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RADON INFILTRATION BUILDING ENVELOPE TEST SYSTEM: EVALUATION OF BARRIER MATERIALS

Janet Gaskin, Yunyi Ethan Li, Gnanamurugan Ganapathy, Gang Nong, Jeffrey Whyte and Liang Grace Zhou*
Construction Research Centre, National Research Council Canada, 1200 Montreal Road, Ottawa, ON K1A 0R6, Canada

*Corresponding author: Liang.Zhou@nrc-cnrc.gc.ca

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The performance of radon barrier materials currently available for housing foundations was evaluated using a unique radon infiltration building envelope test system that was designed to test radon prevention and mitigation systems using real world construction techniques. The reduction in radon concentration measured across the air barrier in the foundations has been used to evaluate five representative barrier materials installed in the radon infiltration building envelope test facility. The reduction in radon concentration in the mock house varied from 68% for 6 mil polyethylene to 98% for the spray polyurethane foam. The five representative barrier materials were selected after determining the radon diffusion coefficient and the corresponding radon resistance from samples of 14 barrier materials in a radon diffusion testing chamber. The Canadian experience evaluating whether radon barrier materials would satisfy building code requirements was described.

INTRODUCTION

Radon, a colourless, odourless, radioactive gas, is a very modifiable environmental exposure that is the second most important cause of lung cancer[1]. Population radon exposures result primarily from housing, which can be reduced by installing radon preventive measures in new buildings at the time of construction. For example, the inclusion of a continuous air barrier system constructed from impermeable materials to separate a conditioned indoor space from the ground can be effective[1].

The diffusion of radon through a material is typically described by the radon diffusion coefficient. Tested in the radon diffusion test chamber located in the Czech Republic a decade ago, the radon diffusion coefficients were reported for 10 vapour barrier membranes commonly used in Canada[2] and of 360 materials used in Europe[3]. Recently, a radon resistance parameter was proposed that explicitly includes the thickness of the barrier material in addition to the radon diffusion coefficient[4].

A prescriptive requirement for radon barrier material has been adopted in many national building codes, such as in England, Ireland and Finland. In designated radon affected areas in England, a 300-μm thick polyethylene membrane or equivalent is required as a combined radon and dampness barrier system in new housing[5]. Similarly, in designated high radon areas in Ireland, a radon membrane must meet or exceed specified parameters for low-density polyethylene, including having a radon diffusion coefficient that is 12×10^{-12} m^2 s^{-1} or lower[6]. Bitumen felt strips are required to seal the joint between the floor slab and the side walls in housing with two foundation types in Finland, homes with slab on ground foundations and homes with walls in contact with the ground[7].

Partially performance-based criteria are used in Germany to specify a minimum thickness for radon barrier material, dependent on the radon diffusion coefficient (or diffusion length), but can lead to overly thick barriers for materials with low radon diffusion coefficients[8]. In the Czech Republic, performance-based criteria incorporate characteristics of the radon barrier material, the radon exhalation from the soil and the dimensions of the home to determine a minimum radon resistance[8]. In Canada, the minimum prescriptive requirement for an air barrier system is 6 mil polyethylene (PE) or equivalent, specified for radon protection in housing and small buildings in the 2015 National Building Code (NBC). The Canadian Construction Materials Centre (CCMC), supported by the Government of Canada and in collaboration with NRC researchers, will assess and publish technical information when requested regarding the compliance of a specific construction product with Canadian building, energy and safety codes[9]. The CCMC in partnership with the senior author of this paper have co-developed a technical guide to determine whether a new air barrier system can be designated an alternative solution compliant with the building code. The performance of radon barrier materials currently available for housing foundations in Canada was evaluated in this study, characterized by the radon diffusion coefficient, the radon resistance and the reduction in radon concentration measured across the air barrier system using the radon infiltration building envelope test system (RIBETS).

MATERIALS AND METHODS

The performance of radon preventive housing technologies is conducted using two new facilities at the Construction Research Centre (CRC), on the Ottawa campus of the National Research Council (NRC) Canada: a radon diffusion testing chamber (RDTC) and the RIBETS. RIBETS is a unique facility that was designed to test the performance of radon prevention and mitigation systems using real world construction techniques.

The radon diffusion coefficient or radon resistance can be used to demonstrate whether an air barrier system provides an equivalent or better prevention of radon ingress than the air barrier system prescribed in a building code, such as 6 mil PE in the NBC in Canada. The RDTC was used to evaluate whether a barrier material showed promise for reducing radon ingress; the radon diffusion coefficient and the corresponding radon resistance were determined from a sample of the barrier material. The performance of a representative selection of barrier materials was then evaluated in RIBETS. To ensure that the integrity and the performance as a radon barrier of the *in situ* applied spray polyurethane foam (SPUF) products can be maintained after the construction process, radon resistance testing after mechanical damage was also conducted. During such tests, SPUF products were subjected a specific load level that simulated the in-service loads experienced in typical basement construction practice.

Radon diffusion testing chamber

Tests in the radon diffusion testing chamber were performed following the standardized measurement protocol, ISO standard 11665-13[10]. A sample of the radon barrier material was installed between two air-tight cylindrical compartments having a 4″ diameter and 6″ height made from aluminium. Barrier membrane samples were placed between the dosing and receiving compartments and sealed by O-rings to ensure airtightness, whereas thicker products, such as foam insulation, were inserted in a sample holder made of a stainless steel sleeve, with paraffin wax was applied to seal the thicker samples to the sample holder. The RDTC was located inside a glove box to contain potential leaks, in which the radon concentration was monitored hourly.

As a preliminary step, argon gas was used to check the seal between the barrier material and the RDTC, with pressure maintained above 2240 Pa in the RDTC compartments for at least 24 h. The radon source was introduced into the dosing compartment, and once stable radon diffusion through the sample had been established, the receiving compartment was vented with radon-poor ambient air in the glove box. Measurement was continued for 2–3 weeks until equilibrium between the dosing and receiving compartments was reached. The radon concentration, temperature, pressure and relative humidity were monitored every 10 min in the dosing and the receiving compartments (Table 1). The radon source was a Pylon 2000A, which has an activity level of 5 kBq and can be used to maintain a radon concentration higher than 1.5 MBq m^{-3} in the dosing compartment. Due to the high radon concentration that occurred during testing, the fitting at the inlet and outlet of 2 AlphaGuard PQ 2000 Pro continuous radon monitors in the RDTC was replaced by Teflon and copper tubing to prevent radon leakage along the monitor connections.

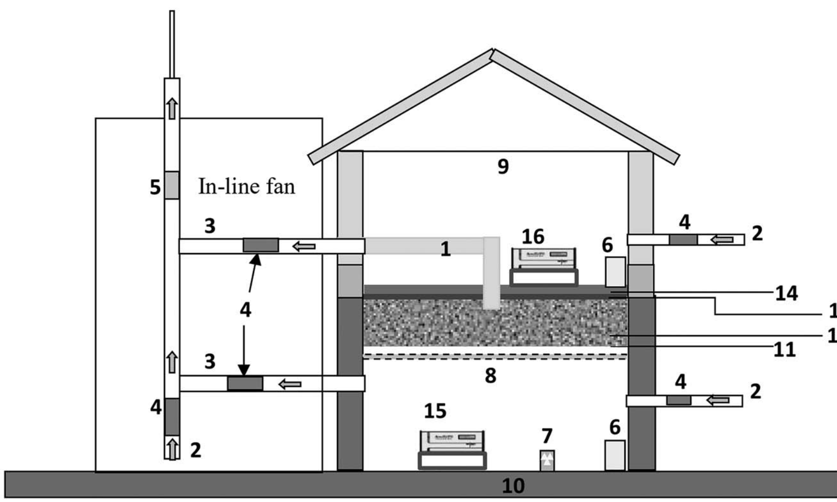
Radon infiltration building envelope test system

The RIBETS facility consists of a mock house with an interior footprint that is 1.5 m (4.9 ft) in width by 1.5 m (4.9 ft) in depth, characterized by a floor assembly that can be installed and subsequently removed in order to test a wide variety of construction elements (Figure 1). The height in the receiving and dosing compartments is 1.5 m (4.9 ft) and 1.2 m (3.9 ft), respectively. The concrete structure upon which the floor assembly of the mock house is built provides a controlled dosing chamber to simulate soil radon gas exposure. The radon source is a Pylon model-Rn 1025 source, which has an activity level of 83.4 kBq and can generate typical sub-slab radon exposures under the floor assembly.

Radon concentrations in the dosing chamber and the interior of the mock house were monitored every 10 min by 2 AlphaGuard PQ 2000 Pro continuous radon monitors set to diffusion mode, and the test was conducted for 2–3 weeks once equilibrium had been reached. Temperature, humidity and pressure in both spaces were also continuously monitored (Table 2). The data logging equipment is housed in an adjoining trailer. The RIBETS facility has the capacity to monitor pressure differentials resulting from typical sub-slab depressurization systems used for radon control and also to evaluate the effect of in-home ventilation systems such as heat or energy recovery ventilators. Outdoor environmental parameters such as temperature, pressure, wind speed and direction were also logged by local weather station on the NRC campus in the vicinity of RIBETS. A number of safety systems were incorporated to allow the radon generator to be shut off remotely and the air volume within the building envelope to be vented and purged rapidly.

Table 1. Instrumentation for parameter measurement in the RDTC

Parameter	Equipment	Sampling interval	Specification
Radon levels in dosing and receiving compartments	AlphaGuard PQ 2000 Pro	10-min (flow mode)	Measurement range: 2–2 000 000 Bq m^{-3} Instrument calibration error: ±3%
T, *P* and RH in dosing and receiving compartments	AlphaGuard PQ 2000 Pro	10 min	Measurement ranges *T*: −15 to +60°C *P*: 80 000–105 000 Pa RH: 0–99%
Radon concentration in glove box	Corentium Pro	1 h	Measurement range: 0–100 000 Bq m^{-3} Measurement uncertainty: 1 day SD <7% + 5 Bq m^{-3} 7 days SD <5% + 2 Bq m^{-3}
Pressure for leakage test	Omega HHP-2080 digital manometer	2 s	Measurement range: 0–2488.4 Pa Accuracy: −10 to 50°C 0.15% rdg + 0.15% FS



1-Radon ASD stack; 2-Makeup air stacks; 3-Exhaust stacks; 4-Control dampers; 5-In-line fan; 6-Baseboard heater; 7-Radon source; 8-Dosing compartment; 9-Receiving compartment; 10-Concrete foundation pad; 11-Perferated stainless steel plate; 12-Gravel (8”); 13- Air barrier test sample; 14-Concrete floor slab; 15- AlphaGuard PQ 2000 Pro on a stand in dosing compartment (diffusion mode); 16- AlphaGuard PQ 2000 Pro on a stand in receiving compartment (diffusion mode).

Figure 1: The conceptual design of the radon infiltration building envelope test system.

Radon diffusion coefficient and radon resistance

The one-dimensional equation derived from Fick’s law for radon diffusion through a material is

$$D\partial^2 C_{(x,t)}/\partial x^2 - \lambda\, C_{(x,t)} = \partial C_{(x,t)}/\partial t \qquad (1)$$

where D is the diffusion coefficient ($m^2\ s^{-1}$), C is the concentration of Rn (Bq m^{-3}), x is the diffusion distance (m), t is the time (s) and λ is the natural radon (Rn-222) decay constant, $2.1 \times 10^{-6}\ s^{-1}$.

The radon diffusion coefficient can be calculated from the radon level in the dosing compartment,

Table 2. Instrumentation for parameter measurement in RIBETS

Parameter	Equipment	Interval	Specification	Location
Radon concentration	AlphaGuard PQ 2000 Pro	10 min	Measurement range: 2–2 000 000 Bq m^{-3} Instrument calibration error: ±3%	Dosing and receiving compartments
Airflow rate	Nailor 36 FMS with Setra 264	15 s	Measurement range: 0–106 l s^{-1} Accuracy: ±1.0% FS	Radon rough-in PVC pipe
Temperature and relative humidity	AlphaGuard PQ 2000 Pro	10 min	Measurement ranges: T: −15 to +60°C P: 80 000–105 000 Pa RH: 0–99%	Dosing and receiving compartments
Pressure	Setra 264	15 s	Measurement range: 0–249 Pa Accuracy: ±1% FS	Above and below test sample in dosing and receiving compartments

the slope of the linear regression representing the increase of radon level over time in the receiving compartment, the dimensions of the sample of radon barrier material separating the dosing and receiving compartments, the dimensions of the receiving compartment and the Rn-222 decay constant[10, 11].

The radon flux from the soil into a house is a function of the radon diffusion through the type of barrier material and the thickness of the foundation barrier installed. The radon transmittance of a material can be estimated from the radon exhalation rate through the barrier material and from its interior surface, based on its radon diffusion coefficient[4]. The radon resistance, R_{Rn} (s m^{-1}), is defined as one divided by the radon transmittance and is a useful parameter because it includes the thickness of the barrier material and is adjusted for the increase in radon resistance that results from a non-linear radon distribution within barrier materials with a ratio of thickness to diffusion length over 0.8[8]:

$$R_{\mathrm{Rn}} = \sinh\,(d/l)/\lambda l \quad (2)$$

where, d is the thickness of the sample (m) and l is the diffusion length of radon (m) [$l = (D/\lambda)^{1/2}$].

The effectiveness of the radon barrier, defined as a percentage, was based on the ratio of the reduction in radon across the barrier membrane or system:

$$\mathrm{Eff} = 100\,(1 - C_r/C_d) \quad (3)$$

where, C_{r} is the steady-state radon concentration in the receiving compartment and C_{d} is the steady-state radon concentration in the dosing compartment.

RESULTS

The radon concentration in the dosing compartment and the receiving compartment of the RDTC for each material tested was listed in Table 3. The mean and range (min–max) values for radon diffusion coefficient (D) and radon resistance (R_{Rn}) for barrier materials were listed where multiple test results were available, in addition to the ratio of the radon resistance of each barrier material to that of 6 mil PE. Differences in temperature, relative humidity and pressure between the dosing and receiving compartments were negligible. The mean radon diffusion coefficients were comparable for PE and modified bitumen membranes, ranging from 6×10^{-12} to 2×10^{-11} m^2 s^{-1}, to roughly 2×10^{-10} m^2 s^{-1} for rigid foam and #2 SPUF insulation after the mechanical damage test. The was no increase in the radon level in the receiving compartment over time for the two SPUF insulations and the 20 mil membrane with PE and EVOH resins, indicating that these materials functioned very effectively as radon barriers. The lowest mean radon resistance was 1.1×10^7 s m^{-1} for 6 mil PE and ranged to a high value of 8.5×10^9 s m^{-1} for #2 SPUF after mechanical damage, while several materials were too resistant to radon for a value to be estimated. As Equation (2) suggests, the radon resistance of the barrier material was higher when the radon diffusion coefficient was lower and/or when the thickness was greater. The ratio of the radon resistance to that of 6 mil PE ranged from 2 to 28 for thicker PE and modified bitumen membranes, with a higher value of 7.7×10^2 for the SPUF after mechanical damage.

The mean reduction in radon estimated from the RDTC results, represented by the ratio of the radon concentration in the receiving compartment

Table 3. Radon diffusion test chamber results

Barrier material	Material thickness (m)	Dosing concentration C_d (MBq m^{-3}) mean (range)	Receiving concentration C_r (kBq m^{-3}) mean (range)	C_r/C_d (%) mean (range)	Diffusion coefficient D (m^2 s^{-1}) mean (range)	Radon resistance R_{Rn} (s m^{-1}) mean (range)	$R_{Rn}/R_{Rn\,(6\,mil)}$ mean
1) 6 mil PE membrane	0.00015	2.0 (1.5–2.8)	280 (201–342)	14 (12–17)	1.6×10^{-11} (8.1×10^{-12} to 2.4×10^{-11})	1.1×10^{7} (6.3×10^{6} to 1.9×10^{7})	1
2) 10 mil PE membrane	0.00025	1.8 (1.7–1.8)	131 (131–131)	7 (7–8)	1.2×10^{-11} (9.5×10^{-12} to 1.5×10^{-11})	2.3×10^{7} (1.7–2.7×10^{7})	2
3) 15 mil PE membrane	0.00038	1.8 (1.8–1.8)	62 (62–62)	4 (4–4)	9.3×10^{-12} (8.3×10^{-12} to 1.0×10^{-11})	4.2×10^{7} (3.8–4.6×10^{7})	4
4) 20 mil PE membrane	0.00051	1.7 (1.3–1.8)	47 (40–52)	3 (2–4)	5.7×10^{-12} (3.5–7.9×10^{-12})	1.0×10^{8} (6.5×10^{7} to 1.5×10^{8})	9
5) #1 modified bitumen membrane	0.001	1.7 (1.4–2)	121 (109–143)	7 (7–8)	2.0×10^{-11} (1.9–2.1×10^{-11})	5.0×10^{7} (4.9–5.3×10^{7})	5
6) #2 modified bitumen membrane	0.0015	1.8 (1.7–2)	84 (71–108)	5 (4–5)	1.8×10^{-11} (8.6×10^{-12} to 2.4×10^{-11})	1.1×10^{8} (6.6×10^{7} to 1.9×10^{8})	10
7) #3 modified bitumen membrane	0.0027	1.7 (1.5–2)	13 (10–19)	0.8 (0.7–1)	1.1×10^{-11} (1.0–1.1×10^{-11})	3.1×10^{8} (3.0–3.3×10^{8})	28
8) #1 rigid foam insulation with tape	0.025	1.4	45	3	2.5×10^{-10}	6.4×10^{7}	6
9) #2 rigid foam insulation with tape	0.025	1.6	8.5	0.5	1.2×10^{-10}	9.7×10^{8}	88
10) #1 SPUF insulation	0.050	1.9	3.1×10^{-1}	0.02	—[a]	—[a]	—[a]
11) #1 SPUF insulation after mechanical damage	0.050 (minus indents)	1.5	9.3×10^{-2}	6×10^{-3}	—[a]	—[a]	—[a]
12) #2 SPUF insulation	0.050	1.7	7.8×10^{-2}	5×10^{-3}	—[a]	—[a]	—[a]
13) #2 SPUF insulation after mechanical damage	0.050 (minus indents)	9.5×10^{-1}	1.9	2×10^{-1}	1.6×10^{-10}	8.5×10^{9}	7.7×10^{2}
14) 20 mil membrane with PE and EVOH resins	0.00051	1.9	4×10^{-3}	2×10^{-4}	—[a]	—[a]	—[a]

Notes: C_r/C_d represents the ratio of radon concentration in the receiving compartment relative to the dosing compartment, as a percentage $R_{Rn}/R_{Rn\,(6\,mil)}$ represents the ratio of the radon resistance of the membrane relative to the radon resistance of a 6 mil PE membrane.
[a]Neither radon diffusion coefficient nor radon resistance could be calculated for these materials because there was no increase in radon in the receiving compartment during the test period

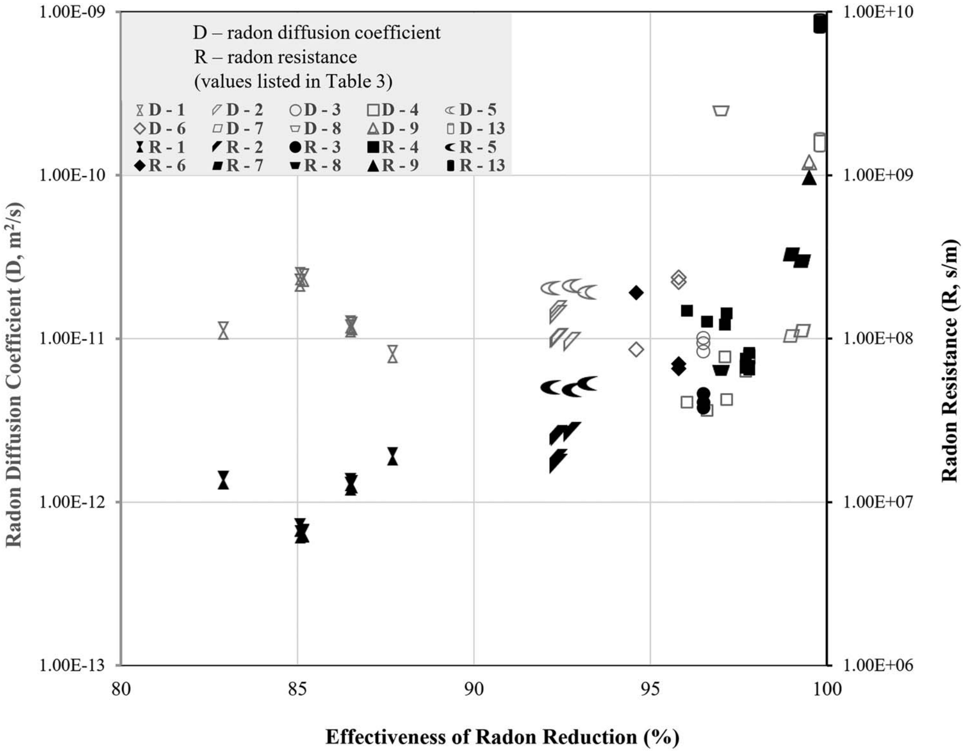


Figure 2: Radon diffusion coefficient and radon resistance versus effectiveness of radon reduction for barrier materials.

(C_r) to that in the dosing compartment (C_d), ranged from 14% for 6 mil PE to 2×10^{-4}% for the 20 mil membrane with PE and EVOH resins. The corresponding effectiveness of radon reduction ranged from 86–100%.

The calculated radon diffusion coefficient and radon resistance from each barrier material test (barrier material identified by number as listed in Table 3) were both plotted versus the effectiveness of radon reduction in Figure 2. Although no clear trend was apparent between the radon diffusion coefficient and effectiveness of radon reduction, a relationship was evident between radon resistance (plotted on a logarithmic scale) and the effectiveness of radon reduction for these barrier materials. Figure 2 demonstrated that both the thickness of the barrier and the diffusion coefficient of the material were required to characterize the effectiveness of the radon barrier, indicating the value of the radon resistance parameter.

The radon barrier systems evaluated in the RIBETS facility were selected from those listed in Table 3 to represent the range in values for the effectiveness of radon reduction determined in the RDTC. The steady-state radon concentration in the dosing and receiving compartments for each barrier material evaluated in the RIBETS facility was summarized in Table 4. The effectiveness of radon reduction resulting from the installation of the barrier systems in the mock house ranged from 68 ± 11% for 6 mil PE to 98 ± 2% for #1 SPUF. Neither the difference in the average temperature nor the relative humidity between the dosing and receiving compartments during the testing period was considered significant, being a couple of degrees Celsius and about 10%, respectively. The difference in pressure between the dosing and receiving compartments was minimal, differing by <1 Pa. All four alternative radon barrier systems evaluated in RIBETS exceeded the performance of the 6 mil PE at reducing radon ingress through the floor assembly into the interior of the mock-house.

DISCUSSION

The effectiveness of radon reduction determined for each barrier material in RIBETS was lower than that calculated using radon diffusion test chamber results. The use of 20 mil PE membrane in RIBETS roughly halved the radon ingress relative to 6 mil PE, while the use of the two SPUF insulations and the 20 mil

Table 4. Radon reduction across barrier systems in RIBETS

Barrier material	Dosing radon concentration C_d mean ± SD ($kBq\ m^{-3}$)	Dosing temperature mean ± SD (°C)	Dosing relative humidity mean ± SD (%)	Receiving radon concentration C_r mean ± SD ($Bq\ m^{-3}$)	Receiving temperature mean ± SD (°C)	Receiving relative humidity mean ± SD (%)	Eff mean ± SD (%)
1) 6 mil PE membrane	1.60 ± 0.18	24 ± 0	68 ± 2	516 ± 173	24 ± 1	75 ± 4	68 ± 11
4) 20 mil PE membrane	2.26 ± 0.28	22 ± 2	51 ± 6	348 ± 157	19 ± 2	45 ± 7	85 ± 8
10) #1 SPUF insulation	2.01 ± 0.23	26 ± 2	84 ± 3	40 ± 18	24 ± 3	79 ± 2	98 ± 2
12) #2 SPUF insulation	3.06 ± 0.37	24 ± 1	82 ± 2	86 ± 30	25 ± 0	77 ± 3	97 ± 1
14) 20 mil membrane with PE and EVOH resins	3.36 ± 0.61	24 ± 3	83 ± 5	124 ± 82	26 ± 4	70 ± 5	96 ± 3

Notes: Eff represents the effectiveness of the reduction in radon by the membrane, as a percentage.

membrane with PE and EVOH resins resulted in minimal radon ingress. As a result of the increased resistance to radon ingress compared to 6 mil PE, two SPUF products and a 20 mil membrane with PE and EVOH resins have been officially recognized by the CCMC as alternative radon barriers that conform to the national building code requirements in Canada.

The radon diffusion coefficient and radon resistance were reported for 650 radon barrier materials available in Europe[(12)]. The range of values of radon diffusion coefficient for the most common vapour barrier materials used in Europe, reported to range between 3.0×10^{-11} and 3.0×10^{-12} $m^2\ s^{-1}$, was comparable to that of the most common radon barrier materials that were tested in the RDTC in this analysis. The corresponding range of values of radon resistance for these common vapour barrier materials, between 1.0×10^7 and 3.0×10^9 $s\ m^{-1}$, was also comparable to this study, and a similar relationship between radon resistance and the ratio of membrane thickness to diffusion length was described. The mean radon diffusion coefficients of commonly used barrier membranes in this study were comparable to those reported in Canada a decade ago, ranging from 6×10^{-12} to 2×10^{-11} $m^2\ s^{-1}$[(2)]. The reduction in radon of 68% achieved by the radon barrier system in the mock house using 6 mil PE was comparable to that of 70% reported for a bedroom after the installation of a low density polyethylene radon membrane underneath the concrete floor in a pilot house in a high radon region in Romania[(13)].

The use of a second facility to test the performance of a barrier system in a real world setting was a strength of this study. Each radon barrier was tested over a period of several weeks in the outdoor RIBETS facility, during which it was exposed to similar climatic conditions as the housing stock. The performance of the radon barrier systems evaluated, as listed in Table 4, reflected the pattern in radon resistance values calculated from the RDTC results (Table 3). The effectiveness of a barrier material installed in a real world setting depends on the sealing of the material sheets to itself and to the walls, and to the influence of climatic factors such as wind, in addition to the radon resistance of the material. While the uncertainty associated with all the instruments used in the diffusion chamber and the RIBETS facility were listed, other contributions to uncertainty associated with the results were more difficult to quantify. The composition of construction materials such as radon membranes can differ by production batch[(3)]. The uncertainty in radon reduction was lower for very effective barrier materials and highest for 6 mil PE.

Radon ingress into buildings can only be estimated from the radon resistance of the material in an intact barrier system because transport can be dominated by radon seeping through cracks and joints in the foundation floor and walls. Problems have been reported with self-sealing tapes used for joining membranes and self-adhesive bitumen membrane strips used between the membrane and walls, resulting in gaps through which radon has penetrated[(14)]. In addition, external forces such as dead loads from the structure and those resulting from movement due to differential settlement or expansion/shrinkage of adjoining materials may affect the integrity and the performance of air barrier materials. Barrier material test results based on real construction techniques, such as from RIBETS, can be used to extend and validate numerical models. A model of radon ingress from the soil and through a slab on grade house foundation into indoor air was recently developed that represents radon diffusion and advection through the soil, diffusion through the radon barrier materials and gaps or cracks in the radon barrier systems, and was validated using published results from field and analytical or numerical studies[15]. The model predicted exponentially increasing indoor radon for a 1-mm thick membranes under the slab with increasing radon diffusion coefficient (larger than 10^{-10} m^2 s^{-1}).

In the future, the effectiveness of radon control systems determined in experimental houses could be used to complement modelling approaches. It would be helpful for a minimum requirement of radon resistance for air barrier products to be defined in countries that currently have a prescriptive requirement. It is also worthwhile noting that the development of Net-Zero Energy Ready model codes in several countries will require the floor slab to be insulated. The radon diffusion testing results presented in this paper demonstrate that certain rigid foam insulation and SPUF can also prevent or reduce radon ingress effectively and these materials should be considered in the design of radon barriers in housing.

CONCLUSIONS

The radon barrier materials determined to have higher radon resistance in the radon diffusion testing chamber were also more effective at reducing radon infiltration in the mock house. The effectiveness of radon reduction across the barrier system installed in RIBETS ranged from 68% for 6 mil PE to 98% for SPUF, with four barrier systems performing better than 6 mil PE. These results illustrate the potential for future requirements of barrier materials for radon control in the NBC of Canada to continue to incorporate more stringent criteria. This approach enables innovative products developed by the construction industry, once tested by the research team and approved by the CCMC, to demonstrate equivalence to code-prescriptive solutions and to improve the indoor environment and the health of residents.

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