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Publication Date
2008-10-15

LBL-33681
UC-402

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ENERGY & ENVIRONMENT DIVISION

To be presented at the Indoor Air '93, The Sixth International Conference on Indoor Air Quality and Climate, Helsinki, Finland, July 5–8, 1993, and to be published in the Proceedings

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January 1993

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Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

To be Published in Proceedings of Indoor Air '93, the 6th International Conference on Indoor Air Quality and Climate, July 5-8, 1993, Helsinki, Finland

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This work was supported by the Director, Office of Energy Research, Office of Health and Environmental Research, Health Effects and Life Sciences Division, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

THE DISTRIBUTION OF EXPOSURE TO RADON: EFFECTS OF POPULATION MOBILITY

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ABSTRACT

The distribution of population exposures to radon, rather than the distribution of indoor radon concentrations, determines the fraction of population exposed to exceptionally high risk from radon exposures. Since this fraction at high risk has prompted the development of public policies on radon, it is important to first determine the magnitude of this fraction, and then how it much would decrease with different implementation program options for radon mitigation. This papers presents an approach to determining the distribution of population exposures to radon from public domain data, and illustrates it with application to the state of Minnesota. During this work, we are led to define a radon entry potential index which appears useful in the search for regions with high radon houses.

INTRODUCTION

For assessing the fraction of population at substantial health risk from indoor radon, it is the estimate of the distribution of individual exposures--rather than of house concentrations--that is required. Such estimates would be useful for assessment of the costs and benefits of health risk reduction arising from different strategies for controlling radon in the U.S. housing stock. Examinations of consistency of the public policy on mitigation of indoor radon with the treatment of other health risks would also find such estimates useful.

The frequency distribution of human exposures to radon differs from the distribution of indoor radon concentrations, because most people move between several different exposure settings over their lives. The most important exposure setting, the residential one, is the subject of this work. Most people live in several or many homes during their lives. Their lifetime exposures thus arise from the time-weighted averages of radon concentrations in these houses. For estimating the distribution of radon exposures among the populations, one must therefore know, not only the distribution of radon concentrations in the housing stock but also how the population has moved within this stock.

The problem is carefully posed as estimating the distribution of the lifetime-average residential exposure *rate* to radon. This has the advantage that the results can be directly compared to the distribution of indoor radon concentrations. (Exposure rates and indoor radon concentrations have the same units.) The net exposure rate can be obtained by a procedure similar to that outlined here, but with time-activity data for the population folded in to provide appropriate occupancy rates in different locations (residential, occupational indoors, and outdoors), as was undertaken in a similar study for California residents for whom detailed time-activity data are available (1).

We present an approach to estimating the distribution of residential radon exposures rates using existing data on the frequency distribution of indoor concentrations and census data on population mobility. We demonstrate this approach by its preliminary application to data for Minnesota.

METHODS AND DATA SOURCES

Our approach is to construct the exposure rate distribution using a statistical analog, using the Monte Carlo method, from the regional distributions of indoor radon concentrations and mobility patterns. We first construct (or derive) distributions of residential living-level radon concentration for Minnesota regions, and a transition probability matrix for moves between and within these regions and also for migration into and out of Minnesota. Simulations of indoor exposures accumulated by 10,000 persons over their lifetimes are then carried out. In-or out-migration of the persons is also simulated. Based on the simulations for the 10,000 persons, the distribution of exposure rates is obtained and characterized.

Indoor radon concentration distributions have been found to be close to lognormal for many data sets (2), with a few exceptions where the distribution could be closely approximated by a mixture of two (or, in any case, very few), lognormal distributions (3). The conformity of the indoor concentration distribution to lognormality can be expected to be high for houses located in geographical proximity (similar climates, soils, and with similar building construction characteristics). Counties provide a convenient spatial scale for grouping houses both because of relative geographical homogeneity, as in Minnesota, and because population mobility data on a county basis are easily available. However, in this work, the small numbers of radon survey data points for the individual counties force us to cluster counties expected to have similar radon distributions. The subsequent treatment is then at the aggregation level of county clusters, rather than at individual counties. This could change as more data become available for individual counties.

Transition Probability Matrix

The transition probability matrix provides an estimate, for each county, of the probabilities that during a given interval (here 5 years), a resident would either stay in the same home, or would move to another home in the same county, or would move out to each of the other counties represented in the matrix. In this work, the transition matrix is limited to Minnesota. A row and a column are assigned to each of the Minnesota counties. An additional column is assigned to represent those who did not move at all (i.e. stayed in the same house in the same county, as opposed to moved to another house within the same county). Finally, one more row and column are added to represent the world outside Minnesota (the rest of the U.S. and also other countries). Thus for the 87 counties of Minnesota, the size of the transition matrix is (88×89). The value of $(i, j)^{th}$ element of the transition matrix equals the probability of a person moving from county i to county j, within 5 years. The matrix is derived from the 1980 U.S. Census (4).

Ideally, the integration period for the transition matrix definition should be much shorter than the mean time between moves. Since it is not, the number of missed moves in the intervening period might be significant. This would underestimate the reduction in the GSD from population mobility. Thus the results provide a useful upper limit on the spread of the real distribution.

For this work we assume that the patterns of migration in Minnesota have not changed significantly from those measured in 1980 census, and will stay the same throughout the simulated lifetimes of the 10,000 individuals in the study.

Long-term Living-level Radon Concentration Distributions

Indoor radon concentrations in homes are principally surveyed using one of the two methods: short term (typically two to three days) screening tests, usually based on charcoal cannisters, and long-term tests based on alpha track detectors (ATDs). However, indoor radon levels are highly variable (by over a factor of 10 within a day). In addition, a large time-scale seasonal variability is often observed. ATDs are placed at the living levels, while the charcoal cannisters are placed at the lowest level, almost always the basement for Minnesota houses. Thus the ATD results are a far better indicator of the radon concentrations to which the house occupants are actually exposed. Surveys using charcoal cannisters are cheaper and easier to organize than those using ATDs.

During the late 1980's, the U.S. Environmental Protection Agency (EPA), as part of its program of radon surveys in individual states, conducted a survey of radon concentrations in Minnesota homes in association with the Minnesota Department of Health (MDH), Section of Radiation Control (5). The sample consisted of 1003 single family homes that met the EPA requirements for state surveys. (These requirements exclude rental units, apartments or multiple family residential units. This exclusion will bias slightly upwards the estimate of population lifetime exposure to radon based on these data.) Radon concentrations in the sampled houses were monitored with charcoal cannisters, according to the EPA screening protocol. Ninety seven houses, randomly chosen out of the 1003, also received two or more alpha track detectors (ATDs).

The ATD data are not numerous enough to directly estimate the long-term living-level radon distributions in different parts of Minnesota. Therefore we must rely on the relatively more abundant data from charcoal screening tests. Even these data are not sufficiently numerous to obtain the radon concentration distribution for each county. So we grouped the counties into county-clusters, each with an adequate number of screening test data. These data were then transformed to obtain the distribution of living-level annual average radon concentrations.

Several workers (e.g. 6, 7) have studied the relationship between the results of short-term and long-term radon measurements for individual houses. However, the transformations for individual houses are not appropriate for transforming distributions of short-term tests into distribution of long-term living-level concentration data. For this transformation, we used the following simple method. The screening test data for Minnesota were fitted to a lognormal distribution, as were the ATD data (representing the annual average living levels). Ratios between the GMs and GSDs of the two distributions were then obtained. We assumed that these ratios hold for each of the regional county clusters. This allows us to obtain the distribution of annual average living level concentrations for each regional county cluster from the distribution of screening test results for houses in that cluster. A more systematic approach to undertake this transformation requires more data than are available, and its discussion would be out of place in this brief paper.

The 1003 data points from the screening tests have a GM of 127 Bq/m^3 (3.43 pCi/l), and GSD of 2.27. The 97 data points from ATD tests have a GM of 82 Bq/m^3 (2.22 pCi/l), and a GSD of 2.68.

Clustering Scheme

The four significant locational factors affecting indoor radon concentrations are: 1) soil radium content, 2) soil radon emanation coefficient, 3) soil permeability, and 4) climate. Similarity in the last factor, the climate, is assured by requiring that only neighboring counties (forming a contiguous area) will be put together in a cluster. For estimating the first three factors, we used two data sets in the public domain: the NURE data set and the detailed surface geology maps of Minnesota counties. These are described below.

NURE refers to the airborne survey of most of the continental U.S carried out during 1973-1983 by the Department of Energy for the National Uranium Resource Evaluation (NURE) Program. These data (with some limitations) provide direct estimation of the radium concentration in the surface soils or rocks of the United States. The GMs of county-wide radium concentrations obtained from the NURE data by Revzan et al. (8) were used as a numerical score for radium concentrations in the near-surface soils in Minnesota.

The emanation coefficient (also sometimes called the emanation fraction) equals the fraction of radon generated in the soil grains (as a result of radium decay) that reaches the soil pores, and thus becomes part of the soil-gas. Detailed soil survey maps, prepared under the Minnesota Soil Atlas Project by the Agricultural Experimental Station, University of Minnesota show (on a scale of 1:250,000) the soil type within the first 2 meters of the soil-surface, and the soil type underneath. We assigned scores for the emanation coefficient and permeability qualitatively for each soil combination, as shown in Table 1. Since each county is comprised of several different soil types, we arithmetically averaged the numerical scores for emanation coefficient for the soils for each county weighted by the fraction of the county area belonging to each soil type. This yielded a second numerical score, for radon emanation coefficient for each county. Similar treatment of soil permeability yielded the third numerical score, for the soil permeability for each county.

Table 1: Qualitative Scores for Emanation Coefficient and Permeability by Soil Type

Soil Type	Emanation	Permeability
Sandy on Sandy	Low	High
Sandy above or below Loamy	Low to Moderate	High
Loamy on Loamy	High	Moderate
Loamy above or below Clayey	Moderate to High	Moderate
Clayey on Clayey	Low to Moderate	Low
Rocky and Loamy, or Rocky	Low to Moderate	Low
Peat	High	High

The following numerical values were assigned to each of the above classification.

Low = 1
Low to Moderate = 1.5
Moderate = 2
Moderate to High = 3
High = 4

Next, each of the three scores were rescaled to span a range that more closely reflects our (subjective) assessment of the relative importance of the parametric variation on radon entry. The ranges selected were (1-100) for radium content, (1-100) for soil permeability and (30-100) for emanation coefficient. Alternate range selection are possible and were experimented with. However, these alternate selections lead to substantially the same county clusterings. The scores were combined to obtain a numerical score for the radon entry potential index, REPI, for each county defined as the product of the three rescaled indices.

As an aside, we checked and found good correlation between the county REPI scores and the GMs of the radon data from those counties. This has led to further development of the indexing methodology for the search for areas in the U.S. where most of the high radon houses (e.g., indoor annual average concentrations more than 740 Bq/m^3 (20 pCi/l)) may be located.

Based on their REPI scores, the 87 Minnesota counties were organized into 14 clusters. Cluster definition was guided by three rules:
1) Each cluster must have at least 45 screening test data points,
2) Each cluster must be a contiguous group of counties, and
3) The counties in each cluster should have REPI scores close to one another.
Rules 1 and 2 were applied rigorously, and within the constraints imposed by them, rule 3 was implemented as far as possible.

Estimating the Exposure Rate Distribution

Distribution of charcoal data for each cluster was converted into the distribution of annual-average radon concentrations using the transformation extracted from all the Minnesota data. These distributions formed the basis of the calculations of lifetime accumulated indoor radon exposure rates. Simulations with the bootstrap method directly using transformed data points (rather than fitted lognormals) give practically the same results as presented here.

The transition matrix described earlier was used to simulate the lifetime indoor radon exposure for 10,000 persons. Simulations were undertaken for three slightly different cohorts of population: those born in Minnesota, those currently residing in Minnesota, and those who will be Minnesota residents at the time of their death. The simulations did not distinguish between male and female populations (which have somewhat different lifespans), although this feature could be modeled if desired.

The life-span of each simulated person was chosen based on the (1987) U.S. life-tables. Having selected the life-span, the county cluster of this person's birth was selected randomly, the probabilities being weighted by the cluster populations. The residential mobility of this person was then simulated over the selected life-span, recalculating the residential location every 5 years with the transition matrix. The indoor radon concentration in each residential location was randomly selected from the distribution of annual average living level radon levels for that county cluster, estimated as described above.

At the end of the life-span, the average rate of radon exposure for the person was calculated. To keep the age distribution of Minnesota population unaffected by the in- and out-migration, a person moving out of Minnesota was matched with a person moving into Minnesota of the same age and lifespan. Owing to the current small net out migration from Minnesota however, only 99.19% of the out-migrants were so matched. Each matched in-migrant brought his/her own exposure history. This history was simulated assuming random moves within the U.S. residential radon concentration distribution (2) at 5-year intervals, with a move probability equal to the total move probability over the same period for Minnesota residents.

RESULTS

The exposure rate distributions for the three cohorts are essentially the same. As expected, they are significantly narrower than the distribution of annual average living level radon concentrations. The distribution for the cohort of native-born Minnesotans has a GM of 80 Bq/m^3). Those for the cohorts of the current Minnesota residents, and those that will be Minnesota residents at the time of their death, have GMs of 76 and 80 Bq/m^3) (2.0 and 2.1 pCi/l) and GSDs of 1.74 and 1.75 respectively. Note that these GSDs are significantly smaller than the GSD for the distribution of ATD results, 2.68.

The annual average living level radon concentration distribution (smooth curve) and the radon exposure rate distribution of the cohort of current Minnesota residents (histogram) are shown in Fig. 1. The figure excludes the top 0.04% of the concentration data since it is off scale (the maximum data point is at less than 1,800 Bq/m^3). The exposure distribution has a noticeably smaller spread (i.e. smaller GSD), and a lower tail. Thus the fraction of population with radon exposure rate equivalent to living in houses with a given high radon level is smaller than the fraction of houses having that high radon level. The difference is significant for higher radon levels. Results from such simulations would allow us to quantify the the number of persons exposed to high radon risk, and the potential reductions in this number resulting from implementation of different public radon policy options with different societal costs. That study, however, is outside the scope of this paper.

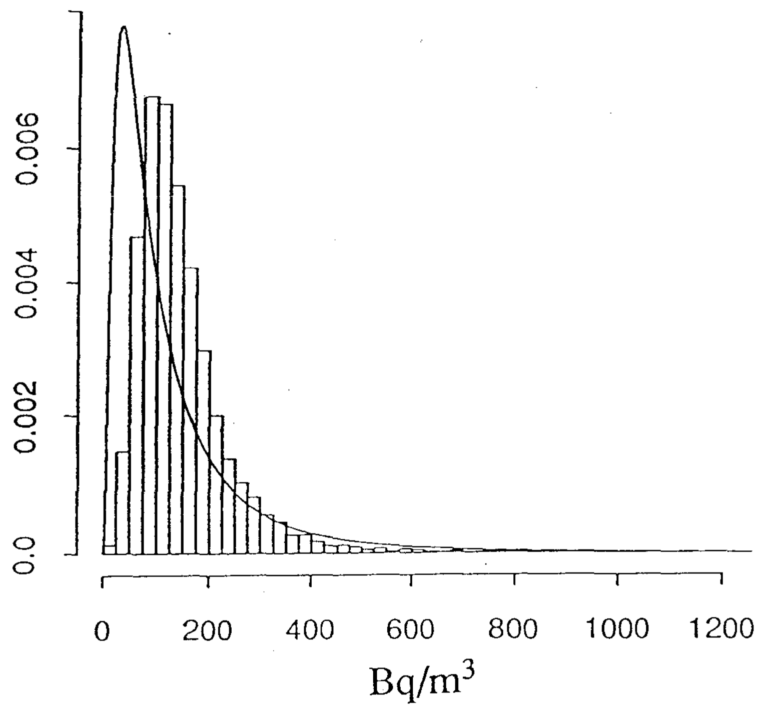

Figure 1. Exposure Rate and Concentration Distributions

CONCLUSIONS AND DISCUSSION

We have developed a method to use public domain demographic and geologic data, together with the data from State-EPA radon surveys for estimating the distribution of rate of exposure to indoor radon for the population. We have demonstrated this method by using it for preliminary estimation of exposure rate distribution of the population of Minnesota.

We have defined a Radon Entry Potential Index (REPI), and used it to define clusters of counties which are then treated as having a single distribution of screening test data. Although REPI numbers were developed for each county based purely on geological and NURE information (without any reference to the screening test data for the counties), we have found that REPI numbers correlate reasonably well with the GMs of county-level screening test distributions. This approach could be developed further, and has obvious applications for the proposed search for high-radon houses in the U.S.

The proposed method would be a useful tool for public policy assessment regarding radon mitigation, in the particular context of evaluating the fraction of population at high risk from radon exposure (and the changes in this fraction resulting from various levels and costs of radon mitigation measures in the U.S. housing stock).

ACKNOWLEDGEMENTS

We thank Y.C. Bonnefous, K. Garbesi and R.G. Sextro for valuable comments on the manuscript. This research was supported by the Director, Office of Energy Research, Office of Health and Environmental Research, Health Effects and Life Sciences Division of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

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