FINAL REPORT

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QUANTITATIVE ASPECTS OF

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HIGHLY EMANATING GEOLOGIC MATERIALS

AND THEIR ROLE IN CREATING HIGH INDOOR RADON

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Project Abstract

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Indoor radon hot spots, areas where indoor radon commonly exceeds 20 pCi/L, are often caused by unusually highly emanating soils or rock and their interaction with ambient climatic conditions and a building's architecture. Highly emanating soils and rocks include glacial deposits; dry fractured clays; black shales; limestone-derived soils; karst and cave areas, fractured or sheared granitic crystalline rocks; mine tailings; uraniferous backfill; and most uranium deposits. The above list probably accounts for 90% of the Nation's indoor radon over 20 pCi/L. In several of these high indoor radon areas, there appears to be a link between the nature of the radon source in the ground, the architecture of the home, and the relative magnitude and ease of mitigation of the indoor air problem. Quantification of geologic materials in terms of their radon potential with respect to climatic and architectural considerations has never been accomplished. Recent studies have attempted semi-quantitative rankings but rigorous analysis has not been done. In this investigation we have attempted to develop the quantitative aspects of geologic materials for prediction of very high indoor radon at several scales of observation from national to census tract.

Specific Project Objectives

The objective of this project was to quantify the geologic control on the distribution of high indoor radon, focusing on four areas of research: (1) Quantification of geologic data; (2) Calibration of geologic characteristics for the high radon homes model; (3) Application of Geographic Information Systems to the radon problem (4) Detailed site experiments

Our previous work in this program of investigation has focused on understanding the geologic processes involved with creating anomalously high concentrations of radon in soil. The nature of radon anomalies, especially those anomalies associated with shear zones in rock, glacial deposits, uraniferous granites, and limestone soils have been examined in a number of areas across the country. We have found the observational results of our research to be very effective in making broad regional and semi-quantitative predictions of indoor radon. To forecast a specific concentration of indoor radon in a specific area, however, requires quantification of these geologic processes in a manner not previously done before. Further, the interaction of climate and architecture with the radon source must be factored into any analysis of geologic control. Environmental emulation of indoor radon is one of the ultimate goals of this project. Our part of the emulation will consist of defining those geologic factors that can be imported into an analytical model for radon.

Background and Significance of Project

Previous research on geologic quantification and prediction of indoor has focused on being able to measure the source parameter (soil radon or radium) at an individual site and then factor in other parameters such as permeability into an equation to produce an index for radon availability or predicted indoor radon. Other assessments have relied on observational data at the specific site and construction of empirical models for specific geologic areas. The empirical models from these studies have been essential in making national assessments but have limitations. The work completed in this project has provided the geologic portion of a cooperative research effort between the Department of Energy (DOE) and the Environmental Protection Agency (EPA) to design and develop a methodology that will identify the proportion of homes in an area where occupants are suffering high exposures to radon decay products, specifically concentrations that exceed the occupational radiation limit, equivalent to 20 pCi/L (740 Bq/m³). This kind of an assessment has not been attempted before. Identification of high-radon homes is an important goal, since targeting these areas will permit efficient prioritizing of strategies for:

- conveying to the public specific information on high-radon areas;
- adopting associated programs to encourage and assist residents in monitoring and remediation;
- adopting area-specific procedures and codes for property transfers and new construction;
- continuing research and confirmatory investigations of high-radon areas.
- providing a quantitative national database for epidemiological studies.

Most importantly, the high homes cooperative is an exposure assessment rather than a prediction of the radon source strength.

Accomplishments

- As part of the DOE/EPA Cooperative, we appended 20 geological and soil parameters to the National Residential Radon Survey (NRRS) that was conducted by the Environmental Protection Agency. A list of these characteristics is given in Appendix A. The NRRS database contains alpha-track detector measurements of the annual-average radon concentrations in a random scientific sample of 5,694 year-round occupied housing units. The housing units are dispersed among 993 small areas in 120 counties throughout the U.S. The database contains associated data on the housing units' construction and heating, ventilation and air conditioning characteristics and data on the occupants living habits. However, the database did not contain geologic data. After augmentation of geologic data to the NRRS, a 2-step regression analysis of the data was performed and those factors which exhibit important associations with radon concentrations were incorporated into an analytical structure for a national correlation analysis.

Several demonstration projects were also conducted using the methodology in Minnesota and in the Mid-Atlantic States of EPA Region 3. USGS consulted as modeling progressed, supplying geologic information to understand anomalies and patterns of correlation. This modeling, in cooperation with Lawrence Berkley Laboratories yielded several publications. (Under this project, USGS contracted with Phil Price to complete the modeling.) Our geologic information directly contributed to:

Price, P. N., 1997, Predictions and Maps of County Mean Indoor Radon Concentrations in the Mid-Atlantic States, *Health Physics*, Vol. 72, No. 6, pp. 893-906.

- We have examined the factors for very high indoor radon in New York State and found that the black shales of the region and the soils and glacial deposits derived from them can account for the majority of high indoor radon in the state. Further classification of the geology by glacial unit can be used to discriminate between high and low concentrations of radon. This is important for evaluating very high radon in the glaciated states. See attached publication:

Gundersen, L.C.S., and Schumann, R. S, 1997, Mapping the radon potential of the United States: Examples from the Appalachians: *Environment International*, v. 22, no. 3, p.829-837.

- We examined factors that effect the emanation coefficient of soil and rocks across the United States. This research has directly contributed to understanding how geology correlates with indoor radon and has helped us understand numerous anomalies found in the correlation models developed with Lawrence Berkley Laboratory. Many of these findings were summarized in the following publication:

Schumann, R.R. and Gundersen, L.C.S., 1997, Geologic and climatic controls on the radon emanation coefficient: *Environment International*, v. 22, no. 3, p. 439-446.

- Query software for the National Uranium Resource Assessment (NURE) aerial gamma data grid file was written. The program takes a list of lat-lon locations and looks up the eU (radium), eTh, K, or total gamma-ray exposure values at that point. The NURE grid files, both on the USGS NURE CD-ROM are in several formats, and some are projected into the Albers Equal-area map projection. The computer program decodes these different formats and projects/de-projects points as necessary. Besides making the data accessible for this project, this program can be used for other purposes in the future for other environmental problems such as estimating total gamma exposure or rapidly determining the surficial uranium or radium concentration at a site.

- Working with the University of Rhode Island, we utilized a geographic information system and detailed sampling of uranium and radon coupled with indoor radon to create radon potential maps of the State of Rhode Island. These maps were displayed at the Geological Society of America meeting in March of 1995:

Veeger, A.I, Hermes, O.D., **Gundersen, L.C.S.**, Cain, J.A., D'Angelo, J., Hamidzada, N., and "The Radon Gang", 1995, Development of a geologic radon potential map for Rhode Island: Geological Society of America Abstracts With Programs, v. 27, no. 1.

Project Bibliography

Web Sites:

<http://energy.cr.usgs.gov:8080/radon/>

<http://eande.lbl.gov/IEP/high-radon/hr.html> (see Appendix B attached for the first three pages of this web site that summarize the results of the cooperative exposure prediction portion of this project.

Publications and Abstracts

Gundersen, L. C.S. and Schumann, R.R., 1995, Developing Geologic Tools for finding very high indoor radon: Examples from the midwestern and eastern United States, Proceedings of the 1995 International Radon Symposium, American Association of Radon Scientists and Technologists, Omnipress, p. III-2.

Gundersen, L.C.S., and Gates, A.E., 1995, Mechanical response, chemical variation, and volume change in the Brookneal and Hylas shear zones, Virginia: Journal of Geodynamics, v. 19, no. 3/4, p. 231-252.

Gundersen, L.C.S. and Szabo, Zoltan, 1995, Human Health and Natural radionuclides in earth, air, and water: Proceedings of the 1995 McKelvey Forum: U.S. Geological Survey Circular 1108, p. 22-24.

Gundersen, L.C.S., and Schumann, R. S, 1997, Mapping the radon potential of the United States: Examples from the Appalachians: Environment International, v. 22, no. 3, p.829-837.

Schumann, R.R., **Gundersen, L.C.S.**, and Tanner, A.B., 1994, Chapter 6--Geology and Occurrence of Radon: *in* Nagda, N.L., (ed.) Radon: Measurement, Prevalence and Control, American Society for Testing and Materials, Philadelphia, PA, p. 83-96.

Schumann, R.R., Asher-Bolinder, S., Finch, W.I., **Gundersen, L.C.S.**, Otton, J.K., Owen, D.E., Pierson, C.T., Reimer, G.M., and Zielinski, R.A., 1995, Radionuclides: Energy resources and environmental hazards (extended abstract): Energy and the Environment--Application of Geosciences to decision-making: Proceedings of the 10th V.E. McKelvey Forum on Mineral and Energy Resources: U.S. Geological Survey Circular 1108, p. 111-113.

Schumann, R.R. and Gundersen, L.C.S., 1997, Geologic and climatic controls on the radon emanation coefficient: Environment International, v. 22, no. 3, p. 439-446.

Veeger, A.I, Hermes, O.D., **Gundersen, L.C.S.**, Cain, J.A., D'Angelo, J., Hamidzada, N., and "The Radon Gang", 1995, Development of a geologic radon potential map for Rhode Island: Geological Society of America Abstracts With Programs, v. 27, no. 1.

APPENDICES:

A. Soil And Geologic Factors Appended to the NRRS Database for the High Radon Homes Project

B. Website pages on the High Radon homes Project

Reprint
Reprint C. Publication: Gundersen, L.C.S., and Schumann, R. S, 1997, Mapping the radon potential of the United States: Examples from the Appalachians: Environment International, v. 22, no. 3, p.829-837.

D. Publication: Schumann, R.R. and Gundersen, L.C.S., 1997, Geologic and climatic controls on the radon emanation coefficient: Environment International, v. 22, no. 3, p. 439-446.

Reprints removed for separate processing

APPENDIX A: Soil And Geologic Factors Appended to the NRRS Database, High Radon Homes Project

SOIL FACTORS

1. SOIL CLASSIFICATION: This is the SCS classification of the soil, for example, Udic Ustipammments. These terms contain in them syllables that identify the temperature and moisture characteristics as well as general soil characteristics such as whether the soils have a clayey B horizon, whether they are friable, organic-rich, etc. This is a text field.

2. TEXTURE (OF C HORIZON): Describes the dominant grain size of the soil. There are 12 basic textural classes ranging from clay through silt to sand. We have added a 13th class for organic soils. They are coded 0 through 12 as follows:

0. Organic soils (peat, muck)	7. silt
1. clay	8. silt loam
2. silty clay	9. loam
3. sandy clay	10. sandy loam

4. silty clay loam
5. clay loam
6. sandy clay loam

11. loamy sand
12. sand

3. **PARENT MATERIAL:** The geologic parent material of the soil as described by the SCS. This is a text field containing terms such as windblown sand, shale, granite, glacial till, etc.

4. **DEPTH TO BEDROCK (in):** This term describes the total thickness of the soil layer, in inches.

5. **DEPTH TO HIGH WATER TABLE (ft):** This term gives the depth to the seasonal high water table, in feet. This is generally the highest level that the water table reaches during the year.

6. **SEASON OF HIGH WATER TABLE:** Relates to factor 5, the time of year during which the water table is at its highest, coded using the starting and ending months of high water table.

7. **DRAINAGE CLASS:** A term describing how well water drains from the soil. It is related to slope, elevation, and permeability. The SCS recognizes 7 drainage classes, which we have coded from 1 -7:

1. very poorly drained	5. well drained
2. poorly drained	6. somewhat excessively drained
3. somewhat poorly drained	7. excessively drained
4. moderately well drained	

8. **% SLOPE:** A measure of the inclination of the land surface from level, measured in percent. A 100% slope corresponds to a 45° slope angle. Relates to drainage characteristics and permeability. SCS defines 7 slope classes, coded 1-7 as follows:

1. nearly level (0-3%)	5. hilly (15-25%)
2. undulating (2-8%)	6. steep (25-35%)
3. gently rolling (8-12%)	7. very steep (35-70%)
4. rolling (12-15%)	

9. **SHRINK-SWELL POTENTIAL:** A measure of the tendency of the soil to swell when wet and shrink and crack when dry. Relates to permeability and possible damage of house foundation, allowing greater radon entry from the soil. SCS ranks shrink-swell potential as low (1), moderate (2), or high (3).

10. **HYDROLOGIC GROUP:** Refers to soils grouped according to their runoff-producing characteristics. According to SCS it is an index of the "inherent capacity of bare soil to permit infiltration". The hydrologic group incorporates aspects of slope, drainage, and permeability. SCS groups the soils into four groups, labeled A through D: in group A, Soils have a high infiltration rate and low runoff potential. In group D, at the other extreme, soils have a slow infiltration rate and a high runoff potential. Group D soils typically have a hardpan or clay layer near the surface, have a permanent high water table, or are shallow over impervious bedrock.

11. **% ORGANIC MATTER:** The amount of organic matter in the near-surface soil layers. Important because organics are known concentrators of radium and other radionuclides. We have coded this factor by its median value and range, i.e., 12 ± 6 corresponds to a range of 6-18 given by SCS.

12. **DEPTH OF B HORIZON (in):** noted to help quantify other factors related to the B and C horizons.

13. **DEPTH OF C HORIZON (in):** as in factor 12.

14. **PERMEABILITY OF B HORIZON:** Coded by SCS permeability class, as follows:

1. **LOW:** < 0.2 inches per hour (in/hr)
2. **LOW TO MODERATE:** permeabilities range from < 0.2 to > 0.2 in/hr
3. **MODERATE:** 0.2 – 6.0 in/hr
4. **MODERATE TO HIGH:** permeabilities range from < 6.0 to > 6.0 in/hr
5. **HIGH:** > 6.0 in/hr

15. **PERMEABILITY OF C HORIZON:** As above, but for C horizon.

16. **% CLAY IN B HORIZON:** Usually given by SCS as a range. Comparisons of this and other soil factors between the B and C horizons should give important clues about radon transport at the basement floor level and about capping effects and other radon concentrating mechanisms. We have coded this factor by its median value and range, i.e., 12 ± 6 corresponds to a range of 6-18 given by SCS.

17. **% CLAY IN C HORIZON:** Same as factor 16, for C horizon.

GEOLOGIC FACTORS

I) Bedrock or surficial geology class. Bedrock is divided into 4 principal Classes: (1) igneous; (2) metamorphic; (3) sedimentary; and (4) glacial. These groups are then subdivided by

composition based on radon potential and are listed approximately from highest to lowest potential. Felsic means a rock composition dominated by the minerals quartz and feldspar or the lighter elements Si, Na, and K. Felsic composition rocks in the igneous and metamorphic classes tend to be higher in uranium. Mafic rocks, which are dominated by metals such as Fe, Ti, Mg, Mn and often have Ca, tend to have less uranium. Carbonaceous, glauconitic, phosphatic, and graphitic rocks tend to be higher in uranium. Permeability and composition are most important in glacial deposits.

Class 1: Igneous

(1) igneous, felsic	(3) igneous, intermediate
(2) pegmatite, felsic to intermediate	(4) igneous, mafic

Class 2: Metamorphic

(1) metamorphic, carbonaceous-graphitic	(6) metavolcanic, felsic
(2) metamorphic, felsic	(7) migmatite, mafic
(3) migmatite, felsic	(8) metamorphic, mafic
(4) metasedimentary	(9) metavolcanic, mafic
(5) contact metamorphosed sedimentary	

Class 3: Sedimentary

(1) Carbonaceous shale/siltstone	(7) phosphatic sandstone/siltstone
(2) shaly limestone/dolomite	(8) phosphatic clay
(3) dolomite	(9) fluvial sandstone
(4) limestone	(10) conglomeratic sandstone
(5) glauconitic sandstone/siltstone	(11) noncarbonaceous shale/siltstone
(6) glauconitic clay	(12) marine quartz sandstone

Class 4: Glacial

These will be annotated by a bedrock number to indicate source and composition.

(1) Gravel: esker/kame	(4) sand/gravel: coarse till/outwash
(2) glacial till or lake clay, dry	(5) poorly sorted: till, silt/clay matrix
(3) loess	(6) glacial till or lake clay, moist

(II) Equivalent radium from the Duval and others (1989) NURE map.

This will be the average value for the group of pixels in the segment, in ppm eU or pCi/g eRa.

(III) Radionuclide siting

Where uranium and radium are located in the source rock or glacial deposits is extremely important to radon emanation.

(1) oxides in fractures or on mineral grains	(4) resistate mineral sites
(2) finely disseminated	(5) mixed sites
(3) labile mineral sites	

IV) Degree of deformation and or fracturing/cave and cavity development.

Deformation, fractures, and karst or cave development may dramatically enhance the amount of radon available.

(1) sheared	(5) highly foliated
(2) highly fractured/faulted-macrofractures	(6) folded
(3) highly fractured/faulted-microfractures	(7) not deformed
(4) extensive karst and caves	

V) Density/porosity

These data are derived from standard tables and will be entered in their given values, density in g/cm^3 , porosity in percent.

APPENDIX B

of
**Lawrence Berkeley National Laboratory
United States Geological Survey**

supported by
**U.S. Department of Energy
U.S. Environmental Protection Agency**

This high-radon project has been developing a statistical methodology for providing improved estimates of local indoor radon concentrations across the United States. The purpose is to enable State or other agencies to identify high-radon counties, or portions thereof, more precisely so that indoor monitoring and control efforts can be focussed more effectively. This page describes the project and how to obtain results.

- basic approach and types of results
- project investigators at LBNL and USGS
- background and purpose of the project
- overall scientific summary
- interpretation and variability of results
- titles and abstracts of high-radon reports
- high-radon files and documentation
- registering for receiving project updates

Many of the project's analytical results cited here are given as estimates of geometric mean (GM) indoor concentrations by state or county. In interpreting such area GMs, however, it is important to realize that within any such political unit some smaller areas will have higher GMs and, further, that--because of the variability within any area--some homes will have indoor concentrations considerably higher than the area GM.

Basic approach and types of results

The basic approach used by the high-radon project is, for a state or region, to examine the statistical correlation between available indoor radon monitoring data and information on physical factors affecting indoor concentrations. These factors may include house structure types, radium concentrations in surface soils, other soil and geological characteristics, meteorological variables, and other predictive variables. The resulting correlation model is then used to make predictions of local concentrations for counties (or smaller geographic units) that are more precise than are possible using the monitoring data alone, because representative data are invariably relatively sparse.

This approach therefore results in a topology of indoor radon for the state or region for which the analysis is performed, or even for the U.S. as a whole if applied across the country. The purpose of developing this topology is to identify more reliably the areas having indoor concentrations that are substantially higher than average. Monitoring and remedial efforts could then be focussed on these areas, resulting in relatively rapid help to the occupants of houses that have very high levels of indoor radon.

Our project has been devoted to developing these analytical tools and to identifying the data needed to perform the analyses effectively. In the course of this research effort, we have of course performed specific analyses for several states, selected because of their particular levels or distribution of radon concentrations or because of the relative availability of suitable predictive information. We have also performed analyses using a national data set and, perhaps more importantly for practical purposes, performed a series of regional analyses that include most of the 48 contiguous states, based on several national datasets that are available. (Cf. a map of the United States. [after it is normalized to long-term concentrations] see image below) In both state and regional analyses, we have often found that our statistical models account for about 80% of the variability in mean county concentrations, or more precisely in the logarithm of the county geometric mean indoor concentrations - a level of success that corresponds to predicted county means that are relatively certain.

Predicted Geometric Mean (GM) Indoor Radon Concentration by State. These GMs are for annual-average living-area (AALA) indoor radon concentrations and were estimated based on a correlation of two national databases, one having AALA concentrations from about 5000 homes selected nationally and the other having about 40,000 short-term (several day) screening measurements (usually taken in the basement if there was one). The AALA data are reasonable measures of the concentrations that occupants are actually exposed to annually, but there are many more screening measurements. The correlation between the two permits use of the screening data to make better estimates of state of local AALA concentrations. With regard to the state estimates, note that there is considerable local variability in indoor concentrations within states and smaller areas.

These analytical results are available from the project, either via articles published in scientific journals (as discussed in the overall scientific summary) or, in the case of the regional analyses, via file transfers from this home page or using FTP. These results from the project itself do not include predictions for smaller geographic scales, such as census tracts or townships. Such results can be obtained by performing detailed analyses using monitoring data and other information prepared in digital form at these smaller scales. However, the computer (subroutine) programs, documentation, and some of the data sets for performing these focussed state analyses (as well as for improving the regional analyses) are being made available as discussed in the overall scientific summary. The wide use of these methods for developing a more detailed and accurate topology of indoor radon concentrations is the principal objective of the high-radon project.

Project investigators at LBNL and USGS

The high-radon project is being carried out by two groups with substantial experience relevant to the problem of indoor radon.

The Indoor Environment Program, part of the Environmental Energy Technologies Division, at Lawrence Berkeley National Laboratory has since 1977 had an active indoor radon group, devoted to investigating the origin, behavior, concentrations, and control of radon in homes and other buildings. This group's efforts have included, not only experimental studies, but also development of theoretical models for transport of radon from the (usually) soil source into the indoor environment. But, based on its interest in exposures to and behavior of indoor radon, the indoor radon group began several years ago to investigate statistical correlations between indoor radon and physical factors and how they might be used to provide predictors of local concentrations that are superior to those from the monitoring data themselves or from various types of radon "potential" maps, including those

incorporating results from available physical models. Research personnel have included scientists from the Indoor Environment Program, faculty from the Statistics Department of the University of California, Berkeley, and students from various departments of the University. This project has been viewed as one of the more important environmental research efforts at Lawrence Berkeley National Laboratory.

The radon research group in the Geologic Division of the U.S. Geological Survey previously developed a set of geologic radon potential books and associated maps in cooperation with the Environmental Protection Agency. It also investigated various questions of radon generation and transport, such as the relationship of soil-gas radon concentrations to surficial uranium concentrations, soil-gas transport through porous media, and geochemical influences on radon emanation.

Background and purpose of the high-radon project

Data from monitoring radon in U.S. homes indicate that indoor concentrations are approximately lognormally distributed, with an average concentration in (the living areas) of single-family homes of about 55 Bq m^{-3} (1.5 pCi/l) and 50,000 to 100,000 (or about 0.1% of) houses having levels exceeding 740 Bq m^{-3} (20 pCi/l). At this level, occupants are receiving exposures comparable to the occupational radiation dose limit. Although broad-scale radon control efforts of the last decade aim to limit indoor levels to within a factor of two or three of the average, they do not focus efforts strongly in identifying the houses that have levels an order of magnitude or more higher than the average, even though the occupants of these houses are thought to be at the highest risk. (See the high-radon methodology article)

Various monitoring efforts demonstrate that the concentration distribution of indoor radon is approximately lognormal both on a national scale and on a local scale, but the mean concentration varies substantially from one locale to another, as does the fraction of houses having concentrations exceeding various levels of concern, such as 4, 10, or 20 pCi/l. Homes with high indoor concentrations tend to "cluster" geographically, suggesting that systematic identification of "high-radon" areas would increase the efficiency and speed of identification of high-radon homes. For example, preliminary analysis by LBNL of the national indoor radon concentration distribution and of the variance of geometric means (GMs) with area, together with the distribution of surficial radium concentrations (estimated from the aerial gamma-ray data of the National Uranium Resource Evaluation (NURE)) and data on infiltration rates, suggests that approximately 90% of 20-pCi/l homes might be found among only 10% of areas (or, more specifically, housing groups, such as those associated with the population in a census tract).

This project is aimed at using various classes of information, including monitoring data and information on pertinent physical factors, in a self-consistent analytical framework for predicting local indoor radon concentrations by county or smaller geographic areas. The project is intended both to develop the analytical methods, through development of demonstration models for selected states or regions, and also to provide these tools in a usable form for other scientists and in particular for State agencies and other entities that wish to use them for help in identifying high-radon areas.

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