UNITED STATES DEPARTMENT OF THE
INTERIOR GEOLOGICAL SURVEY


SOIL GAS RADON COMPARED TO AERIAL AND GROUND
GAMMA-RAY MEASUREMENTS AT STUDY SITES
NEAR GREELEY AND FORT COLLINS, COLORADO


by

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## INTRODUCTION

In 1985, a house located within the Pensylvania part of the geological province known as the Reading Prong of Pennsylvania and New Jersey was discovered to have indoor radon concentrations exceeding 2000 picoCuries per liter (pCi/L) and other houses with elevated indoor radon concentrations were identified in the same neighborhood (Gaertner, 1987). The state of Pennsylvania initiated a large program to determine the radon levels in homes within and near the Pennsylvania part of the Reading Prong (Gerusky, 1987). The results of this program showed that more than fifty percent of the houses measured had indoor radon levels exceeding the 4.0 pCi/L guideline set by the U.S. Environmental Protection Agency. Because the geological environment of the Reading Prong province is not unique, potentially hazardous levels of radon are expected to occur across the United States.

Because radon is part of the $^{238}U$ (U-238) decay series, the activity of which can be measured by aerial and ground gamma-ray surveys, the nationwide data obtained as part of the National Uranium Resource Evaluation (NURE) Program sponsored by the U.S. Department of Energy may provide a means of rapidly assessing the potential for radon in soil gas on a regional scale. Radon is the isotope $^{222}Rn$ (Rn-222) which is the immediate daughter of $^{226}Ra$ (Ra-226) which is a relatively long-lived (half-life = 1602 years) member of the uranium decay series. Figure 1 shows the part of the U-238 decay series that begins with Ra-226. Rn-222 decays via several short-lived radionuclides to produce $^{214}Bi$ (Bi-214). The decay of Bi-214 produces several gamma rays which have intensities that can be readily detected by modern gamma-ray detectors. The intensity of the 1.76 million-electron-volt (MeV) gamma ray of Bi-214 is measured to determine the concentration of the parent nuclei in the soil. Because gamma-ray data have most often been collected in connection with uranium exploration, the data are normally presented as equivalent parts per million of uranium (ppm eU). The term equivalent is used because the calibration procedures assume that the entire uranium decay series is in secular equilibrium.

Because Bi-214 is separated from Rn-222 by short-lived isotopes, the gamma-ray measurements provide an estimate of the radon in the near surface rock and soil. The concentrations of radon in soil gas, however, depend upon the radon emanation power of the rock or soil, soil moisture, and permeability. The radon emanation power is defined as the fraction of the total radon that escapes into soil and rock pores. The emanation power depends upon
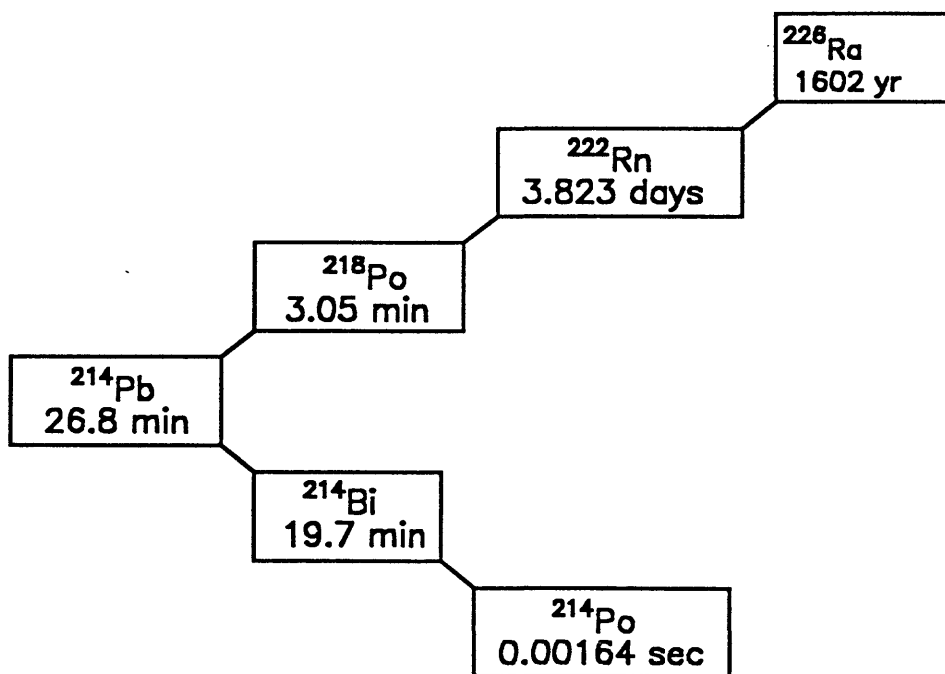
Figure 1. Part of the $^{238}$U decay series beginning with $^{226}$Ra.

the location of the Ra-226 within the earth materials (Tanner, 1964). The presence of soil moisture can increase the amount of radon in the soil gas (Kirikov,Bogoslovskaya, and Gorshkov, 1932; Hahn, 1936; Starik and Melikova, 1957), but as the soil moisture increases the effective emanation power approaches zero because the water fills the pore spaces and inhibits the movement of radon in the pore spaces. Permeability controls radon migration and determines whether radon moves by diffusion or convection.

Nazaroff, Moed and others (1986) present theoretical equations and calculations that show that radon transport by diffusion is dominant for materials with intrinsic permeability coefficients of $k = 10^{-9}$ $cm^2$ or less and that convection is the dominant process for values of $k = 10^{-5}$ $cm^2$ or greater. The transport equation suggests that convection and diffusion are about equally important for an intrinsic permeability of $k = 2.3 \times 10^{-7}$ $cm^2$. For typical dry materials the radon diffusion length is on the order of 1 m and for water-saturated materials the diffusion length is 1 cm or less. This suggests that materials with permeabilities less than $k = 10^{-6}$ $cm^2$ will supply radon for distances of 1 m or less. For materials with permeabilities greater than $k = 10^{-4}$ $cm^2$, the transport distances can be 5 m or more (Nazaroff, Lewis, and others, 1986).

The purpose of the work being reported here is to investigate the validity of the NURE aerial gamma-ray data with regard to the estimated concentrations of uranium in the rocks and soils. This research also seeks to assess the use of surface gamma-ray measurements to estimate the relative amounts of radon in soil gas.


NURE AERIAL SURVEYS

The NURE Program sponsored aerial gamma-ray surveys of the United States including Alaska. Figure 2 shows the nominal flight-line spacings for the surveys in the 48 contiguous states. Flight-line spacings in Alaska are generally 10 km. The aerial surveys were flown using both fixed-wing and helicopter systems with detector volumes of 33-50 L of thallium-activated sodium iodide crystals. The nominal survey altitude is 122 m. The data were fully corrected by the contractors for background from aircraft con- tamination and cosmic rays, altitude variations, airborne Bi-214, and Compton scattering. The depth of detection is on the order of 30 cm (Duval, Cook and Adams, 1971). The ground coverage provided by these surveys is less than 10 percent (Pitkin and Duval, 1980) and the data are only suitable for producing regional scale maps of 1:1,000,000 or smaller or for studies restricted to the flight path of the aircraft.

EXPERIMENTAL DESIGN AND PROCEDURES

In order to compare ground gamma-ray measurements to the aerial data, the ground measurements must be made beneath and parallel to the flight path of the aircraft. Pitkin and Duval (1980) present a technique for calculating the relative contributions of strips
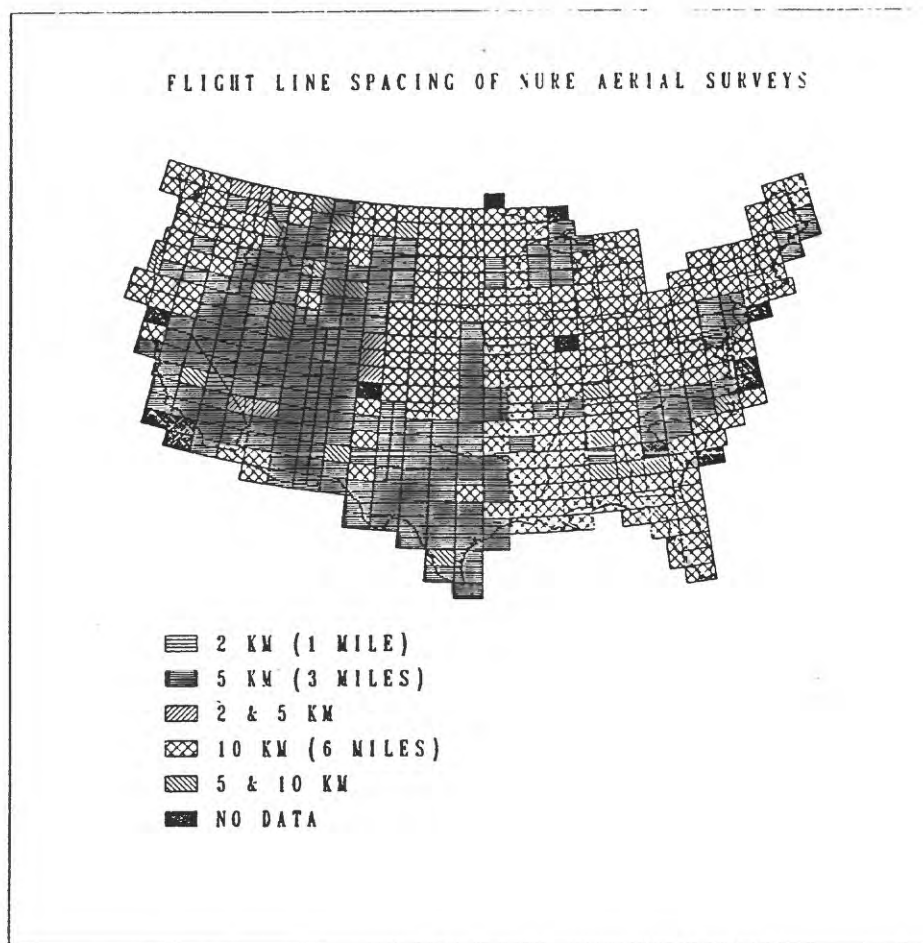
Figure 2. Nominal flight-line spacings for the NURE aerial gamma-ray surveys in the 48 contiguous states.
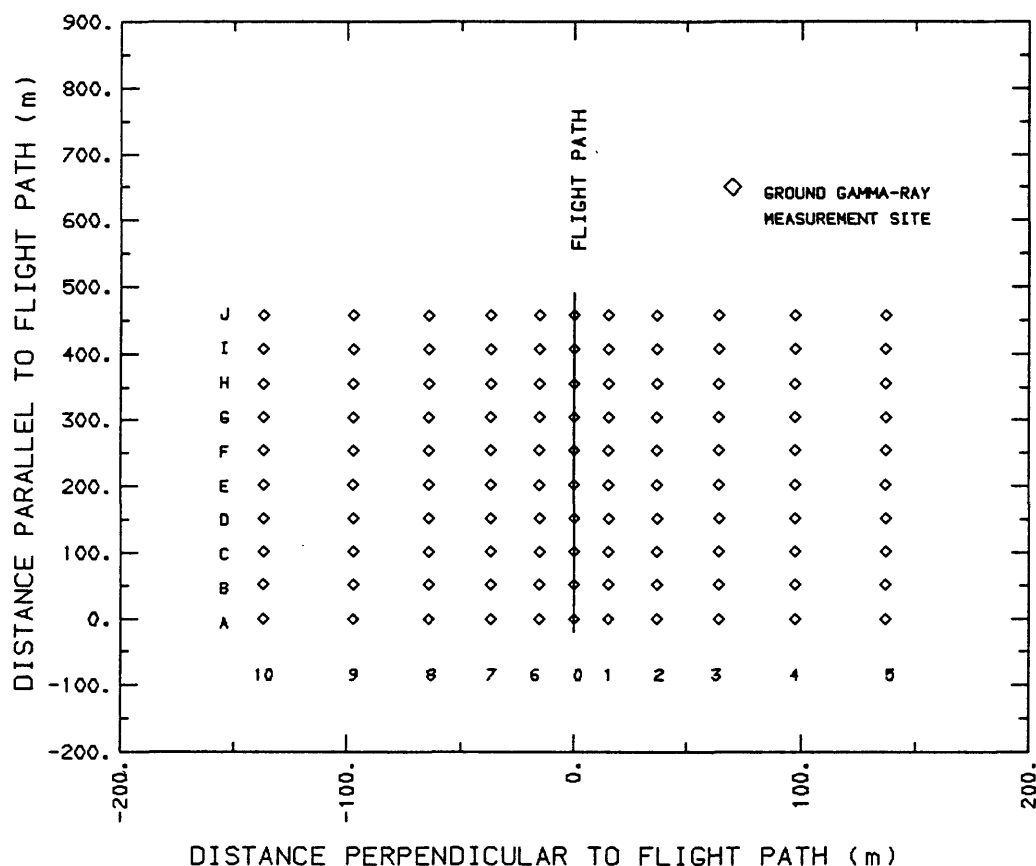
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**Figure 3.** Sampling scheme used for the ground gamma-ray spectrometer.

of ground to the measured gamma-ray flux. For our investigation, calculations using the same technique were made to determine different widths of strips of ground parallel to the flight line that contribute approximately equally (assuming an infinite, homogeneous source). Ground gamma-ray measurement sites were located at the centerline of each strip and figure 3 shows the sampling plan. The sampling distance along the flight line was chosen as 61 m because it approximates the distance flown in one sample period of the fixed-wing systems and is also about half of the survey altitude. A circle of radius 61 m contributes approximately 25 percent of the gamma-ray flux at any instant of time (Duval, Cook, and Adams, 1971) for a gamma-ray detector 122 m above the ground.

The portable ground gamma-ray systems were calibrated at the DOE calibration facilities at Grand Junction, Colorado (Ward, 1978). Background measurements were made in a boat on a lake large enough to permit a minimum distance of 100 m from land. For the ground measurements the gamma-ray detectors were suspended about

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1 m above the ground which results in integration of the flux from an area approximately 30 m in diameter (Duval, Cook, and Adams, 1971). The crystal volume of the portable systems used is 0.35 L and the measurement time used was 5 minutes. Three gamma-ray spectrometers were used during the fieldwork. To ensure accurate comparisons of the data, all three spectrometers were used to measure each sample site along the flight path. In addition repeated simultaneous measurements were made at a single location.

## RADON SOIL GAS MEASUREMENTS

Soil-gas sampling is an integral part of the scientific methodology used to study the distribution, migration, and availability of radon gas. Some of the factors that affect the concentrations of radon in soil gas are the Rn-226 concentration in the soil, the emanation characteristics of the soil materials, the soil porosity, permeability, and moisture content, and meteorological conditions. There are also various factors that must be considered when designing a system for collection of soil gas for analysis of its radon content. Samples are typically collected by boring a hole or driving a probe into the ground. Some methods place a film detector in the hole for a time-integrated measurement and others pump gas from the ground to obtain a more rapid analysis of the pore-space radon. Because all of the various techniques disturb the soil environment to some degree, the selection of a specific technique involves compromises and is based upon considerations such as requirements for a particular sample size, the need for special pumping or pressure differences, and the desire to sample at different soil horizons or depths.

The technique chosen for this study has been described by Reimer (1990) and is one that has advantages for a sampling program in which the relative distribution of radon concentrations is to be determined for the surface environment. This technique uses a hollow steel probe which is pounded into the ground. The sample of soil gas is extracted using a hypodermic syringe and the samples are analyzed on an electronic alpha-particle scintillometer. The advantages of this technique are that it allows rapid sampling and, because the sample size is small, the disturbance to the soil environment is minimal. The sample collection system can also be used to measure the soil permeability at the sample site. The primary disadvantage is that it is a "grab-sample" technique and only characterizes the soil gas in the immediate vicinity of the probe tip and only for the environmental and meteorological conditions that exist at the time of collection.

The sampling system is shown in figure 4. The probe is small-diameter, thick-walled carbon steel tubing. The outside diameter can range from 6 to 9 mm and the inside diameter from 2 to 3 mm. Sizes in these ranges have been found to give the best strength from materials that are readily available. The length of the probe can also vary but practical experience has shown that lengths of 0.75 to 1.0 m are more easily used and that longer lengths tend to
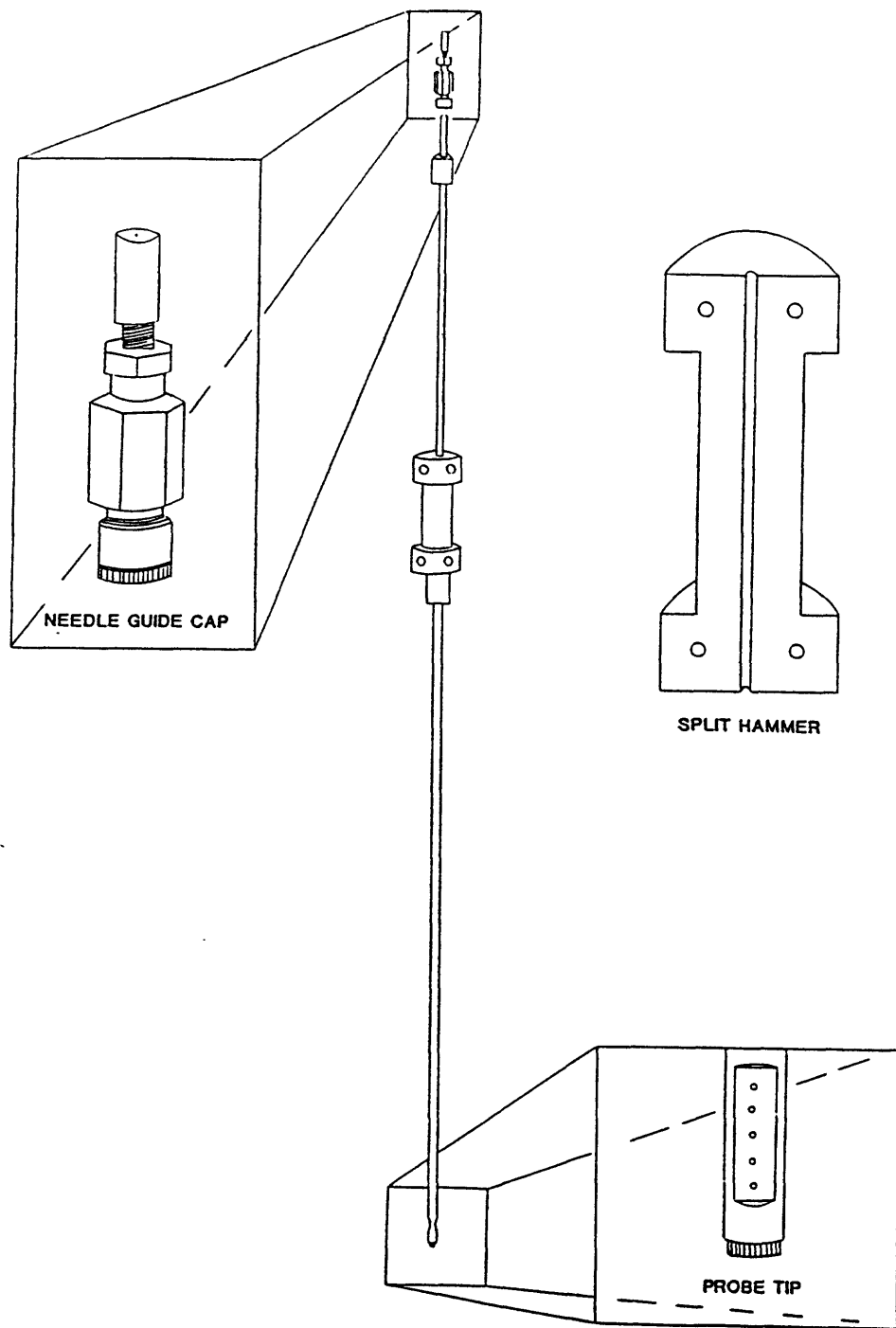
NEEDLE GUIDE CAP

SPLIT HAMMER

PROBE TIP

Figure 4. Schematic showing the design of the radon soil-gas sampling probe.

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bend and frequently cannot be inserted to their full length. Sampling depths in the range of 0.75-1.0 m are generally below the depth at which major meteorological influences are found and also frequently encounter the lower B or upper C soil horizons (Reimer, 1980; Hesselbom, 1985). The choice of the carbon alloy is limited by the availability of the thick-walled tubing which is normally only available in grades of 1015, 1018, or 1020. These numbers refer to particular grades of carbon-based steel (e.g. the number 1015 refers to carbon-based steel with 0.15 percent carbon content). Other alloys would provide greater strength but are more expensive. Stainless steel probes are softer but can be used for applications where a permanent probe for long-term monitoring is desired.

The schematic in figure 4 shows some of the details of the probe design. The probe is driven into the ground by pounding with a sliding hammer on the upper end of the probe. Two pounding collars which are 3 cm in diameter and 5 cm long are soldered onto the probe separated by about 60 cm. The sliding hammer is a split, barbell-shaped deadweight made of machined steel and is about 18 cm long and about 6 cm in diameter. The hammer is fitted over the probe tubing and fastened together with screws.

The probe tip can be designed in a variety of ways. The U. S. Geological Survey uses two designs. In one design, a small screw is threaded into the tip of the probe to seal the end of the probe. About 2 cm above the end of the probe, opposite sides of the probe are flattened by removing about 0.5 mm of material along a length of about 4 cm. Four or five holes are drilled through the probe along the flattened area and the hole diameters are approximately equal to the inside diameter of the probe. A wire is inserted into the probe to prevent dirt entering the holes. In the second design, the end of the probe is closed using a loosely fitting rivet. Once the probe has been pounded to the desired depth, it is retracted a few centimeters which causes the rivet to come out of the probe and results in a small cavity from which a sample can be drawn. This latter design is particularly useful for obtaining samples in soils with either high moisture content or fine silts that tend to clog the sampling holes.

The gas sample is taken from the open end at the top of the probe. Tubing can be slipped over the probe end and a sample pumped to a detector, or an o-ring fitting containing a septum can be used to obtain a discrete sample volume. In either case the atmospheric air in the probe must be extracted and discarded before drawing a sample for analysis. Because of the small internal diameter of the probe, a 1-m probe has an internal volume of only about 3 $cm^3$. The technique used for this study includes extracting 10 $cm^3$ to purge the probe prior to collecting a sample for analysis.

The gas samples can be stored in the syringes if the needle is capped to prevent gas loss or exchange. Tests with helium have shown that the syringes are capable of retaining the gas for a period of several days before diffusion causes dilution (Reimer and others, 1979).

Soil gas samples were obtained using the sampling pattern shown in Figure 5. This sample pattern was chosen because it
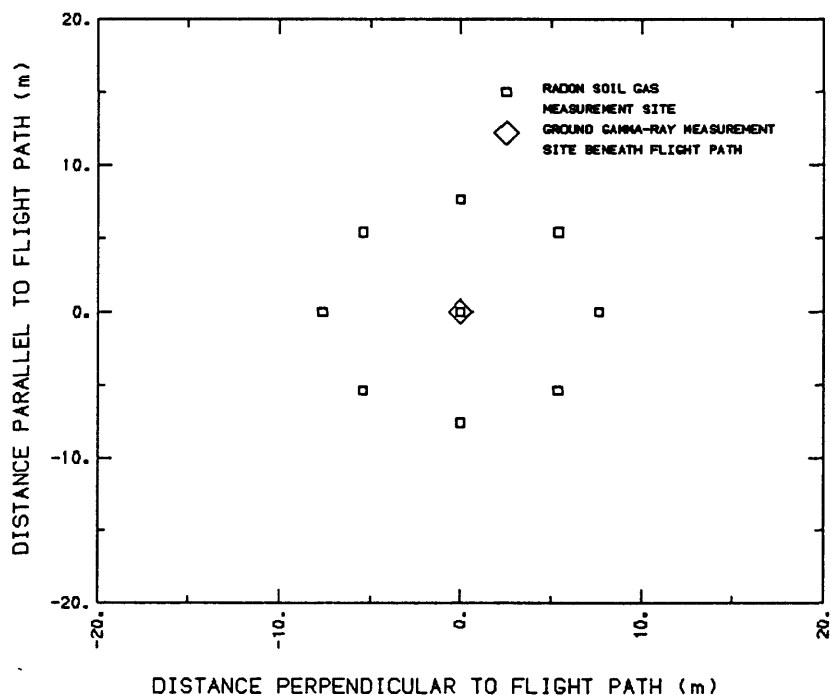


Figure 5.    Sampling pattern used to collect radon soil-gas samples.

provides coverage that might sample any variations in the geologic materials.  More samples at each site would have provided a smaller variance but the number of samples had to be limited because of the time needed to collect and analyze the gas samples.  The sample sizes collected ranged from 20 to 50 cc.

The soil gas samples are analyzed using a portable alpha-scintillometer.  The samples from the syringes are injected into a phosphor coated cell in the scintillometer.  Depending on the type of cell, the internal volume is about 100-300 cm$^3$.  Prior to use the cells are evacuated and a background reading is made before each sample is counted.  The scintillometers were calibrated using the U.S. Bureau of Mines radon facility in Denver, Colorado.  The samples are counted immediately after injection into the cell to minimize the buildup of the background in the cell.  When the background level in a cell exceeds a count rate equivalent to 50 pCi/L, the cell is set aside and not used again until the radon daughter nuclei have decayed.

## EMANATION MEASUREMENTS

The relative emanation of radon from the soil samples collected was measured by placing about 200 gm of soil in a sealed 250 ml flask. The seal was made using a rubber stopper with a septum to permit extraction of a gas sample. After extraction of a gas sample the seal was tested by injecting air to over-pressurize the container. If the overpressurization remained stable, the container was considered to have been adequately sealed. The flasks were left undisturbed for 30 days prior to sampling. As a check on the repeatability of the measurements, about 10 percent of the flasks were opened, resealed, and reanalyzed after another 30 day period.

This technique only provides a relative measure of the emanation power of the soils because the soil has been removed from its natural setting and the packing density has changed as well as the soil moisture. Nevertheless, if all samples are treated
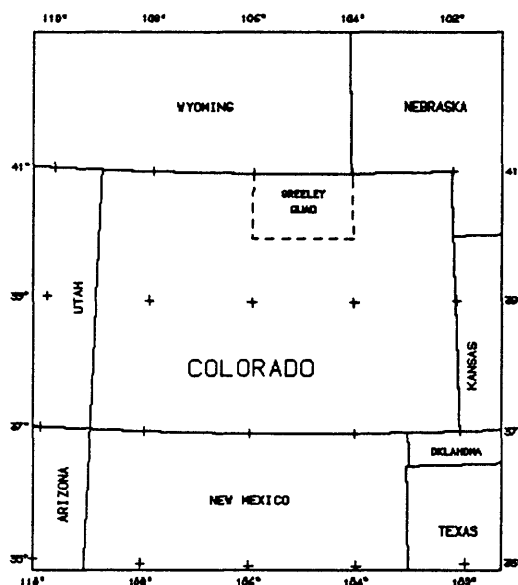
Figure 6a.    Index map showing the location of the Greeley Quadrangle.

identically, the relative emanation powers can provide useful information.

<center>SITE SELECTION</center>

Figure 6a shows the location of the Greeley Quadrangle, Colorado which was chosen as the aerial gamma-ray data set to be examined. The choice of the Greeley Quadrangle was based upon familiarity with the data and proximity to Denver where most of the project personnel are stationed. Selection of the study areas within the quadrangle was governed by the need to have variation in the soil parameters. Figure 6b shows the general locations of
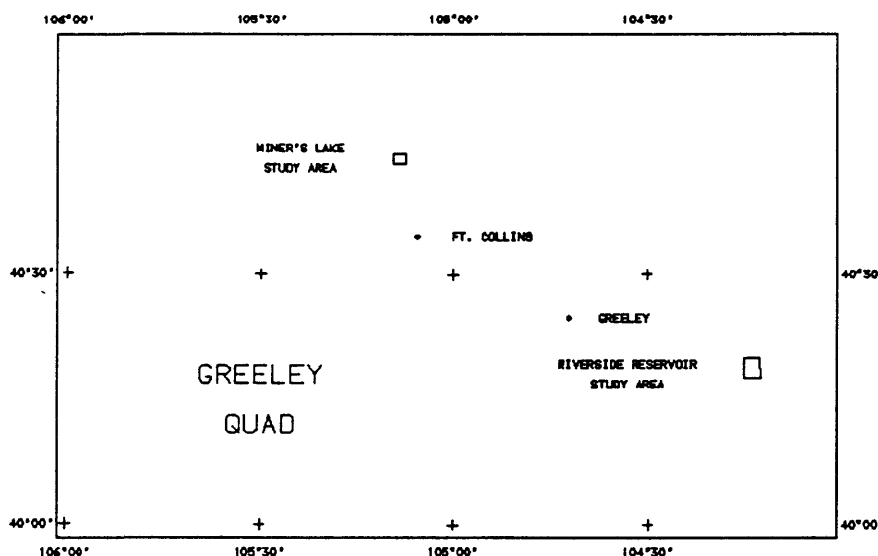


Figure 6b. Index map showing the locations of the Riverside Reservoir and Miner's Lake study sites.

the field sites. The Riverside Reservoir site near Greeley, Colorado was chosen because it is characterized by low uranium concentrations (1-2 ppm eU) and high permeability. The high soil permeability occurs because the near-surface lithology is aeolian sand. The Miner's Lake site near Fort Collins, Colorado was chosen because it provides a range of uranium concentrations (4-8 ppm eU) and expected low permeabilities because the bedrock geology consists of shales overlain by residual soils with high clay content.

Soils at the Riverside Reservoir study site are deep,

<center>11</center>

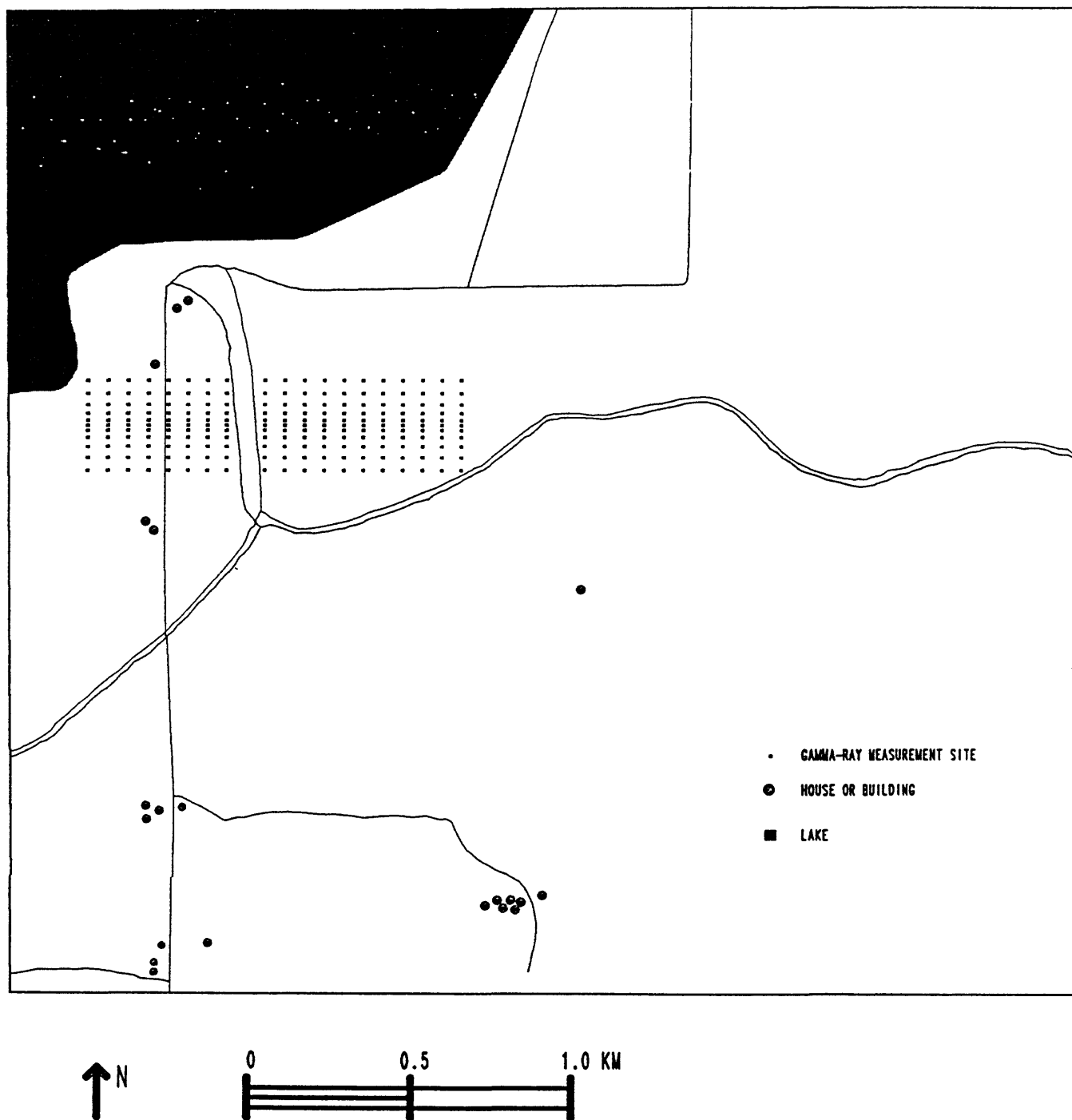Figure 7.  Map of Riverside Reservoir study area showing the locations of sites where ground gamma-ray measurements were made.

LEGEND:
- SITE WITH GAMMA-RAY AND RADON MEASUREMENTS
- HOUSE OR BUILDING
- LAKE

N
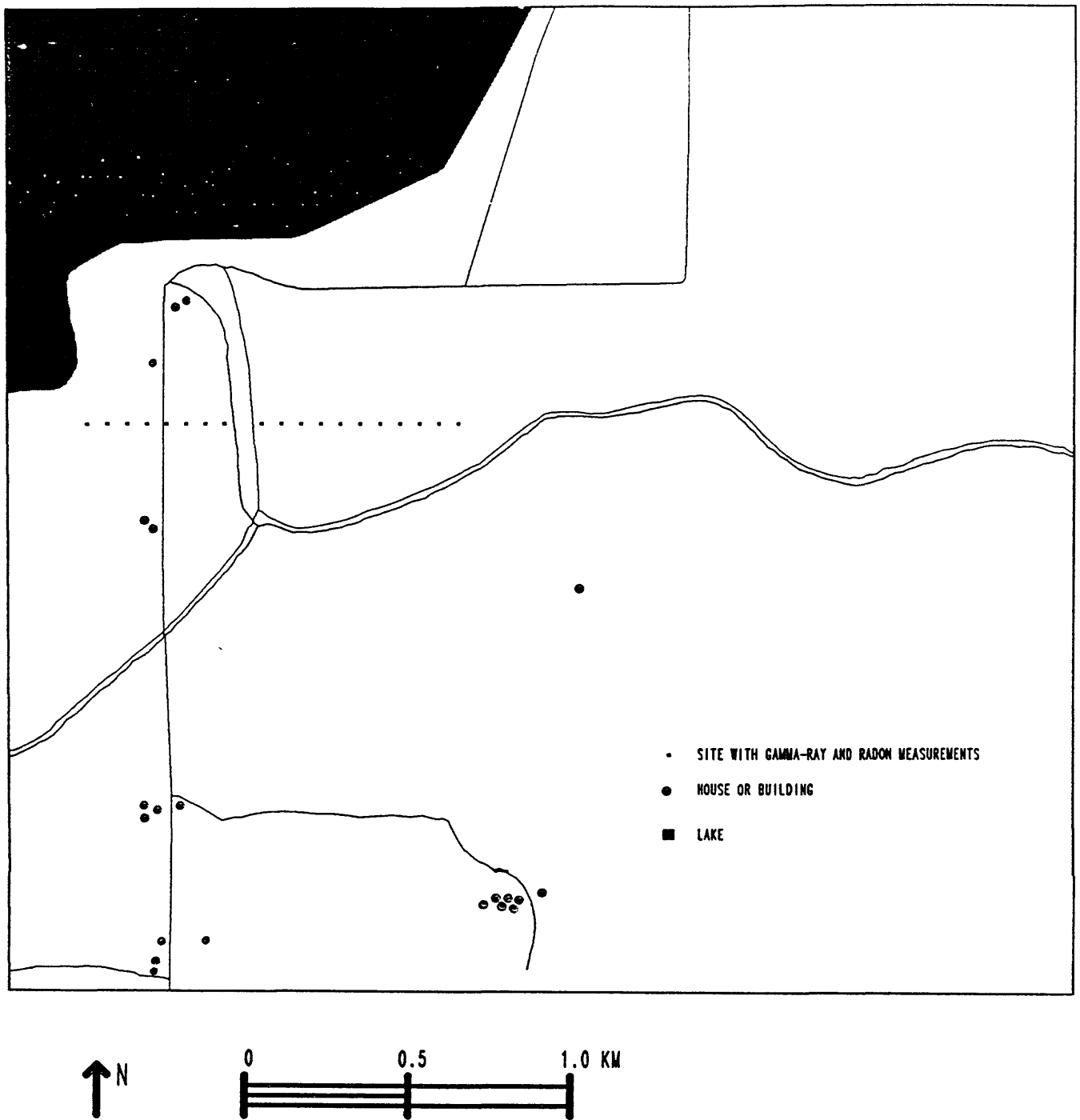
0        0.5        1.0 KM

Figure 8.   Map of Riverside Reservoir study area showing sites
            where both ground gamma-ray and radon soil-gas
            measurements were made.

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excessively drained sands developed on Quaternary eolian deposits. The soil is composed of fine to coarse sand to a depth of at least 1.5 m and is rapidly permeable (6-20 in/hr in standard percolation tests) (Crabb, 1980). Two 1-m deep trenches were excavated at station F0 and S0 to examine the soil profile which revealed that the soil is poorly developed at this site, but the presence of silica in coatings and minor cements on sand grains suggests that some materials have been leached from near-surface soil horizons, transported downward, and reprecipitated deeper in the soil profile. Total gamma activity was measured with a portable gamma scintillometer at 20 cm intervals through the soil profile and exhibited an increase from about 35 counts per second (cps) near the surface to about 52 cps at 60 cm and deeper; however, laboratory uranium analyses of samples collected at 20-cm intervals showed a slight decrease from about 1.8 and 1.5 ppm U at the surface to 1.6 and 1.3 ppm at 100 cm at stations F0 and S0, respectively.

Soils in the Miner's Lake study area are primarily clay loams derived on Upper Cretaceous shales. The soils are better developed than at the Riverside Reservoir site and consist of an A horizon of clay loam from about 0 to 10 cm, a B horizon from 10 to about 50 cm consisting primarily of clay and clay loam with subangular blocky to prismatic structure, with thin, discontinuous secondary $CaCO_3$ coatings in the lower 20 cm, and a C horizon below 50 cm consisting mainly of heavy clay with subangular blocky to prismatic structure and secondary $CaCO_3$ coatings, grading downward into weathered clay shale bedrock. Depth to noticeable $CaCO_3$ accumulations generally ranges from 15 to 50 cm. The soils have low permeability (0.06-0.2 in/hr) but are generally well drained (Moreland, 1980). These soils contain swelling clays that form desiccation cracks which can significantly increase the gas permeability of the soil over that measured in a standard water percolation test when the soils are dry. Uranium concentrations in soil samples collected at 20-cm-depth intervals in two trenches excavated at stations A0 and H0 exhibited increases from about 8.2 ppm at the surface to 9.5 ppm at 100 cm at station A0, and 6.6 ppm at the surface to 11.2 ppm at 100 cm depth at station H0.

RIVERSIDE RESERVOIR STUDY AREA

Figure 7 shows the Riverside Reservoir study area with the locations of the sampling positions used to obtain the ground gamma-ray data. Figure 3 shows the details of the sampling scheme. The sample positions were labeled as positions A through S from west to east. The center location (labeled as A0, B0, etc.) is directly beneath the flight path of the aerial gamma-ray system. At each position along the flight path the measurement positions perpendicular to the flight line were labeled from 1 to 5 proceeding to the north and from 6 to 10 proceeding to the south with stations 5 and 10 being farthest from the flight line (e.g. A1, A2, A3, A4, A5 to the north, and A6, A7, A8, A9, A10 to the south).

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Figure 8 shows the study area with the locations along the flight line at which radon soil gas measurements were made and soil samples were collected. Figure 5 shows the soil-gas collection scheme used at each location.

Figure 9 shows the surface concentrations of potassium versus the ground position, as measured by the ground and aerial gamma-ray systems. Also included in figure 9 is a curve of filtered aerial data multiplied by a correction factor of 0.8 which makes the average value of the aerial data equal the average ground value. Figure 10 shows the apparent surface concentrations of uranium versus the ground position as well as a curve of filtered aerial data multiplied by a correction factor of 7.56. Figure 11 shows the apparent surface concentrations of thorium versus the ground position plus a curve of filtered aerial data without a correction factor. The ground data shown in figures 9, 10, and 11 have been averaged for all of the stations (e.g., A0 - A10, Figure 3) at each position along the flight path. The corrected aerial data are presented as filtered data to facilitate the comparison. The filtered data were calculated using a 17-point gaussian filter.

Both the potassium (Figure 9) and uranium (Figure 10) values determined by the ground system are significantly different from the values from the NURE data base of aerial gamma-ray measurements. The ground system gives an average value of 2.6 percent K versus 3.3 percent K from the aerial system and a ground value of 1.8 ppm eU versus an aerial value of 0.27 ppm eU. The aerial thorium data (Figure 11) show a greater variance (1.4 ppm eTh) than the ground data (0.6 ppm eTh) with an average ground value of 6.6 ppm eTh versus an average of 6.8 ppm eTh from the aerial data. Because of the large disagreement between the ground and aerial measurements of uranium, the details of the NURE data were investigated. The information in the data archive shows that the original data for the Greeley quadrangle were delivered to DOE by the aerial survey contractor as unconverted counts per second and the data were converted to concentration units by the DOE subcontractor (Bendix Field Engineering, Inc.). The results of this study suggest that the calibration constants used to make the conversion calculations are incorrect.

Because of the possibility of variations in the radon in the soil gas caused by changes in temperature and pressure, measurements at sample location E0 were repeated at 30 minute intervals for one day. Figure 12 presents the data for the apparent surface concentrations of uranium and the radon concentrations in the soil gas versus the time of day. These data do not show any obvious simultaneous variations and the correlation coefficient is 0.26. The air temperature was also measured and Figure 13 presents the radon soil gas concentrations and the air temperature versus the time of day. The correlation coefficient calculated for these parameters is -0.15. Figure 14 shows the radon soil gas concentrations and the ground temperature at a 10 cm depth versus the time of day and the calculated correlation coefficient is 0.08. Figure 15 presents the apparent surface concentrations of uranium and the air temperature versus the time of day. The calculated correlation

coefficient for these data is
-0.72. Figure 16 presents the apparent surface concentrations of uranium and the ground temperature versus the time of day and the calculated correlation for these parameters is -0.23. Although the radon concentrations were apparently not affected by the temperature variations, the apparent uranium concentrations show a tendency to vary inversely with the temperature. As a check to see whether there might be some temperature effects on the gamma-ray spectrometer, the data for uranium, potassium, and thorium were filtered with a 3-point median filter to reduce some of the statistical variations while preserving any possible step functions in the data. Figure 17 shows the filtered uranium and potassium data versus the time of day and Figure 18 shows the filtered thorium and uranium data versus the time of day. These data show that the apparent uranium concentrations decreased during the hottest part of the day but the potassium and thorium measurements are approximately constant. Because the changes in the apparent uranium concentrations occur over time periods of 30 minutes or less, the changes cannot be related to changes of radon concentrations in the ground. If the changes were related to the radon in the soil gas, the variations would have to show a lag time controlled by the decay of the Rn-222 daughter nuclei. The most likely cause of the eU variations is the change of the effective concentration of Bi-214 in the atmosphere.
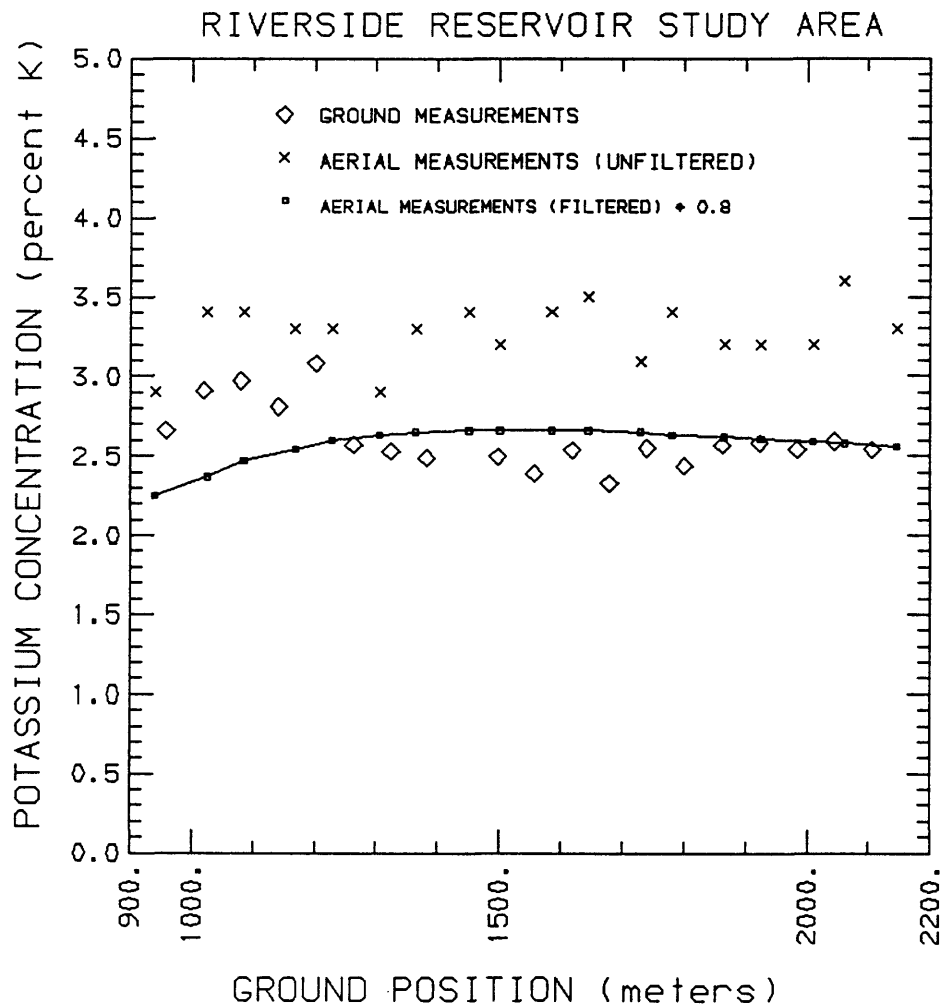
Figure 9. Apparent surface concentrations of potassium measured by the aerial and ground gamma-ray systems at the Riverside Reservoir study area. Ground position is relative to an arbitrary origin.
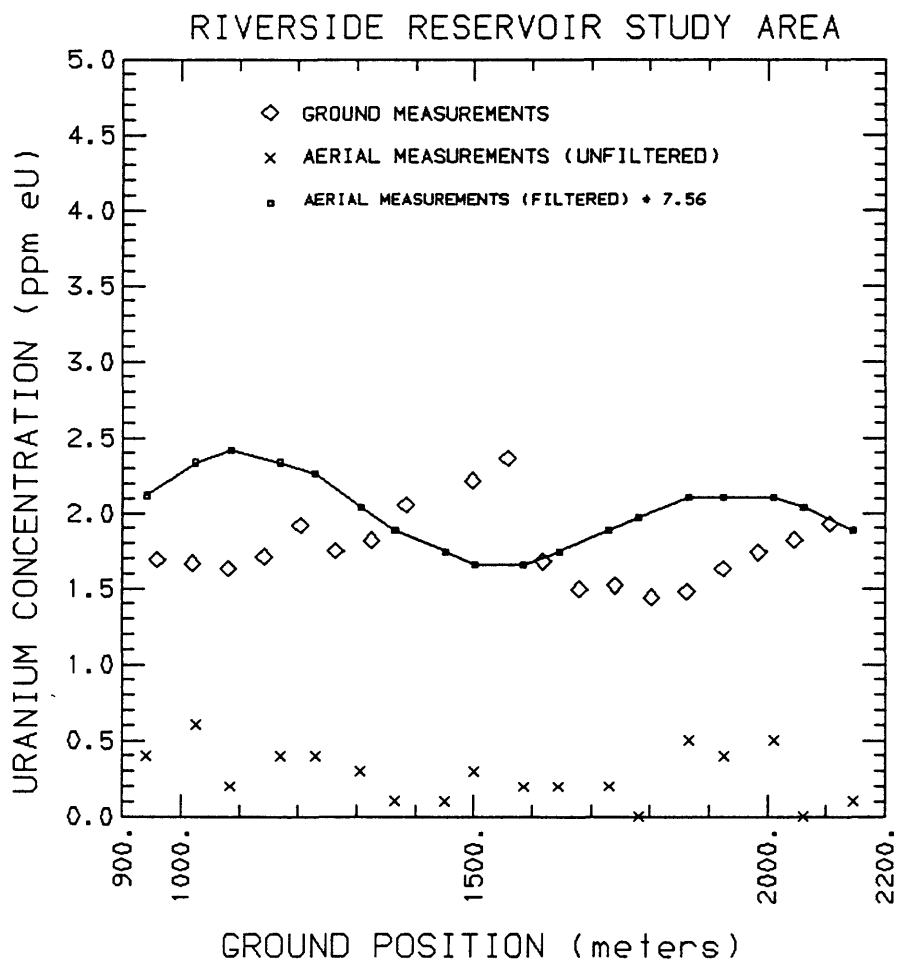
Figure 10. Apparent surface concentrations of uranium measured by the aerial and ground gamma-ray systems at the Riverside Reservoir study area. Ground position is relative to an arbitrary origin.
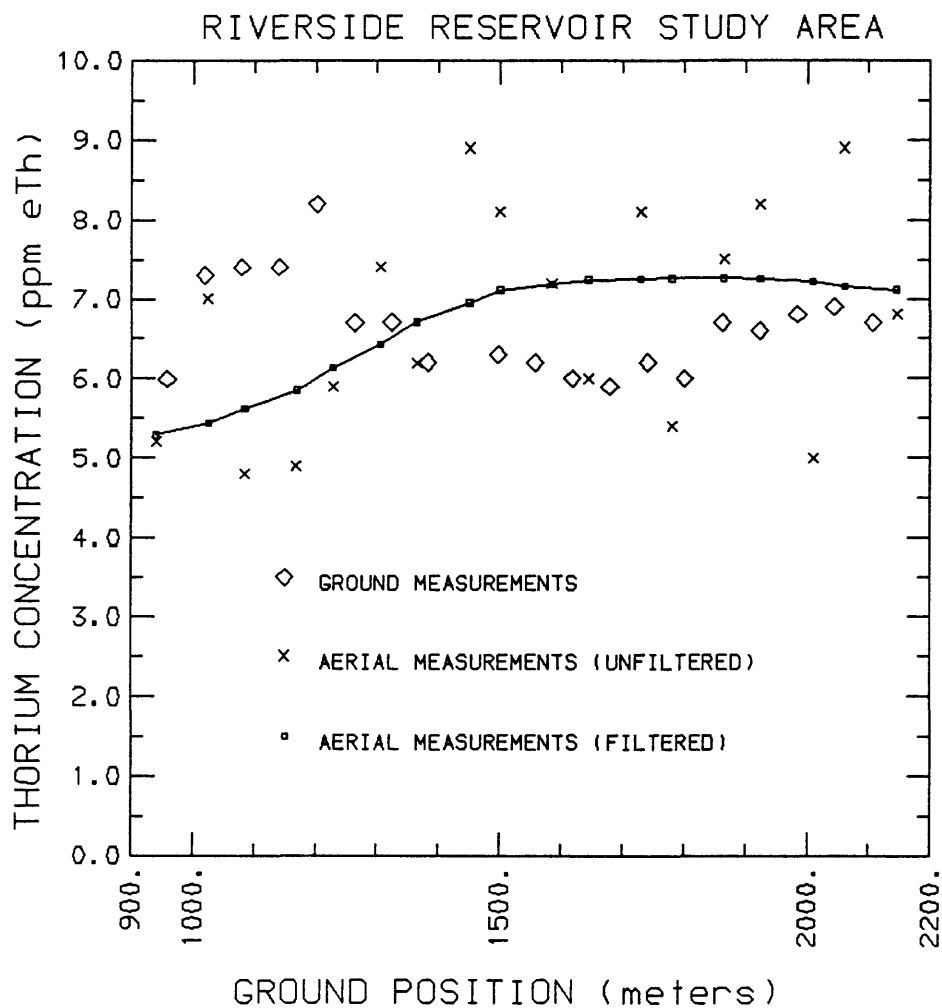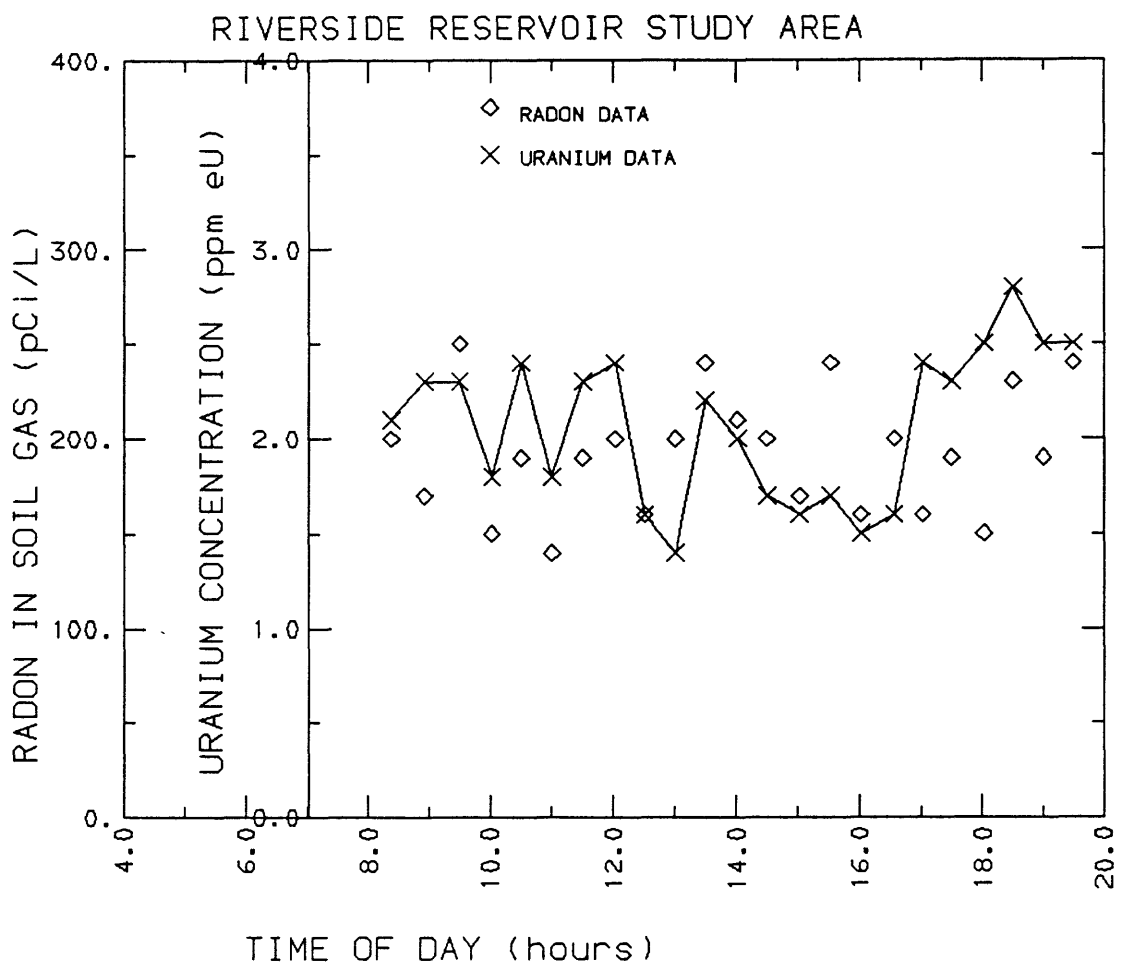
Figure 11. Apparent surface concentrations of thorium measured by the aerial and ground gamma-ray systems at the Riverside Reservoir study area. Ground position is relative to an arbitrary origin.

Figure 12. Concentrations of radon in the soil gas and the apparent surface concentrations of uranium versus the time of day at the Riverside Reservoir sampling location E0.
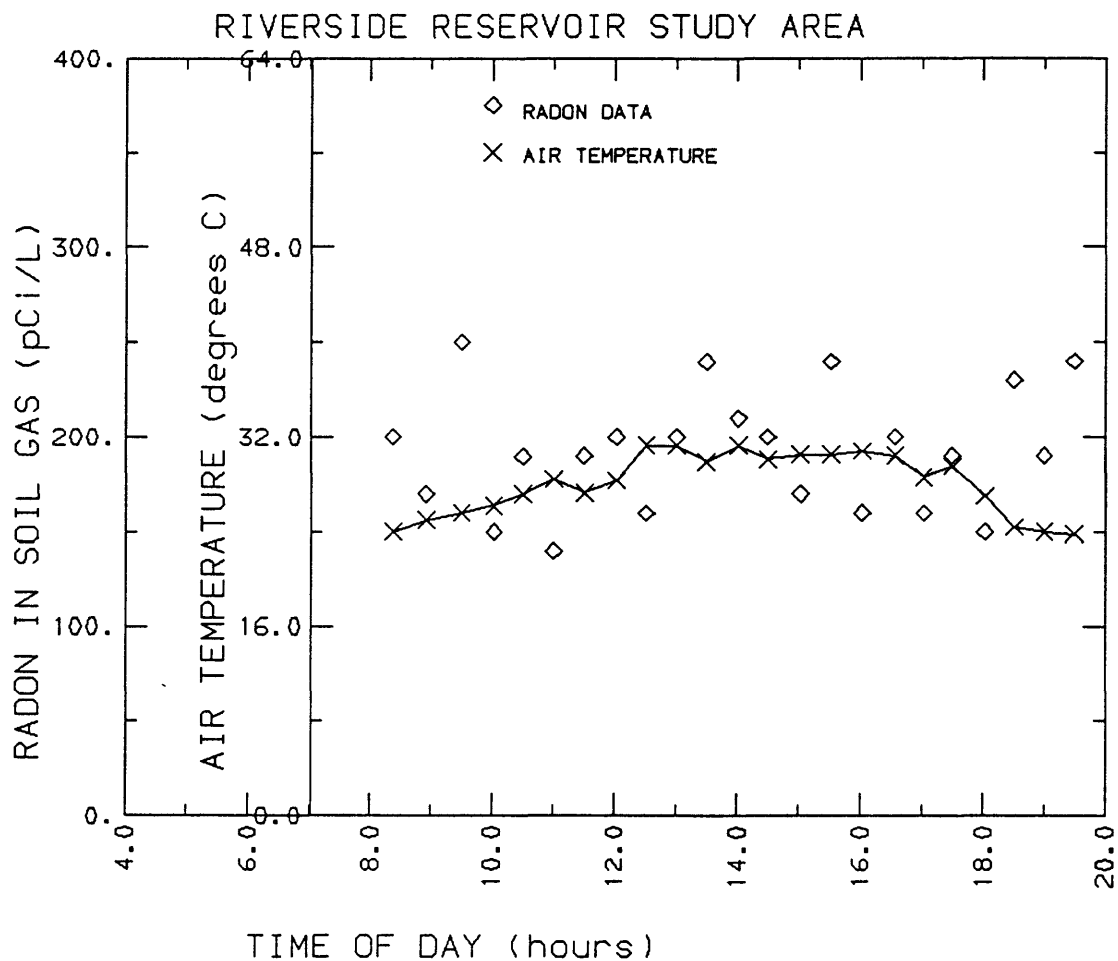
Figure 13. Concentrations of radon in the soil gas and the air temperature versus the time of day at the Riverside Reservoir sampling location E0.
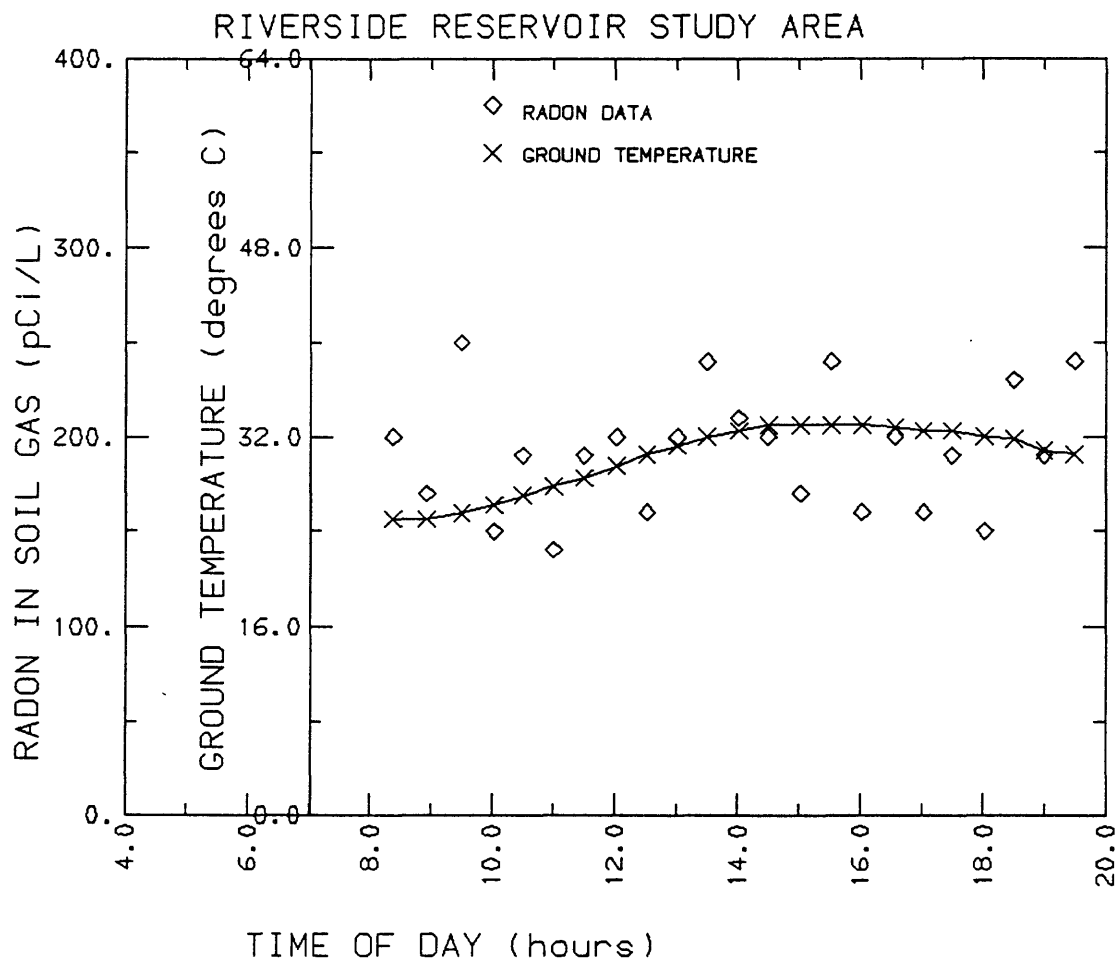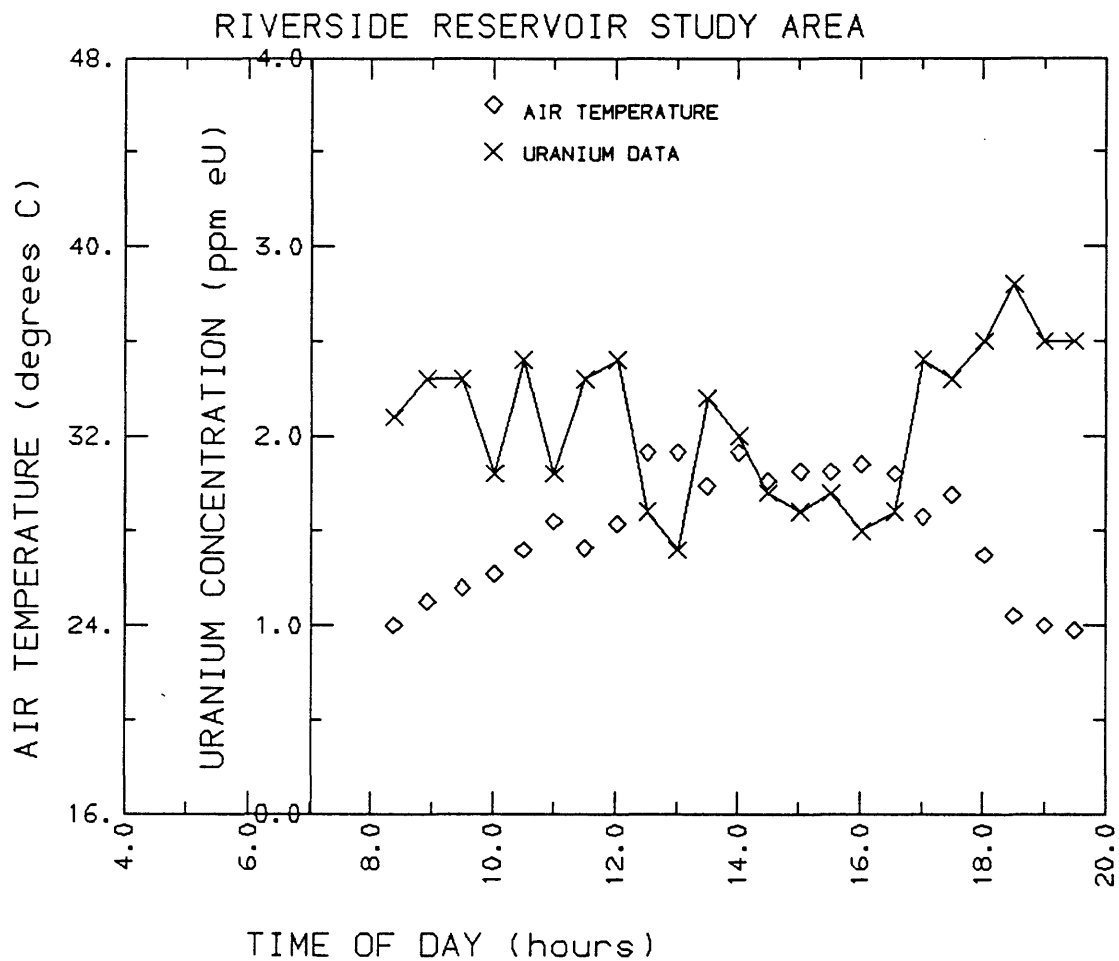
Figure 14. Concentration of radon in the soil gas and the ground temperature versus the time of day at the Riverside Reservoir sampling location E0.

Figure 15. Apparent surface concentrations of uranium and the air temperature versus the time of day at the Riverside Reservoir sampling location E0.
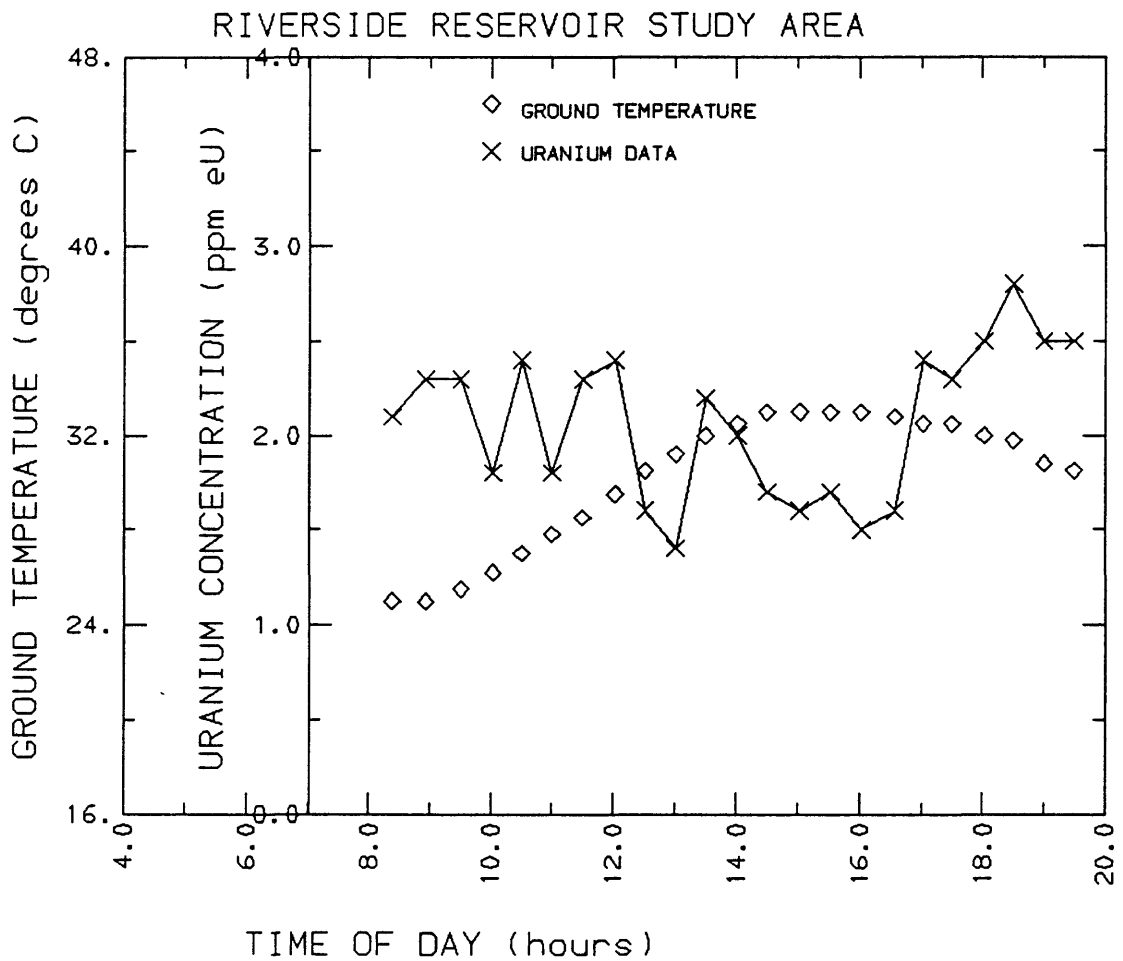
Figure 16. Apparent surface concentration of uranium and the ground temperature versus the time of day at the Riverside Reservoir sampling location E0.
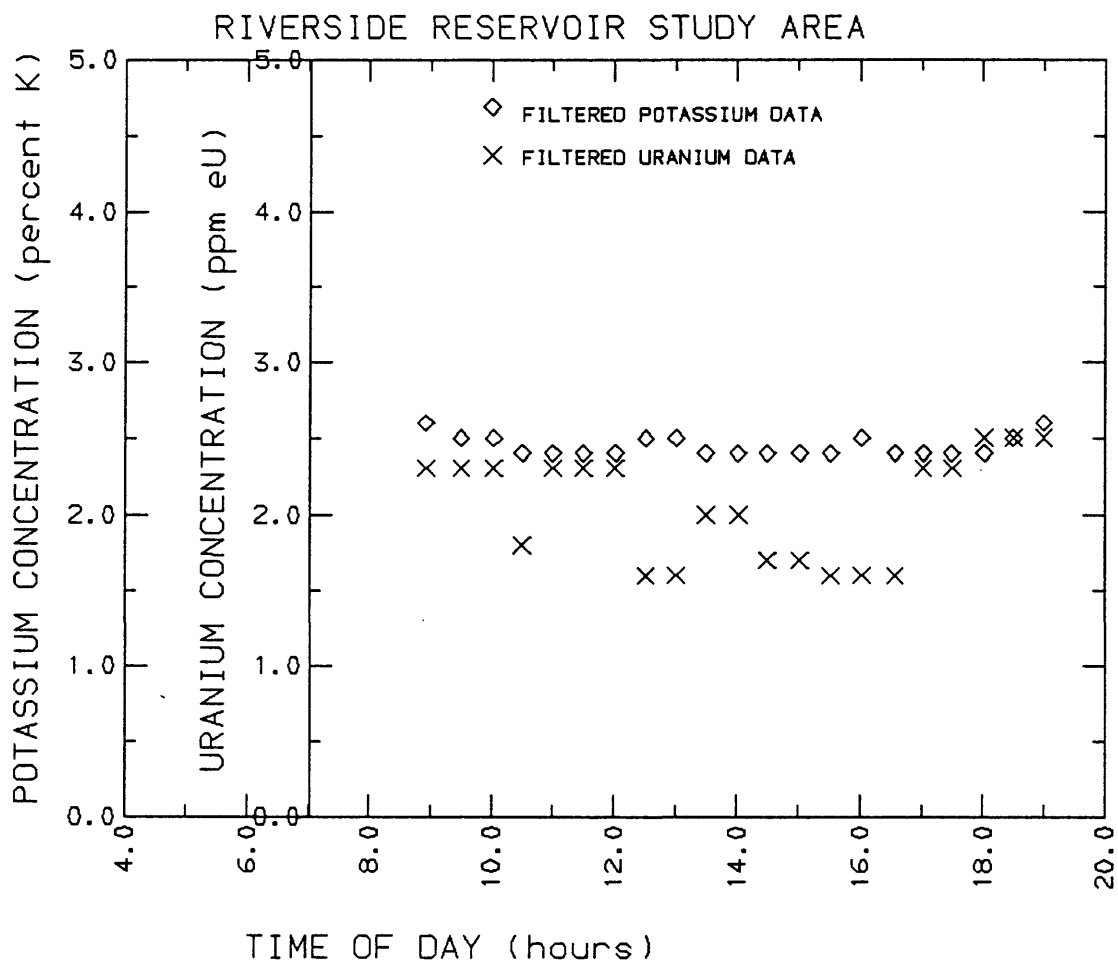
Figure 17. Apparent surface concentrations of potassium and uranium versus the time of day at the Riverside Reservoir sampling location E0. Data filtered with a 3-point median filter.
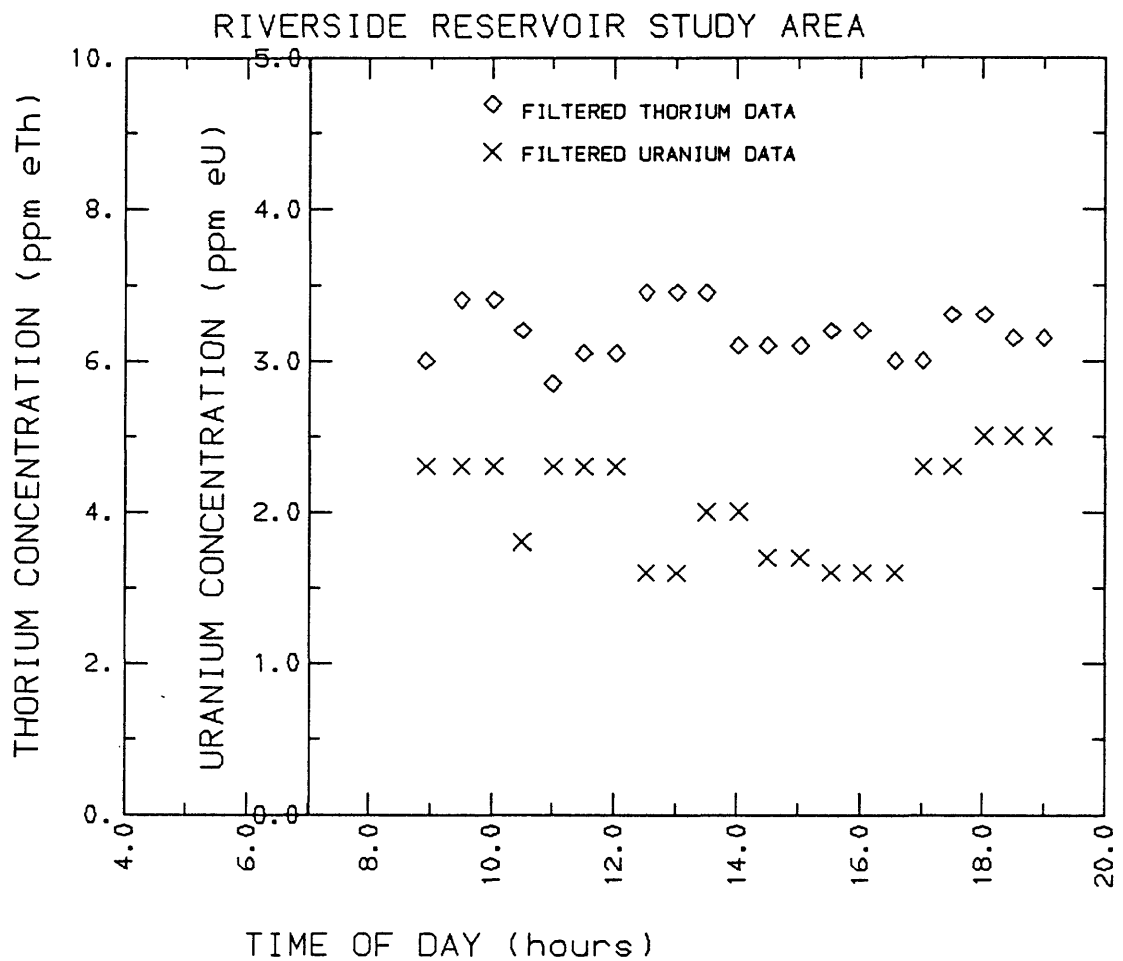
Figure 18. Apparent surface concentrations of thorium and uranium versus the time of day at the Riverside Reservoir sampling location E0. Data filtered with 3-point median filter.

Figure 19 shows the Miner's Lake study area with the locations of the sampling positions used to measure the ground gamma-ray data. Figure 3 shows the details of the sampling scheme. The sample positions were labeled as positions A through W from east to west. The center location (labeled as A0, B0, etc.) is directly beneath the flight path of the aerial gamma-ray system. At each position along the flight path the measurement positions perpendicular to the flight line were labeled from 1 to 5 proceeding to the north and from 6 to 10 proceeding to the south with stations 5 and 10 being farthest from the flight line (e.g. A1, A2, A3, A4, A5 to the north, and A6, A7, A8, A9, A10 to the south). Figure 20 shows the study area with the locations along the flight line at which radon soil gas measurements were made and soil samples were collected. Figure 5 shows the soil gas collection scheme used at each location.

Figures 21, 22, and 23 show the apparent surface concentrations of potassium, uranium, and thorium, respectively, as measured by the ground and aerial gamma-ray systems versus the ground position. The ground data at each position along the flight path have been averaged. The potassium, uranium, and thorium values determined by the ground system are significantly higher than the values from the NURE data base of aerial gamma-ray measurements. The figures also include curves of the aerial data after multiplication by correction factors. The correction factors used for the data at this site are different from those used for the Riverside Reservoir data. The adjusted aerial data are presented as filtered data to facilitate the comparison and were calculated using a 17-point gaussian filter. In order to achieve better agreement with the ground data, the Miner's Lake aerial data clearly require different correction factors than the Riverside Reservoir data but the reasons for the differences are unknown. Even with the different correction factors, the data along the western part of the line section studied remain significantly lower than the values given by the ground measurements and a single factor cannot bring both sections of the aerial data into agreement. The data along the western section of the flight line were acquired by a helicopter-borne gamma-ray system and the eastern part as well as the Riverside Reservoir data were acquired by a fixed-wing system. The aerial data do, however, match at the point where the data from the two systems overlap. Because the overlap of the helicopter and fixed-wing surveys is only a few data points, the possibility remains that the two surveys require some adjustments. Experience of the senior author (J.S. Duval) with matching the data of the Greeley quadrangle with adjacent quadrangles suggests that adjustments between the helicopter and fixed-wing surveys would be minor and would not eliminate the disagreement between the ground and aerial data.
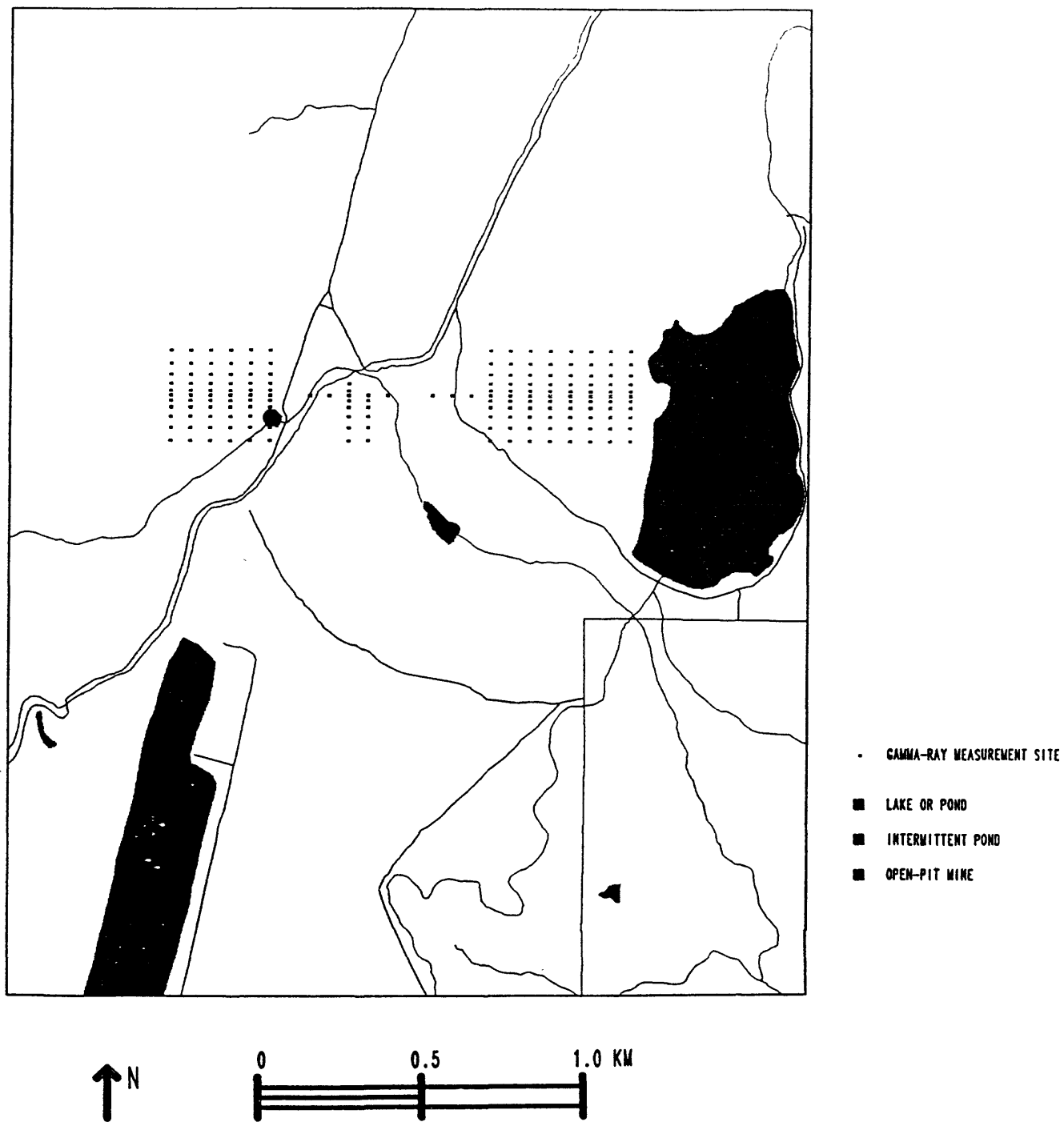
# MINER'S LAKE STUDY AREA



Figure 19.  Map of Miner's Lake study area showing locations
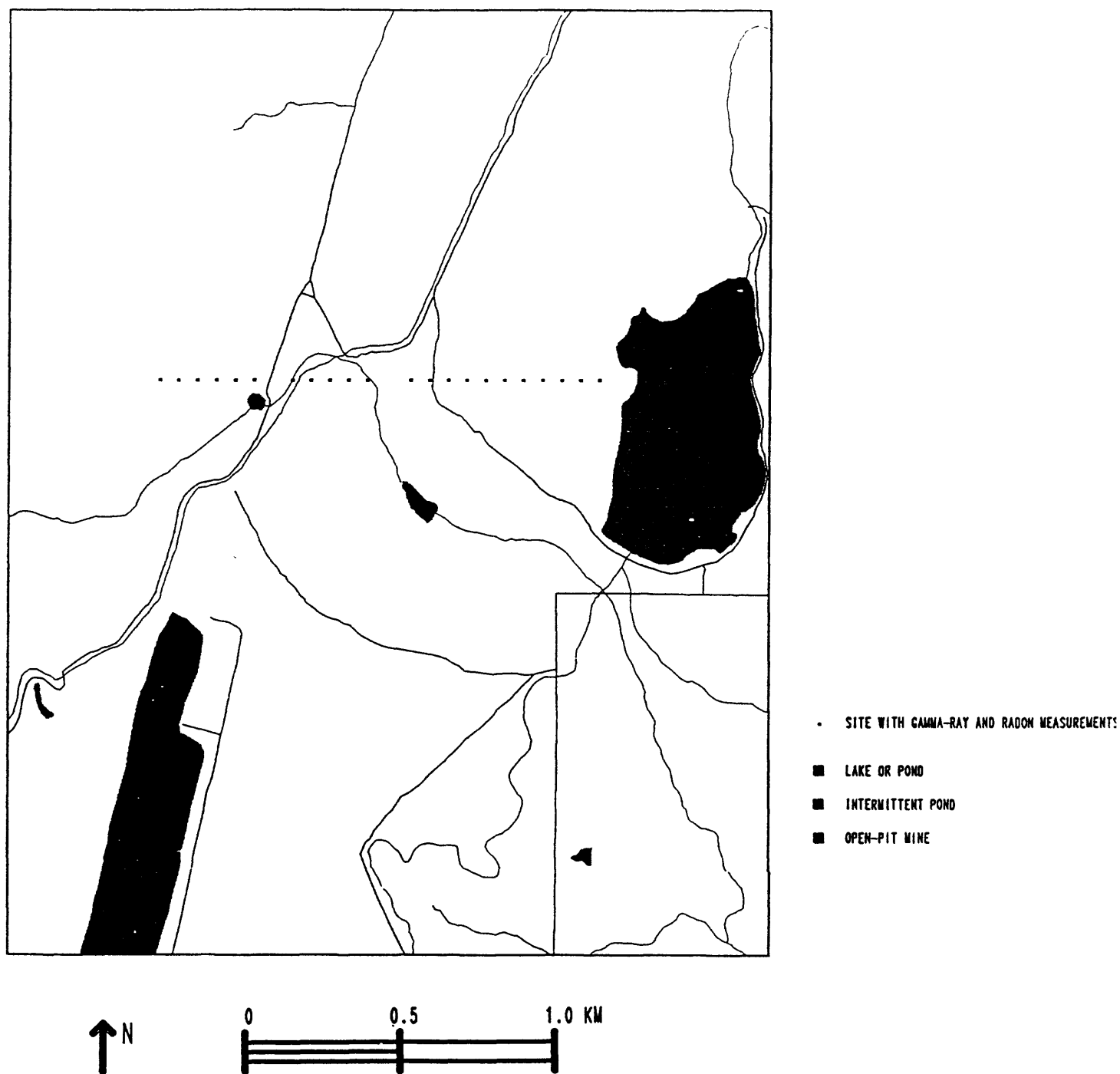where ground gamma-ray measurements were made.

Figure 20. Map of Miner's Lake study area showing locations where both ground gamma-ray and radon soil-gas measurements were made.
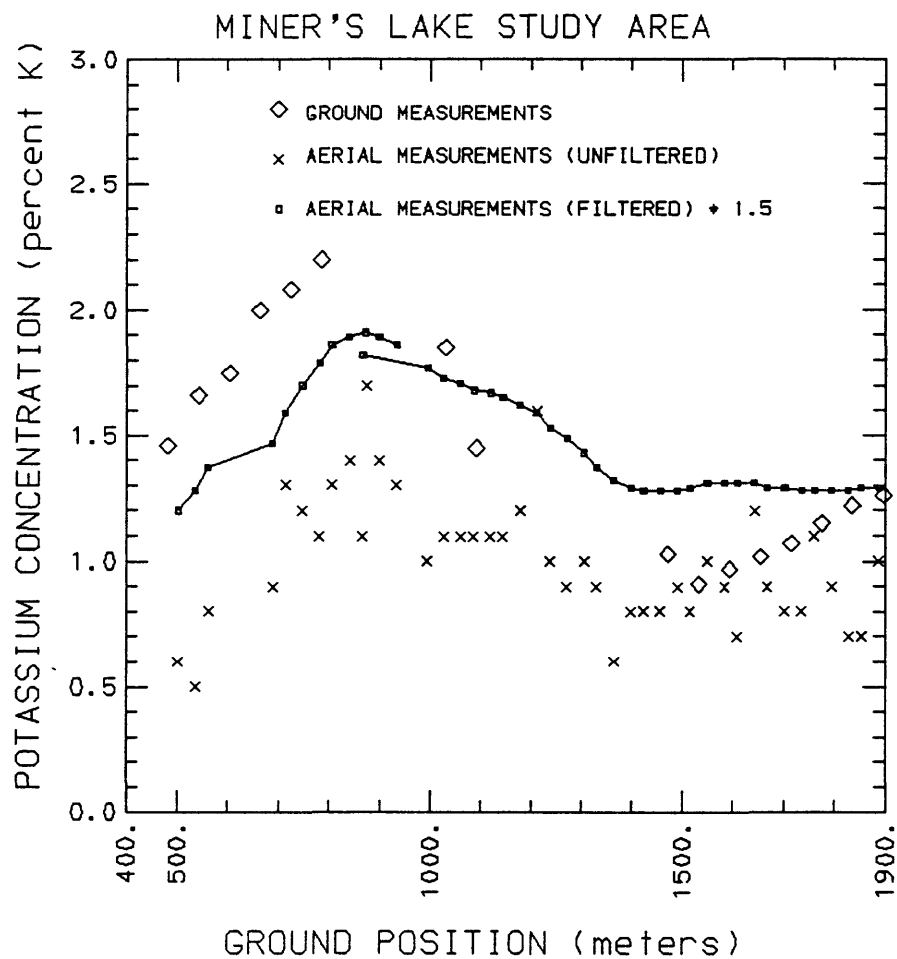
Figure 21. Apparent surface concentrations of potassium measured by the aerial and ground gamma-ray systems at the Miner's Lake study area. Ground position is relative to an arbitrary origin.

Figure 22. Apparent surface concentrations of uranium measured by the aerial and ground gamma-ray systems at the Miner's Lake study area. Ground position is relative to an arbitrary origin.
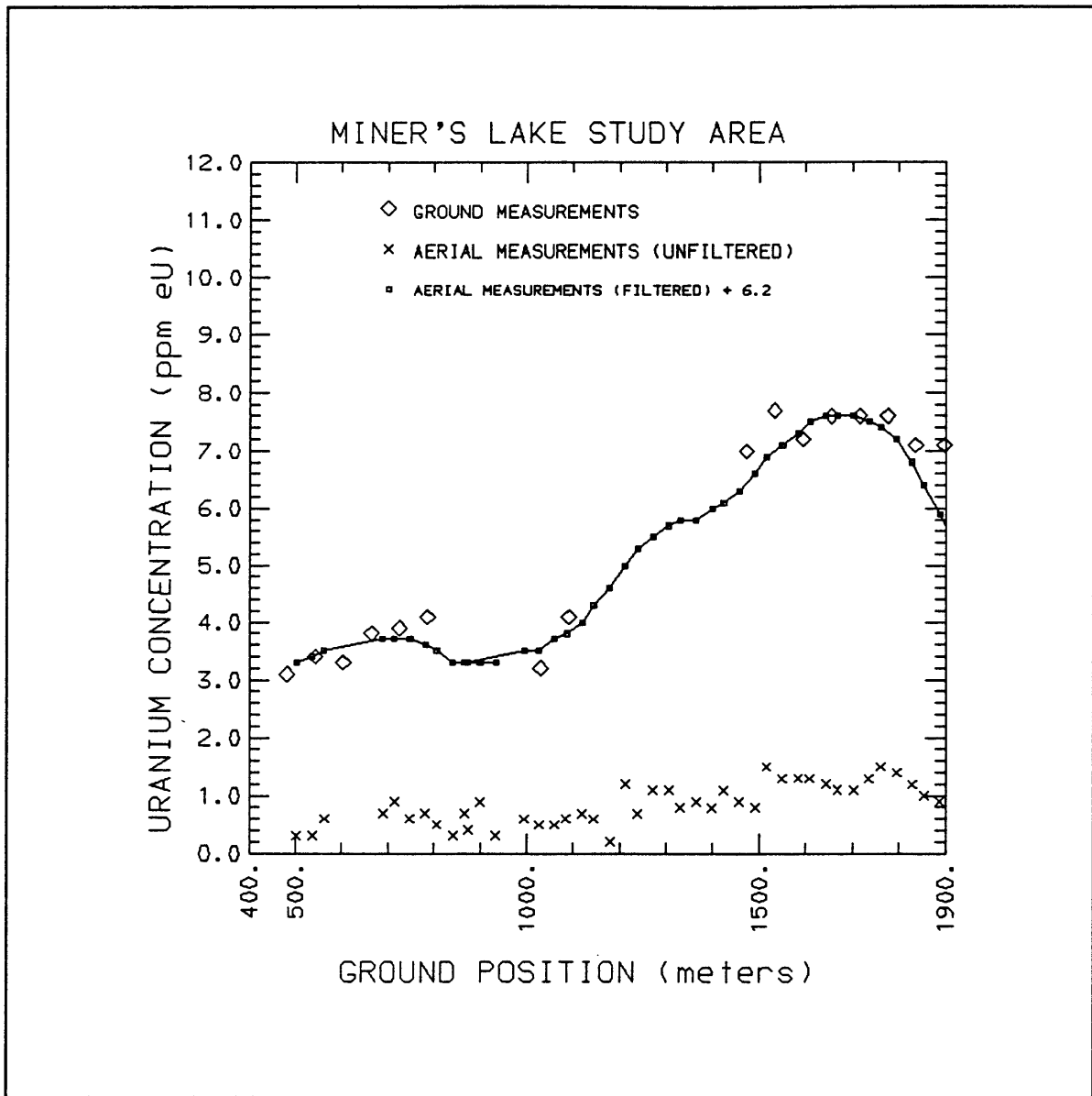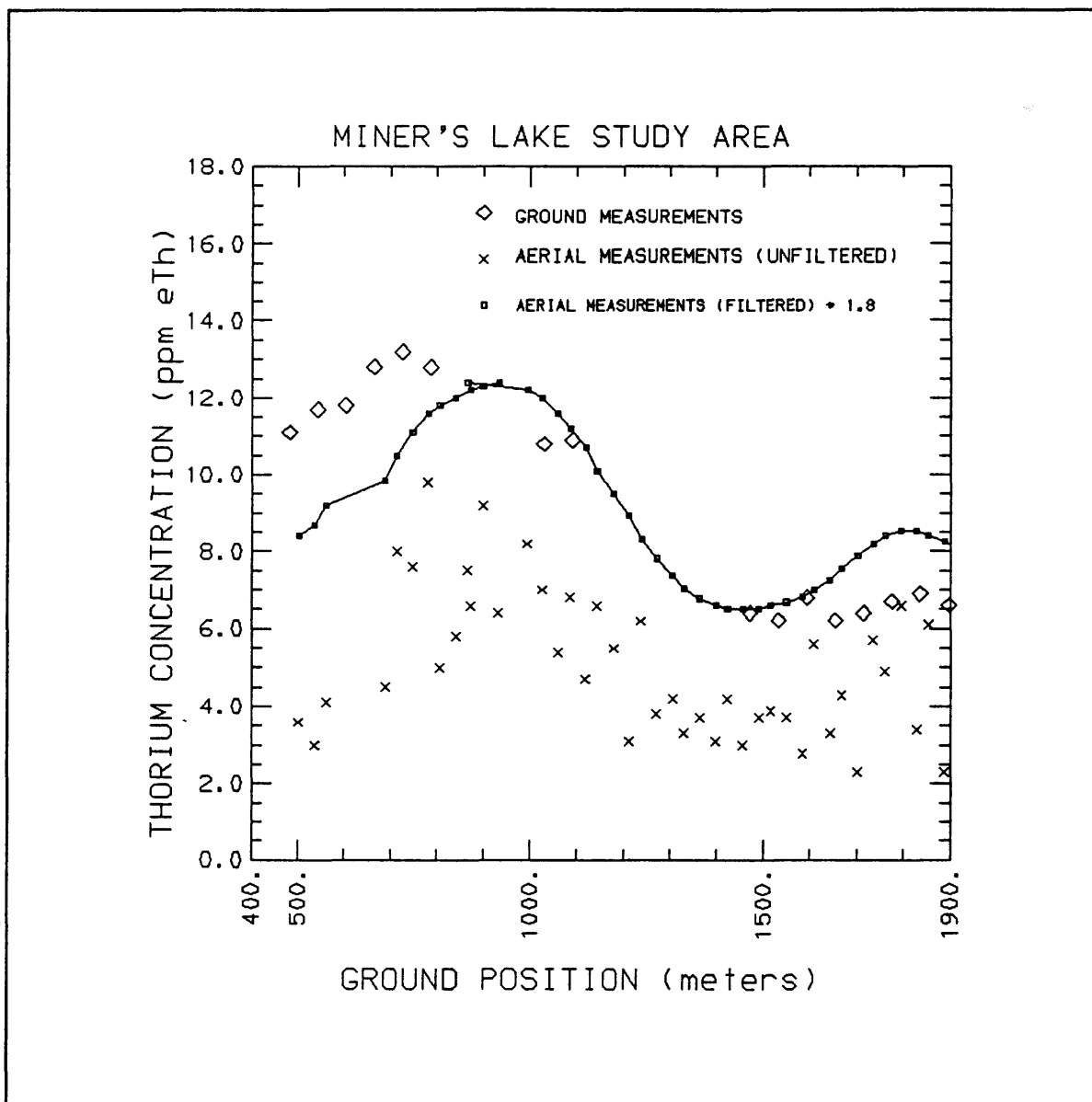
Figure 23. Apparent surface concentrations of thorium measured by the aerial and ground gamma-ray systems at the Miner's Lake study area. Ground position is relative to an arbitrary origin.

RADON IN SOIL GAS VERSUS GAMMA-RAY DATA

The data from both study areas were grouped according to the gamma-ray signatures of the sample locations such that data from sites with similar potassium, uranium, and thorium concentrations were in the same group. The uranium concentrations and radon soil-gas data were averaged for each group and Figure 24 shows the radon soil-gas concentrations plotted versus the average uranium concentrations. Although these data show some scatter, there is a predictive relationship between the average uranium concentrations and the average radon concentrations in the soil gas. The data suggest that an average uranium concentration of 1 ppm eU produces approximately 90 pCi/L radon in the soil gas. Figure 25 shows similar data collected by the authors in Maryland. These data suggest that an average uranium concentration of 1 ppm eU produces approximately 1000 pCi/L radon in the soil gas. One possible explanation for the different relationships between the uranium concentrations and radon in the soil gas in Colorado and Maryland is that the more extensive weathering in Maryland has leached the uranium from the top part of the soils. The gamma-ray measurements are made at the surface but the radon soil-gas samples are obtained at a depth of 75 cm. Regardless of the complete explanation for the difference, the data show that uranium versus soil-gas radon relationships determined in one region cannot be applied in another region with different climatic and geochemical environments.


LABORATORY RESULTS

Surface Samples

For the Riverside and Miner's Lake study areas, soil samples were collected at each of the sample locations along the line beneath the aerial flight line. Composite soil samples were obtained by collecting soil from various points within a circle of radius 25 m centered on the ground gamma-ray sample location. The total amount of soil collected was about 2 kg. Each composite sample was mixed and splis of approximately 600 g were sealed in airtight containers and submitted for laboratory gamma-ray analysis. The samples were allowed to sit for 21 days to achieve approximate radioactive equilibrium between the radon and the parent radium. Figures 26, 27, and 28 show the results of the laboratory analyses versus the ground gamma-ray measurements for uranium, thorium, and potassium, respectively. The solid lines in the figures are the lines (with a slope of 1) along which all of the points would fall if the agreement between the measurements were perfect. Figure 26 shows that the laboratory produced generally lower values of uranium than the field spectrometer and the thorium data in figure 27 are systematically lower in the laboratory measurements. The potassium data show generally good agreement although the data do suggest a slope not equal to 1 which
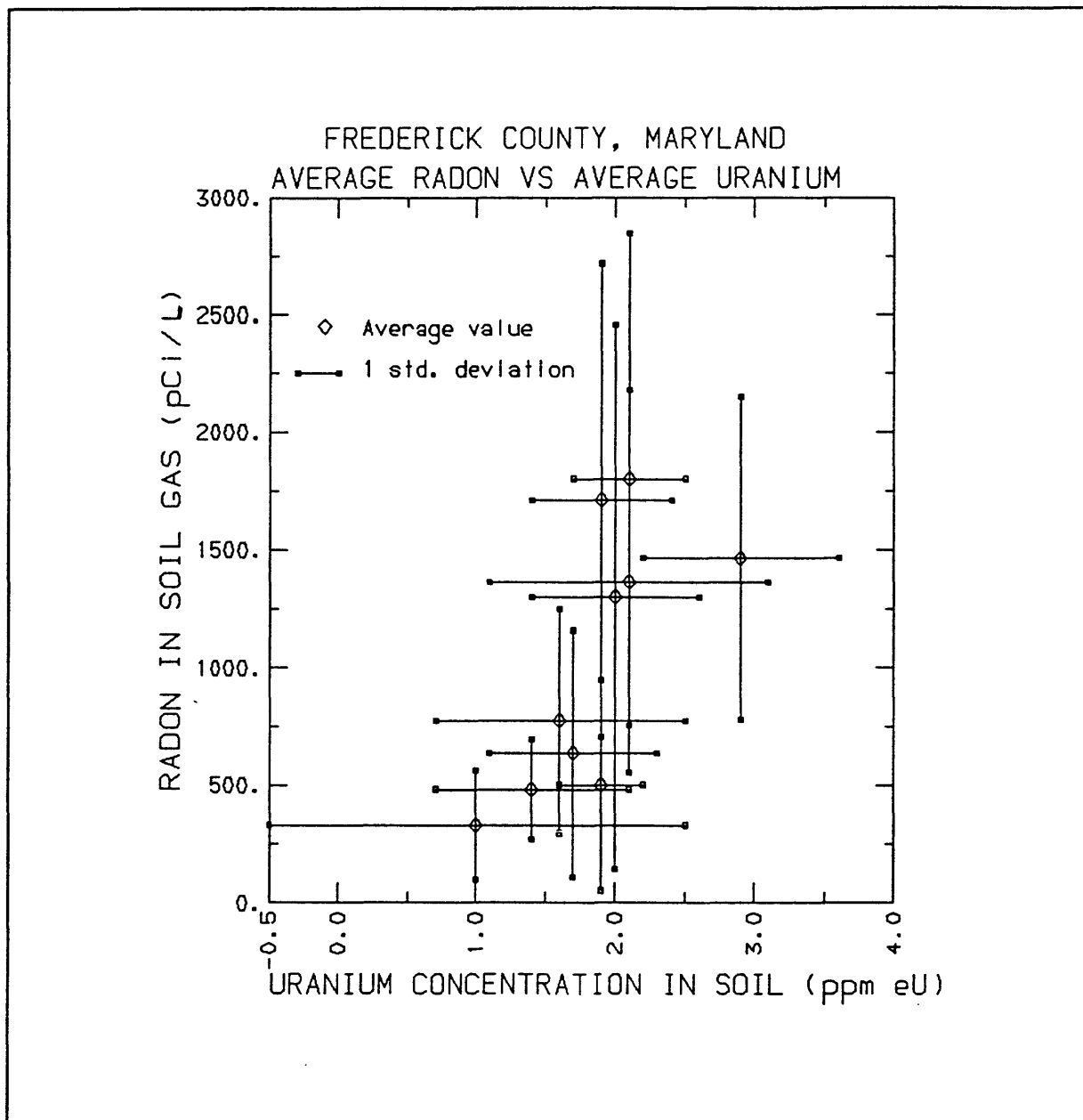
33

Figure 25.  Average radon soil-gas concentrations versus the average uranium concentrations for soils in Maryland.
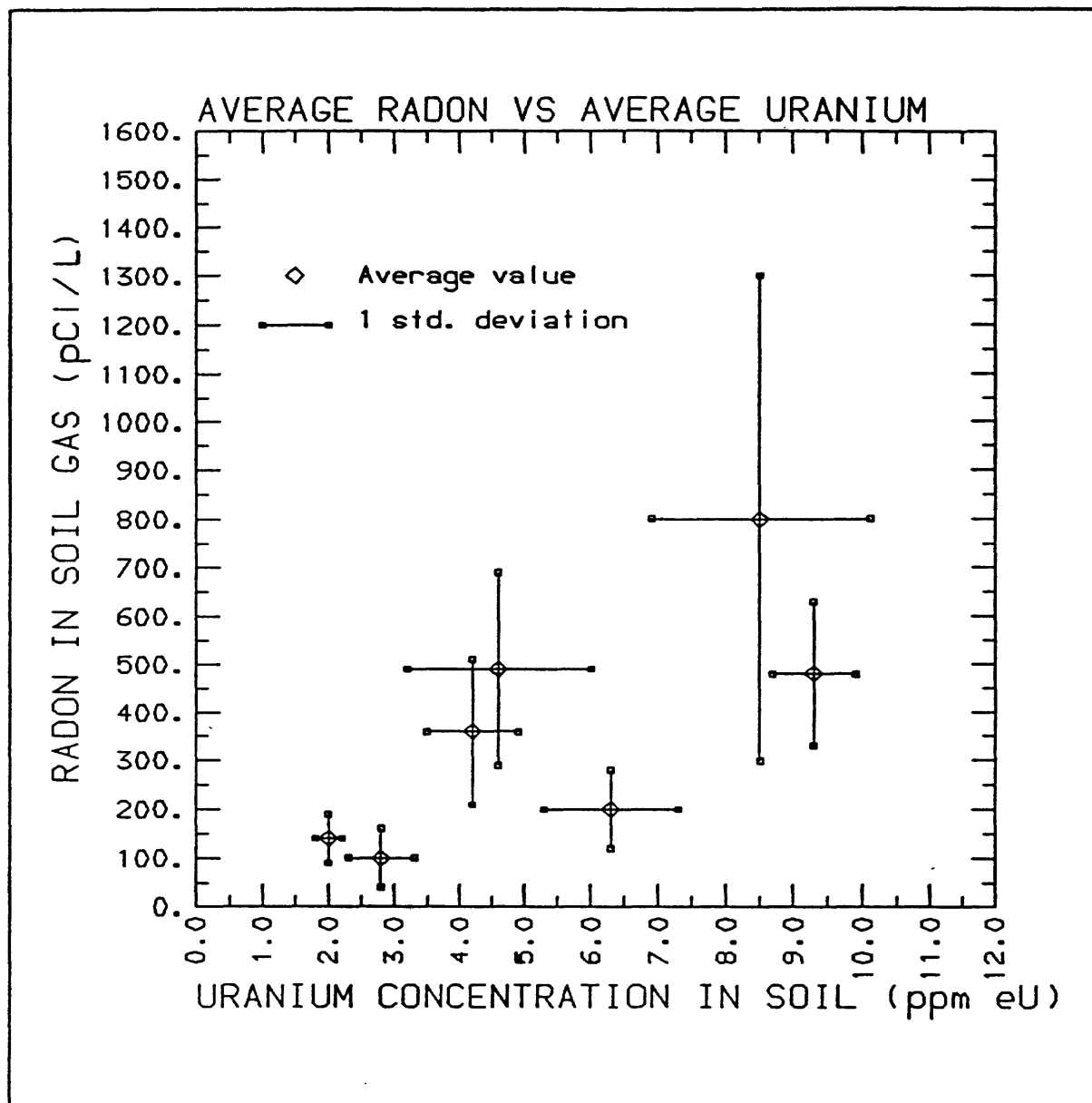
Figure 24.  Average radon soil-gas concentrations versus the
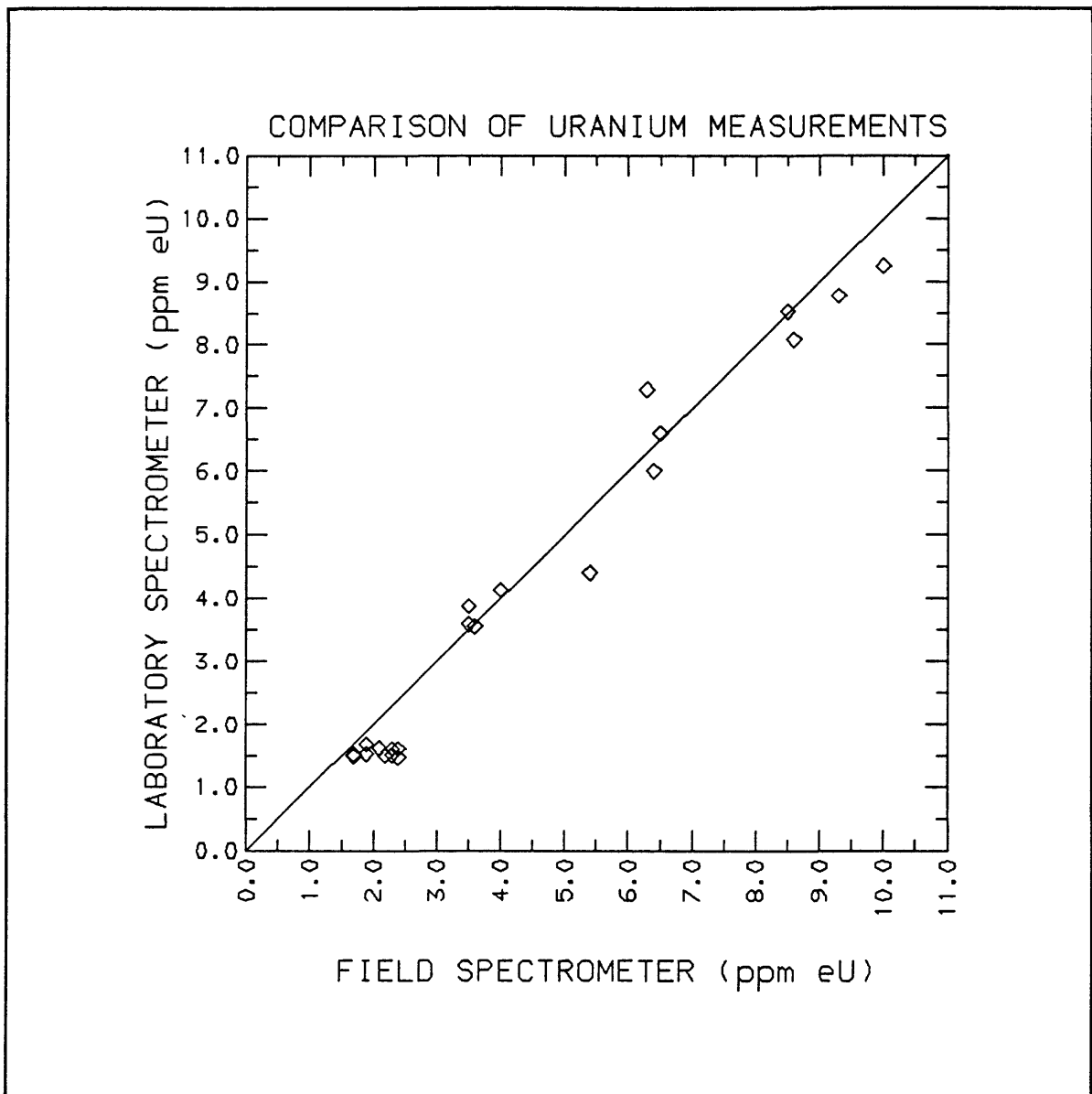average uranium concentrations for soils in
Colorado.

Figure 26.  Comparison of the apparent uranium concentrations measured in soil samples using a laboratory gamma-ray spectrometer with the values measured by a field spectrometer.
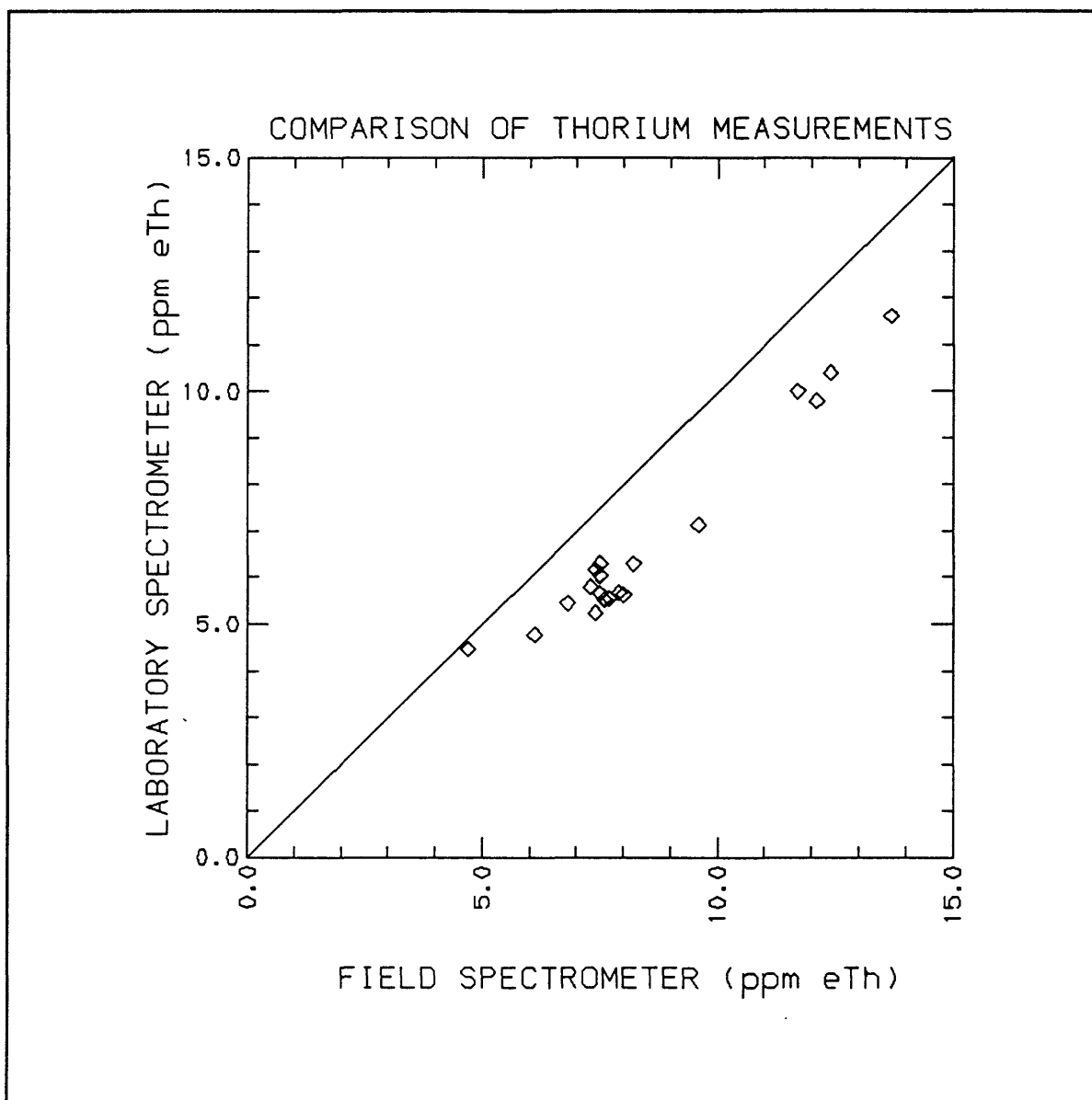
Figure 27. Comparison of the apparent concentrations of thorium in soil samples measured with a laboratory gamma-ray spectrometer with values measured by a field spectrometer.
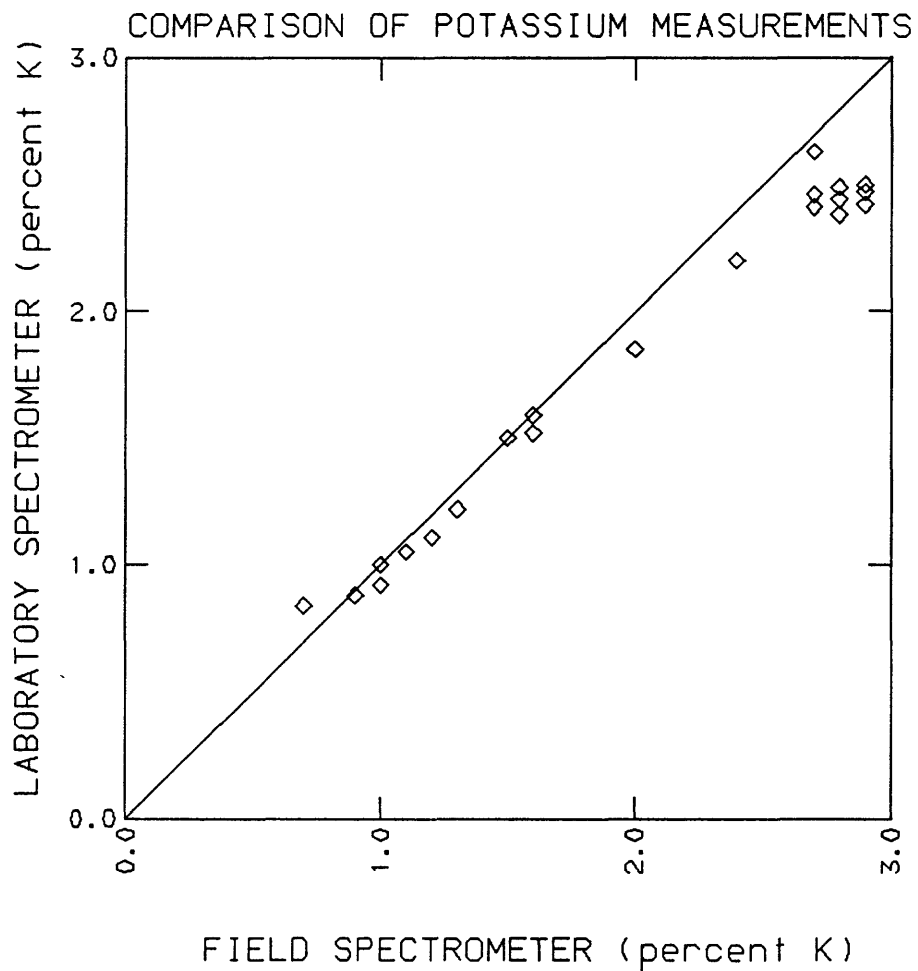
Figure 28. Comparison of the concentrations of potassium in soil samples measured using a laboratory gamma-ray spectrometer with values measured by a field spectrometer.

implies a calibration error.

The largest difference in the uranium data is 63 percent and the mean difference is 20 percent with a variance of 20 percent. Given the counting errors and estimated calibration errors, we expect the absolute accuracy of the field spectrometer to be about 20-30 percent. The laboratory errors are estimated to be less than 5 percent and, therefore, the agreement is good. The largest difference in the thorium data is 42 percent and the mean difference is 27 percent with a variance of 10 percent. The estimated accuracy of the field thorium measurements is about 30 percent and on that basis the agreement with the laboratory results is judged to be good. The largest difference between the potassium measurements is 30 percent and the mean difference is 10 percent with a variance of 8 percent. The estimated accuracy of the field potassium measurements is about 30 percent and the agreement with the laboratory results is judged to be good.

Although the agreement between the field and laboratory measurements is good, the data clearly show that there are systematic differences in the thorium and potassium data. The systematic difference in the thorium data can only be explained by an error in the background correction applied to the field measurements. The fact that the potassium data have a slope not equal to 1 can be explained by errors in the potassium calibration and background corrections used for the field spectrometer.

Subsurface Samples

Soil samples were also collected from trenches dug at selected sites. At the Miner's Lake study area trench samples from site A0 showed radium concentrations ranging from 2.7 pCi/g at the surface to 3.2 pCi/g at a depth of 100 cm. At Miner's Lake site H0, the trench samples show an increase from 2.2 pCi/g at the surface to 3.7 pCi/g at 100 cm. At the Riverside Reservoir study area, trench samples from site F0 show a decrease from 0.6 pCi/g at the surface to 0.5 pCi/g at 100 cm. At Riverside Reservoir site S0 the trench samples show a decrease from 0.5 pCi/g at the surface to 0.4 pCi/g at 100 cm.

Radon Emanation Results

Measurements of the relative emanation power of 19 soil samples from the two study areas show emanation powers ranging from 10 to 71 percent. The average emanation power of the samples from the Riverside Reservoir study area is 35 percent with a standard deviation of 22 percent. The average emanation power of the samples from the Miner's Lake study area is 34 percent with a standard deviation of 18 percent. The average emanation power of all of the samples is 34 percent with a standard deviation of 19 percent.

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# CONCLUSIONS

The primary conclusion from this study is that surface gamma-ray measurements can be used to estimate the amounts of radon in soil gas. This conclusion must, however, be qualified by the facts that soil permeability can significantly affect radon movement and the soil chemistry will differ from one region to another. This latter fact will change the relationship between the surface gamma-ray data and the radon concentrations in soil gas. What this means is that a relationship determined for soils in Colorado will not be correct for soils in locations with significantly different climatic and near surface geochemical environments.

The data obtained as part of this study do show a temperature dependence of the Ra-226 concentrations measured by in situ gamma-ray instruments but no such dependence was observed in the radon concentrations in the soil gas. We believe that the observed temperature difference was caused by the expansion and contraction of the air which resulted in apparent changes in the concentration of Bi-214 in the air.

The comparison of the ground measurements to the aerial measurements suggested that the calibration of the aerial measurements is wrong. The data further suggest that the adjustments made to bring the helicopter and fixed-wing surveys into agreement may also be incorrect. An alternate explanation for the different factors needed to make ground measurements agree with the helicopter and fixed-wing data is that the flight geometry of the helicopter data (which was in a valley with surrounding hills) was not consistent with the way the ground measurements were made. We do not believe this alternate explanation to be the correct one.

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