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Indoor Radon: A Selected and Annotated Bibliography

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Indoor Radon: A Selected and Annotated Bibliography

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February 1987

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Introduction

Within the last ten years, dangerously high levels of radon have been found in homes all over the world. Indoor radon has become one of the most serious health issues of the decade. The Environmental Protection Agency (EPA) estimates that radon contaminates one in eight U.S. homes and may be responsible for as many as 20,000 lung cancer deaths each year.[1] Radon is a naturally-occurring radioactive gas that enters buildings through the soil, water, or may even be present in the building materials themselves. The recent trend toward weatherizing homes has compounded problems, because the energy-efficient measures often reduce air circulation, thus trapping radon indoors, and building up dangerously high levels of the gas. Certain geographical areas are also more prone to contamination than others. Radium-rich soils (from which radon emanates) contribute greatly to the levels of radon measured in indoor air.

This bibliography covers U.S. and Canadian research[2] into the causes, effects, and methods of reducing indoor radon. The materials are loosely grouped into sections that deal with the main emphasis of the research. Of course, most cover more than one subject, and each section should be reviewed for articles of interest. The indoor radon problem has only been identified within the last ten years, so the citations are relatively current. Articles dealing with the radon problems associated with uranium mill tailings and radon in mines have been excluded. However, citations that address the problems associated with homes and subdivisions built over the reclaimed mining waste piles have been included.

Much of the research on indoor radon is government-sponsored, and performed by leading national laboratories, most notably: Lawrence Berkeley, Argonne, Oak Ridge, and Brookhaven. These reports are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA, 22161. NTIS order numbers are given where applicable, to make these materials easier to find.

This bibliography is directed toward people in the fields of community planning, civil engineering, environmental health, and the construction trades. However, anyone with an interest in this serious radiation problem will find these sources helpful.

The appendix, on page 24, provides citations to popular literature. These articles, while less technical and somewhat sensational in nature, provide an added dimension to the complexity of the indoor radon problem.

[1]U.S. Environmental Protection Agency. Office of Radiation Programs. "Health risks due to radon in structures." In: *Radon and indoor air pollution* , page 4.

[2]For an overview of foreign (mainly European) research on indoor radon, see Clemente, G.F., et al., page 2.

General Overviews

Bonneville Power Administration. *Environment and Power. Issue backgrounder: Energy efficient new homes and indoor air pollutants* . (NTIS DE86001929). Portland, Ore.: The Administration, 1985.

_____. *Information on indoor air quality and building energy-efficient homes* . (NTIS DE85007997). Portland, Ore.: The Administration, 1984.

This booklet is written for organizations with responsibility for adopting building codes or meeting established model conservation standards. It contains information on indoor air pollutants.

Clemente, G.F., et al, eds. "Indoor exposure to natural radiation and associated risk assessment: Proceedings of an international seminar held at Anacapri, Italy, Oct. 3-5, 1983." *Radiation Protection Dosimetry* 7, no. 1-4 (1984): 367-380 (special issue).

Most of the papers presented at this conference are from the European community, and they represent a good overview of the research being done outside the United States.

Colle, R., and Preston E. McNall, Jr. *Radon in buildings: Proceedings of a roundtable discussion of radon in buildings held at Gaithersburg, Md. on June 15, 1979* . (NTIS PB80-195712). Washington, D.C.: National Bureau of Standards, 1980.

Representatives with interests in radiation protection, measurement and construction technology provide their views on the problems and needs associated with radiation exposure due to radon in buildings.

Conservation and Renewable Energy Inquiry and Referral Service. *Indoor air pollution* . 2d ed. (NTIS DE85013097). Silver Springs, Md.: The Service, 1985.

The current knowledge about radon (and other indoor pollutants), sources, abatement and control equipment is reviewed in this three-page fact sheet.

Coon, D. *Indoor air quality in tight houses: A literature review* . (NTIS PB85-162022). Toronto, Ontario: Ontario Ministry of Municipal Affairs and Housing, 1984.

George, A.C., et al, eds. *EML (Environmental Measurements Laboratory) indoor radon workshop, 1982* . (NTIS DE83017341). New York: Environmental Measurements Laboratory, 1983.

These are the proceedings of a conference in which thirty papers were presented, covering recent developments in indoor radon research and development. Articles on standardization and quality assurance of measurement methods, measurement strategies, physical mechanisms of radon transport, and development of guidance standards for indoor exposures are addressed.

Harley, N.H. *Factors controlling indoor radon levels. Annual report, June 1983-May 1984* . (NTIS DE84012712). New York: New York University, Department of Environmental Medicine, 1984.

Hileman, Bette. "Indoor air pollution." *Environmental Science and Technology* 17, no. 10 (Oct. 1983): 469a-472a.

This article outlines the EPA's role in formulating policies on indoor air pollution. Radon and passive smoking are discussed.

Kusuda, T., C.M. Hunt, and P.E. McNall. "Radioactivity (radon and daughter products) as a potential factor for building ventilation." *ASHRAE Journal* 21, no. 7 (July 1979): 30-34.

This is a review of the existing literature on the presence of radon in indoor air. The authors call for further research in this area.

Lepman, S.R., M.L. Boegel, and C.D. Hollowell. *Radon: A bibliography*. Berkeley, Calif.: Lawrence Berkeley Laboratory, 1981.

The physical properties of radon, instrumentation for its measurement, health effects, and regulatory information are outlined in this review of the literature.

Letourneau, E.G., R.G. McGregor, and W.B. Walker. "Design and interpretation of large surveys for indoor exposure to radon." *Radiation Protection Dosimetry* 7, no. 1-4 (1984): 303-308 (special issue).

This is a review of the Canadian experience in carrying out large-scale surveys for indoor exposure to radon.

Meyer, Beat. *Indoor air quality*. Reading, Mass.: Addison-Wesley, 1983.

This book addresses indoor air quality in general, highlighting the infiltration of radon, its health effects, and control measures currently available. Many other indoor air pollutants are also discussed.

Meyer, Beat, and Robert Hartley. *Inventory of current indoor air quality-related research*. (NTIS PB82-127952). Cincinnati, Ohio: Industrial Environmental Research Lab, 1981.

Mueller Associates, Inc. *Indoor air quality environmental information handbook: Radon*. (NTIS DE86005006). Baltimore, Md.: Mueller, 1986.

This is a handbook designed to explain the issues around indoor radon for both the homeowner and the technical person with an interest in indoor air quality issues.

National Research Council. *Indoor pollutants*. Washington, D.C.: National Academy Press, 1981.

This is a study on indoor air pollutants in general, prepared for the EPA. Sections on radioactivity (including radon) describe sources, concentrations, and control measures. Other chapters cover factors that influence exposure, monitoring, and health effects.

Nero, A.V. "Indoor concentrations of radon-222 and its daughters: Sources, ranges and environmental influences." In *Indoor air and human health, proceedings of the 7th life sciences symposium, Knoxville, Tn., Oct. 29-31, 1984* , edited by Richard Gammage, and Stephen Kaye, 43-67. Chelsea, Miss.: Lewis, 1985.

Studies conducted around the world show a wide variability in the amount of radon entering homes. However, for any given entry rate, ventilation rates are a key factor in indoor concentrations. This is a review of the presently known factors that influence indoor air concentrations of radon.

_____. *Indoor radiation exposures from radon and its daughters: A view of the issue* . (NTIS DE82005144). Berkeley, Calif.: Lawrence Berkeley Laboratory, 1981.

Indoor concentrations of radon, the associated risks, and the effects of measures to save energy by reducing ventilation rates are all reviewed in this article. Indoor air quality standards and energy consumption can coexist by employing appropriate control measures.

Nero, A.V., and W.W. Nazaroff. *Characterizing the source of radon indoors* . (NTIS DE84002928). Berkeley, Calif.: Lawrence Berkeley Laboratory, 1963. [Also in: *Radiation Protection and Dosimetry* 7 (1984): 23-39.]

Is soil the predominant source in many cases where indoor radon concentrations are high? The authors suggest that other sources, such as water and building materials account for concentrations on the low end of the observed range.

Parker, G.B. *Residential weatherization—indoor air pollution* . (NTIS DE82018850). Richland, Wash.: Battelle Northwest Laboratory, 1982.

Radiation Policy Council. *Report of the Task Force on Radon in Structures: Position paper* . (NTIS PB81-166258). Washington, D.C.: The Council, 1980.

High levels of radon have been found in structures, and there is a trend toward even higher exposures in more energy efficient buildings. The task force recommends that large scale programs should not be undertaken until more is known about the prevalence of high levels of radon, and ways of controlling those levels.

Steva, D.P. "Elevated radon levels in today's 'air tight' homes." In *Proceedings of the Ninth National Passive Solar Conference* , edited by J. Hayes and A. Wilson, 355-357. Boulder, Colo.: American Solar Energy Society, 1984.

Sources and pathways of radon into homes are described, along with measures that can be taken to reduce radon levels.

U.S. Congress. House. Committee on Science and Technology. *Radon and indoor air pollution* . Washington, D.C.: The Committee, (GPO), 1985.

This Government report covers all aspects of the effects of radon indoors. Contributions from several scientists and government agency representatives along with their testimonies before Congress make this an important tool in formulating future U.S. policies regarding indoor radon.

University of Pittsburgh. *Progress in indoor radon measurement: Review of previous research (July 1981-February 1985).* (NTIS DE8600448). Pittsburgh: University of Pittsburgh, 1985.

This is a review of the university's research programs involved in the measurement and detection of radon in buildings.

Radon Sources

Assendelft, A.C.E., and H.M. Sachs. *Soil and uranium as controlling factors in indoor radon in eastern Pennsylvania* . Princeton, N.J.: Princeton University, Center for Energy and Environmental Studies, 1982.

Auxier, J.A., et al. *Contribution of natural terrestrial sources to the radiation dose of man* . Oak Ridge, Tenn.: Oak Ridge National Laboratory, 1973.

Becker, III, A.P., and T.M. Lachajczyk. *Evaluation of waterborne radon impact on indoor air quality and assessment of control options.* (NTIS PB84-246404). St. Louis: Envirodyne Engineers, 1984.

Colle, R., et al. *Radon transport through and exhalation from building materials: A review and assessment.* (NTIS PB82-112384). Washington, D.C.: National Bureau of Standards, 1981.

This report, prepared for the EPA, discusses the routes by which radon enters buildings. The effects of the microstructural properties of the building materials on exhalation rates and transport of radon, measurement techniques, and the exhalation process from soils are also discussed. Recommendations for further research are presented.

Eaton, R.S., and A.G. Scott. "Understanding radon transport into houses." *Radiation Protection Dosimetry* 7, no. 1-4 (1984): 251-253 (special issue).

Eaton and Scott describe the "Radon Index Number" (RIN), which is derived as a simple function of soil radium content and permeability. This number can be used as a guide for estimating average radon concentrations in new and existing homes based on the site's RIN.

Gesell, Thomas F. "Background atmospheric 222-radon concentrations outdoors and indoors: A review." *Health Physics* 45, no. 2 (Aug.1983): 289-302.

Gesell, Thomas F., and H.M. Prichard. "The Contribution of radon in tap water to indoor radon concentrations." In *Natural radiation in the environment III*, edited by Thomas F. Gesell, and W.M. Lowder, (vol. 2) 1347. Oak Ridge, Tenn.: Oak Ridge National Laboratory, 1980.

Hawthorne, A.R., R.B. Gamage, and C.S. Dudney. *Effect of local geology on indoor radon levels: A case study* . (NTIS DE84016601). Oak Ridge, Tenn.: Oak Ridge National Laboratory, 1984.

This is a further refinement of the results for ORNL's forty home radon monitoring study, which is listed under Hawthorne, A.R., on page 18.

Hess, C.T., et al. *Radon-222 in potable water supplied in Maine: The geology, hydrology, physics and health effects.* (NTIS PB80-116304). Orono: Maine University, 1979.

Horton, T.R. *Nationwide occurence of radon and other natural radioactivity in public water supplies*. Montgomery, Ala.: U.S. Environmental Protection Agency, Eastern Environmental Radiation Facility, 1985.

Samples from 2500 public water supplies in thirty-five states, along with representative groundwater samples were collected and analyzed for radon and other sources of radioactivity. Horton summarizes the results by arithmetic mean, geometric mean, and population-weighted arithmetic mean. Individual public water supply results are also included.

Ingersoll, John G. " A Survey of radionuclide contents and radon emanation rates in building materials used in the U.S." *Health Physics* 45, no. 2 (Aug. 1983): 363-368 (special issue).

Landman, K.A. "Diffusion of radon through cracks in a concrete slab." *Health Physics* 43, no. 1 (July 1982): 65-71.

Landman develops a mathematical model to describe the diffusion of radon through cracks and gaps in concrete slabs used for building foundations.

Nazaroff, W.W., and S.M. Doyle. "Radon entry into homes having a crawl space." *Health Physics* 48, no. 3 (Mar. 1985): 265-281.

Nazaroff and Doyle suggest that in the test homes they studied, fifty percent or more of the radon released from the soil entered the living area through the crawl space. Meteorlogical factors such as wind speed, indoor-outdoor temperature differences, and rate of barometric pressure change were also examined.

Nazaroff, W.W., and A.V. Nero. *Transport of radon from soil into residences*. (NTIS DE84015966). Berkeley, Calif.: Lawrence Berkeley Laboratory, 1984. [Also in: *Proceedings of the 3rd International Conference on Indoor Air Quality and Climate*, vol. 2, 15-20. Stockholm: Swedish Council for Building Research, 1984.]

Nazaroff, W.W., S.M. Doyle, and A.V. Nero. *Potable water as a source of airborne radon-222 in U.S. dwellings: A review and assessment*. Berkeley, Calif.: Lawrence Berkeley Laboratory, 1985.

Partridge, J.E., T.R. Horton, and E.L. Sensintaffar. *A Study of radon-222 released from water during typical household activities*. Washington, D.C.: U.S. Environmental Protection Agency, 1979.

Rudnick, S.N., and E.F. Mahler. "Surface deposition of 222-Rn decay products with and without enhanced air motion." *Health Physics* 51, no. 3 (Sept. 1986): 283-293.

Ryan, M.T., et al. *Radon dosimetry: A Review of radon and radon daughter exposure conditions in dwellings and other structures.* (NTIS DE83-015033). Oak Ridge, Tenn.: Oak Ridge National Laboratory, 1983.

This is a review of available data on radon released from waste piles, backfill and construction material used in homes, schools, and other buildings.

Sachs, Harvey M., T.L. Hernandez, and J.W. Ring. "Regional geology and radon variability in buildings." *Environment International* 8, no. 1-6 (1982): 97-104.

This paper identifies the factors that influence radon concentrations in buildings, such as water supply, soil, and geological substrate. Meteorological conditions, building materials, and ventilation rates also affect indoor concentrations.

Tartaglia, Mark, et al. "Radon and its progeny in the indoor environment." *Journal of Environmental Health* 47, no. 2 (Sept./Oct. 1984): 62-67.

Walsh, Phillilp J. "Radon." In *Indoor air quality* , edited by Phillip J. Walsh, Charles Dudney, and Emily D. Copenhaver, 143-158. Boca Raton, Fla.: CRC Press, 1983.

Walsh discusses the sources of indoor radon, air concentrations and exposure levels, plus health and risk assessments associated with this pollutant.

Weiffenbach, Conrad V. *Radon, water, and air pollution: Risks and control* . (NTIS PB93-206789). Orono: Maine University, 1982.

Wilkening, M. *Source characterization and transport processes affecting levels of radon and its decay products in an indoor environment.* (NTIS DE84015254). Socorro: New Mexico Institute of Mining and Technology, 1984.

Wilkening studies exhalation rates of radon, measures indoor radioactivity, and creates models, and develops instrumentation. The issue of radon levels and air exchange rates in caves is also addressed.

Radon Concentrations and Behavior in Indoor Air

Abu-Jarad, F., and J.H. Fremlin. "Activity of radon daughters in high-rise buildings and the influence of soil emanation." *Environment International* 8, no. 1-6 (1982): 37-44.

Radon concentrations have been shown to decrease as distance increases from the ground level, suggesting that a considerable part of radon contamination arises from soil exhalation.

Bruno, Ronald C. "Verifying a model of radon decay product behavior indoors." *Health Physics* 45, no. 2 (Aug. 1983): 471-480.

Fleischer, R.L., A. Mogro-Campero, and L.G. Turner. "Indoor radon levels: Effects of energy-efficiency in homes." *Environment International* 8, no. 1-6 (1982): 105-110.

The authors argue that homes must be monitored year-round, to determine actual levels of radon infiltration, because of fluctuations between the summer and winter seasons.

Gunning, C., and A.G. Scott. "Radon and thoron daughters in housing." *Health Physics* 42, no. 2 (Apr. 1982): 527-528.

Thoron, though less prevalent in buildings than radon, may occur where there are large areas of unpainted concrete and poor ventilation, provided that the transit time of soil gas into the building is so short that thoron does not decay in transit.

Israeli, Miron. "Deposition rates of Rn progeny in houses." *Health Physics* 49, no. 6 (Dec. 1985): 1069-1083.

Moschandreas, D.J., and H.E. Rector. "Indoor radon concentrations." *Environment International* 8, no. 1-6 (1982): 77-82.

High levels of indoor contaminants are often found in energy efficient homes. The authors contend that the use of air-to-air heat exchangers can help reduce the level of radon concentration by increasing the air ventilation rate.

Nagda, N.L., M.D. Koontz, and Harry E. Rector. *Energy use, infiltration, and indoor air quality in tight, well-insulated residences*. Germantown, Pa.: Geomet Technologies, 1985.

Two identical houses were studied for relationships among air exchange, energy consumption, and indoor pollutants. One house was retrofitted, and equipped with an air-to-air heat exchanger, the other house remained in its initial state. The retrofit house had reduced air leakage and infiltration, which means increased heating efficiency. However, it also had higher levels of radon and radon progeny. The heat exchanger generally improved the indoor air quality.

Nero, A.V., et al. "Radon and its daughters in energy efficient buildings." In *Natural radiation environment*, edited by K.G. Vorha, et al, 473-480. New Delhi: Wiley Eastern, 1982.

Porstendofer, J. "Behavior of radon daughter products in indoor air." *Radiation Protection and Dosimetry* 7, no. 1-4 (1983): 107-113.

Wilkening M., and S.D. Schery. *Physical processes affecting levels of radon, thoron, and their decay products in an indoor environment*. (NTIS DE85009121). Socorro: New Mexico Institute of Mining and Technology, 1985.

Measurements and Modeling Techniques

Alter, H. Ward, and Robert L. Fleischer. "Passive integrating radon monitor for environmental monitoring." *Health Physics* 40, no. 5 (May 1981): 693-702.

The authors describe track-etch alpha particle detectors and their applications in indoor radon monitoring situations.

Beak Consultants. *Indoor air quality: 20 existing homes.* (NTIS PB85-135382). Toronto, Ontario: Ontario Ministry of Municipal Affairs and Housing, and Ontario Ministry of Energy, 1984.

In this study, quick measurements of air quality conditions in homes were examined to see if any problems existed. Attempts to gather information on air exchange rates, lifestyles of the residents, and other factors were also made. The results indicated a reduced bias and enhanced data recovery when compared to other surveys.

Bigu, J., and R. Raz. "Passive radon/thoron personal dosimeter using an electrostatic collector and a diffused-junction collector." *Review of Scientific Instruments* 56, no. 1 (Jan. 1985): 82-103.

Bigu and Raz describe a personal radon dosimeter that was originally developed for mine workers. The radon dosimeter mounts on top of an ordinary miner's cap battery.

Canada. Atomic Energy Control Board. *Review of existing instrumentation and evaluation of possibilities for research and development of instrumentation to determine future levels of radon at a proposed building site.* Ottawa: The Board, 1983.

Computer studies of radon movement through soil provide a radon index number (RIN). The RIN would be proportional to the radon entry rate into a typical house. Regional and area RIN estimates could be produced from airborne gamma survey maps, agricultural soil classification maps and portable gamma spectroscopy equipment.

D'Ottavio, T.W., and R.N. Dietz. *Errors resulting from the use of single zone ventilation models on multi-zone buildings: Implications for energy conservation and indoor air quality studies.* (NTIS DE85010548). Upton, N.Y.: Brookhaven National Laboratory, 1985.

George, A.C. "Characterization of radon levels in indoor air." In *Annual meeting of the Air Pollution Control Association*, New Orleans, La., June 20, 1982. (NTIS DE83008743). Pittsburgh: Air Pollution Control Associations, 1983.

The author describes various types of monitoring and sampling techniques that are used to determine the radiation burden of the general public from radon and its daughters.

George, J.L. *Procedure manual for the estimation of average indoor radon daughter concentrations using the radon grab-sampling method*. (NTIS DE86012078). Grand Junction, Colo.: Bendix Field Engineering, 1986.

This manual describes a radon grab-sampling method that uses a scintillation cell.

Grimsrud, D.T., et al. *Continuous measurements of radon entry in a single-family house*. (NTIS DE84001820). Berkeley, Calif.: Lawrence Berkeley Laboratory, 1983.

The results of this six-month investigation, provide detailed measurements of radon concentrations, ventilation rates, and other factors that influence radon infiltration in a house.

Harley, N.H. *Direct determination of 222Rn gas using the electret to remove daughters at formation.* (NTIS DE82005465). New York: New York University Medical Center, 1981.

Harley, N.H., and S.M. Altman. *Measurement of 222Rn indoors and outdoors.: Progress report, June 1, 1982-May 31, 1983*. (NTIS DE83013008). New York: New York University Medical Center, 1983.

Hawthorne, A.R., et al. "Experimental protocol and preliminary results of air infiltration rate measurements in Tennessee Valley homes." In *Air Pollution Control Association Annual Meeting and Exhibition, Minneapolis, Minn. June 22, 1986*. (NTIS DE86008496). Pittsburgh: Air Pollution Control Association, 1986.

Hess, C.T., R.L. Fleischer, and L.G. Turner. "Field and laboratory tests of etched track detectors for 222-Rn: Summer-vs-winter variations and tightness effects in Maine houses." *Health Physics* 49, no. 1 (July 1985): 65-79.

Ingersoll, J.G., B.D. Stitt, and G.M. Zapalac. *Method for measuring the exhalation of radon from building materials*. (NTIS DE82013877). Berkeley, Calif.: Lawrence Berkeley Laboratory, 1982.

The authors examine a method that involves sealing a small sample of the building material in a glass container for one to three days, and then measuring the radioactivity released from the sample. Radon emanation and exhalation rates per unit mass can then be determined.

James, A.C. "Dosimetric approaches to risk assessment for indoor exposure to radon daughters." *Radiation Protection Dosimetry* 7, no. 1-4 (1984): 353-366.

Knutson, E.O., et al. "Measurement of radon daughter particle size." *Radiation Protection and Dosimetry* 7, no. 1-4 (1984): 121-125.

Kusuda, T., S. Silberstein, and P.E. McNall, Jr. "Modeling of radon and daughter concentrations in ventilated spaces." *Journal of the Air Pollution Control Association* 30, no. 11 (Nov. 1980): 1201-1207.

Nagda, Niren L., and Harry E. Rector. *Guidelines for monitoring indoor air quality*. (NTIS PB83-264465). Rockville, Md.: Geomet Technologies, 1983.

Nazaroff, W.W., M.L. Boegel, and A.V. Nero. *Measuring radon source magnitude in residential buildings*. (NTIS DE82000774). Berkeley, Calif: Lawrence Berkeley Laboratory, 1981.

The authors describe sampling procedures used in residential studies. Successive measurements in six houses in the northeastern United States showed considerable variability in source magnitude within a given house. The study suggests that soil gas influx can be an important transport process for indoor radon. (This is also mentioned in *International Meeting on Radon-Radon Progeny Measurements*, on page 14.)

Nazaroff, W.W., F.J. Offermann, and A.W. Robb. "Automated system for measuring air-exchange rate and radon concentration in houses." *Health Physics* 45, no. 2 (Aug. 1983): 525-537.

Nazaroff, W.W., K.L. Revzan, and A.W. Robb. *Instrumentation for a radon research house*. (NTIS DE82003717). Berkeley, Calif.: Lawrence Berkeley Laboratory, 1981.

This report focuses on a highly automated monitoring and control system that is used for studying radon behavior in a residence.

Nero, A.V., et al. "Radon concentrations and infiltration rates measured in conventional and energy-efficient homes." *Health Physics* 45, no. 2 (Aug.1983): 401-406.

Parker, G.B., R.N. Lee, and G.W. Dennis. *Monitoring indoor pollutants in two small office buildings to support a modeling study*. (NTIS DE84010900). Richland, Wash.: Battelle Northwest Laboratory, 1984.

Parker, G.B., P.C. Owczarski, and W.F. Sandusky. *Predicting indoor air pollution levels*. (NTIS DE83003470). Richland, Wash.: Battelle Northwest Laboratory, 1982.

Paschoa, A.S., M.E. Wrenn, and J.A. Torrey. "A Mathematical model for indoor radon and daughters." *Radiation Protection Dosimetry* 7, no. 1-4 (1984): 139-142.

The authors present a computer model for predicting radon levels at steady state, based on ventilation rates, outdoor radon concentrations, and radon source strengths associated with soil-building materials.

Rogozen, M.B. *Dynamic simulation of radon daughter expsoure in apartments using solar rockbed heat storage*. Los Angeles: Science Applications, 1980.

In this study, Rogozen focuses on the potential for increased radon levels in passive solar homes.

Ronca-Battista, M., et al. *Interim indoor radon and radon decay product measurement protocols*. (NTIS PB86-215258). Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation Programs, 1986.

Toohey, R.E., et al. *Measurements of the deposition rates of radon daughters on indoor surfaces*. (NTIS DE84006410). Argonne, Ill.: Argonne National Laboratory, 1983. [Also in *Radiation Protection Dosimetry* 7, no. 1-4 (1984): 143-146.]

U.S. Environmental Protection Agency. *International meeting on Radon-Radon Progeny Measurements*. Washington, D.C.: U.S. Environmental Protection Agency, 1983.

Health Effects

Andelman, J.B. "Human exposures to volatile halogenated organic chemcials in indoor and outdoor air." *Environmental Health Perspectives* 62 (Oct. 1985): 313-318.

Bonneville Power Administration. *Issue backgrounder: The health impacts of home weatherization.* (NTIS DE 83-017908). Portland, Ore.: The Administration, 1983.

Brambley, M.R., and M. Gorfein. "Radon and lung cancer: Incremental risks associated with residential weatherization." *Energy* 11, no. 6 (June 1986): 589-605.

The authors argue that increases in radon concentrations associated with reduced air exchange rates in buildings represent significant health risks. They recommend prudent energy conservation measures, especially where radon concentrations are known to be high.

Budnitz, R.J., et al. *Human disease from radon expsoures: The impact of energy conservation in buildings.* Berkeley, Calif.: Lawrence Berekely Laboratory, 1978. [Also in *Energy and Buildings* 2 (1979): 209-215.]

The reduced rate of fresh air infiltration increases the concentration of indoor air contaminants, including radon. Speculation is made that radiation levels from radon daughters account for much of the lung cancer in nonsmokers.

Burkart, Werner. "Assessment of radiation dose and effects from radon and its progeny in energy-efficient homes." *Nuclear Technology* 60 (Jan. 1983): 114-123.

The higher indoor radon concentrations in energy-efficient homes are mainly due to reduced air exchange rates. This may lead to an additional one hundred lung cancer deaths per million/per year. Burkart also discusses possible means for reducing radon levels in existing buildings.

Cross, F.T., et al. "Influence of radon daughter exposure rate, unattachment fraction and disequilibrium on occurance of long tumors." *Radiation Protection Dosimetry* 7, no. 1-4 (1984): 381-384.

Hess, C.T., C.V. Weiffenbach, and S.A. Norton. "Environmental radon and cancer correlation in Maine." *Health Physics* 45, no. 2 (Aug. 1983): 339-348.

National Council on Radiation Protection and Measurement. *Evaluation of occupational and environmental exposures to radon and radon daughters in the United States.* Bethesda, Md.: The Council, 1984.

______. *Exposures from the uranium series with emphasis on radon and its daughters.* Bethesda, Md.: The Council, 1984.

Nero, A.V., et al. *Radon daughter exposures in energy-efficient buildings*. (NTIS DE82003711). Berkeley, Calif.: Lawrence Berkeley Laboratory, 1981. [Also in *Proceedings of the Specialist Meeting on the Assessment of Radon and Daughter Exposure and Related Biological Effects*, edited by G.F. Clemente, et al, 144-152. Salt Lake City: RD Press, 1982.]

When energy use in buildings is reduced by natural infiltration or mechanical ventilation, radon exposure rates may rise to an unacceptable level. This study addresses the issue of high radon rates that are found in energy-efficient homes.

Owczarski, P.C., and G.B. Parker. *Computing transient exposure to indoor pollutants*. (NTIS DE83014500). Richland, Wash.: Battelle Northwest Laboratory, 1983.

The authors describe a computer program that is used to determine transient levels of gases (radon) and respirable particulates, such as smoke from wood stoves and cigarettes. Results of radon tests for a mother and child over a period of twenty-four hours revealed that exposures are 13 times greater than background for the child, and 4.5 times the background for the mother.

Radford, Edward P. "Potential health effects of indoor radon exposure." *Environmental Health Perspectives* 62 (Oct. 1985): 281-288.

Indoor concentrations of radon are highly variable, depending on the type of bedrock under a dwelling and house foundation characteristics, etc. The author estimates that about twenty-five percent of lung cancers among nonsmokers over the age of sixty, and five percent in smokers, may be attributable to radon exposure in the house.

Rasmussen, S., et al. *Relationship between indoor radon and lung cancer: A study of feasibility of an epidemiological study*. (NTIS PB84-192673). Cambridge, Mass.: Massachusetts Institute of Technology, 1981.

This report estimates that ten percent of lung cancers in Maine can be attributed to residential radon exposure. Several models for sample and size estimation, along with cost estimates for case-control studies are addressed.

Sandusky, W.F., et al. *Expanded BPA (Bonneville Power Administration) residential weatherization program: Summary of regional health effects*. (NTIS DE86007715). Richland, Wash.: Battelle Northwest Laboratory, 1984.

_____. *Estimated health effects from a regionwide weatherization program*. (NTIS DE84003959). Richland, Wash.: Battelle Northwest Laboratory, 1983.

Turiel, Isaac. "Radon." In *Indoor air quality and human health*, 33-43. Stanford, Calif.: Stanford University Press, 1985.

This chapter on radon provides an overview of the problems associated with radon exposure. The author suggests identifying and investigating the areas in the United States with high concentrations of radium in the soil.

U.S. General Accounting Office. *Indoor air pollution: An emerging health problem* . Washington, D.C.: The Office, (GPO), 1980.

This report on the health effects of radon and other indoor pollutants, discusses the problems and roles of various federal agencies, and describes actions that can be taken to help resolve indoor air quality issues outside the workplace.

Walsh, Phillip J., and Wayne M. Lowder. *Assessing the risks from exposure to radon in dwellings* . (NTIS DE83016347). Oak Ridge, Tenn.: Oak Ridge National Laboratory, 1983.

Walsh and Lowder review the human health risks from exposure to radon in dwellings. They identify sources of indoor radon, and formulate risk-per-dose values.

Geographic Studies

Bonneville Power Administration. *Report on the Bonneville Power Administration's radon monitoring in the residential weatherization program* . (NTIS DE86008854). Portland, Ore.: The Administration, 1986.

Cohen, Bernard L. "Survey of one-year average Rn levels in Pittsburgh area homes." *Health Physics* 49, no. 6 (Dec. 1985): 1053-1069.

Cohen's radon measurement results taken from 169 houses indicate that radon levels are higher on lower floors than on upper floors; radon concentrations are lower in drafty homes than in less-drafty homes, and radon levels are higher in houses exposed to wind, than in those sheltered from the wind. He includes other findings, as well.

_____. "A National survey of 222-Rn in U.S. homes and correlating factors." *Health Physics* 51, no. 2 (Aug. 1986): 175-183.

This is a survey of radon levels in 453 homes across the nation assessed the physical properties of the house, as well as geological and meterological factors. The results indicate that geographical location is the primary reason for higher than normal concentrations.

Doyle, S.M., W.W. Nazaroff, and A.V. Nero. "Time-averaged indoor radon concentrations and infiltration rates samples in four U.S. cities." *Health Physics* 47, no. 4 (Oct. 1984): 579-586.

Fifty-eight homes were studied during a four to five month period in the winter and spring of 1981-1982. The authors found that radon entry rates were generally higher in houses in Fargo, North Dakota and Colorado Springs, Colorado, than in houses in Portland, Maine and Charleston, North Carolina.

Fleischer, R.L., and L.G Turner. "Indoor radon measurements in the New York capital district." *Health Physics* 46, no. 5 (May 1984): 999-1011.

Fleischer and Turner found that radon measurements in twenty-one energy-efficient homes and fourteen conventional homes showed significantly higher concentrations of radon in the energy-efficient homes.

George, A.C., M. Duncan, and H. Franklin. "Measurements of radon in residential buildings in Maryland and Pennsylvania, U.S.A." *Radiation Protection Dosimetry* 7, no. 1-4 (1984): 291-294.

Hawthorne, A.R. "Results of a forty-home indoor-air-pollutant monitoring study." In *Air Pollution Control Association annual meeting , Atlanta, Ga., June 19, 1983*. (NTIS DE83014138). Pittsburgh: Air Pollution Control Association, 1983.

In this study, homes in the Oak Ridge and Knoxville, Tennessee area were monitored for indoor air pollutants. Hawthorne found that radon concentrations correlated with house location, while other pollutants were due to operations of indoor kerosene heaters, gas ranges, and wood or coal stoves. Formaldehyde levels were found to be higher in new homes.

Hess, Charles T., and R.C. Hill. *Effect of weatherization on radon levels in Maine dwellings.* (NTIS DE85005210). Orono: Maine University, 1984.

This is a study performed before and after weatherization, on thirty Maine dwellings. After-weatherization levels show higher radon concentrations than the before-weatherization levels. Mobile homes were found to have lower radon concentrations than houses.

Jones, R.F., et al. *Case study of the Brookhaven House.* (NTIS DE85012573). Upton, N.Y.: Brookhaven National Laboratory, 1984.

Moed, B.A., et al. *Identifying areas with potential for high indoor radon levels: Analysis of the national airborne radiometric reconaissance date for California and the Pacific Northwest.* (NTIS DE85000792). Berkeley, Calif.: Lawrence Berkeley Laboratory, 1984.

The authors have analyzed aerial radiometric data for seven western states, to provide information on the distribution of radium (radon's progenitor). A field validation study in the Spokane, Washington area revealed close correspondence between the aerial data and the situ mearsurements both in radium content and radon flux in the soil.

Moschandreas, D.J., and H.E. Rector. "Indoor radon concentrations." *Environment International* 8, no. 1-6 (1982): 77-82.

This is a sampling of indoor radon levels from energy-efficient homes in the Washington, D.C. area.

Nazaroff, W.W., et al. "Radon transport into a detached one-story house with a basement." *Atmospheric Environment* 19, no. 1 (1985): 31-46.

In this study, a house near Chicago was monitored continuously for a five-month period, for radon concentrations, air exchange rates, and radon and weather source parameters.

Nero, A.V., et al. "Distribution of airborne radon-222 concentrations in U.S. homes." *Science* 234 (Nov. 21, 1986): 992-997.

The authors have taken the accumulated data of indoor radon research in the United States and systematically appraised the distribution of radon concentrations in U.S. homes. The results, taken from thirty-eight different locations, indicate wide fluctuations in the amount of radon detected indoors. Consequently, the levels of health risks also vary greatly.

Prichard, Howard M., et al. "Associations between grab sample and integrated radon measurements in Maine and Texas." *Environment International* 8, no. 1-6 (1982): 83-88.

Indoor radon concentrations are generally higher in Maine than in Houston. The authors conclude that geological and hydrological factors are primarily responsible for the difference.

Rundo, J., and R.E. Toohey. "Radon in homes and other technologically enhanced radioactivity." (NTIS DE83011731). In *National Council of Radiation Protection and Measurement*, annual meeting, April 6, 1983, Bethesda, Md., 1984.

This is a study of 110 homes in the Chicago area showed significant levels of radon concentrations, some greater than those monitored in Grand Junction, Colorado, where homes were built over uranium mill tailings deposits.

Rundo, J., F. Markum, and N.J. Plondke. "Observation of high concentrations of radon in certain houses." *Health Physics* 36, no. 6 (June 1979): 729-730.

This study indicates that the average exposure to radon in U.S. homes may be much higher than reported in previous studies. Homes in Florida, Massachussetts, and Tennessee were evaluated for radon exhalation rates which had been inhaled in the home overnight.

Sachs, H.M., et al. "Radon concentrations and ventilation rates in eastern Pennsylvania." In *Proceedings of an engineering foundation conference on management of atmospheres in tightly enclosed spaces, Santa Barbara, Ca., Oct. 17-21, 1983*, 81-93. Washington, D.C.: U.S. Department of Energy, 1984.

U.S. Environmental Protection Agency. Office of Radiation Programs. *Preliminary findings: Radon daughter levels in structures constructed on reclaimed Florida phosphate land.* (NTIS PB-257 679/1). Washington, D.C.: The Office, Division of Criteria and Standards, 1975.

Wilkening, Marvin, and Andreas Wiche. "Seasonal variations in indoor Rn at a location in the southwestern United States." *Health Physics* 51, no. 4 (Oct. 1986): 427-436.

Results show that winter concentrations of indoor radon exceed summer levels by a factor of two to three, mainly due to higher air exchange rates in the summer.

Reduction and Removal Techniques

Brennan, Terry, and Bill Turner. "Defeating radon." *Solar Age* 11 (Mar. 1986): 33-37.

Diagnosing and reducing radon problems in homes is the focus of this article. The authors present ideas for retrofiting basements, increasing air exchange rates, and cleaning air.

Canada. Atomic Energy Control Board. *Report on investigative and remedial measures, radiation reduction and radioactive decontamination, in Uranium City, Saskatchewan.* Regina, Ottawa: The Board, 1978.

The authors describe early experiences with radon abatement. They also report on sealants, ventilation, and filtration test results, as well as other more extreme measures, such as soil excavation.

Clavensjoe, B., et al. *Radon in dwellings: Constructional steps to reduce the concentrations of argon in indoor air.* (NTIS DE83701098). Stockholm: Swedish Council for Building Research, 1982.

Test results of various methods to reduce radon infiltration into homes are presented. The authors report that replacement of filling around basements, increased ventilation, and re-papering with aluminum foil were all effective methods for reducing radon.

Culot, Michel V.J., Hilding G. Olson, and Keith J. Schiager. "Field applications of a radon barrier to reduce indoor airborne radon progeny." *Health Physics* 34 (1978): 498-503.

A report on the application of a barrier to reduce radon infiltration in a school and in Grand Junction, Colorado homes, where uranium mill tailings have been used as leveling and backfill material.

Fitzgerald, Joseph E., Jr., Richard J. Guimond, and Roger A. Shaw. *A Preliminary evaluation of the control of indoor radon daughter levels in new structures.* (NTIS PB81-102204). Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation Programs, 1976.

Technologies for cost-effectiveness in reducing radon exhalation through building foundations are evaluated in this work. Improvements such as ventilation, polymeric sealants, excavation, ventilated crawl spaces and improved slab construction are also discussed.

Henschel, D.B., and A.G. Scott. *EPA program to demonstrate mitigation measures for indoor radon: Initial results.* (NTIS PB86-176039). Research Triangle Park, N.C.: U.S. Environmental Protection Agency, Air and Energy Engineering Research Laboratory, 1986.

This report covers the initial results of an EPA test involving radon mitigation techniques in eighteen concrete block basement homes in the Reading Prong area of eastern Pennsylvania. Where major openings in the block walls can be closed effectively, suction on the wall voids has been helpful in reducing radon infiltration. Inaccessible gaps in walls limit the suction performance on the void network, and reduce effectiveness.

Hinds, W.C., et al. "Control on indoor radon decay products by air treatment devices." *Journal of the Air Pollution Control Association* 33, no. 2 (Feb. 1983): 134-136.

The authors evaluate the effectiveness of household air cleaning devices on radon decay products.

Holub, R.F., et al. "Radon-222 and 222-Rn progeny concentrations measured in an energy-efficient house equipped with an heat exchanger." *Health Physics* 49, no. 2 (Aug. 1985): 267-277.

The results of this report indicate that forced flow ventilation by means of a heat exchanger decreases radon levels by increasing air exchange rates.

Jonassen, N., and J.P. McLaughlin. "Air filtration and radon daughter levels." *Environment International* 8, no. 1-6, 1982): 71-76.

_____. "Removal of radon daughters by filtration and electric fields." *Radiation Protection and Dosimetry* 7, no. 1-4 (1984): 407-411.

Moeller, D.W., and K. Fujimoto. "Cost of control measures for indoor radon progeny." *Health Physics* 46, no. 6 (June 1984): 1181-1193.

Moeller and Fujimoto evaluate a number of methods for reducing indoor radon concentrations in existing homes for cost effectiveness.

Nazaroff, W.W., et al. "The Use of mechanical ventilation with heat recovery for controlling radon and radon-daughter concentrations in houses." *Atmospheric Environment* 15, no. 3 (1981): 263-270.

The use of air-to-air heat exchangers in homes with high levels of radon, showed significant reduction in radon levels and in general air quality.

Offerman, F.J., et al. *Control of respirable particles and radon progeny with portable air cleaners* . (NTIS DE84013878). Berkeley, Calif.: Lawrence Berkeley Laboratory, 1984.

This is a study of eleven portable air cleaning devices. The best devices were effective at removing both particulates and radon progeny. However, concentrations of unattached radon progeny were found to increase when air cleaning was increased.

Sandia National Laboratory. *Indoor air quality handbook: For designers, builders, and users of energy efficient residences* . (NTIS DE83002315). Albuquerque, N.M.: Sandia National Laboratory, 1982.

Scott, A.G., and W.O. Findlay. *Demonstration of remedial techniques against radon in houses on Florida phosphate lands* . (NTIS PB84-156157). Columbia, Md.: American Atcom., 1983.

Scott and Findlay review the current building practices used to reduce radon's routes of entry into residential dwellings.

Sextro, R.G. *Control of indoor radon and radon progeny concentrations* . (NTIS DE86000622). Berkeley, Calif.: Lawrence Berkeley Laboratory, 1985.

Three methods used to control radon concentrations in indoor air are: restriction of radon entry, reduction of indoor concentrations by air cleaning or filtration, and removal of the airborne radon progeny. Sextro describes techniques used to implement these methods.

U.S. Environmental Protection Agency. *Radon reduction methods: A homeowner's guide* . Washington, D.C.: The Agency, (GPO), 1986.

Various methods for reducing the levels of radon in homes are described in this guide. The methods are intended to prevent radon entry and/or to replace contaminated air.

_____. Radon reduction techniques for detached houses: Technical guidance. Washington, D.C.: The Agency, (GPO), 1986.

The EPA prepared this guidance manual for state environmental officials, building contractors, and concerned homeowners. It focuses on how to modify houses to reduce indoor radon.

Windham, S.T., E.D. Savage, and C.R. Philips. *The Effects of home ventilation systems on indoor radon-radon daughter levels* . (NTIS PB-291 925/6). Montgomery, Ala.: Eastern Environmental Radiation Facility, 1978.

Appendix

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Bliss, Steve. "Breathing free, part 1: How to battle with formaldehyde and radon in houses." *Solar Age* (Nov. 1984).

"Calculating homely radon's daughters." *Science News* 129 (Jan. 18, 1986).

"Cancer beneath your home." *Science Digest* 90 (July 1982).

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Cohen, Bernard. "Radon: Our worst radiation hazard." *Consumers' Research Magazine* (Apr. 1986).

"Concern over radon in houses triggers plan for national survey." *Chemical and Engineering News* (Apr. 28, 1986).

"Danger! Radon." *Changing Times* (Aug. 1986).

Duffy, Gordon. "In the calm before the storm let's determine radon's hvac impact." (editorial). *Air Conditioning, Heating and Refrigeration News* (Sept. 15, 1986).

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Gilbert, Susan. "Getting rid of radon: Ventilation is freeing some homes of the cancer-causing gas." *Science Digest* 94 (June 1986).

Hanson, David J. "High radon levels in homes spark moves to combat pollutant." *Chemical & Engineering News* (Nov. 18, 1985).

Holzman, David. "Builders can reduce radon hazard." *Builder* (May 1986).

"Homely radon—how much to expect." *Science News* 122 (Sept. 18, 1982).

"How insulation traps the bad and the good." *Business Week* (Dec. 24, 1979).

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Kelsey, Patricia A. "Radon-resistant home building methods approved." *Air Conditioning, Heating and Refrigeration News* (Mar. 4, 1985).

Kirsch, Laurence S. "Behind closed doors:The problem of indoor air pollutants." (part 1). *Environment* 25 (Mar. 1983).

Lafavore, Michael. "Warning! This house contains radon: Five million American homes may face the same problem." *Reader's Digest* 128 (June 1986).

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Lees, Al. "Home tests for radon." *Popular Science* 228 (Feb. 1986).

McCann, Matthew. "ASHRAE probes secrets of radon." *Air Conditioning, Heating and Refrigeration News* (Aug. 5, 1985).

McClintock, Mike. "Tight homes, bad air." *Consumers' Research Magazine* 69 (Jan. 1986).

"More on homely radon." *Science News* 128 (Nov. 23, 1985).

Murphy, Jamie. "The Colorless, odorless killer: A million U.S. homes may be contaminated by deadly radon." *Time* 126 (July 22, 1985).

Nero, Anthony V., Jr. "The Indoor radon story." *Technology Review* 89 (Jan. 1986).

"The radiation question: Government, independent studies show home insulation may be hazardous." *Consumers' Research Magazine* 63 (Nov. 1980).

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"Radon calling?" *Mother Earth News* (Mar.-Apr. 1986).

This article emphasizes home protection.

"Radon in houses." *Harvard Medical School Health Letter* 11 (May 1986).

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Raloff, Janet. "Environment: Lung cancer and energy efficient homes." *Science News* 120 (Nov. 7, 1981).

Rittenhouse, R.C. "Environmentally speaking: Radon-in-homes update." *Power Engineering* 88 (May 1984).

This is a summary of a study done for the Wisconsin Public Service Corporation on the effectiveness of air-to-air heat exchangers and electrostatic air cleaners for reducing indoor radon concentrations.

Sak, Richard. "N.J. to test for radon contamination." *Air Conditioning, Heating and Refrigeration News* (Aug. 5, 1985).

In this article, the Reading Prong area is tested for health hazards.

Smay, V. Elaine. "Radon exclusive—how dangerous? How widespread?—How you can test for it in your home—what you can do about it." *Popular Science* 227 (Nov. 1985).

Taylor, Ronald A. "Your house may be a death trap: Radioactive gas rising naturally from the earth is seeping into U.S. homes." *U.S. News and World Report* 100 (Mar. 17, 1986).

Thompson, Boyce. "Eastern builders face a deadly threat—radon pollution." *Professional Builder* (Feb. 1986).

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