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MODELS OF RADON ENTRY: A REVIEW

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ABSTRACT

This paper reviews existing models of radon entry into houses. The primary mechanism of radon entry in houses with high indoor concentrations is, in most cases, convective entry of radon bearing soil-gas from the surrounding soil. The driving force for this convective entry is the small indoor-outdoor pressure difference arising from the stack effect and other causes. Entry points for the soil-gas generally are the cracks or gaps in the building substructure, or through other parts of the building shell in direct contact with the soil, although entry may also occur by flow through permeable concrete or cinder block walls of the substructure. Models using analytical solutions to idealized geometrical configurations with simplified boundary conditions obtain analytical tractability of equations to be solved at the cost of severe approximations; their strength is in the insights they offer with their solutions. Models based on lumped parameters attempt to characterize the significant physical behavioral characteristics of the soil-gas and radon flow. When realistic approximations are desired for the boundary conditions and terms in the governing equations, numerical models must be used; these are usually based on finite difference or finite element solutions to the governing equations. Limited data are now available for experimental verification of model predictions. The models are briefly reviewed and their strengths and limitations are discussed.

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Introduction

Although diffusive transport of radon can account for observed radon fluxes from building materials and exposed soil, diffusion alone can not account for the total radon entry rates observed in most single family houses[1,2]. There exist circumstances where use of underground water for household use, and diffusion from building materials can be important contributors to indoor radon concentrations[3,4]. However, it is generally accepted that for most single family residences with elevated concentrations, convective entry of radon bearing soil-gas, driven by small pressure differences between the house and the surrounding soil, is the major radon entry mechanism. This paper focuses on the models of only this mechanism of radon entry into single family houses.

The equations governing radon generation, its release into the soil-gas, and soil-gas and radon transport are reasonably well understood. Different models of radon entry attempt to solve the equations under more or less severe approximations to the physical structure of the soil, entry pathways, and boundary conditions. The purpose for which the models are developed strongly influences the modeling approach.

Although the ultimate motivation behind the model development is to understand the phenomenon of radon entry in terms of measurable properties of the soil, and house construction and operation, the specific near term goals can be different. Models of radon entry have been used for understanding effect of different housing construction practices on radon entry rates, elucidation of the factors influencing the performance of sub-slab ventilation systems for radon mitigation, predicting long term indoor radon concentrations from short term measurements, and assessment of impact of changes in the housing stock characteristics on the distribution of radon exposure to the population.

As a background to the sections that follow, the basis of radon transport and entry model equations is briefly summarized here. In homogeneous soils (or small enough volume elements of soil to be considered homogeneous), the naturally occurring flow of soil-gas drawn into houses follows the well known Darcy law. This law states that the local bulk-average velocity of soil-gas is proportional to the local gradient of pressure. An excellent exposition is found in Bear[5]. The stack effect from the warm (and therefore lighter) air in the house imposes only a small pressure difference between the interior and exterior of the house envelope at the basement level, of the order of -10 pascals (Pa), much smaller than the atmospheric pressure of about 101 kPa. Therefore, in the steady state flow, the soil-gas can be considered incompressible for all practical purposes. This allows the differential equation of conservation of mass for soil-gas to be conveniently combined with the Darcy law equation to obtain the governing equation for pressure in the soil block adjacent to the building substructure. The solution of this equation, with appropriate boundary conditions, yields the pressure field in the soil block; the gradient of pressure directly allows determination of soil-gas velocities and thereby soil-gas entry rates into the house. The governing equation for pressure under the above described conditions is the Laplace's equation, which has been studied for more than a century because it also applies to electrostatics and conduction of heat in solids. As a result, some of the classic texts on applications of Laplace's equations (e.g. Carslaw and Jaeger[6]) have direct applicability to soil-gas flows driven by pressures differences imposed by houses. If a sub-slab ventilation system is installed and operated in the house, the flow of soil-gas no longer follows the Darcy law. Under these circumstances, solutions to the Laplace's equation are inadequate descriptions of the soil-gas pressure field, and more powerful solution techniques must be employed to obtain the pressure field and soil-gas velocities. In either case, once the soil-gas flow is determined, the differential equation for radon generation, transport and decay can be solved separately, taking the soil-gas flow field as its input. Generally, this requires a numerical method to obtain the solution.

In the following sections, the three major approaches to modeling of radon entry are described. These are 1) analytical solutions, 2) lumped parameter models, and 3) numerical methods. A fourth approach to modeling radon entry in the housing stock is usually directed towards its geographical characterization for improved targeting of efforts to mitigate indoor radon. This approach is based on developing an index to describe the propensity of housing stock to have high levels of indoor radon. The index is usually based on a combination of geologic factors (radium content, permeability, radon emanation coefficient), climatic factors (e.g. average winter temperatures), and includes some way of distinguishing between relevant characteristics of the housing construction (e.g. houses with basements as opposed to those with a crawl space or slab-on-grade). This approach is not addressed in this paper.

This paper does not attempt to provide a complete bibliography of all the recent modeling work undertaken on radon entry. However, the references in the papers cited in this text would provide many useful pointers to past and current work on the subject. Some of the earliest ideas on the subject that preceded later development of detailed analytical and numerical models models were suggested by Scott[7].

Analytical Models

Analytical closed form solutions have the power of clarity and can elucidate the functional dependence of results on the input parameters. Mowris and Fisk[8] simplified the problem to the point where an analytic solution could be found to the problem of the flow of soil-gas alone (without attempting a solution to the radon transport equation). In this work, they used the simplying assumption that the soil-gas flow into a depressurized basement through a crack between the basement slab and the footer (see footnote 1) can be approximated by soil-gas entry into a depressurized horizontal cylindrical cavity in the soil (with its long axis parallel to the soil surface). The soil was assumed homogeneous and isotropic, and the solution to the pressure field was found from analogy to the problem of heat conduction from a horizontal cylinder buried in a semi-infinite medium. Bipolar coordinates allow an exact solution to the pressure equations, and for the flow of soil-gas into the cavity. Mowris and Fisk verified their analytic solutions by comparing them with predictions from a two dimensional finite difference model, and obtained useful results regarding the importance of changing the crack resistance, and implications of the use of exhaust ventilation, in enhancing soil-gas and radon entry rates into houses located in soils of various permeabilities. However, they did not calculate the radon concentrations entering the cavity explicitly, since an analytic solution to the governing equations for radon transport even under these simplifying assumptions has not been yet published.

Nazaroff[9], and Nazaroff and Sextro[10] make the same simplifying assumptions regarding the soil and the boundary conditions. However, they use the solution of the pressure field, (and thus also of the soil-gas velocity field), to obtain streamlines of air flow starting from the soil surface, where fresh air enters the soil, to the appropriate point of entry on the surface of the cylindrical cavity. A small computer program solves the radon transport equation along each selected streamline. Integrating the results over the surface of the cylinder yields the radon entry rate into the cavity. Nazaroff and Sextro demonstrated quantitatively the results of radon depletion of the soil (owing to large soil-gas flow rate and the resulting short residence time of air parcels in the soil) on the radon entry rate into the cylinder. They also demonstrated that radon concentrations of more than 500 pCi/l were possible in houses situated in soils of normal radium content, but having large permeability.

More recently, Reddy et al[11] and Gadsby et al[12] have used an analytical model for studying the extension of depressurization in sub-slab regions of houses installed with sub-slab depressurization (SSD) systems (see footnote 2). They model the soil-gas flow in the gravel bed as radial flow of a gas in a shallow cylindrical gravel bed bounded between two impermeable disks, with suction applied at the center. An annulus of soil surrounds the cylinder of gravel to capture the effect of the soil in the backfill region (see footnote 3) on the depressurization. The model[13] has been used to calculate the relative importance of permeability of sub-slab gravel, and the permeability of the soil around the foundation walls and in the back-fill region peripheral to the basement walls. The model results are expected to be compared against field experimental data in future work.

Lumped Parameter Models

The simple analogy to pressure driven flow of soil-gas is voltage difference driving a current in an electrical circuit. In this analogy, pressure differences (represented as voltage differences) drive gas flow (represented as current) in proportion to the driving force. A simple model of the system seeks to represent the complex (and in reality a continuum) system as a discrete system with lumped parameters. The values of the parameters can be be evaluated by different means, e.g. with experiments that estimate soil-gas entry into a house under artificial short-term depressurization. Once the system configuration is identified and parameter vales estimated, this information can be used to predict the soil-gas and radon entry rates under a variety of realistic driving forces (e.g. depressurization from wind and stack effects, effects of mechanical exhaust ventilations, unbalanced duct systems).

Lumped parameter models have at least two uses: 1) such a model could be used to assess the winter (or annual average) indoor radon levels once the house parameters are identified, and some reasonable estimate is used for the driving forces, and 2) the models could be used for broad characterization of the housing stock with respect to radon entry rates, if the parameter identification of the houses is a relatively rapid experimental procedure.

Turk et al[14] develop a purely resistive network model to calculate soil-gas entry potentials and radon entry potentials for various points in the basement of four houses. The points with high radon entry potential are observed to agree with the intuitively identified locations for successful sub-slab ventilation (SSV) system installation. In a similar effort to interpret data from short term depressurization tests of six New Jersey houses, Gadgil et al[15] were only moderately successful, presumably owing to limitations of the experimental methods and initially unexpected complexities in the radon entry routes in the houses. Arvela et al[16] also have presented a simplified model of diffusive and advective entry of radon into a house governed by equations that imply a purely resistive model for soil-gas entry, and have compared its predictions to observed variations in the indoor concentration.

A recent advance in simulating the radon and soil-gas entry mechanism with lumped parameter circuits has resulted from the separation of the circuits used to model soil-gas and radon entry into the house[17]. Each of the two circuits then can separately address the time-dependent (or dynamic) behavior of the fluid being modeled in either the time or the frequency domain. The two circuits are linked by defining a current source strength in the radon circuit that depends on the soil-gas flow rate obtained in the soil-gas circuit. This two-circuit model enables the incorporation of the effects of radon diffusion, radon generation and decay inside the soil, radon concentration depletion in the soil at high soil-gas entry rates, as well as the dynamic behavior of soil-gas and radon entry under transient pressure differences. This is current work, and at the present has been subjected to only limited experimental verification tests. The results of the comparison appear encouraging.

Numerical Models

Several numerical methods have been available for some time for solving problems of flow in porous media, and heat conductions problems. These can be easily adapted to solve the soil-gas flow equation in the soil block surrounding the house. The equation for radon generation, transport (by diffusion and advection), and decay can then be solved separately given the soil-gas flow field to derive both a radon concentration field in the soil, and the radon entry rate into a building.

The recent availability of relatively inexpensive powerful computers has made sophisticated and detailed modeling of soil-gas and radon entry into houses a widely accessible exercise. The main limitations of the approach remain in the hands of the user. Since explosive growth in this modeling approach can be anticipated in the near future, a short list of cautions to a novice to this field may be in order. These would include: care in the definition of the problem, its boundary conditions and the geometry; attention to the choice of the solution algorithms; detailed examination of predicted flow, concentration and pressure fields to search for physically counter-intuitive results (or trends in results) as signals for errors in programming or execution; attention to the sensitivity of the predicted results to the selection and magnitude of convergence criteria, changes in grid spacing, and (if applicable,) relaxation parameters.

There are three main classes of approaches to the solution of the transport problem of soil-gas, and the advection-diffusion problem of radon that the soil-gas carries with it. The following three sections address the numerical models accordingly.

1. Finite Difference Models

The approach essentially consists of converting the differential equation to a difference equation based on discretization of space (and, if applicable, time). The unknown field variables are then defined at the nodes of the grids, and are expressed as a set of coupled difference equations (usually of the first order). A direct solution of the equations by matrix inversion is usually out of the question, and an iterative method is employed to reach the final solution within acceptable error. This is by far the most widely used class of solution approaches to modeling radon entry at the present.

Loureiro[18, 19] addresses in detail the finite difference solution approach to the equations, and also reviews previous work on the subject. He developed a fully three dimensional finite difference formulation of the problem of soil-gas and radon entry through cracks in the basement of a house situated in a soil block. The house geometry was assumed symmetrical about two orthogonal horizontal axes, which allowed him to model only one quadrant of the problem. In the same year, Dimbylow[20] published a finite difference solution to the convective entry of soil-gas and radon into a house through cracks in the basement. This has been followed by several others who developed the approach further, refined the geometry and boundary condition definition, and investigated the importance of secondary effects, (e.g., the effect on radon entry of the buoyancy of the soil-gas conductively warmed by a heated basement in winter)[21-23]. Rogers extended their one dimensional model of diffusive radon transport developed for radon release from uranium mine tailings to a two dimensional cylindrical model[24] that can simulate advection and diffusion of radon leading to entry with soil-gas into a basement. Hintenlang and Furman[25] used a finite difference using only Darcy flow to assess design of SSV systems for low permeability soils. Cohilis et al[26] also report application of a finite element model initially developed for heat conduction in solids for simulating soil-gas under SSV operation. Their model too is limited to Darcy flow. Gadgil et al[27] use a fully three dimensional non-symmetrical finite difference model that incorporates non-Darcy flow to assess the influence of sub-slab gravel permeability (and selected other factors), on the performance of sub-slab ventilation (SSV) systems for reduction in radon entry rates. Their model predictions provide satisfactory agreement with data from field experiments in selected houses.

Finite difference methods are easy to implement, and straight forward to understand. Several good texts are available on the subject. However, since the field variables are solved on the nodes of intersection of grid lines which must be continuous, the models usually suffer from having to carry a large density of grid nodes (and the resulting computational burden) in uninteresting regions adjacent to the areas of interest. This increased burden can prove prohibitive when attempting to model the usually complex geometry of a real house with a basement.

2. Finite Element Models

Finite element methods also discretize space, but in this case, the discretization is based on a net of nodes that leads to elements defined by interconnections between the nodes. This affords greater freedom in the choice of node locations, node densities and field resolution, (and therefore avoidance of unnecessary computational burden of nodes in uninteresting regions of space).

The most extensive family of finite element models of radon transport and entry is associated with the work reported by Holford et al[28] and Owczarski et al[29]. The codes are developed in two and three dimensions, and have been used to model the effect of wind in reducing sub-slab radon concentrations under houses laid over gravel beds, and radon transport in dry cracked soils. Garbesi and Sextro[30] have used an existing finite element ground water model to simulate the flow of soil-gas and its contaminants into basements having permeable concrete block walls.

3. Integrated Finite Difference Models

The integrated finite difference method has enjoyed pre-eminence in underground reservoir modeling and hydrological transport problems for several years. The method is based on integrating the differential equation over volumes of explicitly defined subdomains (or elements), which have user-defined connectivities (thus two and three dimensional problems are treated identically). The physical variables, such as pressure or concentration, take values equal to properly defined averages over the subdomains. Finite differences are used to evaluate gradients for the Darcy law.

This method has been used over the last two decades for simulations of drainage and wetting of variably saturated soil columns under pressure deformation, constant rate or constant draw-down well tests for ground water reservoir diagnostics in porous media with multiply fractured rocks, internal drainage into mines expanding with time, analysis of geothermal fields, and nuclear waste disposal sites[31-33].

The integrated finite difference method has recently been used for simulation of radon entry into basements owing to variations in barometric pressure. Narasimhan et al[34] address the problem of a basement with open soil as its floor, exposed to a steady sinusoidal variation in barometric pressure (of realistic amplitudes and periods). Owing to the lag in the propagation of the pressure pulse into the soil, the basement floor experiences enhanced entry of soil-gas from this "pumping" effect. The soil-gas entering the basement would be charged with radon, but the basement air sucked into the soil would be relatively radon free. Thus this mechanism may allow another route of radon entry into houses located on low permeability soils. Tsang and Narasimhan[35] have followed up this work with a more detailed model in which the radon transport equation is explicitly solved.

Conclusions and Future Directions

Models of radon entry allow insights into the interplay of parameters governing radon entry, and shed light on effectiveness of possible strategies for controlling indoor radon levels. Since the purposes for which the models are developed are different, so are the approaches to the models.

The most time consuming (and important) task at hand is undertaking an adequate field validation of the models that are being developed. A wealth of carefully documented data on radon entry dynamics is expected from the "small structures" series of experiments now in progress at LBL[36]. Various degrees of success is reported in the literature in comparing model predictions with field data (e.g. Refs. 10, 15, 21, 27). However, none of the models are at the point where they can be claimed to be fully validated against extensive field data.

There is a striking similarity between the evolution of different models (for different applications and end-uses) to predict energy use for heating and cooling of buildings, and models of radon entry in buildings. Just as for radon, there are large sophisticated (and computationally intensive) models for building energy use, simplified lumped parameter models, as well as simpler models that predict energy use based on envelope area and conductance, and an effective leakage area for the envelope. It is interesting to note that none of the modeling approaches have proved so overwhelming superior that it has led to the abandonment of all others; there are a multiplicity of niches for models. This is also expected to be the case for models of radon entry.

Radon entry rate is in many ways similar to building energy use: for a given climate, weather and geographical location, a real house has commonly some variances from its design (which itself has a variety of acceptable practices). This leads to differences in radon entry rates (and energy use) even in houses that are identically designed and are at the same location. There is a further variation in radon entry rates (also in energy use) owing to the differences in how the occupants operate otherwise identical houses. This complicates the analysis of public policy measures and their benefits and costs. Possibly, development of an analysis technique for radon entry in large housing stocks, similar to the one used in analysis of energy use (e.g. PRISM - the Princeton Scorekeeping Method[37]) may be helpful for this purpose.

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References

1. Nero, A. V., and Nazaroff, W. W. *Characterizing the Source of Radon Indoors*, Rad. Prot. Dosim., Vol. 7, Nos. 1-4, pp. 23-39, (1984).
2. Nazaroff, W. W., Moed, B. A., and Sextro, R. G. *Soil as a Source of Indoor Radon: Generation, Migration and Entry*, in Radon and its Decay Products in Indoor Air, Ed. by W. W. Nazaroff and A. V. Nero, John Wiley and Sons, ISBN 0-471-62810-7, New York, (1988)
3. Nazaroff, W. W., Doyle, S. M., Nero, A. V., and Sextro, R. G. *Radon Entry via Potable Water*, in Radon and its Decay Products in Indoor Air, Ed. by W. W. Nazaroff and A. V. Nero, John Wiley and Sons, ISBN 0-471-62810-7, New York, (1988)
4. Stranden, E. *Building Materials as a Source of Indoor Radon*, in Radon and its Decay Products in Indoor Air, Ed. by W. W. Nazaroff and A. V. Nero, John Wiley and Sons, ISBN 0-471-62810-7, New York, (1988)

5. Bear, J. *Dynamics of Fluids in Porous Media*, Dover Edition, ISBN: 0-486-65675-6 (1972).

6. Carslaw, H. S., and Jaeger, J. C. *Conduction of Heat in Solids*, Second Edition 1959, Reprinted 1988, ISBN: 0-19-853368-3, Clarendon Press, Oxford.

7. Scott, A. *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*, Research Report INFO-0096, prepared by DSMA Atcon Ltd. for the Atomic Energy Control Board, Ottwa, Canada, January 18, 1983.

8. Mowris, R. J., and Fisk, W. J. *Modeling the Effects of Exhaust Ventilation on 222Rn Entry Rates and Indoor 222Rn Concentrations*, Health Physics, Vol. 54, pp. 491-501, (1988).

9. Nazaroff, W. W. *Predicting the Rate of 222Rn Entry from Soil into the Basement of a Dwelling due to Pressure Driven Air Flow*, Rad. Prot. Dosim, Vol. 24, pp 199-202, (1988).

10. Nazaroff, W. W., and Sextro, R. G. *Technique for Measuring the Indoor 222Rn Source Potential of Soil*, Environmental Science and Technology, Vol. 23, pp 451-458, (1989).

11. Reddy, T. A., Black, H. E. III, Gadsby, K. J., Harrje, D. T., and Sextro, R. G. *Modeling Air Flow Dynamics through a Homogeneous Gravel Porous Bed using Subslab Depressurization*, Report PU/CEES 246, Princeton University, Center for Energy and Environmental Studies, (1990).

12. Gadsby, K. J., Reddy, T. A., de Silva, R. and Harrje, D. T. *A Simplified Modeling Approach and Field Verification of Airflow Dynamics in SSD Radon Mitigation Systems*, Preprint from the 1990 International Symposium on Radon and Radon Reduction Technology, U.S. Environmental Protection Agency Report EPA/600/9-90/005c. Session V-I. February 19-24, 1990, Atlanta.

13. Gadsby, K. J., Reddy, T. A., and Craig, A. B. *The Effect of Subslab Aggregate Size on Pressure Field Extension*, Preprints: 1991 International Symposium on Radon and Radon Reduction Technology, sponsored by U.S. Environmental Protection Agency. April 2-5, 1991, Philadelphia.

14. Turk, B. H., Harrison, R. J., Prill, R. J., and Sextro, R. G. *Developing Soil Gas and 222Rn Entry Potentials for Substructure and Assessing Rn Control Diagnostic Techniques*, Health Physics, Vol 39, No. 4, pp. 405-419, (1990), also Report LBL-27319, Lawrence Berkeley Laboratory, Berkeley, CA (1989).

15. Gadgil, A. J., Najita, J. S., Revzan, K. L., Harrison, J., and Turk, B. H. *An Experiment with Depressurization Tests as Indicators of Radon Availability in 6 New Jersey Houses*, Report LBL-28690, Lawrence Berkeley Laboratory, Berkeley, CA (1990).

16. Arvela, H., Voutilainen, A., Makelainen, I., Castren, O., and Winqvist, K. *Comparison of Predicted and Measured Variations of Indoor Radon Concentrations*, Rad. Prot. Dosim., Vol. 24, No. 1/4, pp. 231-235, (1988).

17. Andersen, C. E., Gadgil, A. J., and Sextro, R. G. *A Status Report on Lumped Parameter Modeling of Radon Transport Dynamics* Report LBL-31133 DRAFT, Lawrence Berkeley Laboratory, Berkeley, CA (1991).

18. Loureiro, C. O., Simulation of the Steady State Transport of Radon from Soil into Houses with Basements under Constant Negative Pressure, Report LBL-24378, Lawrence Berkeley Laboratory, Berkeley, CA (1987).

19. Loureiro, C. O., Abriola, L. M., Martin, J. E., and Sextro, R. G. *Three Dimensional Simulation of Radon Transport into Houses Under Constant Negative Pressure*, Environmental Science and Technology, Vol. 24, pp. 1338-1348, (1990).

20. Dimbylow, P. J. *The Solution of the Pressure Driven Flow Equation for Radon Ingress through Cracks in Concrete Foundations*, Rad. Prot. Dosim., Vol. 18, No. 3, pp. 163-167, (1987).

21. Revzan, K. L., Fisk, W. J., and Gadgil, A. J. *Modeling Radon Entry into Houses with Basements: Model Description and Verification*, Indoor Air, Vol. 1, No. 2, pp. 173-189, (1991).

22. Revzan, K. L., and Fisk, W. J. *Modeling Radon Entry into Houses with Basements: the Influence of Structural Factors*, Report LBL-28109, Lawrence Berkeley Laboratory, Berkeley, CA (1990). Submitted to Indoor Air.

23 Revzan, K. L., Fisk, W. J., and Sextro, R. G. *Modeling Radon Entry into Houses with Concrete Block Stem-walls*, Report LBL-30005, Lawrence Berkeley Laboratory, Berkeley, CA (1991).

24. Rogers, V. C., and Nielson, K. K. *Benchmark and Application of the RAETRAD Model*, Preprint VI-1 in Preprints of 1990 International Symposium on Radon and Radon Reduction Technology, February 19-23, 1990, Atlanta. Preprint Volumes published by U.S. EPA, document number EPA/600/9-90/005, January 1990.

25. Hintenlang. D. E., and Furman, R. A. *Sub-slab Suction System Design for Low Permeability Soils*, Preprint C-V-1, in Preprints of 1990 International Symposium on Radon and Radon Reduction Technology, February 19-23, 1990, Atlanta. Preprint Volumes published by U.S. EPA, document number EPA/600/9-90/005, January 1990.

26. Cohilis, P., Wouters, P., and L'Heureux, D. *Prediction of the Performance of Various Strategies of Subfloor Ventilation as Remedial Action for Radon Problems*, presented at the 11th AIVC Conference, "Ventilation System Performance", Belgirate, Lake Magiore, Italy, 18-21 September 1990.

27. Gadgil, A. J., Bonnefous, Y. C., Fisk, W. J., Sextro, R. G., Prill, R. J., and Nematollahi, M. *Influence of Sub-slab Aggregate Permeability on Sub-slab Ventilation System Performance*, Report, LBL-31160 DRAFT, Lawrence Berkeley Laboratory, Berkeley, CA. (1991).

28. Holford, D. J., Schery, S. D., Wilson, J. L., and Philips, F. M. *Radon Transport in Dry Cracked Soil: Two-Dimensional Finite Element Model*, Report PNL 7116, Pacific Northwest Laboratory, Richland, WA (1989).

29. Owczarski, P. C., Holford, D. J., Burk, K. W., Freeman, H. D., and Gee, G. W. *Effect of Winds in Reducing Sub-slab Radon Concentration under Houses Laid over Gravel Beds*, Presented at the 1991 International Symposium on Radon and Radon Reduction Technology, Philadelphia, PA, April 2-5, 1991. Proceedings to be published by U.S. Environmental Protection Agency, Washington D. C.

30. Garbesi, K., and Sextro, R. G. *Modeling and Field Evidence of Pressure-Driven Entry of Soil Gas into a House through Permeable Below-Grade Walls*, Environmental Science and Technology, Vol. 23, pp. 1481-1487, (1989).

31. Edwards, A. L. *TRUMP: A Computer Program for Transient and Steady State Temperature Distributions in Multi-Dimensional Systems*, National Technical Information Service, National Bureau of Standards, Springfield, VA (1972).

32. Narasimhan, T. N., and Witherspoon, P. A. *Numerical Model for Saturated-unsaturated Flow in Deformable Porous Media: 3. Applications*, Water Resour. Res., 14(6), pp. 1017-1034, (1978).

33. Narasimhan, T. N., Alavi, C. W., and Liu, C. W. *CHAMP - a Computer Code for Modeling Transient Fluid Flow and Chemical Transport with Hydrodynamic Dispersion in Variably Saturated Systems/fl, Proceedings, Symposium on Groundwater Flow and Transport Modeling for Performance Assessment of Deep Geologic Disposal of Radioactive Waste: A Critical Evaluation of the State of the Art, Albuquerque, NM, May 20-21, 1985.*

34. Narasimhan, T. N., Tsang, Y. W., and Holman, H-Y. *On the Potential Importance of Transient Air Flow in Advective Radon Entry into Buildings*, Geophysical Research Letters, Vol. 17, pp. 821-824, (1990).

35. Tsang, Y. W., and Narasimhan, T. N. *Effects of Periodic Atmospheric Pressure Variation on Radon Entry into Buildings*, Report LBL-31164 DRAFT, Lawrence Berkeley Laboratory, Berkeley, CA (1991).

36. Fisk, W. J., Flexer, S., Gadgil, A. J., Holman, H. -Y., Modera, M. P., Narasimhan, T. N., Nuzum, T., Revzan, K. L., Sextro, R. G., Smith, A. R., Tsang, Y. W., and Wollenberg, H. A. *Monitoring and Modeling of Radon Entry into Basements: A Status Report for the Small Structures Project*, Report LBL-27692, Lawrence Berkeley Laboratory, Berkeley, CA (1989).

37. Various papers in the Special Issue of Energy and Buildings devoted to "Measuring Energy Savings: The Scorekeeping Approach", edited by Fels, M. F., Volume 9, Nos. 1 & 2, February and May 1986.

FOOTNOTES

1 A "footer" refers to the (usually 30 to 50 cm wide) concrete beam poured in the foundation soil, on which load bearing walls of the house rest.

2 SSD systems seek to depressurize an approximately 10 cm deep bed of gravel placed under the basement slab, and thus reverse the pressure difference which normally draws radon bearing soil-gas into the house.

3 Backfill region refers to the soil region immediately adjacent to the basement walls, which has been excavated during house construction and filled back in (hence "backfill") after the basement walls were erected.

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