quadrangle</u>	<u>State</u>	<u>Bendix Report Number</u>	<u>Author Code</u> ²
Needles	CA,AZ	GJBX-114(79)	GI-HLH
Ogden	UT,WY	GJBX-71(80)	EGG
Okanogan	WA	GJBX-142(79)	LKB
Pendleton	OR,WA	GJBX-291(81)	QEB-HLH
Pocatello	ID	GJBX-126(79)	TI
Preston	WY,ID	GJBX-74(81)	GI
Pullman	WA,ID	GJBX-117(81)	GI
Redding	CA	GJBX-411(81)	WGC
Ritzville	WA	GJBX-126(79)	TI
Roseburg	OR	GJBX-388(81)	WGC
Sacramento	CA	GJBX-51(81)	QEB-HLH
Salem	OR	GJBX-240(81)	QEB-HLH
Salton Sea	CA,AZ	GJBX-127(80)	LKB
San Bernardino	CA	GJBX-214(80)	QEB-HLH
San Diego	CA	GJBX-214(80)	QEB-HLH
San Francisco	CA	GJBX-50(81)	QEB-HLH
San Jose	CA	GJBX-50(81)	QEB-HLH
San Luis Obispo	CA	GJBX-20(81)	QEB-HLH
Sandpoint	ID,WA,MT	GJBX-142(79)	LKB
Santa Ana	CA	GJBX-214(80)	QEB-HLH
Santa Cruz	CA	GJBX-50(81)	QEB-HLH
Santa Maria	CA	GJBX-20(81)	QEB-HLH
Santa Rosa	CA	GJBX-51(81)	QEB-HLH
Seattle	WA	GJBX-135(81)	QEB-HLH
Shelby	MT	GJBX-126(79)	TI
Spokane	ID,WA,MT	GJBX-121(78)	LKB
Susanville	CA	GJBX-410(81)	WGC
The Dalles	OR,WA	GJBX-291(81)	QEB-HLH
Thermopolis	WY	GJBX-64(80)	GI
Trona	CA	GJBX-65(79)	GI-HLH
Twin Falls	ID	GJBX-126(79)	TI
Ukiah	CA	GJBX-390(81)	WGC
Vancouver	OR,WA	GJBX-291(81)	QEB-HLH
Victoria	WA	GJBX-135(81)	QEB-HLH
Vya	NV	GJBX-136(79)	GI-HLH
Walker Lake	CA,NV	GJBX-126(78)	GI-HLH
Wallace	MT,ID	GJBX-111(81)	GI
Walla Walla	WA	GJBX-291(81)	QEB-HLH
Weed	CA	GJBX-391(81)	WGC
Wells	NV,UT	GJBX-137(79)	GI-HLH
Wenatchee	WA	GJBX-136(81)	QEB-HLH
White Sulphur Springs	MT	GJBX-96(79)	GI-HLH
Winnemucca	NV	GJBX-21(79)	GI-HLH
Yakima	WA	GJBX-291(81)	QEB-HLH

¹ All reports were published by Bendix Field Engineering Corporation, Grand Junction, CO.

² EGG: EG&G Geometrics, Sunnyvale, CA
 GI: Geodata International, Inc., Dallas, TX
 HLH: High Life Helicopters, Inc., Puyallup, WA

Table A1. (continued)

² QEB: QEB, Inc., Lakewood, CO
TI : Texas Instruments, Inc., Airborne Geophysical Service, Dallas, TX
WGC: Western Geophysical Company of America, Aero Service Division,
Houston, TX

A hyphen indicates a joint venture.

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Table 1. Concentrations of uranium, thorium, and radium in the major classes of rocks are shown. While clear distinctions among mean radium-226 contents of the classes of rocks are evident, the wide ranges within classes preclude the use of rock type as an *a priori* indicator for site-specific radium-226 content (adapted from Grasty, et al., 1983, after Killen, 1979).

Class of Rocks	Example	U-238 (ppm) ¹ mean (range)	Th-232 (ppm) ¹ mean (range)	Ra-226 (pCi g ⁻¹) ² mean (range)	Ra-224 (pCi g ⁻¹) ² mean (range)
Acid Extrusives	Rhyolite	4.1 (1-16)	11.9 (1-40)	1.4 (0.3-5.4)	1.3 (0.1-4.4)
Acid Intrusives	Granite	4.5 (0-30)	25.7 (0-250)	1.5 (0-10)	2.8 (0-27)
Basic Extrusives	Basalt	0.8 (0-3)	2.2 (0-9)	0.3 (0-1.0)	0.2 (0-1.0)
Basic Intrusives	Gabbro	0.8 (0-6)	2.3 (0-15)	0.3 (0-2.0)	0.2 (0-1.6)
Ultrabasic	Dunite	0.3 (0-2)	1.4 (0-8)	0.1 (0-0.7)	0.2 (0-0.9)
Carbonates	Limestone	2.0 (0-18)	1.3 (0-11)	0.7 (0-6.0)	0.1 (0-1.2)
Chemical Sedimentary Rocks	Gypsum	3.6 (0-27)	14.9 (1-130)	1.2 (0-9.1)	1.6 (0-14)
Detrital Sedimentary Rocks	Sandstone Shale	4.8 (0-80)	12.4 (0-360)	1.6 (0-27)	1.4 (0-39)
Metamorphosed Igneous Rocks	Orthogneiss	4.0 (0-150)	14.8 (0-105)	1.3 (0-50)	1.6 (0-11)
Metamorphosed Sedimentary Rocks	Schist	3.0 (0-53)	12.0 (0-90)	1.0 (0-18)	1.3 (0-10)
Average in Continental Crust ³		2.7	9.6	0.9	1.0

1 mass concentration in parts per million

2 activity concentration in picocuries of radium per gram of rock

3 from Taylor (1964)

Table 2. A summary of the serial measurements of radium-226, grouped by geologic map unit, within the Dillon quadrangle. The geologic map of this quadrangle, which is included as a map supplement at the rear of the report, shows areas covered by each geologic map unit. A legend describing each map unit and associating the codes used for each in the table and on the map is included as the final page of the report.

RADIUM-226 DATA FOR DILLON TOTAL NO. MAP UNITS = 61						
MAP UNIT	RANK	FRACTION OF QUAD. AREA	Ra MEAN (pCi/g)	Ra S.D. (pCi/g)	COEFF. VAR.	NO. Ra #NOMS
AM	13	0.002	0.57	0.17	0.31	1
AQ	48	0.032	0.86	0.27	0.31	1
D	4	0.000	0.45	0.06	0.13	0
DG	17	0.010	0.60	1.54	2.56	0
E	12	0.011	0.56	0.25	0.44	1
ED	7	0.007	0.51	0.24	0.46	2
GFG	35	0.009	0.77	0.22	0.28	0
HG	11	0.007	0.56	0.27	0.49	1
JK	52	0.005	0.97	0.31	0.32	1
K	42	0.021	0.83	0.24	0.29	2
KD	27	0.002	0.65	0.31	0.48	1
KG	34	0.195	0.73	0.34	0.46	28
KGM	59	0.001	1.20	0.29	0.24	0
KTB	28	0.002	0.65	0.17	0.27	1
KTGO	5	0.000	0.46	0.07	0.16	0
KTOM	60	0.000	1.30	0.17	0.13	0
KY	31	0.009	0.69	0.23	0.33	2
M	10	0.001	0.55	0.25	0.46	1
ML	9	0.013	0.55	0.22	0.40	1
MT	1	0.001	0.40	0.18	0.45	0
MJ	44	0.001	0.84	0.52	0.38	0
PEA	3	0.007	0.45	2.46	5.50	0
PEB	38	0.001	0.78	0.18	0.23	0
PEBM	6	0.004	0.49	0.12	0.26	1
PEC	32	0.017	0.72	0.30	0.41	1
PEGS	15	0.011	0.58	0.23	0.39	1
PEL	41	0.009	0.80	0.34	0.42	0
PEN	16	0.028	0.59	0.19	0.32	4
PENM	18	0.034	0.60	0.20	0.32	4
PENB	55	0.008	1.00	0.63	0.63	0
PEP	2	0.006	0.41	0.43	1.06	0
PEPI	40	0.001	0.79	0.19	0.24	0
PEQ	46	0.013	0.84	0.31	0.37	0
PER	39	0.003	0.79	0.28	0.35	3
PES	20	0.035	0.61	0.42	0.69	1
PESR	57	0.030	1.06	0.18	0.17	0
PEW	8	0.009	0.51	0.15	0.30	1
PP	23	0.001	0.63	0.19	0.31	0
PTR	26	0.013	0.64	0.28	0.44	1
Q	22	0.002	0.61	0.36	0.59	1
QAL	29	0.153	0.67	0.28	0.41	16
QG	25	0.013	0.63	0.27	0.42	2
QGL	24	0.035	0.63	0.48	0.77	0
QL	53	0.002	0.99	0.37	0.37	0
QLS	19	0.000	0.60	0.12	0.20	0
QT	49	0.006	0.95	0.22	0.23	0
QV	47	0.000	0.86	0.14	0.17	0
TB	21	0.004	0.61	0.15	0.24	0
TCB	36	0.002	0.77	0.20	0.25	0
TCM	50	0.012	0.96	0.27	0.29	1
TCV	56	0.012	1.04	0.43	0.41	2
TG	43	0.001	0.84	0.19	0.23	0
TGS	54	0.006	0.99	0.23	0.23	2
TKB	30	0.001	0.53	0.23	0.34	0
TKN	14	0.000	0.57	0.15	0.26	0
TKY	58	0.002	0.06	0.27	0.25	1
TL	45	0.015	0.84	0.24	0.28	0
TMD	51	0.001	0.96	0.47	0.49	0
TR	61	0.005	1.58	0.30	0.19	1
TU	33	0.182	0.72	1.03	1.43	7
TV	37	0.015	0.77	0.34	0.44	2

Table 3. Regional radium-226, data presented by quadrangle. Note that the number of radium anomalies, as listed, was not determined by a standard protocol among the quadrangles.

QUADRANGLE-WIDE RADIUM-226 DATA							
STATE	QUADRANGLE	Ra MEAN (pCi/g)	Ra S.D. (pCi/g)	COEFF. VAR.	RANGE OF MAP UNIT Ra MEANS	NO. Ra ANOMS	FLT. LN. SPACING (miles)
OR	ADEL	0.74	0.35	0.48	0.14 - 1.28	159	3
CA	ALTURAS	0.25	0.19	0.76	0.12 - 1.25	17	6
WY	ASHTON	0.81	0.41	0.51	0.18 - 1.39	178	3
CA	BAKERSFIELD	1.07	0.37	0.35	0.64 - 1.71	33	3
IO	BAKER	0.51	0.23	0.45	0.17 - 0.91	16	3
OR	BEND	0.29	0.14	0.48	0.18 - 0.76	15	6
IO	BOISE	0.85	0.55	0.65	0.55 - 1.04	183	3
MT	BOZEMAN	0.69	0.26	0.38	0.27 - 1.11	132	3
UT	BRIGHTON CITY	0.87	0.56	0.65	0.37 - 1.76	90	3
OR	BURNS	0.46	0.22	0.49	0.22 - 0.68	9	6
MT	BUTTE	0.77	0.35	0.46	0.27 - 2.49	106	3
OR	CANYON CITY	0.30	0.15	0.51	0.21 - 0.62	18	6
WA	CAPE FLATTERY	0.21	0.07	0.34	0.17 - 0.31	0	6
IO	CHALLIS	0.80	0.45	0.57	0.27 - 1.80	187	2.5
CA	CHICO	0.35	0.24	0.69	0.10 - 1.33	9	3
MT	CHOTEAU	0.62	0.25	0.40	0.28 - 0.96	52	6
WY	COOY	0.75	0.37	0.49	0.23 - 1.34	132	3
WA	CONCRETE	0.45	0.32	0.72	0.17 - 0.93	27	6
OR	COOS BAY	0.27	0.15	0.57	0.10 - 0.60	61	6
WA	COPALIS BEACH	0.22	0.08	0.36	0.15 - 0.29	0	6
OR	CRESCENT	0.34	0.15	0.44	0.21 - 0.49	24	6
MT	CUT BANK	0.94	0.34	0.37	0.34 - 1.82	56	6
CA	DEATH VALLEY	0.87	0.68	0.78	0.26 - 1.82	164	1
MT	DILLON	0.71	0.60	0.84	0.40 - 1.58	95	3
ID	DRIGGS	0.76	0.29	0.38	0.37 - 1.11	187	3
ID	DUBOIS	0.60	0.27	0.45	0.15 - 1.00	149	3
CA	EL CENTRO	0.84	0.32	0.38	0.51 - 2.06	485	3
IO	ELK CITY	0.57	0.37	0.65	0.22 - 1.71	269	3
WY	ELKO	0.75	0.27	0.36	0.34 - 1.01	331	3
CA	EUREKA	0.32	0.17	0.54	0.11 - 0.44	20	6
CA	FRESNO	1.12	0.44	0.39	0.62 - 2.25	49	3
CA	GOLDFIELD	1.39	0.40	0.29	0.43 - 2.29	196	3
OR	GRANGEVILLE	0.39	0.15	0.38	0.20 - 0.64	33	6
MT	GREAT FALLS	1.33	0.39	0.29	0.60 - 3.10	115	3
ID	HATLEY	0.79	0.39	0.50	0.40 - 1.38	180	3
IO	HAMILTON	0.73	0.46	0.63	0.34 - 1.55	89	4.5
WA	HOQUIAM	0.28	0.11	0.40	0.17 - 0.44	9	6
IO	IDAH0 FALLS	0.84	0.50	0.66	0.29 - 2.44	187	3
OR	JORDAN VALLEY	1.01	0.46	0.45	0.40 - 1.88	118	3
MT	KALISPELL	0.71	0.19	0.27	0.30 - 1.11	48	6
CA	KINGMAN	1.10	0.49	0.44	0.14 - 1.84	159	3
OR	KLAMATH FALLS	0.36	0.20	0.55	0.25 - 0.68	125	3
WY	LANDER	0.82	0.32	0.38	0.10 - 1.35	130	3
CA	LOS ANGELES	1.00	0.41	0.41	0.40 - 1.57	43	3
WY	LOVELOCK	0.86	0.33	0.38	0.32 - 1.63	78	3
CA	MARIPOSA	1.33	0.47	0.35	0.69 - 2.15	24	3
WY	MCDERMITT	0.90	0.29	0.32	0.57 - 1.05	326	3
OR	MEDFORD	0.18	0.14	0.74	0.07 - 0.40	2	3
CA	NEEDLES	1.11	0.47	0.42	0.68 - 1.52	143	3
UT	OGDEN	0.75	0.29	0.38	0.41 - 1.06	291	3
WA	OKANOGAN	0.60	0.28	0.48	0.30 - 1.03	476	2
OR	PENDLETON	0.51	0.21	0.42	0.26 - 0.77	28	6
ID	POCATELLO	0.95	0.38	0.39	0.32 - 1.80	144	3
WY	PRESTON	0.72	0.34	0.48	0.27 - 3.57	86	3
WA	PULLMAN	0.66	0.23	0.35	0.34 - 0.84	51	6

Table 3. (continued)

QUADRANGLE-WIDE RADIUM-226 DATA							
STATE	QUADRANGLE	Ra MEAN (pCi/g)	Ra S.D. (pCi/g)	COEFF. VAR.	RANGE OF MAP UNIT Ra MEANS	NO. Ra ANOMS	FLT. LN. SPACING (miles)
CA	REDDING	0.34	0.19	0.57	0.09 - 0.52	13	6
WA	RITZVILLE	1.00	0.30	0.30	0.68 - 3.43	100	3
OR	ROSEBURG	0.23	0.16	0.68	0.08 - 0.38	43	6
CA	SACRAMENTO	0.76	0.36	0.47	0.31 - 1.55	17	3
OR	SALEM	0.33	0.16	0.48	0.22 - 0.57	5	6
CA	SALTON SEA	1.04	0.39	0.38	0.65 - 2.06	485	3
CA	SAN BERNARDINO	1.07	0.31	0.29	0.71 - 1.73	43	3
CA	SAN DIEGO	0.73	0.28	0.38	0.45 - 1.19	14	3
CA	SAN FRANCISCO	0.86	0.41	0.48	0.52 - 1.50	16	3
CA	SAN JOSE	1.52	0.88	0.58	0.37 - 2.63	24	3
CA	SAN LUIS OBISPO	1.03	0.40	0.39	0.50 - 1.31	55	3
ID	SANDPOINT	0.71	0.36	0.51	0.30 - 2.02	607	1.5
CA	SANTA ANA	0.82	0.29	0.35	0.48 - 1.13	24	3
CA	SANTA CRUZ	1.30	0.75	0.58	0.59 - 2.87	59	3
CA	SANTA MARIA	1.00	0.38	0.38	0.56 - 1.25	22	3
CA	SANTA ROSA	0.64	0.29	0.46	0.27 - 1.18	11	3
WA	SEATTLE	0.28	0.15	0.54	0.15 - 0.41	2	6
MT	SHELBY	0.93	0.24	0.25	0.58 - 1.24	99	4.5
IO	SPOKANE	0.72	0.35	0.49	0.41 - 1.09	65	2.5
CA	SUSANVILLE	0.32	0.25	0.78	0.10 - 1.50	5	6
OR	THE DALLES	0.49	0.26	0.53	0.14 - 0.95	6	6
WY	THERMOPOLIS	0.70	0.41	0.58	0.34 - 3.03	122	3
CA	TRONA	1.07	0.35	0.33	0.72 - 2.14	99	3
ID	TWIN FALLS	1.36	0.41	0.30	0.67 - 2.57	114	3
CA	UKIAH	0.42	0.19	0.44	0.10 - 0.53	35	6
OR	VANCOUVER	0.33	0.17	0.50	0.18 - 0.58	15	6
WA	VICTORIA	0.25	0.09	0.36	0.17 - 0.30	1	6
NV	VYA	0.88	0.39	0.44	0.45 - 1.24	118	3
CA	WALKER LAKE	1.34	0.45	0.34	0.66 - 2.31	62	3
MT	WALLACE	0.74	0.21	0.28	0.34 - 0.84	128	3
WA	WALLA WALLA	0.65	0.17	0.26	0.49 - 0.70	23	6
CA	WEED	0.25	0.17	0.68	0.09 - 0.54	10	6
NV	WELLS	0.88	0.32	0.37	0.41 - 0.99	129	3
WA	WENATCHEE	0.36	0.19	0.53	0.12 - 0.69	3	6
MT	WHITE SULPHUR SPRINGS	0.68	0.24	0.35	0.39 - 0.96	124	3
NV	WINNEMUCCA	0.84	0.40	0.47	0.21 - 1.80	41	3
WA	YAKIMA	0.33	0.14	0.44	0.16 - 0.70	8	5

XBL 842-9619

Figure 1. Decay chain of uranium-238 showing chemical species, atomic number, atomic weight, half life and mode of radioactive decay. The dashed box encloses the radium subchain which is of principal concern for public exposure to natural radiation.

Figure 2. Histograms of near-surface radium content within four quadrangles. The plots are based on statistical summary data; specifically, the mean radium content of each map unit, and the ratio of the number of measurements above each unit to the total within the quadrangle were used.

Legend:

Dot N or E of line implies statistically significant eU/eTh anomaly.

Dot on line implies statistically significant eU anomaly.

Dot S or W on line implies statistically significant eU/K anomaly.

Light outline implies first-priority anomaly with eU, eU/eTh, and eU/K simultaneously anomalous.

Heavy outline implies possible uranium prospect.

Figure 3. Preferred anomaly map for the Butte, Montana quadrangle. This quadrangle is bounded by the coordinates 46 and 47 N latitude and 112 and 114 W longitude. The city of Butte is located near the cluster of anomalies along the southernmost flight line.

Figure 4. Mean near-surface radium-226 concentration by quadrangle for California and the Pacific Northwest. Note that each of the intervals denoted by stripes has a lower radium-226 content than any of the intervals denoted by dots. The average radium-226 content is 0.73 pCi g^{-1} for the entire region.

Figure 5. Standard deviation of the distribution of radium-226 concentrations for each quadrangle in the study area.

XBL 841-9469A

Figure 6. Percent of the area of each quadrangle in which map units whose mean radium-226 concentrations exceed 1.0 pCi g⁻¹ outcrop.

Figure 7. Percent of the area of each quadrangle in which map units whose mean radium-226 concentrations exceed 1.4 pCi g⁻¹ outcrop.

Figure 8. Near-surface radium concentrations as measured by the aerial survey of the Dillon quadrangle, Montana. Dashed segments indicate magnitudes that exceed the distance between flight lines. The intersection of flight lines ML 23 and TL 7 is located within Butte, Montana (after High Life Helicopters and Geodata, International, 1979).

XBL 342 9600

Figure 9. Comparison of aerial data with laboratory measurements of radium-226 and emanating radium-226 for samples collected along the flight line. The area studied is located near Spokane, Washington.

XBL 842-9601

Figure 10. Comparison of aerial data with in situ measurements of radium-226 activity, radon flux from the soil surface, and total gamma exposure rate for the same segment of the flight line as shown in Figure 9. The two profiles of radon flux represent two series of measurements performed two months apart.

XL 842 9599

Figure 11. Comparison of aerial data with laboratory and in situ measurements of radium-226 in soil and with laboratory measurements of emanating radium-226 from soil samples. The area studied is located near Spokane, Washington.

Legend for Geologic Map Supplement^{1,2}

Quaternary Period

Sedimentary rocks

Qal (QAL)	Alluvium
Qg (QG,QGL)	Glacial deposits
Qls (QLS)	Landslides
Qt (QT)	Terrance gravel deposits

Igneous rocks

Qv (QV)	Volcanics
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Tertiary Period

Sedimentary rocks

Tcm (TCM)	Coarse-grained valley fill of the Carmen Formation
Tkt	Coarse-grained valley fill of the Kirtley Formation
Tgs (TGS)	Fine-grained valley fill of the Geertson Formation
Tkn, Tky (TKN, TKY)	Fine-grained valley fill of the Kenny Formation
Tl (TL)	Fine-grained valley fill in Montana
Tu (TU)	Undifferentiated valley fill

Igneous rocks

Tg (TG)	Granite
Tmd (TMD)	Dacite and latite dikes
Tb (TB)	Basalt in Montana
Tc, Tcv (TCV)	Challis volcanics, in Montana and Idaho, respectively
Tcb (TCB)	Basaltic Challis volcanics in Idaho
Tv (TV)	Lowland creek volcanics in Montana
Tsd	Syenodioritic dikes

Cretaceous-Tertiary Boundary

Sedimentary rocks

Tkb (TKB)	Conglomerates of the Beaverhead Formation
TKr	Conglomerates of the Kriley Formation

Igneous rocks

KTqm (KTQM)	Quartz monzonite
KTgd (KTGD)	Granodiorite of the Idaho and Boulder Batholiths

Legend (continued)

Cretaceous Period

Sedimentary rocks

K (K)	Shales, sandstone, and limestones of the Colorado Group and the Kootenai Formation
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Igneous rocks

Kgm (KGM)	Quartz monzonite
Kg (KG)	Granodiorite of the Idaho and Boulder Batholiths
Kib (KIB)	Border zone of the Idaho Batholith
Kd (KD)	Dioritic intrusives
Kv (KV)	Elkhorn Mountain volcanics

Jurassic-Cretaceous Boundary

Sedimentary rocks

JK (JK)	Undifferentiated, includes Colorado, Morrison, and Ellis Groups, and the Kootenai Formation
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Jurassic Period

Sedimentary rocks

J (J)	Shales and sandstones of the Morrison and Ellis Groups
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Igneous rocks

Jmg	Metagabbro dikes
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Triassic Period

Sedimentary rocks

Tr (TR)	Undifferentiated
---------	------------------

Permian-Triassic Boundary

Sedimentary rocks

PTr (PTR)	Limestone, shale, phosphorite, chert, and quartzite of the Amsden, Quadrant, Phosphoria and Dinwoody Formations, undivided
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Legend (continued)

Permian-Pennsylvanian Boundary

Sedimentary rocks

Pp (PP) Undifferentiated

Mississippian Period

Sedimentary rocks

M (M) Limestone of the Lodgepole and Mission Canyon Formations

Devonian Period

Sedimentary rocks

D (D) Dolomites and shales of the Jefferson and Three Forks Formations

Cambrian-Devonian

Sedimentary rocks

GD (ED) Undifferentiated

Cambrian Period

Sedimentary rocks

GD (E) Sandstone, dolomite, and shale of the Flathead, Wolsey, Meagher, Parks, Pilgrim, Red Lion, and Hasmark Formations, undivided

Precambrian Epoch

Sedimentary and Metasedimentary rocks of the Belt Super Group:

Aq	(AQ)	} Quartzites of the Idaho Group
PEq	(PEQ)	
PES	(PES)	
PESr	(PESR)	

Legend (continued)

P6m (PEM)	}	Quartzites, siltites, and argillites of the Missoula Group
P6mu (PEMU)		
P6bm (PEBM)		

P6nb (PENB)	Coarse-grained sandstone and conglomerate of the North Boulder Group
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P6p (PEP)	}	Carbonates, quartzites, and siltites of the Middle and Lower Belt Series, which includes:	Pritchard Formation
P6pi (PEPI)			Piegan Group
p6r (PER)			Revalli Group
p6w (PEW)			Wallace and Helena Fms.
p6a (PEA)			Newland Formation

Igneous rocks

P6g	Granite
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Metamorphic rocks

P6gs (PEGS)	Pony and Cherry Creek Groups, undivided
P6p (PEP)	Pony Group
Dg (DG)	Dillon Granite Gneiss
MI (MI)	Migmatite
P6C (PEC)	Cherry Creek Group, undivided, which includes:
qg (QG,QG1)	quartzofeldspathic gneiss
qg	anthrophyllitic garnet gneiss
p	peridotite
am (AM)	amphibolite
hg (HG)	hornblende gneiss
m (MI)	marble
P6A (PEA)	gneiss, Pre-Cherry Creek Group
gfg (GFG)	Basement complex

¹The codes on the left correspond to those on the map supplement. Those in parentheses correspond to those used in Table 2.

²after Fugro, Inc. (1978)

Map Supplement. Dillon quadrangle, Montana and Idaho: the bismuth-214 standard deviation map is superimposed on the geologic map. The legend describing the geologic map units is provided on the final pages of this report. The standard deviation map is a representation of local bismuth-214 activities, relative to the mean bismuth-214 activity of the corresponding map unit throughout the quadrangle. Local positive deviations from the mean, in terms of multiples of the standard deviation, are indicated by dots above flight lines labelled ML and the the left of flight lines labelled TL (from High Life Helicopters and Geodata International, Inc., 1979).

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Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TL 3

TL 3

114°00'

MIL 10

TL 4

TL 5
113°00'

TL 6

TL 7

TL 8

TL 9

112°00'
46°00'

110°	105°	
WY	HAVRE	GLASSBORO
FALLS	LEWISTOWN	JORDAN
PULPHUR	ROUNDUP	FORSYTH
MAN	BILLINGS	HARDIN
ON	CODY	SHERIDAN

5 0 5 10 15 Miles

Scale 1 : 250,000