Paper

RADON MEASUREMENTS IN UNDERGROUND DWELLINGS FROM TWO PREFECTURES IN CHINA

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Abstract—**Radon, an established lung carcinogen, remains the single most important environmental radiation exposure. Yet, an excess of lung cancer from breathing radon in homes has not been consistently demonstrated in studies conducted to date. To address several major problems that have hindered previous studies of lung cancer and radon in homes, we have embarked upon a lung cancer case-control study in Gansu Province, China, where a substantial proportion of the population live in underground dwellings. In this paper, we report on results of a pilot study in which radon measurements were made for 3 days in the summer in 40 homes under normal occupancy conditions using short-term E-PERM detectors and for 6 months from February through August in 49 homes using long-term alpha-track detectors. Useable E-PERM data were obtained from 38 homes and useable alpha-track data from 47 homes. For both types of detectors, measurements were approximately log-normally distributed. Arithmetic and geometric means were 233 and 185 Bq m^{-3} (range 74–1,590 Bq m^{-3}) for E-PERM measurements and 165 and 158 Bq m^{-3} (range 74–592 Bq m^{-3}) for alpha-track measurements, respectively; 68% of E-PERM measured homes and 55% of alpha-track measured homes exceeded 148 Bq m^{-3}. Alpha-track measurements made at the entry, middle, and rear areas of the underground dwellings did not differ significantly (arithmetic means of 168, 162, and 165 Bq m^{-3} with standard deviations 63, 73, and 48, respectively), which suggests that air circulation may be minimal. The underground dwellings measured in the pilot study had high radon levels and the underground dwellers may provide an excellent population for studying indoor radon and risk of lung cancer.**
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INTRODUCTION

THE PRESENCE of radioactive radon gas (^{222}Rn) and its decay products in homes may represent a major cause of lung cancer in the U.S. and in many parts of the world (Lubin et al. 1994; NRC 1988; Samet 1989). Preliminary to an epidemiologic study of lung cancer and residential radon exposure, with 900 cases and twice as many controls, we conducted a series of long-term and short-term measurements of radon in Gansu Province in northwest China, where a large proportion of the population live in a unique style of housing constructed entirely underground, *yao-dong* in Chinese, literally "cave dwelling." The goals of the measurement study were to demonstrate that underground dwellings can indeed have high radon levels and that the conduct of a measurement protocol was feasible in this remote area. This paper presents results of the pilot study of radon concentrations.

STUDY AREA

The pilot study was conducted in Pingliang and Qingyang Prefectures in Gansu Province, a predominantly rural area of approximately 4 million people. The area is part of a larger 2,000 X 600-kilometer region composed principally of loess soils. Inhabitants have been living in underground dwellings for more than 1,000 years (Golany 1992). Prior to 1949, most residents in the two prefectures lived in underground dwellings. Since 1949, some families, particularly younger or more affluent families, have moved to above ground homes. Currently, it is estimated that about 50% of the population lives in homes built underground, with the remainder living in aboveground homes.

UNDERGROUND HOUSING TYPES

The underground dwellings are generally, constructed around a courtyard, with each room consisting of a tunnel 5–10 m in depth. Air circulation is limited due to a single entrance and windows only on the courtyard-facing wall. Indoor temperatures are generally diurnally stable. Summer temperatures are comfortable, while

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winter temperatures, though stable, are not sufficient and an active heating system is required (Golany 1992).

There are five design categories of homes, depending on their position relative to ground level and type of construction: (1) *Underground cave dwellings* (UGCD) are homes with the entrance/courtyard entirely below ground level; (2) *Open-cut cave dwellings* (OCCD) are homes with rooms tunneled into the side of a hill and with the entrance/courtyard partially below ground level or fronted by a berm; (3) *Ground cave dwellings* (GCD) are homes built into the side of a hill with the entrance/courtyard unobstructed; (4) *Aboveground cave dwellings* (AGCD) are homes built on the surface, but with a thick-walled construction and an interior room design of high cylindrical ceilings that is similar to housing types (l)-(3). AGCD homes generally have more windows than the true underground types (i)-(iii), but fewer windows than more traditional, Chinese aboveground homes; and (5) *Standard aboveground dwellings* (SAGD) are homes built in a style more typical of China, with one or two stories, a single ridged roof and rectangular rooms, often built around a courtyard. Fig. 1 is a photograph of a typical UGCD. Fig. 2 shows approximate interior dimensions for a room in a cave-type home. Although configuration of the underground dwellings may vary, homes are substantial and include living, cooking, and sleeping areas and are usually electrified (Fig. 3). Heating is accomplished in a stove burning coal or other biomass in which the chimney is routed under a sleeping platform, called a *kang* before being vented outside. Fuel is added to the firebox through an access door which may be located either inside or outside the house.

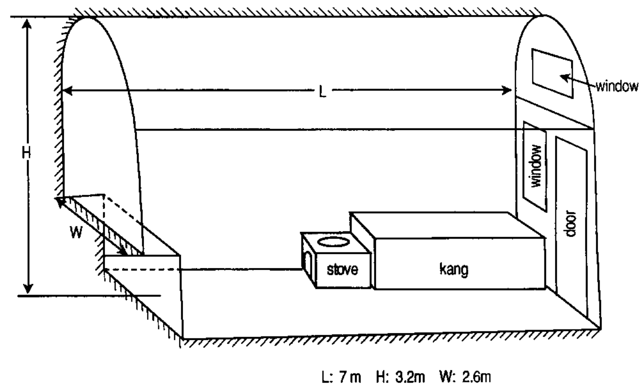

Fig. 2. Dimensions of a typical room (cave) of an underground dwelling.

Fig. 3. Interior of a typical underground dwelling.

MEASUREMENT PROTOCOLS

Two measurement protocols based on short-term and long-term measurement devices were developed and conducted in 1992–93. Houses for the pilot study were selected to include the five types of dwellings. Houses were not selected randomly, so results may not be directly generalizable to residences in the area. The principal criterion for inclusion in the pilot study was accessibility and there was no expectation that the selected houses had unusual radon levels. Because this was a pilot study, quality assurance procedures were limited to co-located detectors and blank detectors.

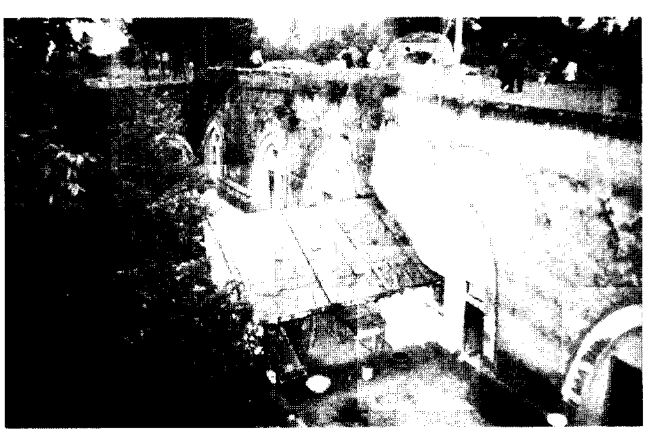

Fig. 1. Surface view of an underground cave dwelling.

Data were analyzed using standard normal linear regression techniques, with the logarithm of Bq m^{-3} as the dependent variable and dwelling type, detector location, and other factors as regressor variables (Draper and Smith 1966). Matched t-tests were employed to evaluate differences in paired detectors. For co-located detectors, i.e., pairs placed side-by-side, we computed coefficients of variation (COV). For co-located detectors, Environmental Protection Agency (EPA) quality assurance guidelines suggest not more than 5% (warning level) and 1 % (control level) of COV values should exceed 0.20 and 0.26, respectively (U.S. EPA 1993; Goldin 1984).

Short-term measurements

The short-term measurements were carried out (1) to assess the radon levels in underground dwellings as a prelude to the long-term measurements in the full scale study; and (2) to evaluate the use of short-term measurements in the full-scale study as a backup procedure for

Table 1. Distribution of short-term measurements of radon concentration in Bq m^{-3} by type of dwelling, using E-PERM detectors.

	Arithmetic		Geometric			
Type[a]	Mean	SD	Mean	SD	Range	No.
GCD	213	91	201	1.5	137–315	3
OCCD	315	373	231	2.0	102–1,591	15
UGCD	169	45	164	1.3	107–248	10
AGCD	205	94	185	1.7	81–300	5
SAGD	149	100	123	2.0	59–289	5
Total	232	246	186	1.8	59–1,591	38

[a] Dwelling types include GCD = ground cave dwelling; OCCD = open cut cave dwelling; UGCD = underground cave dwelling; AGCD = aboveground cave dwelling; and SAGD = standard aboveground dwelling.

lost or defective alpha-track measurements. For short term measurements, we used E-PERM detectors, an acronym derived from Electret Passive Environmental Radon Monitors.[¶] These devices consist of a dielectric material enclosed within an ion chamber to enable long-term storage of electric charge. The electret produces a strong electrostatic field that attracts oppositely charged ions that are formed during radon decay. Radon concentration in the ion chamber is measured in terms of the drop in voltage potential (Kotrappa et al. 1988). The device is available with two types of electrets, “short-term” (high sensitivity) and “long-term” (low sensitivity) (Kotrappa and Stieff 1992). For our measurements, we used the short-term type of E-PERM.

In June 1992, 50 E-PERM devices were placed by trained study personnel for 3 days in 40 homes, 5 standard aboveground dwellings (SAGD), 5 aboveground cave dwellings (AGCD) and the remainder in underground cave dwellings. In 10 OCCD types, co-located devices were placed. Data from 6 detectors were unusable because placement or retrieval dates were missing, detectors were prematurely closed by the homeowners, or were defective. A total of 38 homes were evaluated: 3 GCD, 15 OCCD, 10 UGCD, 5 AGCD, and 5 SAGD (Table 1).

The E-PERM devices were calibrated and read by technical personnel at the U.S. Environmental Protection Agency. E-PERM measurements can be affected by gamma rays. Lacking direct gamma ray measurements in the dwellings, E-PERM measurements were therefore adjusted using default gamma ray levels 2.6n C $kg^{-1} h^{-1}$ (10 μ R h^{-1}).

Long-term measurements

For long-term measurements, we used alpha-track devices,[#] which consist of plastic film enclosed in a filter-covered container. Alpha decay produces tracks in the film, with the number of tracks per unit time approximately proportional to radon concentration. At the completion of the measurement period, the plastic is chemically treated, the tracks enlarged through etching, and the number of tracks per unit area counted (Lovett 1969; Urban and Piesch 1981; Alter and Fleischer 1981; Savage 1983; George and Langner 1986).

A total of 49 underground houses were measured using alpha-track measurement devices in place for 6 months from February through August, 1993. Only cave-type dwellings were measured. A total of 294 devices were placed, 6 in each home. Two devices were co-located above the front entry and away from possible drafts, two in the middle of the room and two at the back of the room, as distant from the entry as feasible. When possible, detectors were suspended from the ceiling. After 6 months, devices were removed by study personnel, sealed, and returned to the U.S. for evaluation.

RESULTS

Short-term measurements

Fig. 4 (upper panel) shows radon concentrations for the E-PERM devices plotted against standard normal quantiles and suggests that data are approximately log-normally distributed, although with some uncertainty in the upper tail. Table 1 shows the arithmetic mean (AM) and arithmetic standard deviation (ASD) and geometric mean (GM) and geometric standard deviation (GSD), overall and by housing type. Overall, the AM was 232 Bq m^{-3} with ASD 246 Bq m^{-3} (6.3 pCi L^{-1} with ASD 6.7), while the GM was 186 Bq m^{-3} (5.0 pCi L^{-1}) with GSD 1.8. The median concentration was 180 Bq m^{-3} (4.9 pCi L^{-1}). The maximum measurement was 1,591 Bq m^{-3} (43 pCi L^{-1}), more than twice the next highest 577 (15.6 pCi L^{-1}). While there was no indication that the maximum value was erroneous, omitting the single value reduced the AM to 195 Bq m^{-3} (5.3 pCi L^{-1}) with ASD 98 and the GM to 176 Bq m^{-3} (4.8 pCi L^{-1}) with GSD 1.6.

The mean concentrations for all dwelling types exceeded 148 Bq m^{-3} (4.0 pCi L^{-1}), the recommended action level in the U. S., and means did not differ statistically by dwelling type ($p = 0.28$). The mean for the AGCD type did not differ significantly from the three underground dwelling types ($p = 0.76$). The contrast between the cave-type dwellings (GCD, OCCD, UGCD, and AGCD types) and the SAGD type suggested that the standard aboveground houses had a lower radon concentration, $p = 0.08$.

[¶] RadElec Inc., Frederick, MD.
[#] Track-etch, TechOps-Landauer, Glenwood, IL.

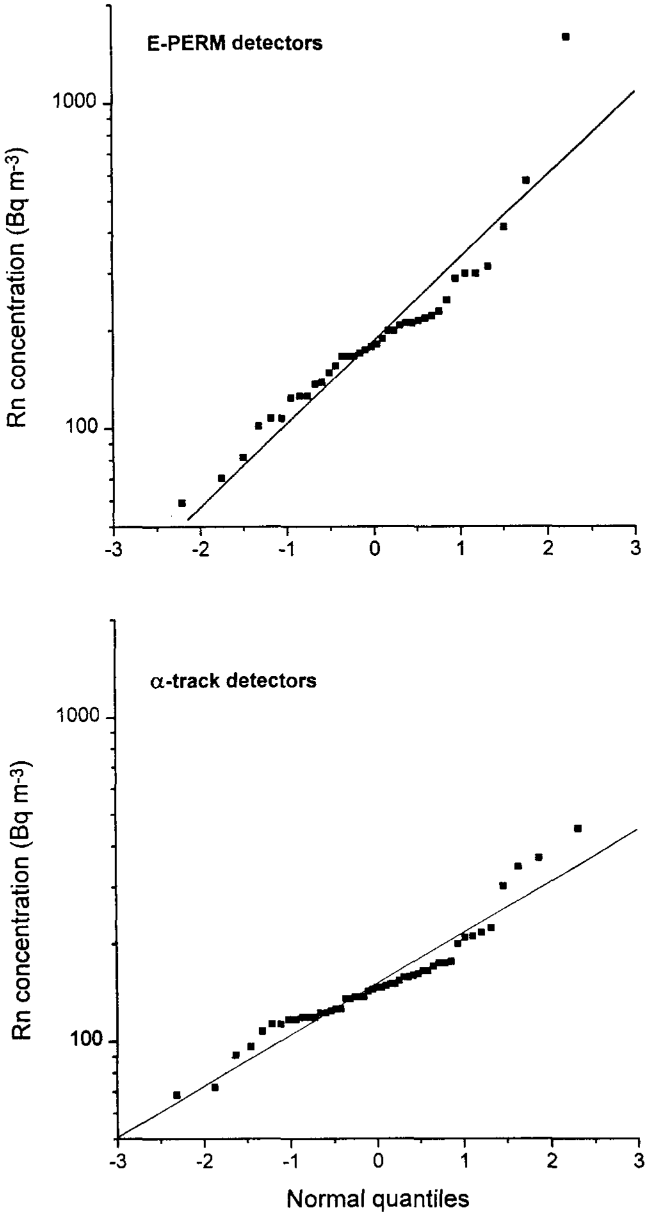

Fig. 4. Radon concentrations by standard normal quantiles for short-term E-PERM devices (upper panel) and long-term alpha-track devices (lower panel). Solid line denotes expected values for a log-normal distribution of measurements. For comparability, E-PERM distribution excludes measurements from standard type above ground dwellings.

In five homes, we placed co-located E-PERM devices. The paired means in Bq m^{-3} (pCi L^{-1}) were 115 and 89 (3.1 and 2.4), 118 and 130 (3.2 and 3.5), 144 and 133 (3.9 and 3.6), 229 and 192 (6.2 and 5.2), and 185 and 215 (5.0 and 5.8); COVS for the co-located pairs were 0.18, 0.06, 0.06, 0.12, and 0.10, respectively—all less than the 0.26 recommended control level. For a sixth home, the pair of measured values was markedly different, 215 and 940 Bq m^{-3} (5.8 and 25.4 pCi 1^{-1}) with COV 0.89, but debris was found on the surfaces of the electret and the readings were therefore deemed unreliable.

Long-term measurements

Fig. 5 shows the COV for each co-located pair of detectors. Since the COV was unrelated to radon concentration, the abscissa for each panel was house sequence number based on the ordered COV value for the pair placed at the back of the room. For the 49 houses with 147 co-located pairs, 11 COVS exceeded the 5% warning level, with 7.5 expected, and 5 COVS exceed the 1% control level, with 1.5 expected. Fig. 5 shows that two houses presented a particular problem, with the COV for 4 of 6 pairs in excess of the 5% level. The two houses had paired values 611 and 440, 104 and 89, and 1,195 and 784 Bq m^{-3} with COVS 0.23, 0.11, and 0.29 for the front, middle, and back detectors, respectively, and 592 and 485, 263 and 159, and 703 and 1,069 Bq m^{-3} with COVS 0.14, 0.35, and 0.29. Omission of these two houses resulted in 7 and 2 COV values out of 141

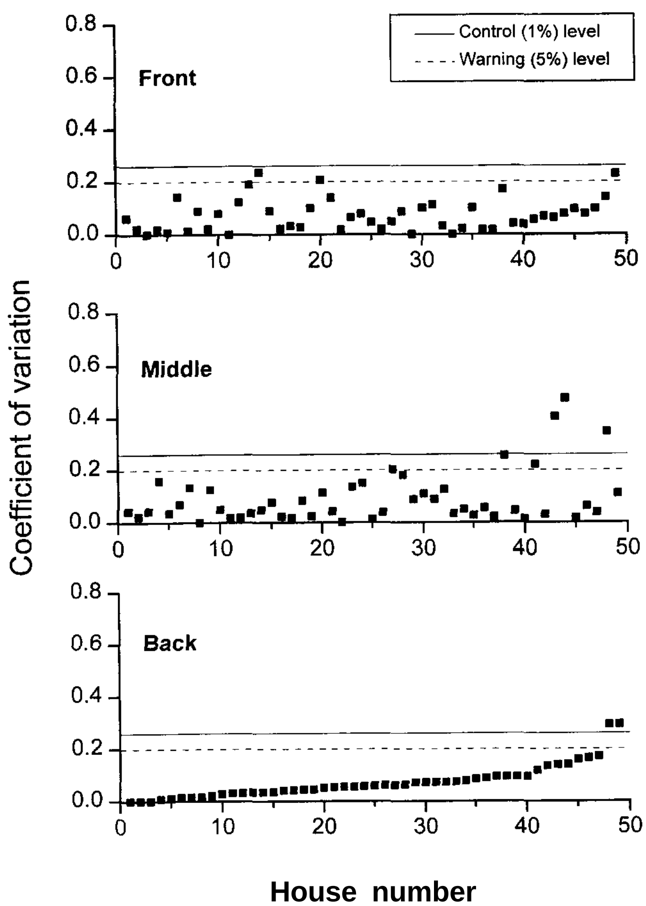

Fig. 5. Coefficient of variation (COV) for radon concentration measurements of co-located (paired) alpha-track devices placed at the front, middle, and back of the principal living room in 47 underground dwellings. Abscissa co-ordinates are ordered based on co-located COV values from the back of the room.

exceeding the 5% and 1% levels, respectively, with 7.1 and 1.4 expected.

It is uncertain why measurements for the two homes differed so substantially. One of the pair could have been inadvertently obstructed or otherwise invalidated, since it is unlikely that such differences could have arisen by chance. For the remaining results, measurements from these two homes are omitted.

Fig. 4 (lower panel) shows radon concentrations for the alpha-track devices plotted against standard normal quantiles and suggests a distribution light in the lower tail and heavy in the upper tail relative to a log-normal distribution. The overall AM was 165 Bq m^{-3} with ASD 56 (4.5 pCi L^{-1} with ASD 1.6), while the GM was 159 Bq m^{-3} (4.3 pCi L^{-1}) with GSD 1.3 (Table 2). Radon concentrations differed significantly by housing type *(p* = 0.01), with aboveground cave dwellings, AGCD, having the lowest mean radon level. For the three underground types, the test for a difference in mean radon levels did not reach statistical significance *(p* = 0.08).

Table 3 shows AMs by housing type and location within the room. There were no significant differences in mean by location within dwellings (*p* = 0.84), suggesting homogeneity of radon levels within the indoor environment.

Table 3. Arithmetic mean and standard deviation (SD) of alpha-track measurements of radon concentration in Bq m^{-3} by type of dwelling and location of detector relative to the entryway. Results omit data from two homes with anomalous readings.

	Location of detector			
Type	Front	Middle	Back	No. of homes
GCD	200	207	184	14
OCCD	157	147	156	15
UGCD	164	151	171	14
AGCD	116	93	109	4
Total	169	162	165	47
SD	63	73	48	

Comparison of measurement devices

Finally, we pooled all E-PERM and alpha-track measurement data for the four types of cave dwellings (GCD, OCCD, UGCD, AGCD). As suggested by Tables 1 and 2, mean radon concentration was higher for the houses measured with the short-term E-PERM device (232 Bq m^{-3}) than with the long-term alpha-track device (165 Bq m) *(p* = 0.04), even after adjustment for housing type *(p* = 0.04). In the pooled data, radon concentration levels did not vary significantly by cave type *(p* = 0.48).

DISCUSSION

There have been seven large-scale case-control studies of indoor radon and lung cancer (Table 4), and results for the risk effects of radon concentration have been mixed (Lubin 1994). The lack of definitive results from these studies may be due to several factors: low mean radon levels, resulting in a small excess risk; misspecification of exposure from the use of contemporary radon measurements to estimate exposures in years past; high mobility of subjects, resulting in gaps in the reconstruction of past radon exposures and a narrowing of the range of exposures; alterations to houses; and use of area measurements in one or two rooms, ignoring other sources of exposure inside and outside the home. The residents of Gansu province offer the opportunity for a case-control study of indoor radon and lung cancer that may overcome many of these limitations. In particular, radon levels in the study area may be substantially higher than in previous studies (Table 4).

Precise estimates of radon levels in homes in the two prefectures are problematic, since our sample was not random and since about 50% of residents do not live in cave-style homes. However, in our selected sample, above ground homes also had high radon levels; 40% (two of five) of standard construction homes and 44% (four of nine) of aboveground cave dwellings exceeded 148 Bq m^{-3}, although the number of above ground houses was small, and the applicability of these percentages to entire population is uncertain.

Radon levels measured with E-PERM devices were significantly greater than levels measured with alpha-track devices. The reasons for this difference are difficult to discern, but may have been due to a chance selection of homes or to special conditions that may have prevailed during the three days of testing. E-PERM measurements were conducted in the summer, when it would be expected that radon concentrations were at their lowest levels. For example, in one area of the U.S. summer measurements have been as much as one-half to one-third annual values (Borak et al. 1989). At the time E-PERM devices were placed, residents were given no special instructions regarding their daily activity or the opening and closing of windows and doors. It is also

Table 2. Distribution of long-term, alphti-track measurements of radon concentration in Bq m^{-3} by type of dwelling. Results omit data from two homes with anomalous readings.

	Arithmetic		Geometric			
Type	Mean	SD	Mean	SD	Range	No. of homes
GCD	197	71	187	1.4	134–357	14
OCCD	154	24	152	1.2	118–194	15
UGCD	162	53	156	1.3	110–311	14
AGCD	106	20	105	1.2	94–136	4
Total	165	56	158	1.3	94–357	47

Table 4. Comparison of radon concentration levels for residential radon studies based on year-long alpha-track measurements, except where noted.

Study area	Mean (Bq m^{-3})	Upper range
Winnipeg, Canada (Létourneau et al. 1994)	118[a]	25% above 148 Bq m^{-3}
Shenyang, China (Blot et al. 1990)	85[b]	20% above 148 Bq m^{-3}
Finland (Ruosteenoja 1991)	211[c]	40% above 184 Bq m^{-3}
Missouri, USA (Alavanja et al. 1994)	67	7% above 148 Bq m^{-3}
New Jersey, USA (Schoenberg et al. 1990)	22[b]	1% above 148 Bq m^{-3}
Stockholm, Sweden (Pershagen et al. 1992)	130	28% above 152 Bq m^{-3}
Sweden (Pershagen et al. 1994)	107[d]	25% above 115 Bq m^{-3}
Gansu Province[e]	198	64% above 148 Bq m^{-3}

[a]Based on bedroom measurements.
[b]Median radon value.
[c]Derived from two-month measurements made in winter.
[d]Derived from three-month measurements made in winter.
[e]Based on four types of cave dwellings; means for 3-d E-PERM and 6-mo alpha-track measurements were 245 and 165 Bq m^{-3}, respectively. Two of five (40%) standard construction, aboveground houses exceeded 148 Bq m^{-3}.

unlikely that the differences in radon levels were due to calibration differences, as the calibration for E-PERMs are expected accurate to about 5% (Kotrappa et al. 1988), or to gamma ray levels, as anecdotal data suggest levels are near the default values which were used for calibration. Thus, at this time, reasons for these differences remain largely unresolved; however, the higher values may be a further indicator of limited ventilation in underground dwellings and of little seasonal variation in radon levels.

In summary, radon concentrations in underground dwellings in our sample exceed those in current epidemiologic studies of indoor radon. As a result of the high radon levels found in our sample and anecdotal evidence of low population mobility and little or minimal modification to homes, we anticipate a wide range of exposures, including cumulative exposures which have been found associated with significant excesses of lung cancer in miners.

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