EPA/600/A-97/013

AN EVALUATION OF INDOOR RADON REDUCTIONS POSSIBLE WITH THE USE OF DIFFUSION-RESISTANT FLEXIBLE CONSTRUCTION MEMBRANES

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ABSTRACT

The importance of foundation construction design and materials used is recognized as critically important to the radon resistance of buildings. Some states have adopted "standards" or guidelines which prescribe methods and materials of construction. This paper provides a modeling assessment of the indoor radon reductions possible through the use of "improved" radon resistant membranes. The analysis focuses on quantifying the impacts on indoor radon concentrations of using "improved radon diffusion resistant membranes" for a typical experimentally determined range of membrane radon diffusion coefficients. The evaluation considers the application of radon resistant membranes to slab-on-grade construction typical of Florida and source strengths and site conditions typical of Florida. Guidance for the extrapolation of findings to non-Florida construction and site conditions is discussed.

ACKNOWLEDGMENT

The inspiration for this paper is derived from a jointly sponsored research effort, CRADA No. 0122-95 of the U.S. EPA and Eastman Chemical Company of Kingsport, Tennessee, intended to develop methods and data on the radon diffusion barrier resistance of construction membranes. The model, RAETRAD 4.1, used for assessing the radon resistance of possible radon barriers, was provided by Rogers and Associates Engineering Corporation of Salt Lake City, Utah. Finally, the assistance of Richard Snoddy of Acurex Environmental Corporation, Research Triangle Park, is acknowledged in exercising the RAETRAD analysis.

INTRODUCTION

Government and private sector responses to dealing with the public health risk of indoor radon are well developed. Federal and state programs of problem assessment, control technology development and demonstration, and the transfer of guidance reached their zenith of effort in the period 1988 to 1995 (EPA88, EPA91, EPA93, EPA94, DCA95). Government efforts are now focussed on outreach programs and privatization of certification programs for radon testing and mitigation (RRTC95). Private sector efforts now play a major role in addressing the remaining problematic aspects of indoor radon.

The current state of the art of radon control technology, as indicated by formalized guidance and extensive demonstrations (Henschel88, Fowler91, Leovic94, Tyson95, Hintenlang95, Najafi95, and Fowler96), indicates that an adequate technical basis exists for dealing with most indoor radon problem situations found in new construction and existing buildings. Yet there are problem situations (e.g., buildings built over high radon potential lands) where more effective or robust control technologies are needed. An early expression of this concern, focused on one control strategy, is found in the proceedings of a workshop on innovative radon barriers sponsored by EPA and held at the National Association of Home Builders headquarters in Washington, DC, on July 21, 1992. Some of the above referenced control technology evaluations of new construction techniques (Tyson95, Hintenlang95, Najafi95, and Fowler96) also support consideration of the use of passive controls (such as vapor barriers) employed and required in all Florida new construction. This paper addresses this technical issue, in the context of all Florida construction (DCA95), by using (1) a computer model (Nielson94) developed and enhanced in support of the Florida Radon Research Program (Sanchez91) and (2) existing literature data on the radon diffusion resistance performance of classes of flexible membranes. The following assessment provides an analytical method for evaluating the indoor radon impacts of newly developed radon resistant construction membranes.

ASSESSMENT APPROACH

Approach

This paper is an applications paper; i.e., it uses tools and information developed within the Florida Radon Research Program and research findings specific to the radon diffusion characteristics of selected flexible membranes as input for a computer model simulation and estimation of resultant indoor radon impacts. The following discussion presents a description of the main technical aspects and data input needed for background and understanding of the context in which the computer simulations are undertaken.

Radon Diffusion Through Flexible Films

The study of gas diffusion as a mass transport process has been well defined since 1855 (Fick1855), and its application to contemporary problems is evidenced by the development of American Society for Testing and Materials (ASTM) standards (ASTM82, ASTM84, ASTM95a, ASTM95b) and research specific to radon transmission through plastic films (Jha82, Hafez86, Nielson96) including ongoing research (Perry96, Mosley96). Table 1 presents the diffusion coefficients determined by this research and some of the characteristics of these research tests. This research defines the diffusion coefficient range relevant to an assessment of the impact on radon entry of the use of improved diffusion barriers. Of special note is the variability of test results, for nominally the same materials, between researchers. This variable result is largely explained by the uncertainty introduced by the quality of test materials and the use of different test methods.

Florida Standard for Passive Radon Resistant New Residential Building Construction

The Florida Standard for Radon Resistant New Residential Construction was the result of a concentrated research effort, undertaken by the Florida Radon Research Program (FRRP) (1989-1995). The FRRP's initial effort was directed at indoor radon problem assessment and the development of diagnostic measurement and assessment tools. This effort was followed by an extensive effort directed at developing a quantitative basis for rank ordering the efficacy of selected radon-resistant construction techniques and control approaches. The results are individually reported in "new house evaluation studies" (Najafi95, Hintenlang95, Tyson95, and Fowler96) and presented in summary in Nielson96 and Nielson95. Tables 2, 3, and 4 present house parameters and site conditions encountered at the study houses. The studies present the typical range of house parameters (e.g., house dimensions and house shell openings) and house conditions (e.g., radon soil gas concentrations and house ventilation rates) which influence radon soil gas entry into a house and which are entered as default values into the RAETRAD simulation model which is later discussed.

Table 1. Comparison of Test Results and Conditions for Radon Diffusion Coefficient Measurements

Publication ⇒	Jha82	Hafez86	Nielson96
Units ⇒	$m^2 s^{-1}$	$m^2 s^{-1}$	$m^2 s^{-1}$
Material ⇓			
Natural Rubber	6.36×10^{-10}		
Cellulose Nitrate	1.24×10^{-11}		
Cellulose Acetate		7.5×10^{-13}	
Polyvinylchloride	5.00×10^{-11}	5.8×10^{-13}	
Polyethylene		7.8×10^{-12}	3.36×10^{-11}
Polyethylene terephthalate		3.0×10^{-13}	
Polyester	1.95×10^{-13}		
Polycarbonate	3.82×10^{-13}	2.4×10^{-12} 5.5×10^{-13}	
Mylar	8.36×10^{-14}		
Test Conditions ⇓			
Exposure Time	to equilibrium	30 d	to equilibrium
Radon Source	ore, Ra @ 1730 pCi/g	not reported	mill tailings
Monitor	alpha	alpha track	alpha
Steady State	yes	yes	not reported
Thickness	not reported	0.5, 1, 3 mil*	6 mil*

* 1 mil = 25 μm

Table 2. House Parameters by Study Cohort

Ref.		Base Area (m^2)	Occup. Vol.[a] (m^3)	Inside Height (m)	Equiv. Wid.[b] (m)	No. Stories	House Const.[c]	Floor Slab: Edge[d] Detail	Floor Slab: Slump (cm)[e]	Floor Slab: Super-plast.[f]	Floor Slab: Rein-force.[g]	SSV Syst.[h]
Nielson 95	Mean	233	683	2.9	10.0	1.4	BL	SSW	20	Y	W	WP
	±S.D.	±59	±198	±0.3	±2.9	±0.5	FR	Mono	± 1	N	F	SP
							BR				PT	VM
"	Mean	212	645	3.0	13.3	1.1	BL	SSW	19	Y	W	WP
	±S.D.	±35	±141	±0.2	±1.5	±0.2	FR	Mono	± 2	N	F	SP
							BR				PT	VM
"	Mean	268	908	3.6	17.6	1.7	BL	SSW	11	Y	W	WP
	±S.D.	±108	±364	±1.2	±5.0	±0.4	FR	Mono	± 1	N	F	SP
							BR				PT	VM
"	Mean	207	618	3.0	16.4	1	BL	SSW	13	Y	W	WP
	±S.D.	±33	±103	±0.2	±1.5	±0	FR	Mono	± 2	N	F	SP
							BR				PT	VM
Nielson 96	Mean	217	623	2.8	10.7		BL	SSW	15	Y	W	WP
	±S.D.	±43	±181	±0.3	±1.0	NR	FR	Mono	±3	N	F	SP
							BR				PT	VM
"	Mean	201	579	2.9	10.3		BL	SSW	10	Y	W	WP
	±S.D.	±21	±93	±0.2	±0.6	NR	FR	Mono	±0.0	N	F	SP
							BR				PT	VM
"	Mean	199	602	3.1	10.0		BL	SSW	16	Y	W	WP
	±S.D.	±81	±286	±1.0	±2.1	NR	FR	Mono	±4	N	F	SP
							BR				PT	VM
"	Mean	258	750	2.9	11.6		BL	SSW	17	Y	W	WP
	±S.D.	±52	±170	±0.3	±1.1	NR	FR	Mono	±4	N	F	SP
							BR				PT	VM

[a]Volume of the occupied space in the house.

[b]Width of the equivalent rectangular area of the house footprint.

[c]Construction: block (BL), frame (FR), or brick (BR).

[d]Slab edge detail: slab poured into stem wall (SSW) or monolithic slab (Mono).

[e]Concrete slump.

[f]Super plasticizer used in slab concrete (Yes or No).

[g]Slab reinforcement: wire mesh (W), glass fiber (F), or post-tensioned (PT).

[h]Sub-slab ventilation system: well point (WP), suction pit (SP), or ventilation mat (VM).

NR = Not Reported

Table 3. House, Soil, and Ventilation Measurements by Study Cohort

Ref.	House ID	Soil Air Permeability (cm^2)	Soil[a] Moist. (% dry)	Fill[a] Moist. (% dry)	Fill Depth (cm)	House Perm.[b] (ach50)	Reported[c] Nat. Vent. (ach)	Slab[d] Crk. Area (cm^2)	Soil Density (g/cm^3)
Nielson 95	Mean ±S.D.	2.3×10^{-7} $\pm 1.1 \times 10^{-7}$	7.2 ±5.4	5.7 ±3.1	35 ±15	5.2 ±1.2	0.29 ±0.07	50. ±67.	1.60[e]
"	Mean ±S.D.	1.1×10^{-7} $\pm 1.2 \times 10^{-7}$	8.6 ±3.6	5.6 ±2.1	33 ±16	5.8 ±1.2	0.31 ±0.08	92. ±200.	1.60[e]
"	Mean ±S.D.	7.4×10^{-8} $\pm 7.8 \times 10^{-8}$	7.3 ±2.5	7.2 ±2.9	28 ±5	NA	0.20 ±0.07	94 ±104	1.60[e]
"	Mean ±S.D.	1.1×10^{-7} $\pm 1.2 \times 10^{-7}$	8.3 ±3.3	7.4 ±1.9	28 ±5	NA	0.18 ±0.02	330 ±240	1.60[e]
Nielson 96	Mean ±S.D.	NA	9.3 ±5.4	NA	NA	NA	0.33 ±0.10	57 ±130	1.59 ±0.11
"	Mean ±S.D.	NA	20.0	NA	NA	NA	0.27 ±0.12	32 ±22	1.79 NA
Nielson 95	Mean ±S.D.	9.1×10^{-7} $\pm 1.9 \times 10^{-6}$	5.2 ±3.5	0 ±0	NA	5.6 ±1.3	0.31 ±0.13	0.015 ±0.005	1.60 ±0.13
"	Mean ±S.D.	9.0×10^{-7} $\pm 1.7 \times 10^{-6}$	3.6 ±1.1	NA	NA	5.8 ±1.2	0.17 ±0.04	0.014 ±0.004	1.63 ±0.09

[a]Moisture percentage, dry-weight basis.

[b]Infiltration air changes per hour at 50 Pa pressure, from blower-door test.

[c]Passive-condition air infiltration rate.

[d]Total area of observed slab cracks.

[e]Assumed typical soil densities, since none were reported.

NA = Not Available

Table 4. Sub-slab and Indoor Radon Measurements in Study Houses (Nielson 96)

House ID	Soil Radon (pCi L^{-1})	Indoor Radon (pCi L^{-1})	Outdoor Radon (pCi L^{-1})	Subslab Radon (pCi L^{-1})	Statistical Summary: Statistic	Soil Radon (pCi L^{-1})	Indoor Radon (pCi L^{-1})	Outdoor Radon (pCi L^{-1})	Subslab Radon (pCi L^{-1})
F-01	5,510	1.6	0.4	4,310					
F-04	5,180	4.1	1.3	12,100					
F-05	19,900	1.5	0.1	4,490					
F-06	3,050	1.6	0.5	4,520					
F-07	2,690	1.4	0.3	4,240					
F-09	14,300								
F-12	5,700	2.7	0.6	6,480	G.M.,	6,230	2.0	0.4	5,640
F-13	5,990	2.5	0.7	6,210	GSD	1.99	1.49	2.23	1.46
F-02	1,480	1.6	0.6	886					
F-03	2,630	3.8	0.3	5,990					
F-08	1,310	3.3	0.3	4,000					
F-10	11,500	8.0	1.3	5,580					
F-11	2,760	1.9	0.4	4,180	G.M.,	2,720	3.1	0.6	4,000
F-14	2,510	3.1	1.3	8,270	GSD	2.17	1.77	1.97	2.19
1	1,680	2.3	0.5	730					
2	2,940	3.0	0.5	970					
3	1,190	2.2	0.5	488					
4	911	2.7	0.5	809					
5	2,900	2.5	0.5	1,220					
7	921	1.2	0.5	722					
9	1,300		0.5						
10	1,060	10.9	0.5	3,870					
11	10,700	2.8	0.5	8,480	G.M.,	2,070	2.8	0.5	5,840
12	6,980		0.5		GSD	2.38	1.86	1.00	1.46

The Florida Standard for Passive Radon-Resistant New Residential Building Construction (DCA95) is a performance based standard requiring the installation of passive construction features. It contains quantitative requirements to ensure a standard quality of construction; e.g., requirements specifying slump of concrete, and the use of ASTM rated sealants and vapor barriers. Figures 1 and 2 show examples of how the Florida standard addresses certain important radon-resistant construction features (Shanker93).

The RAETRAD Model

The RAETRAD (Radon Emanation and Transport into Dwellings) model (Nielson94, Rogers96) is a public-domain computer simulation model developed and refined within the FRRP. It has been used extensively in support of the Florida standard development, especially in evaluations of (1) radon contributions of foundation soils and fill materials,(2) advective and diffusive radon transport, (3) geographic distributions of radon potential in Florida, and (4) the development of simplified models for the assessment of the radon resistance of building features. This paper describes the use of the RAETRAD model to evaluate the indoor radon reduction potential of two distinct vapor membranes on the diffusive entry of radon into a typical Florida standard house built over three distinct radon potential sites. Table 5 presents the scenarios evaluated using the RAETRAD model.

Table 5. Model Simulation Matrix

Scenario	House Parameters (see Table 6)	Soil Parameters Soil Ra Content ($pCiL^{-1}$)	Site Parameters Vapor Barrier Diffusion Coefficient (m^2s^{-1})
1	Set to Default *	5.0	none
2	"	10.0	none
3	"	20.0	none
4	"	5.0	$1.00x10^{-11}$
5	"	10.0	$1.00x10^{-11}$
6	"	20.0	$1.00x10^{-11}$
7	"	5.0	$1.00x10^{-13}$
8	"	10.0	$1.00x10^{-13}$
9	"	20.0	$1.00x10^{-13}$

* See Table 6

MODELING SCENARIOS RESULTS

Introduction

The purpose of the RAETRAD evaluation presented below is to identify the significance of improvements in moisture barrier radon diffusion resistances to the resultant indoor radon. The belief before this evaluation was that technically feasible enhancements to the diffusive resistance of vapor barriers should produce cost effective reductions in indoor radon, especially where (1) small reductions, though hard to come by reductions, in indoor radon are needed or (2) radon source variability is such that more robust passive controls are a prudent addition to the Florida standard. For example, the results of the "new house evaluation projects" identified exceptions to the adequacy of the Florida standard's passive controls, on high radon potential sites, to always produce indoor radon concentrations below EPA's 4 $pCiL^{-1}$ action level (Tyson95, Hintenlang95, Najafi95, and Fowler96).

Baseline Conditions

Table 6 presents the baseline or reference house input parameters used in the RAETRAD model. These conditions are common to all scenarios listed in Table 5. Tables 7 and 8 present the foundation and soil (1) physical characteristics and (2) radiological characteristics input into the baseline (no barrier) and vapor barrier analysis runs. Vapor barrier thicknesses of 6 mils (150 μm) are used for all vapor barrier runs with the only parameter changing among runs being the radial and vertical diffusion coefficients. The diffusion coefficient values used, though hypothetical, are representative of the range of values shown in Table 1.

Table 6. House Parameter Values Used in Model Runs

Dimensions:	28.4 x 54.3 ft. (8.6 x 16.5 m)
Area:	1542 ft^2 (143 m^2)
Fill Thickness:	1 unit (0.9 ft.) (0.27 m)
Footing Depth:	3 units (2.9 ft.) (0.88 m)
Indoor Pressure:	-2.4 Pa
Outdoor Pressure:	0 Pa
Outdoor Radon Conc.:	0 pCiL^{-1}
Floor Openings:	Eliptical Crack at Slab Edges, 1 cm width Utility Penetrations, 2 at 13 ft. (3.9m) from edge

Table 7. Foundation and Soil Characteristics

Materials:	Sand, Concrete, Membranes
Layers:	Soil, Floor, Footing
Parameters:	Density, Porosity, Saturation Fraction, Particle Diameter

Table 8. Foundation and Soil Radiological Characteristics

Materials:	Sand, Concrete, Membranes
Layers:	Soil, Floor, Footing
Parameters:	Radium Content, Emanation Fraction, Diffusion Coefficient, Permeability Coefficient, Adsorption Coefficient

Results

Table 9 presents the indoor radon concentrations predicted by RAETRAD for the selected soil radon potential and radon barrier diffusion coefficient test conditions. Those are compared with the baseline no barrier case.

Table 9. Comparison of Baseline (No Barrier) and Flexible Membrane Barrier Effects on Indoor Radon Concentration

Soil Radon Potential: Soil ^{226}Ra Content ($pCig^{-1}$)	Indoor Radon Concentration ($pCiL^{-1}$) for Selected Barrier Conditions		
		Diffusion Coefficient (m^2s^{-1})	
	No Barrier	1×10^{-11}	1×10^{-13}
5.0	17.4	0.121	0.073
10.0	34.8	0.219	0.077
20.0	69.5	0.414	0.085

Figure 3 presents the above results on a semilog plot to show the overall relationship of indoor radon concentrations to building site radon potentials (soil radium content) for the no barrier (soil) and barrier (10^{-11} and 10^{-13}) conditions. This figure shows clearly the non-linear nature of the radon entry process with respect to diffusion limiting processes (comparing the 10^{-11} and 10^{-13} plots) and the proportionality of indoor radon concentrations to source strength for advective and high diffusion coefficient conditions (as shown by the no barrier and 10^{-11} plot).

CONCLUSION

- Placement of an integral impermeable flexible membrane (vapor barrier) under slab-on-grade construction can produce significant (100 x) reductions in indoor radon concentration from the no barrier case.

- In most cases, even for floating slab-on-grade construction, on moderately high radon potential (10pCig^{-1}, ^{226}Ra) sites, currently available and diffusion resistant membranes can keep indoor radon concentrations below 4 pCiL^{-1}.

- Enhanced radon diffusion limiting membranes (e.g., going from 1×10^{-11} to 1×10^{-13} m^2s^{-1} diffusion coefficients) may become cost effective on high radon potential sites; i.e., sites greater than 20 pCig^{-1} ^{226}Ra.

- The placement of a completely intact vapor barrier is critical to limiting radon entry into new and existing structures even at the well-balanced indoor/outdoor pressure differential condition (-2.4 Pa) used in this analysis.

- Comparison of the performance of new house evaluation study results with RAETRAD model predictions indicates the potential for enhanced radon entry limiting performance of vapor barriers, perhaps through enhanced placement practices.

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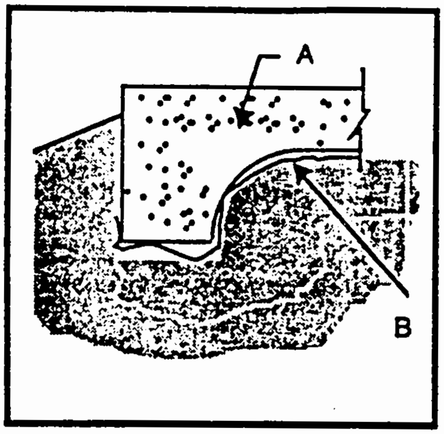
Fig. 1 Monolithic Slab,
Vapor Barrier Installation

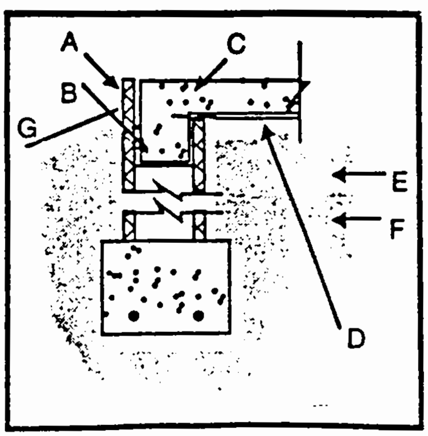
In monolithic slab construction, slab edges are thickened around the perimeter to form a monolithic concrete beam. The soil cover membrane should extend beyond the outer edge of the monolithic slab (see Figure 1). Monolithic slab is recommended for radon resistant construction.



A. 4" (0.10m) thick concrete slab with monolithic edge.
B. 6 mil (152 µm) soil cover membrane continues beyond outside edge of slab.

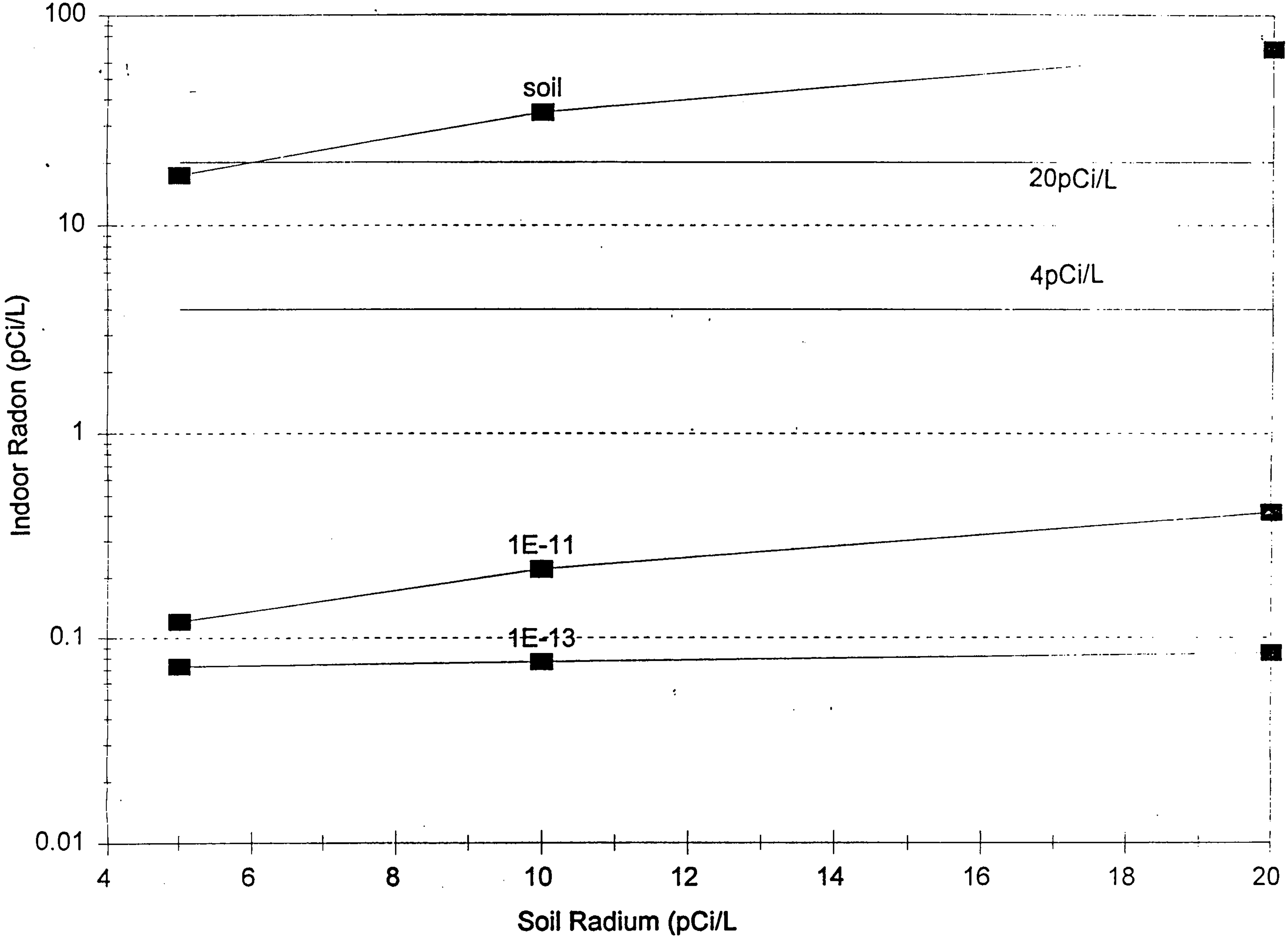
Fig.2 Slab Poured into
Stem Wall Vapor Barrier
Installation

When a slab is poured into a stem wall, concrete header blocks (see Figure 2, part A) serve as forms for the concrete slab. The soil cover membrane should extend at least 1" (0.025m) into the header block. The slab extends to the inside surface of header blocks. The cores of header blocks should be completely filled with concrete.



A. Concrete header blocks.
B. Fill header block cores along perimeter to form 8" (0.20m) thick cap.
C. 4" (0.10m) nominal concrete slab.
D. 6 mil (152µm) vapor barrier at least 1" (0.025m) into the header block.
E. Compacted fill soil.
F. Undisturbed soil.
G. Grade.

Fig. 3 RAETRAD Model Results



NRMRL-RTP-P-153

TECHNICAL REPORT DATA
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1. REPORT NO.	2.	3.
EPA/600/A-97/013		

4. TITLE AND SUBTITLE An Evaluation of Indoor Radon Reductions Possible with the Use of Diffusion-resistant Flexible Construction Membranes	5. REPORT DATE 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) D. C. Sanchez (EPA) and R. Minga and C. Sloan (Eastman)	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Eastman Chemical Company Kingsport, Tennessee 37662	10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. EPA CRADA 0122-95
12. SPONSORING AGENCY NAME AND ADDRESS **EPA, Office of Research and Development** **Air Pollution Prevention and Control Division** **Research Triangle Park, NC 27711**	13. TYPE OF REPORT AND PERIOD COVERED Published paper; 7-8/96 14. SPONSORING AGENCY CODE **EPA/600/13**

15. SUPPLEMENTARY NOTES APPCD project officer is David C. Sanchez, Mail Drop 54, 919/541-2979. Presented at ARRST Int. Radon Symp., 9/30-10/2/96, Haines City, FL.

16. ABSTRACT The paper gives results of a modeling assessment of the indoor radon reductions possible through the use of improved radon resistant membranes. The analysis focuses on quantifying the impacts on indoor radon concentrations of using improved radon diffusion-resistant membranes for a typical experimentally determined range of membrane radon diffusion coefficients. The evaluation considers the application of radon resistant membranes to slab-on-grade construction typical of Florida and source strengths and site conditions typical of Florida. It discusses guidance for the extrapolation of findings to non-Florida construction and site conditions. The importance of foundation construction design and materials used is recognized as critically important to the radon resistance of buildings.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Foundations	Pollution Control	13B
Radon		Stationary Sources	07B
Membranes		Indoor Air Quality	11G, 06P, 06C
Diffusion		Diffusion Resistance	14G
Slab-on-Ground Construction			13M
Slabs			13C

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)