Passive soil depressurization in Canadian homes for radon control

Zhou, Liang (Grace); Berquist, Justin; Li, Yunyi (Ethan); Whyte, Jeffrey; Gaskin, Janet; Vuotari, Mark; Nong, Gang

Publisher's version / Version de l'éditeur:
https://doi.org/10.1016/j.buildenv.2020.107487
Building and Environment, 188, pp. 1-10, 2020-11-28

Passive Soil Depressurization in Canadian Homes for Radon Control

PSD in Canadian Homes for Radon Control

Liang (Grace) Zhou*[1], Justin Berquist[1], Yunyi (Ethan) Li[1], Jeffrey Whyte[1], Janet Gaskin[1], Mark Vuotari[1], and Gang Nong[1]

1 National Research Council Canada
1200 Montreal Road
Ottawa, Ontario, Canada
**Corresponding author: Liang.Zhou@nrc-cnrc.gc.ca (613) 324 7798*

ABSTRACT

Health Canada's cross-Canada residential radon survey from 2012 demonstrated roughly 7% of Canadian homes contain radon levels above the national guideline of 200 Bq/m^3. British Columbia (BC) is the first province in Canada to mandate a full stack passive soil depressurization (PSD) system installed within homes in radon prone areas. All other provinces within Canada require a sealed and capped rough-in pipe. In this study, PSD systems were installed in fifteen new construction homes and retrofitted in six existing homes across three provinces in Canada. This study demonstrated the potential of well-designed PSD systems to reduce radon exposure in Canadian homes, reducing indoor radon concentration below 200 Bq/m^3 in all 21 homes during multiple 30-day periods. During the winter, the PSD system was less effective in several new construction homes, whereas it appeared to operate more consistently in retrofitted existing homes. Further investigation revealed homes with a heat recovery ventilator (HRV), a ground floor bathroom, or no stack insulation were susceptible to degradation in the PSD system performance from the shoulder to winter season. Such performance degradation might be attributed to 1) HRV defrost mode causing a reduction in the ventilation air supply, 2) unsealed ground floor cut outs for the bathroom increasing the building stack effect and inducing more radon ingress through the floor slab during the winter, and 3) stacks without insulation causing frost and restricting the airflow within the stack.

KEYWORDS

Radon, mitigation, passive soil depressurization, cold climate.

1 INTRODUCTION

Radon^{222} (radon through this paper), a colourless and odourless radioactive gas that originates from the ground, is the largest natural source of exposure to ionizing radiation for Canadians [1]. In outdoor air, radon dilutes quickly to concentrations that do not pose a significant health risk [2]. However, radon can infiltrate into buildings and accumulate to concentrations that pose an increased risk of lung cancer [3]. Health Canada's cross-Canada residential radon survey from 2012 demonstrated roughly 7% of Canadian homes contained radon levels above the national guideline of 200 Bq/m^3 and a study from Health Canada's National Radon program found radon accounts for roughly 3,200 deaths per year in Canada [4].

In Canada the National Research Council (NRC) is the steward of Canada's National Building Code (NBC), which is often partially or fully adopted by Canadian provinces and territories. Research related to radon control in buildings is carried out at the NRC to provide impartial scientific evidence to the NBC task group on soil and radon gas mitigation. The main provisions for radon protection in the 2015 NBC include a sub-slab air barrier system of 6 mil polyethylene, a rough-in for a future subfloor depressurization system to extract radon should it be required, and the sealing of cracks and joints in the foundation. Active soil depressurization (ASD) and passive soil depressurization (PSD) are often used to reduce radon entry into buildings. In North America, it is common to use heat or energy recovery ventilators (HRVs or ERVs) to increase overall ventilation rates and improve indoor air quality in residential applications. The westernmost province in Canada, British Columbia (BC) is the first and only province to require PSD for radon control in its radon prone area (Area 1) after December of 2014. Since 2015, the standing committee of NBC has received two building code change requests to include a PSD system in NBC, and a Task Group on Radon and Soil Gas Mitigation has been established to address these requests.

Canada has a national certification program for radon professionals; the Canadian National Radon Proficiency Program (C-NRPP). This program is managed by the Canadian Association of Radon Scientists and Technologists (CARST) with oversight from Health Canada, and sets standards for training and certification in both radon measurement and radon mitigation. The C-NRPP also maintains a list of radon measurement devices approved for use by certified radon professionals. To become certified radon professionals, candidates enroll in courses provided by independent certified trainers, and must then pass the national certification exams. Training may take place in person or online, with the radon mitigation certification including a hands-on mentorship. In this study, two of the lead researchers were certified by the C-NRPP as radon measurement professionals in 2017.

PSD involves the installation of a radon pipe venting system that usually begins beneath a basement floor slab, extends upwards through the conditioned space of the building, and terminates above the roofline of the building. The system takes advantage of the naturally occurring thermal stack effect, which causes radon rich soil gas in the sub-slab area to be drawn up the pipe assembly and exhausted above the roofline to the outdoors. The medium to long-term performance of PSD systems depends on the building type, soil conditions, stack configuration, and climate [5]. However, there is limited data published on the performance of PSD systems for radon mitigation [6]. The installation of a PSD system was reported to have reduced indoor radon concentration in a single home in Austria [7] and Norway [8], but not in a duplex in the US [9]. Lafollette et al. (2011) evaluated PSD systems installed in 46 homes in Illinois, US, that resulted in indoor radon concentrations that were below the US guideline of 148 Bq/m^3 in 27 of the 46 homes [10]. Only one field study [11] has been conducted in Canada, in which short term monitoring showed the PSD systems in 16 homes in BC consistently reduced indoor radon concentrations but did not reduce levels below the Canadian guideline of 200 Bq/m^3 in all homes. Moreover, the authors were unable to find any data published on the impact heat recovery ventilators, ground floor bathrooms, or stack insulation have on the performance of PSD systems. In this paper, ground floor bathroom refers to a bathroom that is located on the slab in contact with the ground. This is hypothesized to impact the performance of radon mitigation systems because the bathroom will require a portion of the slab to be cut out for sanitary piping which could allow additional radon to infiltrate into the home if not sealed.

In this research, the performance of PSD systems was investigated in six existing homes retrofitted with a PSD system between 2017 and 2019 in the National Capital Region (NCR) of Canada (Ottawa, Ontario, and Gatineau, Quebec) and in fifteen newly built homes in Prince George, BC, between 2018 and 2019. The objectives of this study were to 1) determine the key design and installation parameters that influence the performance of the PSD system and 2) evaluate the radon reduction achievable by the PSD system.

2 METHODS

The radon concentration in the basement was monitored during two periods that each consisted of successive 30-day minimum stack open and stack closed conditions to evaluate the performance of the PSD system. The temperature and relative humidity in the basement, sub-slab pressure, and air speed within the stack were also monitored. At the beginning of the study, measurements related to the source of radon were taken for a few homes. This involved measuring radon concentration in soil one meter below the ground by using a Saphymo soil gas probe, an AlphaPUMP, a Saphymo Multisensor Unit, and an AlphaGUARD PQ2000 PRO radon monitor. The measurements showed that the soil gas radon levels varied significantly (between 10,000 and 60,000 Bq/m^3) within a short distance and thus sampling radon from soil was not incorporated in all field study homes. Most indoor radon results from the ingress of soil radon [12,13], although in rare cases, tap water can be a source of indoor radon when supplied by groundwater that flows through granite soil/rock. Only three home in this study relied on groundwater from a well; monitoring the indoor radon concentration in the bathroom in one home showed that showering by the occupants did not lead to an increase, supporting the assumption that the main source of indoor radon was the soil.

The average basement radon concentrations from the successive 30-day stack open and closed conditions were used to calculate the mean effectiveness of the PSD system in reducing indoor radon levels, defined as the Percentage of Radon Reduction in Equation 1:

$$\text{Percentage of Radon Reduction} = \frac{\left(C_{Rn\,stack\,closed} - C_{Rn\,stack\,open}\right)}{C_{Rn\,stack\,closed}} \times 100\% \tag{1}$$

where

$C_{Rn\,stack\,open}$ = indoor radon concentration when the radon stack is open/operational [Bq/m^3]

$C_{Rn\,stack\,closed}$ = indoor radon concentration when the radon stack is closed/non-operational [Bq/m^3]

A 30-day duration for each scenario was selected because it:

1. limits the occupants' exposure to radon when the radon stack is deliberately closed,
2. is short enough that the "open stack" and "closed stack" tests in the same home can be conducted during the same season, and
3. is long enough to reduce the impact of random variations in occupants' behaviour, building operational conditions, and other variable conditions (e.g. weather).

Two case studies were conducted to examine the performance of PSD systems in new construction homes and in retrofitted existing homes in Canada. The first study included six existing homes in the NCR among homeowners who had contacted NRC researchers due to their concerns about indoor radon between 2017 and 2019. The second study included fifteen new construction homes in Prince George, BC, where the PSD systems were installed during construction and tested during 2018 and 2019. The NRC's Research Ethics Board approved the study prior to the recruitment of participants and installation of PSD systems.

The participating homeowners were asked to follow similar conditions as recommended by the United States Environmental Protection Agency (EPA) regarding closed house conditions during tests between 4 and 90 days duration [14]. That is, the participating homeowners were asked to maintain closed-house conditions as much as possible during each testing period, with all windows and doors kept closed except the use of doors for normal entries and exits. Fans or other machines that introduce outdoor air were not to be operated, although the use of exhaust fans (in bathrooms, kitchen, and garage) were allowed for short periods of time and the normal operation of permanently installed HRVs/ERVs was maintained.

During the decisive measurement periods, Corentium Pro continuous radon monitors (CRMs) with SKU#236 were used in each of the new construction homes and retrofitted existing homes to monitor radon concentration, air temperature and relative humidity in the basement at 1 hour intervals. Corentium Pro CRM is one of the radon measurement devices listed by the C-NRPP for the use by certified radon professionals [15]. The project team purchased the Corentium Pro CRMs a few months prior to the measurement periods of the study. All of these CRMs were calibrated by the manufacturer and a calibration certificate was provided. All the radon measurements in this study were conducted before the calibration expired.

To determine the measurement precision, duplicate measurements were obtained in seven new construction homes and four retrofitted existing homes using two Corentium Pro CRMs, allowing the Relative Percent Difference (RPD) to be calculated using Equation 2:

$$RPD = \frac{|[Radon]_{Test1} - [Radon]_{Test2}|}{\left(\frac{[Radon]_{Test1} + [Radon]_{Test2}}{2}\right)} \; X\ 100 \qquad (2)$$

where

$[Radon]_{Test1}$ is the radon concentration in Bq/m^3 from one monitor, and

$[Radon]_{Test2}$ is the radon concentration in Bq/m^3 from the duplicate monitor.

The RPD values calculated from the duplicate measurements in these 11 homes did not exceed the acceptable RPD limit of 36% for an average test result over 150 Bq/m^3 and 67% for an average test result between 75 and 149 Bq/m^3 [16]. There is no limit set for acceptable RPD for an average measurement below 75 Bq/m^3.

2.1 Retrofitted Existing Homes

The radon concentration in potential study homes was first tested using a Corentium Pro CRM SKU#236 for approximately three months. Seven homes were initially selected, having pre-mitigation baseline average indoor radon concentrations ranging from 160 to 550 Bq/m^3. Diagnostic communication tests of the sub-slab area of each house were performed to ensure that installing a PSD system would likely be beneficial. The communication tests involved drilling small holes in the basement floor slabs and installing pressure taps, after which a suction was applied to the sub-slab area using a vacuum. The degree of the pressure field extension in the area under the floor slab was measured, representing the communication within the gas permeable layer. Typically the pressure gradient ranged from -5 to -30 Pa for each home; however, one of the seven homes was excluded because it was determined that there was almost no pressure field (the pressure differentials were so close to 0 they could not be measured), which was a result of airflow paths in the sub-slab causing short-circuiting between the vacuum and outdoors.

Blower door tests were conducted before and after stack installation in each of the retrofitted existing homes to determine the airtightness of the study homes. A smoke pencil was also used to identify soil gas entry points in the floors and walls in contact with the ground, which were then sealed by the certified radon mitigation professional prior to PSD installation. This reduced the indoor radon concentration by 10-50%, resulting in a discrepancy between the pre-mitigation baseline concentration and the closed stack concentration.

The PSD systems installed in the six retrofitted existing homes were equipped with a sliding gate valve to allow the stack to be either in a fully open or a fully closed position. In addition, the section of the passive radon stack passing through the attic of each home and the short section of the stack protruding above the roofline were insulated to R7 and R14, respectively. Such insulation levels for the PSD stacks were chosen to avoid freezing in the stack and were based on previous experimental and simulation results [17]. These two stack sections were insulated to maintain the driving force in the stack sections that pass through the unconditioned attic and that exit above the roof. Table 1 lists pertinent information regarding the six retrofitted existing homes and the corresponding PSD system details.

Table 1. System details for the six retrofitted existing homes.

Home #	Year Built	Type of Home	Basement Status	Stack height	Stack in attic	Stack insulated	Heat recovery ventilator (HRV)	Ground floor bathroom
1	1971	Two-storey †	Finished	7.3 m	1.7 m	Yes	No	Yes
2	1980	Two-storey ‡	Finished	9.4 m	1.5 m	Yes	No	No
3	1980	Two-storey	Unfinished	9.4 m	1.5 m	Yes	No	No
4	1960	Bungalow	Partially	7.5 m	1.8 m	Yes	No	No
5 §	1988	Two-storey	Unfinished	9.8 m	1.5 m	Yes	No	No
6 §	1988	Two-storey	Unfinished	9.8 m	1.5 m	Yes	No	No

† Even though this was a two-storey home, the stack in this home was shorter than the stacks in other two-storey homes. This was due to the stack traveling through a portion of the attic that was directly above part of the first floor and did not have to travel the height of the entire two-storey home.

‡ This two-storey home was an end unit town home. All other two-storey homes were single-detached homes.

§ These homes had a sump pit located in the basement.

Monitoring of the PSD system performance began shortly after their installation in each home. Retrofitted existing homes 1, 2, 3, and 4 were monitored between September 2017 and April 2018; whereas retrofitted existing homes 5 and 6 were monitored between September 2018 and April 2019. The term "shoulder season" will be used throughout this paper to describe the monitoring period during the fall of 2017 (September to November) for retrofitted existing homes 1, 2, 3, and 4 and the fall of 2018 (September to November) for retrofitted existing homes 5 and 6. The term "winter season" will be used throughout this paper to describe the monitoring period during the winter of 2017-2018 (December to February) for retrofitted existing homes 1, 2, 3, and 4 and the winter of 2018-2019 (December to February) for retrofitted existing homes 5 and 6.

2.2 New Construction Homes

Prince George, BC, was selected for the field study of new construction homes because it is located in the area designated as being prone to radon, in which the BC government mandated that all new homes built after December 2014 must incorporate a full-height passive radon stack. The municipality of Prince George provided NRC with a list of new homes built after December 2014 that include a PSD system. Information packages were mailed to 54 homes in the summer of 2018, with the intention of recruiting a maximum of fifteen homes as the study cohort due to instrumentation and resource capacity limitations. Areas of the city chosen for the mailed invitation were based on results from the cross-Canada residential radon survey at the geographic granularity of the forward sortation area (FSA) (the first three digits of the postal code). Once an invitation was accepted, a local certified radon mitigation professional (and former building inspector) conducted a follow-up visit to start the baseline measurement of the radon concentration in the home. Fifteen homes covering all four of Prince George's FSAs were recruited by early fall, a participation rate of roughly 28% (15/54).

Corentium Pro CRMs for decisive radon measurements and gate valves were installed in the passive radon stacks in late October of 2018 in all 15 homes recruited to permit the stack to be either fully open or closed during measurement periods. The stacks were insulated in eight of the fifteen homes, to allow the impact of stack insulation on PSD system performance to be evaluated. The total stack height was measured in all 15 homes, and the length of the sections that passed through the attic specified. The fifteen new construction homes and the corresponding system details are described in Table 2.

Table 2. System details for the fifteen new construction homes.

Home #	Year Built	Type of Home	Basement Status	Stack height	Stack in attic	Stack insulated	Heat recovery ventilator (HRV)	Ground floor bathroom
1	2018	Two-storey	Unfinished	9.4 m	2.0 m	Yes	No	Yes
2	2014	Two-storey	Finished	9.9 m	0.6 m	No	No	Yes
3	2016	Bungalow	Finished	8.8 m	2.0 m	Yes	No	No
4	2016	Bungalow	Finished	7.9 m	3.0 m	Yes	No	No
5	2018	Two-storey	Finished	10.7 m	1.8 m	No	Yes	Yes
6	2014	Two-storey	Unfinished	9.1 m	0.6 m	No	No	No
7	2016	Two-storey	Finished	9.8 m	1.8 m	No	No	Yes
8	2016	Two-storey	Finished	9.4 m	1.8 m	No	No	No
9	2016	Two-storey	Finished	9.9 m	2.4 m	Yes	No	Yes
10	2017	Bungalow	Finished	8.2 m	2.4 m	Yes	Yes	Yes
11§	2017	Bungalow	Finished	7.3 m	1.8 m	No	Yes	Yes
12 †	2016	Two-storey	None	6.9 m	1.2 m	Yes	No	Yes
13	2016	Two-storey	Unfinished	9.8 m	1.8 m	No	No	No
14§	2015	Two-storey	Unfinished	8.5 m	1.2 m	Yes	Yes	No
15 ‡	2014	Two-storey	Finished	10.0 m	7.6 m	Yes	Yes	Yes

† *This home did not have a basement, and the foundation construction in this home was slab-on-grade.*

‡ *This home had a total of 7.6 m (25.0 ft) of stack in the attic, 1.5 m (5.0 ft) was vertical and 6.1 m (20.0 ft) was horizontal.*

§ *These homes had a sump pit located in the basement.*

Monitoring of the PSD system performance began shortly after their installation in each home, between December 2018 and May 2019. For the new construction homes, the term "shoulder season" will be used throughout this paper to describe the monitoring period during the spring of 2019 (March to May) and the term "winter season" will be used to describe the monitoring period during the winter of 2018-2019 (December to February).

3 RESULTS

The proposed method for conducting the PSD field study was implemented in both retrofitted existing and recently built new construction homes. This section displays the radon concentration results obtained from the retrofitted existing and new construction homes, followed by a comparison of the results from new construction homes having similar building design parameters (HRV, ground floor bathroom, and stack insulation).

3.1 New Construction Homes vs. Retrofitted Existing Homes

The reduction in radon achieved by operating the PSD systems installed in the retrofitted existing and new construction homes are summarized in Table 3.

Table 3. Field study measurements in six retrofitted homes (RE) and fifteen new construction homes (NC) during the shoulder and winter season.

Home #	Test condition	Shoulder Season		Winter Season	
		Indoor radon† (Bq/m^3)	Radon Reduction (%)	Indoor radon (Bq/m^3)	Radon Reduction (%)
RE-1††	Stack opened	189 ± 10	-1%	110 ± 6	27%
	Stack closed	187 ± 10		150 ± 8	
RE-2	Stack opened	17 ± 2	88%	12 ± 2	93%
	Stack closed	141 ± 7		165 ± 8	
RE-3	Stack opened	18 ± 2	85%	22 ± 2	85%
	Stack closed	117 ± 6		151 ± 8	
RE-4	Stack opened	141 ± 7	22%	67 ± 4	52%
	Stack closed	180 ± 9		140 ± 7	
RE-5	Stack opened	112 ± 6	79%	68 ± 4	87%
	Stack closed	546 ± 27		507 ± 25	
RE-6	Stack opened	148 ± 8	44%	172 ± 9	46%
	Stack closed	266 ± 13		316 ± 16	
NC-1	Stack opened	94 ± 5	50%	104 ± 6	25%
	Stack closed	187 ± 10		138 ± 7	
NC-2	Stack opened	43 ± 3	66%	107 ± 6	20%
	Stack closed	125 ± 7		134 ± 7	
NC-3	Stack opened	45 ± 3	72%	46 ± 3	74%
	Stack closed	160 ± 8		174 ± 9	
NC-4	Stack opened	70 ± 4	66%	49 ± 3	79%
	Stack closed	205 ± 10		235 ± 12	
NC-5	Stack opened	36 ± 3	40%	106 ± 6	24%
	Stack closed	60 ± 4		139 ± 7	
NC-6	Stack opened	23 ± 2	79%	32 ± 3	67%
	Stack closed	107 ± 6		96 ± 5	
NC-7	Stack opened	43 ± 3	59%	52 ± 4	37%
	Stack closed	104 ± 5		82 ± 5	
NC-8	Stack opened	54 ± 3	82%	102 ± 5	69%
	Stack closed	293 ± 15		333 ± 17	
NC-9	Stack opened	52 ± 3	52%	90 ± 5	13%
	Stack closed	109 ± 6		103 ± 6	
NC-10	Stack opened	17 ± 2	83%	36 ± 3	61%
	Stack closed	99 ± 5		92 ± 5	
NC-11	Stack opened	83 ± 5	55%	157 ± 8	2%
	Stack closed	185 ± 9		160 ± 8	
NC-12	Stack opened	43 ± 3	76%	67 ± 4	63%
	Stack closed	176 ±9		180 ± 9	
NC-13	Stack opened	50 ± 3	89%	95 ± 5	80%
	Stack closed	467 ± 23		475 ± 24	
NC-14	Stack opened	17 ± 2	65%	34 ± 2	29%
	Stack closed	49 ± 3		48 ± 3	
NC-15	Stack opened	11 ± 2	91%	134 ± 7	4%
	Stack closed	117 ± 6		139 ± 7	

† *The radon readings within 24 hours after the gate valve was closed or opened were excluded when calculating the average indoor radon concentration. The total measurement uncertainty of Corentium Pro after 24 hours and after 7 days were calculated as* $\pm\sqrt{(7\%\ of\ average\ reading)^2 + 5^2}$ *and* $\pm\sqrt{(5\%\ of\ average\ reading)^2 + 2^2}$ *Bq/m^3, respectively* [18].

†† *Retrofitted existing home #1 exhibited a negative percentage of radon reduction during the shoulder season. This behaviour is discussed in more detail in the following paragraph.*

Table 3 shows when the stack was open in all retrofitted existing and new construction homes, the average measured basement radon concentration was below the Canadian guideline of 200 Bq/m^3. In addition, opening the stack reduced the radon concentration in all homes except for retrofitted existing home #1 (-1% during the shoulder season). In retrofitted existing home #1 during the shoulder season, basement flooding occurred; therefore, even though the stack was open during this time period, the PSD system was unable to collect and withdraw soil gas from beneath the concrete slab and reduce the indoor radon concentration.

Figure 1 shows a scatterplot of the radon reduction from the operation of the passive stack versus the radon concentration with the stack closed for retrofitted existing homes #2 to #6 and all new construction homes. The slope of a line between the origin and each point represents the effectiveness of the passive stack; therefore, a line from the origin at a 45° angle would represent the elimination of radon (an effectiveness of 100%). A linear trend is clear on the scatterplot formed by the homes with a high effective passive stack, having a radon reduction only somewhat smaller than the closed stack radon concentration. In addition, the effectiveness is consistent across the range of radon concentrations that occurred in these houses with the stack closed. The overall effectiveness of PSD systems is higher for the retrofitted existing homes than for the new construction homes, but the descriptive statistics displayed in Table 4 show the greatest difference occurs between the retrofitted existing homes and the new construction homes during the winter season, with mean (sd) for effectiveness of 0.72 (0.22) and 0.43 (0.28) respectively.

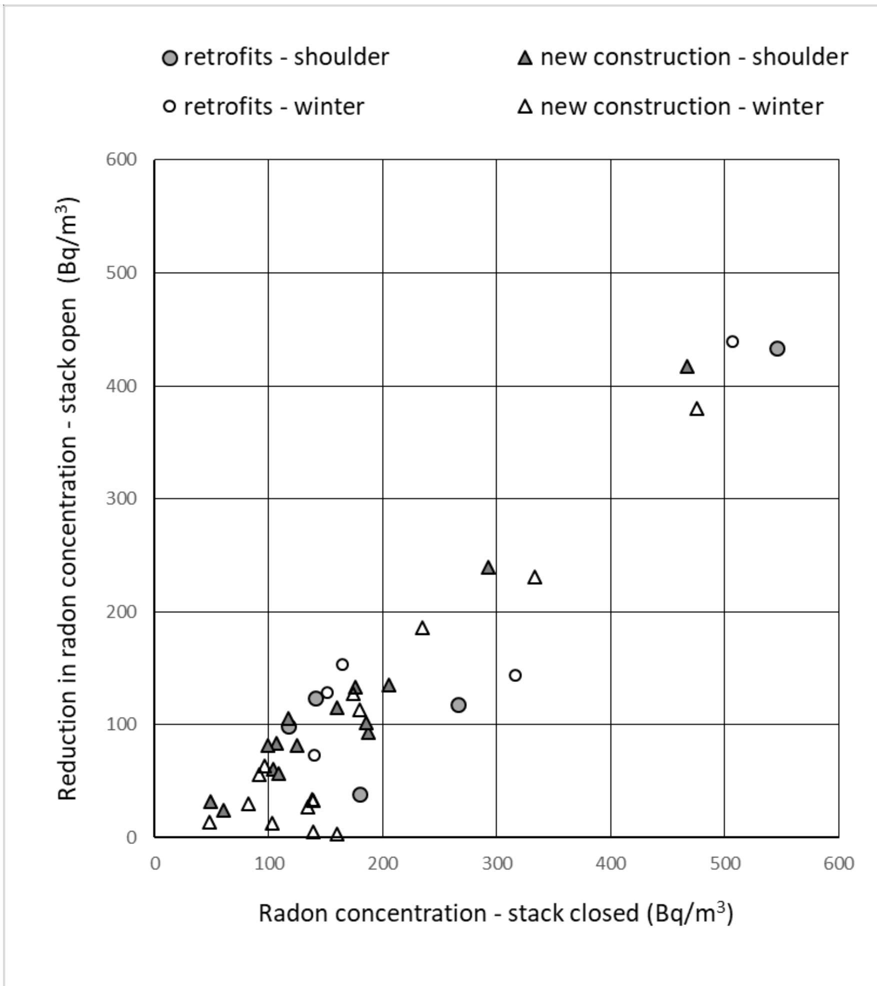

Figure 1. Radon reduction versus stack closed radon concentration.

Table 4. Descriptive statistics for effectiveness of passive stack in homes.

Homes	n	mean	sd	max	min
All Homes	40	0.59	0.26	0.93	0.02
Retrofits	10	0.68	0.25	0.93	0.22
New Construction	30	0.56	0.26	0.91	0.02
Retrofits – shoulder season	5	0.64	0.29	0.88	0.22
Retrofits – winter season	5	0.72	0.22	0.93	0.46
New Construction – shoulder season	15	0.68	0.15	0.91	0.40
New Construction – winter season	15	0.43	0.28	0.80	0.02

The performance of PSD systems in retrofitted existing homes vs. new construction homes was of interest as retrofitted existing homes were generally advantaged by having the PSD systems installed by a certified radon mitigation professional; whereas the new construction homes were advantaged by the fact that the placement of the PSD system was incorporated into the design. Figure 2 shows the percentage of radon reduction for retrofitted existing and new construction homes during the shoulder and winter season. It shows the frequency that homes fell into four percentage of radon reduction ranges (25% bins).

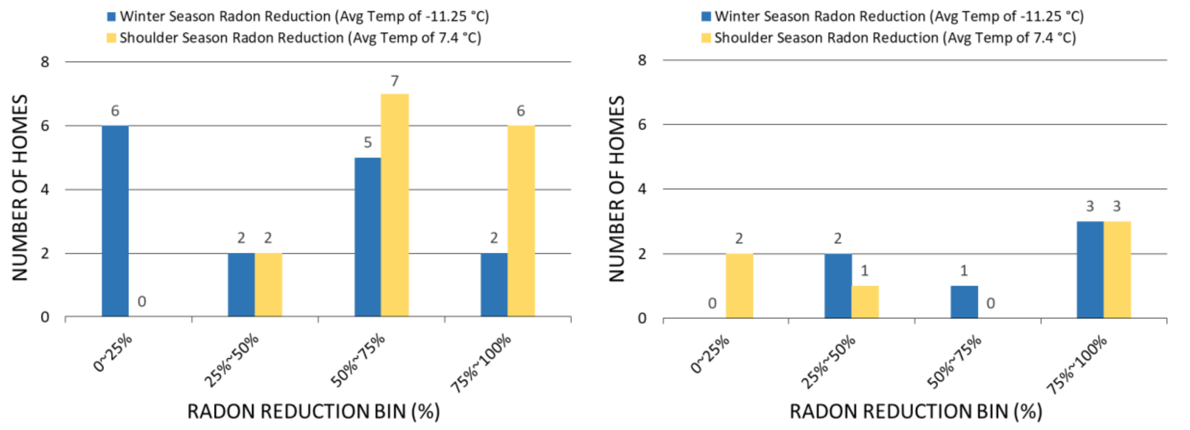

Figure 2. Percentage of radon reduction for NC homes in Prince George (left) and RE homes in NCR (right)

Figure 2 shows that the performance of PSD systems in both the retrofitted existing and new construction homes was highly variable. The figure also shows the average outdoor air temperature during the winter and shoulder seasons in Prince George were -11.25 and 7.40 °C, respectively, and in the NCR were -7.53 and 7.48 °C, respectively. Typically, a lower outdoor air temperature would be associated with improved PSD system performance due to an increase in the thermal stack effect. This was found to be the case for the PSD systems in the retrofitted existing homes as the performance typically increased when the outdoor air temperature decreased from shoulder season to winter season; however, the performance of several of the PSD systems was reduced in new construction homes during the winter season. The increase in the PSD system performance in retrofitted existing homes between the shoulder and winter season, contrasted by the reduction in PSD system performance in new construction homes during the winter was a peculiar occurrence that warranted further investigation. One possible reason could be the characteristics of home design. When evaluating the characteristics of the retrofitted existing homes, it can be seen that none have an HRV installed, all stacks are insulated, and 5 of the 6 homes do not have a ground floor bathroom; whereas several new construction homes operated with an HRV (five of fifteen), a ground floor bathroom (nine of fifteen), and without stack insulation (seven of fifteen).

The presence of any seasonal trends was evaluated within subgroups (Table 5) based on paired data for the effectiveness of PSD in the shoulder and winter season for each home using the nonparametric Wilcoxon signed ranks test, which does not require an assumption of normally distributed results. A significance level (α) of 0.05 was selected, with a one-tailed test where the change in effectiveness all had the same sign for the subgroup of paired data and a two-tailed test where changes of both signs were present in the subgroup of paired data. The existence of a seasonal trend suggesting that PSD was more effective in the winter than the shoulder season for retrofits was supported by the data, where the test W value is equal to or lower than the critical W value. The reverse trend, that PSD was less effective in the winter than the shoulder season, with and without HRV/ERV, was consistent with the data for all new construction. While no evidence of a seasonal trend existed for homes that did not have a ground floor bathroom, there was support for this seasonal trend of reduced PSD effectiveness in the winter for the subgroup of homes that had a ground floor bathroom.

Table 5: Wilcoxon signed rank tests evaluating seasonal difference in effectiveness of PSD

Subgroup	**n**	**W+**	**W-**	**W_{test}**	**W_{crit}**	**Comparison: shoulder to winter season**
Retrofits	5	15	0	0	0	More effective in winter $W_{test} \leq W_{crit}$
New Construction	15	7	-113	7	25	Less effective in winter $W_{test} \leq W_{crit}$
New Construction: with HRV/ERV	5	0	-15	0	0	Less effective in winter $W_{test} \leq W_{crit}$
New Construction: without HRV/ERV	10	7	-48	7	8	Less effective in winter $W_{test} \leq W_{crit}$
New Construction without HRV/ERV: with ground floor bathroom	5	0	-15	0	0	Less effective in winter $W_{test} \leq W_{crit}$
New Construction without HRV/ERV: no ground floor bathroom	5	6	-9	6	0	No trend

Note: α = 0.05 used for critical values of Wilcoxon signed ranks test (W_{crit})

In the following sections, new construction homes in Prince George are the focus when evaluating the impact of specific system characteristics on PSD system performance in order to limit the influence of different weather conditions.

3.2 New Construction Homes with HRVs vs. without HRVs

The impact of HRV operation on percentage of radon reduction and average radon concentration in new construction homes was of interest given the decrease in percentage of radon reduction during the winter season in new construction homes. Figure 3 shows the percentage of radon reduction distribution during the shoulder and winter season in the new construction homes with HRVs (left) and without HRVs (right). It shows the frequency that homes fell into four percentage of radon reduction ranges (25% bins).

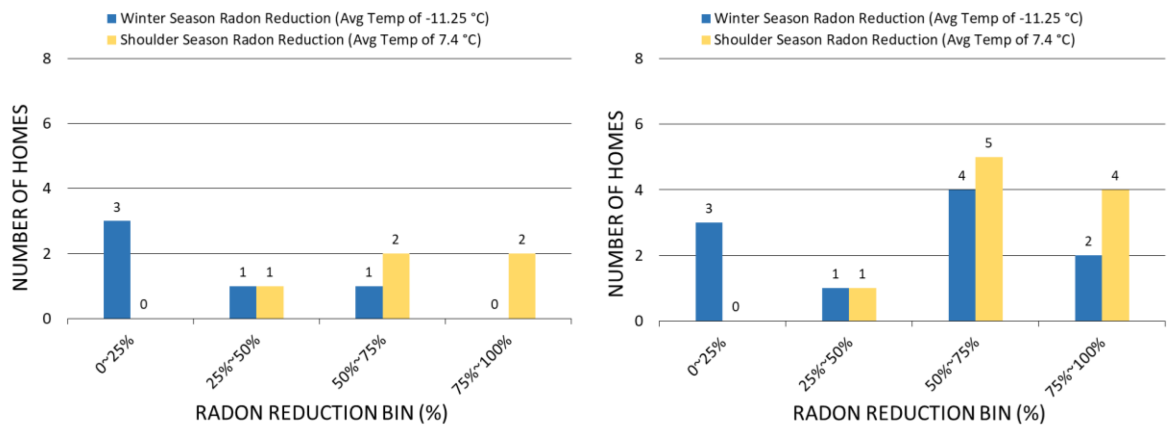

Figure 3. Percentage of radon reduction for new construction homes with HRVs (left) and without HRVs (right).

Figure 3 shows that regardless of whether the new construction homes contained an HRV, the PSD systems reduced the average measured radon concentration. However, in both new construction homes with and without an HRV, there was a decrease in the performance of the PSD system from the shoulder to winter season. This decrease in PSD system performance during the winter was more pronounced in new construction homes with an HRV, which had three of five homes with percentage of radon reductions below 25%, compared to three of ten for new construction homes without an HRV. Moreover, none of the new construction homes with an HRV had a percentage of radon reduction above 75% during the winter, compared to two of ten for new construction homes without an HRV.

The PSD systems in new construction homes without an HRV operating were also less effective in the winter season than in the shoulder season, but to a lesser extent. This could be due to ice formation or snow blockage at the top of the stack during the winter testing period; however, it should be noted that during shoulder season testing a renovation took place in new construction home #1 (no HRV), which consisted of cutting a hole in the sub-slab for a bath tub installation during the open stack period, ultimately causing an increase in the baseline radon concentration in the home and a higher percentage of radon reduction during the shoulder season testing. In addition, the PSD system stack in new construction home #2 (no HRV) was within 0.3 meter from the exterior wall, which could have led to a reduction in system performance during cold weather.

Figure 4 shows the average radon concentrations during stack open and closed periods in both the winter and shoulder seasons in the new construction homes built with and without HRVs.

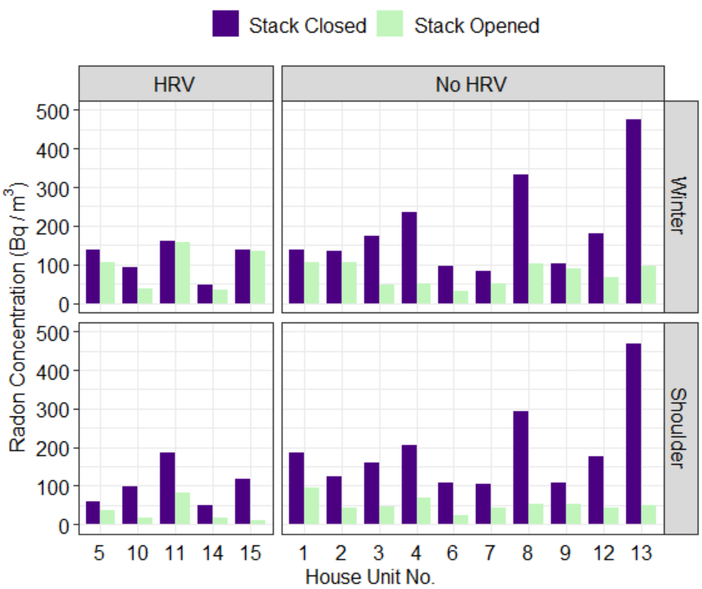

Figure 4. Average radon concentration during stack open and closed periods in new construction homes with HRVs (left) and without HRVs (right) during the shoulder (top) and winter (bottom) season.

While the stack was closed, during both the winter and shoulder seasons, all five new construction homes operating with an HRV had indoor radon concentrations below the Canadian guideline value of 200 Bq/m^3 whereas three of ten homes operating without an HRV had indoor radon concentrations above 200 Bq/m^3. The higher indoor radon concentrations during the stack closed periods for the homes without HRVs was one reason why the percentage of radon reduction in these homes was higher. With the PSD stack closed, the indoor radon concentrations in homes operating with HRVs were already somewhat reduced by mechanical ventilation. The PSD systems in all ten new construction homes without an HRV successfully reduced the indoor radon concentration below about 100 Bq/m^3 during both the winter and shoulder seasons, and in those with HRVs to below 80 Bq/m^3 during the shoulder season.

3.3 New Construction Homes with Ground Floor Bathrooms vs. without

Figure 5 shows the impact of ground floor bathrooms on the percentage of radon reduction in new construction homes built without an HRV. The figure includes the percentage of radon reduction in the ten new construction homes that do not have an HRV and separates the results into two groups: homes with a ground floor bathroom (left) and homes without a ground floor bathroom (right).

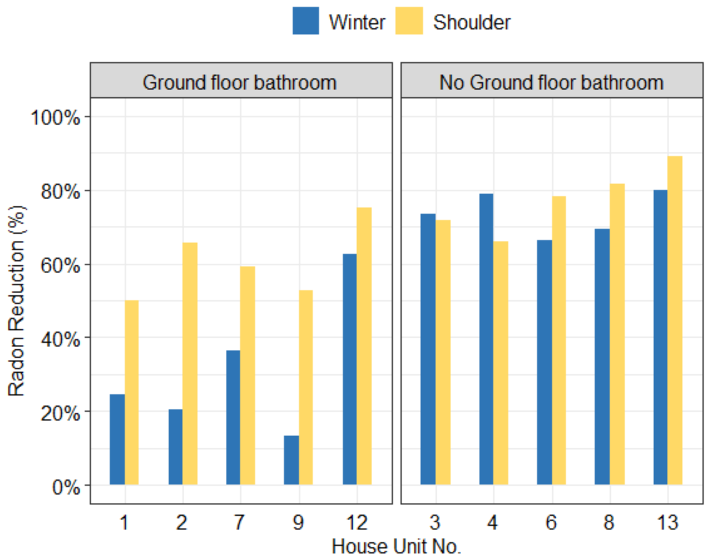

Figure 5. Impact of ground floor bathrooms on radon reduction in ten new construction homes without an HRV.

Figure 5 shows a noticeable decrease in the percentage of radon reduction from the shoulder to winter season in new construction homes with a ground floor bathroom. From the shoulder to winter season, the percentage of radon reductions in new construction homes #1, #2, #7, #9, and #12 decreased from 50 to 25%, 66 to 20%, 59 to 37%, 52 to 13%, and 76 to 63%, respectively. While the new construction homes without a ground floor bathroom operated more consistently in the shoulder and winter seasons. In the shoulder and winter season, the percentage of radon reductions in new construction homes #3, #4, #6, #8, and #13 remained at similar levels: 72 and 74%, 66 and 79%, 79 and 67%, 82 and 69%, and 89 and 80%, respectively.

3.4 New Construction Homes with Stack Insulation vs. without

Figure 6 shows the impact of stack insulation on percentage of radon reduction in new construction homes that have neither an HRV nor a ground floor bathroom. The figure includes the percentage of radon reduction in the five new construction homes that do not have an HRV or ground floor bathroom and separates the results into two groups: homes with stack insulation (left) and homes without stack insulation (right).

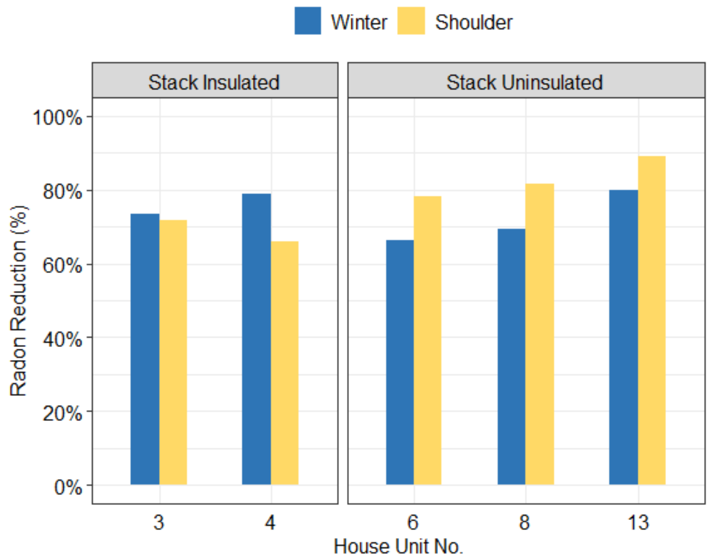

Figure 6. Impact of stack insulation on percentage of radon reduction in the five new construction homes without an HRV or ground floor bathroom.

Figure 6 shows that homes with stack insulation performed better during the winter than during the shoulder season. From the shoulder to winter season, the percentage of radon reductions in new construction homes #3 and #4 increased from 72 to 74% and 66 to 79%, respectively. While homes without stack insulation performed worse during the winter than during the shoulder season. From the shoulder to winter season, the percentage of radon reductions in new construction homes #6, #8, and #13 decreased from 79 to 67%, 82 to 69%, and 89 to 80%, respectively.

4 DISCUSSION

PSD field studies were conducted in both retrofitted existing and new construction homes built after December 2014. This section discusses the results and several key findings from the conducted field studies.

4.1 New Construction Homes vs. Retrofitted Existing Homes

The field study in new and existing homes displayed the value of PSD systems in Canadian homes within Prince George, BC and the NCR – the operation of a PSD system successfully reduced the indoor radon concentrations in fifteen new construction and 6 retrofitted existing homes to a level below the Canadian guideline of 200 Bq/m^3 during the shoulder and winter season. The PSD systems were a little more effective during the winter than in the shoulder season in the retrofitted existing homes but were less effective during the winter in new construction homes.

Part of the reason the percentage of radon reduction in the retrofitted existing homes was more effective in the winter could have been because a certified radon mitigation professional installed the PSD systems in these homes. Certified radon mitigation professionals ensure adequate distance between the stack and exterior wall, minimize the length/height of the stack in unconditioned spaces, ensured stacks are graded to the ground, and identify and seal soil gas entry points in the basement slab and walls.

The more effective radon reduction in the retrofitted existing homes in the winter season could have also been due to a few other aspects of the home design. None of the retrofitted existing homes had an HRV, all had stack insulation, and only one of the six retrofitted existing homes had a ground floor bathroom; whereas several new construction homes operated with an HRV (five of fifteen), a ground floor bathroom (nine of fifteen), and without stack insulation (seven of fifteen). Reduced effectiveness of PSD systems during the winter resulted in new construction homes that either had an HRV/ERV system, a ground floor bathroom, or lacked stack insulation. Statistical analysis of these results was limited by the relatively small sample sizes, so the physical mechanisms underlying the trends are examined in the following paragraphs. Moreover, these results are consistent with the design recommendations presented in the recently published Canadian General Standards Board for radon prevention in new housing [19]. The results will be discussed in greater detail in the following three sub-sections.

4.2 New Construction Homes with HRVs vs. without HRVs

The field study in new construction homes displayed the value of operable HRVs in Canadian homes within BC – during the PSD stack closed period, the five new construction homes that used HRVs had indoor radon concentrations below the Canadian guideline of 200 Bq/m^3, while three of the ten homes without an HRV had indoor radon concentrations above 200 Bq/m^3. Moreover, the five new construction homes operating with an HRV all had the indoor radon concentration reduced to a concentration below 80 Bq/m^3, while the PSD was operational during the shoulder season; however, the PSD system was less effective at reducing indoor radon during the winter season in these homes. This indicated that using a PSD system and HRV in tandem could be a beneficial solution in homes with significant radon issues. It is also important to note that the PSD systems in all ten new construction homes built without an HRV reduced the indoor radon to a concentration below about 100 Bq/m^3 during both the winter and shoulder seasons.

The impact that HRVs had on the initial indoor radon concentration in the new construction homes displayed the value of mechanically supplied ventilation. However, although HRVs may be an effective method of reducing the indoor radon concentration, further considerations are required when deciding to use as a stand-alone radon mitigation method. The operation and maintenance of HRVs can be unreliable – occupants have been known to turn HRVs off [20] and the filters need to be cleaned regularly [21]. HRVs can also be bulky and space in homes (particularly in multi-unit townhouses) can be limited, making the installation of the equipment difficult. Conversely, a PSD system installed in multi-unit townhouses may be capable of serving more than one home. In addition, HRVs could enter into defrost mode periodically if the outdoor inlet air temperature gets below a certain threshold. As a result, HRVs will frequently shut off the supply of ventilation when they enter into defrost mode. The impact of this occurrence may be displayed in the results for the new construction homes with HRVs – new construction homes #5, #11, and #15 had lower percentages of radon reduction in the winter compared to during the shoulder season. It is important to acknowledge that in addition to HRV operation, these three new construction homes could have also experienced ice formation or snow blockage at the top of the stack as the PSD system stack in new construction home #5 and #11 was uninsulated, while the PSD system stack in new construction home #15 was insulated, but contained 20 feet of horizontal length in the unconditioned attic.

4.3 New Construction Homes with Ground Floor Bathrooms vs. without

The field study in new construction homes displayed the importance of properly sealing any soil gas entry points in the sub-slab in Canadian homes within BC – of the ten new construction homes without an HRV, all homes with a ground floor bathroom experienced a noticeable decrease in the percentage of radon reduction from the shoulder to winter season, while the new construction homes without a ground floor bathroom operated more consistently in the shoulder and winter season. The decrease in percentage of radon reduction in the homes with a ground floor bathroom could have been due to the additional leakage at the base of the home leading to an increased stack effect in the building that would be exacerbated with colder temperatures during the winter time (average outdoor air temperature of -11.25 °C).

During the winter time, the building stack effect is in its fullest effect, if there is a substantial hole or opening at the base of the house and/or the roof, there will be substantial infiltration.

Since the hole is in the basement floors in contact with the ground more radon rich soil gas will be driven through the sub-slab into the building. Conversely, the homes without ground floor bathrooms operated more consistently between the winter and shoulder season which was likely because these homes have less leakage area in the basement floor slab and thus were less impacted by the increased building stack effect during the winter time. As a general precaution it is recommended to cover and seal any sanitary cut outs to limit leakage through the basement floor slab in contact with the ground.

4.4 New Construction Homes with Stack Insulation vs. without

The field study in new construction homes displayed the importance of insulating PSD system stacks in Canadian homes within Prince George. The potential impact of not insulating the passive stack in unconditioned spaces was displayed by the decrease in the percentage of radon reduction in all new construction homes without stack insulation (NC #6, #8, and #13). These three new construction homes did not contain an HRV nor a ground floor bathroom, and all experienced a decrease in percentage of radon reduction. Conversely, the PSD systems in new construction homes #3 and #4 with stack insulation performed better during the winter than during the shoulder season.

As a result of increased stack effect through the stack, PSD systems should be more effective during the winter, as was the case for homes with stack insulation. However, homes without insulation on the stack had a reduced performance during the winter. The reduced performance in the winter time in homes without stack insulation could be due to the low outdoor air temperatures. The low outdoor air temperatures (average outdoor air temperature of -11.25 °C) combined with no stack insulation can lead to increased cooling of the air through the stack, which could cause the humid soil gas within the PSD stack to reach its dew point temperature, leading to condensation forming on the inside of the stack and freezing during the winter. This could add additional resistance to the airflow through the stack, ultimately leading to a reduction in PSD system performance.

It should be noted that new construction homes #11 and #15 experienced the lowest radon reduction during the winter season and both contained an HRV and a ground floor bathroom. As previously mentioned, the PSD stack in new construction home #11 was uninsulated, whereas the PSD stack in new construction home #15 was insulated, but contained 20 feet of horizontal length in the unconditioned attic.

4.5 Other Observations

The results of this study were comparable to those reported in the two previous field studies evaluating the performance of PSD systems in a group of homes: 46 homes in Illinois, US, [10] and 16 homes in British Columbia, Canada [11]. In both studies, operating PSD stacks reduced the indoor radon concentration in all homes, but the range in percentage of radon reduction achieved was very large: from less than 25% to more than 75% [10], and from about 33% to more than 75% [11]. In the US study, indoor radon concentrations were reduced below 148 Bq/m^3 while the PSD system was operational in 27 of the 46 homes. The indoor radon concentrations were below 200 Bq/m^3 in 13 of the 16 homes while the PSD systems were operational in BC, Canada [11]. The indoor radon concentrations were higher than the guideline value in five homes in the BC study while the PSD systems were capped, and the indoor radon was reduced while the PSD systems were operational to concentrations below 200 Bq/m^3 in four of the five homes [11]. The operational PSD system reduced the indoor radon concentration in all homes in the current study, including the five homes in which indoor radon concentrations were above the Canadian guideline value when the system was closed. The reduction in average indoor radon could have been more reliable in this study because a longer period of 30 days was used to monitor the radon concentration for each operating condition of the stack, whereas the test period in [11] was limited to 48 hours.

A strength of this study was the 30 days period used to monitor the indoor radon concentration during each operating condition of the PSD system. Large variations in radon concentration can occur diurnally and weekly, as well as seasonally, and a measurement period of at least one month is, therefore, recommended to characterize average indoor radon exposure [13]. Although indoor radon concentrations are usually higher during the colder seasons when heating systems are used [13,16], recent research in Western Canada has identified some houses where indoor radon concentrations were higher in the summer than in the winter [22]. Evaluation of the performance of PSD systems year-round is important, and continued indoor radon measurements with the stack open showed that the reductions in radon were maintained in homes over the spring months in this analysis. Another strength was the use of a certified radon mitigation professional to retrofit the PSD systems in the existing homes, as previously mentioned. However, the use of the home builder to install the PSD systems in the new construction homes could have been a limitation of the study. In addition, only 21 homes in two locations were included in this field study, and so the results cannot be extrapolated to all geographic and climatic regions in Canada.

5 CONCLUSIONS

In this research, the PSD systems installed in fifteen new construction homes located in Prince George, BC, and retrofitted in six existing homes located in the National Capital Region (Ottawa, Ontario and Gatineau, Quebec), all reduced or maintained the indoor radon concentrations below the Canadian guideline value of 200 Bq/m^3. PSD systems installed by a certified radon mitigation professional were typically effective at reducing indoor radon concentrations during the shoulder and winter season. Conversely, degradation in the performance of the PSD system from the shoulder to winter season was observed in homes having either an HRV, a ground floor bathroom, or no stack insulation. An HRV operating in defrost mode during the winter can reduce the quantity of ventilation air supplied to the home. A ground floor bathroom can increase leakage through the basement floor slab in contact with the ground to a greater extent during the winter due to the extreme temperature difference between the indoor and outdoor air, which can enhance the stack effect within the building and draw more soil gas into the building. Condensation forming on the inside of an uninsulated stack and freezing during the winter can add additional resistance to the airflow through the stack, leading to a reduction in PSD system performance. This radon preventive measure is particularly suited to new construction considering the cost and benefit implications, and improved knowledge about the performance of PSD systems in Canadian housing will provide guidance to homeowners and home builders as well as national, provincial, and municipal building officials and inspectors. The results of this field study suggest the potential of PSD systems to effectively reduce indoor radon exposure and associated lung cancer risk for Canadians.

A better estimate of the optimal performance of PSD systems could be obtained by having them installed by certified radon mitigation professionals in all homes included in the study, so that design flaws identified in this study can be avoided in the future. This would ensure that stack piping is routed optimally up through the building envelope (avoiding proximity to exterior walls for example and improper slope), any basement slab cut outs (i.e. basement bathrooms, etc.) are properly sealed, and the stack is insulated where it passes through the attic and above the roofline. Further research is recommended to better understand the conditions required for consistent reduction of indoor radon when simultaneously operating both PSD and HRV systems, and the impact of various home design parameters on PSD system performance. It would also be beneficial to evaluate PSD system performance in additional provinces, so that uncertainty will be reduced when extrapolating the effect of PSD systems to the housing stock across Canada. It should be noted that, starting in 2019, the researchers contracted three certified radon mitigation professionals to install PSD systems in 25 new construction homes in four provinces of the country (including British Columbia, Manitoba, Ontario, and Quebec), in attempt to avoid or minimize the causes of PSD system deficiency.

This work will provide useful data for a guide of practice that can be used by builders and building inspectors and will also provide useful data to support the National Building Code radon and soil gas control task groups evaluating code change requests.

ACKNOWLEDGEMENTS

The authors of this publication gratefully acknowledge that this study was enabled by funding through the Canadian Government's initiative "Taking Action on Air Pollution".

This work was undertaken as part of an annual collaborative research project between NRC and Health Canada's National Radon Program.

The NRC's Research Ethics Board protocol numbers for the studies in the retrofitted existing homes and the new construction homes are 2017-18 and 2018-58, respectively.

REFERENCES

[1] Canada's Nuclear Safety Commission, "Radon in Canada's Uranium Industry," 2012. [Online]. Available: http://nuclearsafety.gc.ca/eng/pdfs/Fact_Sheets/Radon-Fact-Sheet_e.pdf.

[2] Health Canada, "Summary Report on Active Soil Depressurization (ASD) Field Study," 2016. [Online]. Available: https://www.canada.ca/content/dam/hc-

sc/migration/hc-sc/ewh-semt/alt_formats/pdf/radiation/radon/active-soil-depressurisation-2016-depressurisation-active-sol-eng.pdf.

[3] N. K. Shammas and L. K. Wang, “Shammas 2009.pdf,” in *Handbook of Advanced Industrial and Hazardous Waste Treatment*, 2009.

[4] J. Chen, D. Moir, and J. Whyte, “Canadian Population Risk of Radon Induced Lung Cancer: A Re-assessment Based on the Recent Cross-Canada Radon Survey,” *Radiat. Prot. Dosimetry*, vol. 152, pp. 9–13, 2012.

[5] N. M. Rahman and B. L. Tracy, “Radon control systems in existing and new construction: A review,” *Radiat. Prot. Dosimetry*, vol. 135, no. 4, pp. 243–255, 2009, doi: 10.1093/rpd/ncp112.

[6] Public Health England, “Passive Remediation of Radon in UK Homes,” 2019.

[7] F. J. Maringer, M. G. Akis, H. Kaineder, P. Kindl, and C. Kralik, “Results and conclusions of the Austrian radon mitigation project ‘SARAH,’” pp. 159–167, 2001.

[8] J. P. Rydock, A. Næss-Rolstad, and J. T. Brunsell, “Effectiveness of Radon Mitigation Measures in 12 Houses 10 Years after,” no. 0314, pp. 38–43, 2002.

[9] C. C. Lutes, R. S. Truesdale, B. W. Cosky, J. H. Zimmerman, and B. A. Schumacher, “Comparing Vapor Intrusion Mitigation System Performance for VOCs and Radon,” *Remediation*, 2015, doi: 10.1002/rem.

[10] S. Lafollette and T. Dickey, “Demonstrating Effectiveness of Passive Radon-Resistant New Construction,” *J. Air Waste Manage. Assoc.*, vol. 51, no. 1, pp. 102–108, 2011, doi: 10.1080/10473289.2001.10464256.

[11] D. Rogoza, H. Roberts, and B. Swoveland, “A Comparison of Three Radon Systems in British Columbia Homes: Conclusions and Recommendations for the British Columbia Building Code,” *BC Lung Assoc.*, 2014.

[12] World Health Organization, "Radiological aspects," in *Guidelines for Drinking-Water Quality*, 2017, pp. 203–218.

[13] International Atomic Energy Agency, "Design and Conduct of Indoor Radon Surveys," 2019.

[14] Environmental Protection Agency, "EPA Protocols for Radon and Radon Decay Product Measurements in Homes," 1993.

[15] C-NRPP, "Listed Radon Measurement Devices," 2020. https://c-nrpp.ca/approved-radon-measurement-devices/ (accessed Oct. 01, 2020).

[16] Health Canada, "Guide for Radon Measurements in Residential Dwellings (Homes)," 2017. [Online]. Available: https://www.canada.ca/content/dam/hc-sc/documents/services/publications/health-risks-safety/guide-radon-measurements-residential-dwellings/radon-measurements-homes-eng.pdf.

[17] M. Ghobadi and L. Zhou, "Thermal Insulation of Radon Systems to Avoid Freezing," in *Proceedings of the International Building Physics Conference*, 2018.

[18] Airthings, "Correntium Pro Specifications." [Online]. Available: https://cdn2.hubspot.net/hubfs/4406702/Website/Product Sheets/Pro/Pro Product Sheet.pdf.

[19] Standards Council of Canada, "CAN/CGSB-149.11-2019 - Radon control options for new construction in low-rise residential buildings," 2019. [Online]. Available: https://www.scc.ca/en/standardsdb/standards/30173.

[20] I. R. C. A. Van Holsteijn, I. W. L. Li, I. H. J. J. Valk, and I. Wim, "Improving the Energy and IAQ Performance of Ventilation Systems in Dutch Dwellings," vol. 3315, 2016, doi: 10.1080/14733315.2016.11684093.

[21] VENMAR, "HRV and ERV - Maintenance," 2020. https://www.venmar.ca/26-detail-

advice-hrv-and-erv-maintenance.html (accessed Sep. 19, 2020).

[22] F. K. T. Stanley *et al.*, “Radon exposure is rising steadily within the modern North American residential environment , and is increasingly uniform across seasons,” *Sci. Rep.*, pp. 1–17, 2019, doi: 10.1038/s41598-019-54891-8.