Two Case Studies on Ventilation for Indoor Radon Control

Justin Berquist*, Liang Grace Zhou, Jeffrey Whyte, Yunyi Ethan Li, Mark Vuotari and Gang Nong

National Research Council Canada
1200 Montreal Road
Ottawa, Ontario, Canada
**Corresponding author: Justin.Berquist@nrc-cnrc.gc.ca*

ABSTRACT

Health Canada's cross-Canada residential radon survey report from 2012 demonstrated that roughly 7% of Canadian homes contain radon levels above the Canadian guideline of 200 Bq/m^3. The research outlined in this paper evaluates the effect of ventilation rates on radon levels in two homes located in Ontario, Canada. The first case study consisted of short-term (2 day) radon monitoring in a home using three ventilation strategies; one heat recovery ventilator (HRV) running, two HRVs running, and both HRVs turned off. The results displayed the potential benefits of increasing the ventilation rate in an airtight home to reduce occupants' radon exposure. When both HRVs were off the measured air exchange rate was 0.05 h^{-1} and maximum radon concentration was 222 Bq/m^3. When both HRVs were operating, the air exchange rate was 0.40 h^{-1}, and within four hours the lowest radon concentration measured was 33 Bq/m^3. The first case study provided justification for conducting longer-term radon monitoring (2.5 months) in a second home using three ventilation strategies. During this time period, an energy recovery ventilator (ERV) was successively operated in three different modes: continuously, running 20 minutes per hour, and turned off. When the ERV was off, the average basement radon concentration was 872 Bq/m^3 and the air exchange rate was 0.16 h^{-1}. When the ERV in the house was operating continuously, the air exchange rate rose to 0.28 h^{-1}. However, possibly a result of the second home being leakier and the initial radon concentration being higher than in the first home, it was not possible to reduce the average radon concentration (242 Bq/m^3) below the Canadian guideline of 200 Bq/m^3 solely via ventilation. The results obtained in both homes suggest, 1) studies using a larger number of homes would be beneficial for evaluating ventilation as a solution for radon control and 2) when considering ventilation as a radon reduction technique, both the initial radon concentration and the natural ventilation rate of the home should be considered.

KEYWORDS

Radon, mitigation, and ventilation

1 INTRODUCTION

Radon is a naturally occurring radioactive gas. It is the direct decay product of radium-226, stemming from the decay of uranium-238 (Shammas and Wang 2009). As such, radon originates below the ground and migrates to the earth's surface (Zhukovsky and Vasilyev 2014). This is problematic because of the risks associated with the inhalation of radon and radon decay products. Radon decay products are not gases, as such, it is common for them to lodge in the lining of the lungs (American Cancer Society 2015). As further decay of these products occur, alpha particle radiation is given off that can cause various cellular damage, leading to the development of lung cancer (American Cancer Society 2015).

Outside, radon dilutes to concentrations that do not pose a significant risk (Shammas and Wang 2009). However, the accumulation of radon in buildings is problematic (Shammas and Wang 2009). Radon is the second leading cause of cancer, after smoking (American Cancer Society 2015). Between 3 and 14% of a country's lung cancer occurrences can be attributed to radon, although the severity in each country depends on the national average radon level and smoking prevalence (World Health Organization 2016).

Due to the danger of high radon levels, many countries around the world have implemented guidelines and regulations for indoor radon. Canada and the United States have national *guidelines* of 200 Bq/m^3 and 148 Bq/m^3, respectively. Meanwhile, European Union mandates that Member States enforce *regulations* to ensure indoor radon concentrations are below 300 Bq/m^3, as required by the Basic Safety Standards 2013 Directive. In addition, the World Health Organization has established a national *reference level* of 100 Bq/m^3 (World Health Organization 2009).

The risk associated with indoor radon is a major threat to Canadians as they spend over 90% of their time indoors (Khan et al. 2018) and 7% of Canadian homes have been found to contain radon levels above the Canadian guideline of 200 Bq/m^3 (Health Canada 2012). There are several methods to prevent and reduce radon entry into buildings. The most common methods are active soil depressurization, passive soil depressurization, increasing overall ventilation rates, avoiding depressurization inside the building, and sealing soil gas entry routes into the building.

In this research, two case studies explore the effectiveness of using ventilation for radon control. This paper begins by outlining previous, relevant case studies, followed by a description of the case study and the presentation of the obtained results. The paper then finishes with a discussion of the obtained results and conclusions.

2 LITERATURE REVIEW

This section provides a review of various worldwide case studies that evaluated the effectiveness of ventilation as a solution for radon control. All of which were conducted outside of Canada; New Jersey, USA (Turk et al., 1988), New Jersey, USA (Socolow and Varma., 1994), Czech Republic (Jiranek and Kacmarikova., 2014), Sweden (Akbari and Oman., 2013), Hong Kong (Chao and Hu., 2004), and Washington (Turk et al., 1991).

Jiranek and Kacmarikova (2014) monitored radon in four rooms, for 1 year, before and after an energy-saving retrofit. Although the retrofit reduced the annual heat demand 2.8 fold, it also reduced the air exchange rate to below 0.1 h^{-1}. The authors suggested that this caused the average annual radon concentration to increase from 337 to 1117 Bq/m^3. Akbari and Oman (2013) studied the impact of ventilation on energy consumption and radon concentrations in a house. When inducing an air exchange rate of 0.25, 0.5 and 1 h^{-1}, the average radon concentration was 150, 65, and 36 Bq/m^3, respectively. Chao and Hu (2004) developed a dual-mode (carbon dioxide and total volatile organic compound) demand controlled ventilation strategy for a lecture hall. In the study, the radon concentration decreased below 100 Bq/m^3 when ventilation rates were increased. However, low ventilation rates caused radon concentrations to rise above 700 Bq/m^3 at times. Socolow and Varma (1994) studied radon mitigation by natural and mechanical ventilation. They found the ground floor living area's outdoor air supply had no effect on radon concentration. Turk et al. (1991) studied the long-term performance of two houses that used ventilation to reduce the indoor radon concentration. The radon levels were inversely proportional to the ventilation rates. Moreover, after modifying the ventilation system in one home, a further reduction in radon occurred. Turk et al. (1988) increased ventilation capacity in one home by approximately 0.5 h^{-1}. As a result, the basement and first floor radon levels decreased from 1036 to 592 Bq/m^{3}and 666 to 518 Bq/m^3, respectively.

There is a need to evaluate the effectiveness of many ventilation systems worldwide since an optimal mitigation strategy largely depends on the building type, soil conditions, and climate (Rahman and Tracy 2009). However, the literature review revealed a limited number of research papers (6) pertaining to ventilation as a solution for radon control, all of which were conducted outside of Canada. Therefore, this research will build on previous studies that used ventilation for radon control with two case study homes located in Ontario, Canada.

3 METHODOLOGY

This section provides a description of the measurements and two case study homes used to evaluate the effectiveness of ventilation as a solution for radon control.

3.1 Measurement Description

This subsection outlines the equipment used to monitor the radon concentration and measure the air exchange rate in the two case study homes.

3.1.1 Radon Measurements

The two case studies measured radon concentration with different devices, the AlphaGUARD PQ 2000 Pro (Home #1) and Corentium Plus (Home #2) radon monitors. The AlphaGUARD PQ 2000 Pro uses an ionization chamber to detect radon (Saphymo 2012), while the Corentium Plus uses digital detector technology (Airthings 2019).

The AlphaGUARD PQ 2000 Pro has a range of 2 to 2,000,000 Bq/m^3 and is accurate to ± 3%. The AlphaGUARD PQ 2000 Pro has measurement cycles of 10 or 60 minutes. The duration that the device can measure depends on the interval of the measurement cycle. Data collection capacity is approximately 21 days when using a 10-minute measurement cycle and approximately 4 months when using a 60-minute measurement cycle.

The Corentium Plus radon monitor has a range of 0 to 9,999 Bq/m^3 and is accurate to within 5% ± 5 Bq/m^3. The Corentium Plus continuously monitors radon concentrations in a space and outputs a short and long-term average of the radon concentrations in the space. However, data can only be stored internally at 1-hour intervals. At this time interval, the internal memory storage capacity will last approximately 10 years.

3.1.2 Air Exchange Rate Measurements

In both case studies, tracer gas decay tests were performed to determine the ventilation rate during each control strategy. In tracer gas decay tests, a small amount of tracer gas (SF_6 in this case) is released into the house, and its concentration is recorded as a function of time. The air exchange rate of a building can be determined based on the decay in the tracer gas concentration. An exponential trendline equation can be used to characterize the obtained decay, and the exponent within this equation represents the air exchange rate.

The current study used SF_6 as the tracer gas for the following reasons:

- SF_6 is very inert and relatively low in toxicity
- the environment does not naturally contain SF_6; therefore, ambient background levels are low, and although background levels have been steadily rising due to its use in many fields, it is present at a fraction of the level being measured in this research
- SF_6 is readily available in compressed cylinders, and the research team has been using an in-house developed dosing unit on a routine basis

In the two case study homes, the tests were conducted when the pressure differential across the building envelope could be assumed insignificant (i.e. limited wind). The tests used an INNOVA 1303 Multipoint Sampler and Doser unit to sample SF_6 at six locations in each home and an INNOVA 1312 Photoacoustic Multi-gas Monitor to analyse the samples.

3.2 Case Study Description

This subsection describes the two case study homes monitored in this research. Described first is Home #1, which consisted of short-term (two-day) radon monitoring. Described second is Home #2, which expanded the study to long-term (monthly) radon monitoring.

3.2.1 Home #1

The first home consists of a basement, ground and second storey floor. The total floor area and volume of the home, excluding the basement, is 133.4 m^2 (1,435 ft^2) and 549 m^3 (19,380 ft^3), respectively. The house contains two heat recovery ventilators (HRVs), one along the main ductwork into and out of the furnace and a second stand-alone unit in the basement. This allowed for the effect of three ventilation strategies to be analysed: one HRV on, both HRVs off, and both HRVs on.

The tracer gas concentration was measured at six locations within the house. The six sampling locations included the basement general area, basement stairwell, ground floor kitchen, ground floor front entrance, second floor hallway, and second floor bedroom. The basement was equipped with an AlphaGUARD radon monitor. Radon concentration measurements started July 11th, 2017 at 8:45 am and continued at 10-minute intervals until July 12th, 2017 at 1:00 pm. Table 1 shows the tracer gas decay test and radon monitoring schedule for the three ventilation strategies implemented in Home #1.

Table 1: Home #1 tracer gas decay test and short-term radon monitoring schedule for each ventilation strategy

Control Strategy	Start Date	Start Time	End Date	End Time
1 HRV on	July 11th, 2017	9:45 am	July 11th, 2017	2:00 pm
Both HRVs off	July 11th, 2017	2:22 pm	July 12th, 2017	8:45 am
Both HRVs on	July 12th, 2017	9:00 am	July 12th, 2017	1:00 pm

3.2.2 Home #2

The second home also consists of a basement, ground and second storey floor. The total floor area and volume of the home, including the basement, is 227.6 m^2 (2,450 ft^2) and 736 m^3 (26,000 ft^3), respectively. It has a variety of features found in energy efficient homes. The house is equipped with continuous building envelope insulation and foam board insulation underneath the concrete slab. There is also an energy recovery ventilator (ERV) located in the basement of the house, supplying outdoor air to the return air plenum of the furnace. In addition, there is an active soil depressurization radon mitigation system within this home. However, for the purposes of this ventilation case study, the active soil depressurization system was disabled. This allowed for three ventilation strategies to be analysed: ERV operating continuously, 20 minutes per hour, and turned off.

The tracer gas concentration was measured at six locations within the house. The six sampling locations included the basement recreation room, basement stairwell, ground floor kitchen, ground floor front entrance, second floor hallway, and second floor master bedroom. Due to equipment availability, the tracer gas decay tests were conducted at different times than radon monitoring. Table 2 shows the tracer gas decay test schedule for the three ventilation strategies implemented in Home #2.

Table 2: Home #2 tracer gas decay test schedule for each ventilation strategy

Control Strategy	Start Date	Start Time	End Date	End Time
ERV 20/60	January 29th, 2019	3:00 pm	January 30th, 2019	7:00 am
ERV On	January 30th, 2019	3:00 pm	January 31st, 2019	9:00 am
ERV Off	January 31st, 2019	9:00 am	January 31st, 2019	3:30 pm

During the long-term radon monitoring, the basement was equipped with a Corentium Plus continuous radon monitor. The Corentium Plus continuous radon monitor measured radon concentrations between March 6th, 2018 and May 22nd, 2019. Table 3 shows the radon monitoring schedule for the three ventilation strategies implemented in Home #2.

Table 3: Home #2 long-term radon monitoring schedule for each ventilation strategy

Control Strategy	Start Date	End Date
ERV 20/60	March 6th, 2018	March 23rd, 2018
ERV On	April 15th, 2018	May 6th, 2018
ERV Off	May 6th, 2018	May 22nd, 2018

4 RESULTS

This section displays the results obtained for the two case study homes. Presented first are the short-term test results for Home #1, followed by the long-term test results for Home #2.

4.1 Home #1

The first case study monitored short-term radon concentrations in a home using three ventilation strategies; one HRV on, both HRVs off, and both HRVs on. Presented first are the tracer gas decay test results, followed by the short-term radon monitoring results.

4.1.1 Tracer Gas Decay Testing

To determine the ventilation rate for each ventilation strategy, tracer gas decay tests were performed. The average concentration from six locations in the house was used to approximate the overall ventilation rate of the house. Figure 1 shows the average tracer gas decay and exponential line of best fit for each control strategy. Note that for clarity purposes, the entire decay period of SF_6 while both HRVs were off was not included in Figure 1; however, the displayed exponential line of best fit does consider the entire decay period.

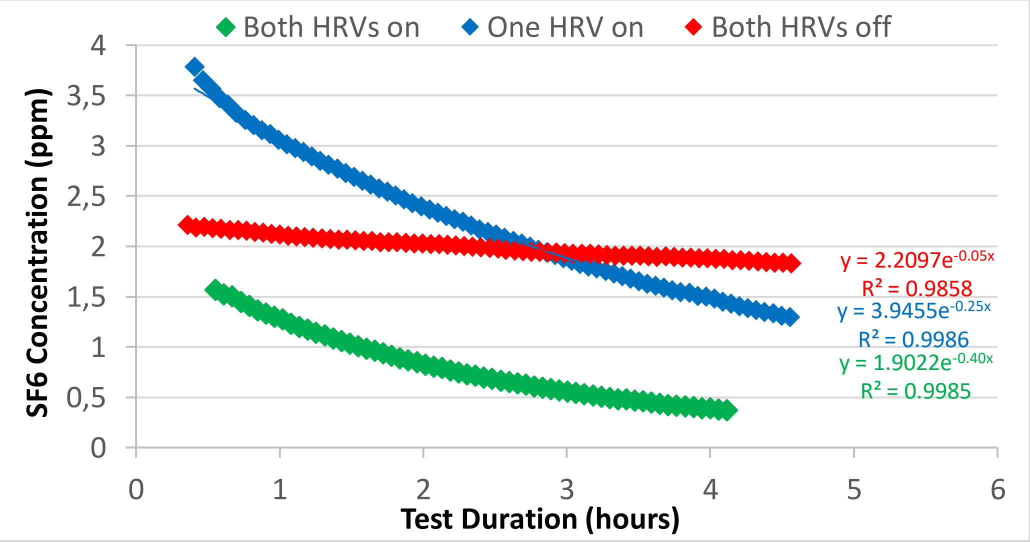

Figure 1: Home #1 tracer gas decay test results for each ventilation strategy

Figure 1 shows the air exchange rates for each ventilation strategy. When one HRV was on, the air exchange rate was 0.25 h^{-1}. When both HRVs were off, the air exchange rate was 0.05 h^{-1}. When both HRVs were on, the air exchange rate was 0.40 h^{-1}.

4.1.2 Radon Monitoring

Short-term radon monitoring was used to evaluate the effectiveness of each ventilation strategy in Home #1. Figure 2 shows the radon concentration measurements in the basement general area during each ventilation strategy on July 11th and 12th, 2017.

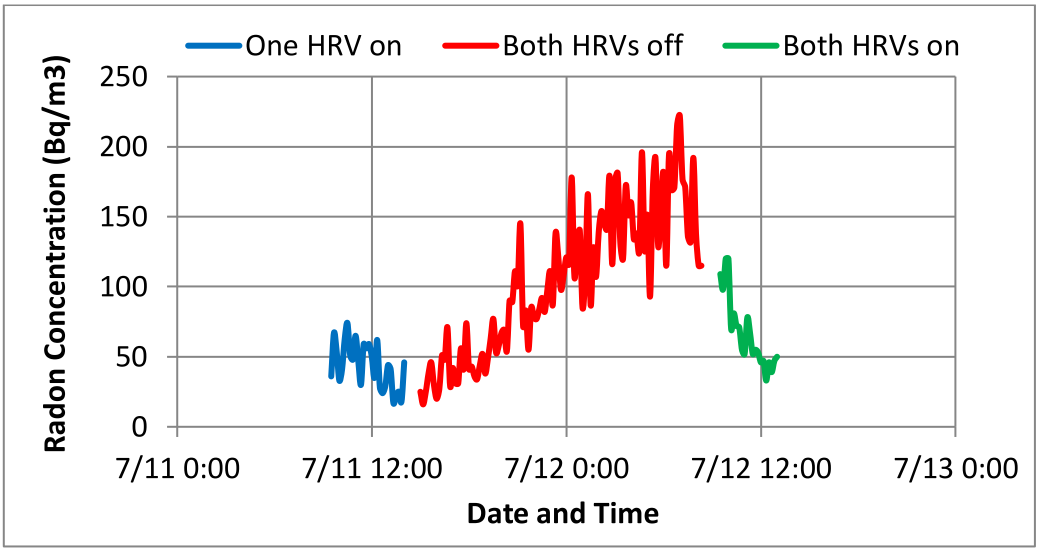

Figure 2: Home #1 short-term radon monitoring results for each ventilation strategy

Initially, the operation of one HRV limited the average radon concentration in the basement to 44 Bq/m^3. Within 15 hours of the HRVs being turned off, the basement radon concentration increased to a peak of 222 Bq/m^3. Within 4 hours of the HRVs being turned on, the basement radon concentration dropped to 33 Bq/m^3.

4.1.3 Summary of Results

Table 4 summarizes the key results obtained from the tracer gas decay tests and short-term radon monitoring within Home #1. Included in Table 4 are the average, maximum, and minimum basement radon concentrations, as well as the air exchange rates for the home, for each ventilation strategy. However, the short duration that each ventilation strategy was implemented should be considered when viewing the average, minimum, and maximum radon concentrations and drawing conclusions related to causality.

Table 4: Home #1 short-term radon monitoring results for each ventilation strategy

Control Strategy	**Average (Bq/m^3) AlphaGUARD**	**Minimum (Bq/m^3) AlphaGUARD**	**Maximum (Bq/m^3) AlphaGUARD**	**ACH (h^{-1})**
Both HRVs off	106	16	222	0.05
1 HRV on	44	17	74	0.24
Both HRVs on	66	33	120	0.40

The two-day study displayed the potential benefits of providing additional ventilation for radon mitigation. When both HRVs were off, the basement radon concentration ranged between 16 and 222 Bq/m^3, with an average concentration of 105 Bq/m^3. When one HRV was on, the basement radon concentration ranged between 17 and 74 Bq/m^3, with an average concentration of 44 Bq/m^3. When both HRVs were on, the basement radon concentration ranged between 33 and 120 Bq/m^3, with an average concentration of 66 Bq/m^3.

4.2 Home #2

A second case study monitored radon concentrations long-term within Home #2. Three ventilation control strategies were implemented: no mechanical ventilation (ERV off), ventilation supply for 20 minutes per hour (ERV 20/60), and constant mechanical ventilation (ERV on). Presented first are the tracer gas decay test results, followed by the long-term radon monitoring results.

4.2.1 Tracer Gas Decay Testing

Performing tracer gas decay tests in the case study home allowed for the determination of ventilation rates when the ERV was off, supplying outdoor air for 20 minutes per hour, and constantly supplying ventilation. Tracer gas samples were taken at six locations in the house and the average concentration was used to approximate the overall ventilation rate of the house. Figure 3 shows the average tracer gas decay and exponential line of best fit for each ventilation strategy.

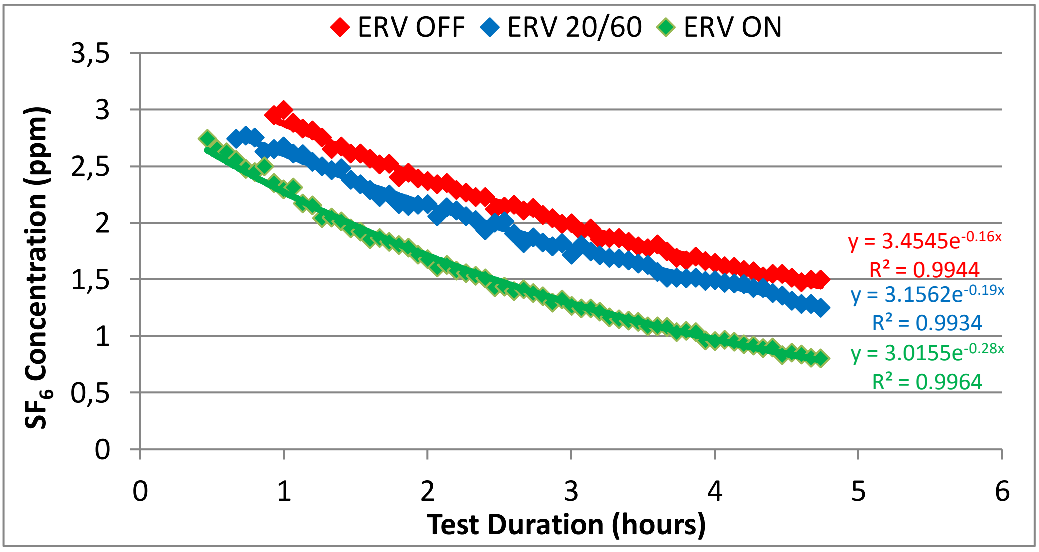

Figure 3: Home #2 tracer gas decay test results for each ventilation strategy

Figure 3 shows the air exchange rates for each control strategy. When the ERV was off, the air exchange rate was 0.16 h^{-1}. When the ERV was supplying outdoor air for 20 minutes per hour, the air exchange rate was 0.19 h^{-1}. When the ERV was on continuously, the air exchange rate was 0.28 h^{-1}.

4.2.2 Radon Monitoring

Long-term radon monitoring was used to evaluate the effectiveness of each ventilation strategy in Home #2. Figure 4 shows the radon concentrations in the basement recreation room during each ventilation strategy between March 6th and May 22nd, 2018.

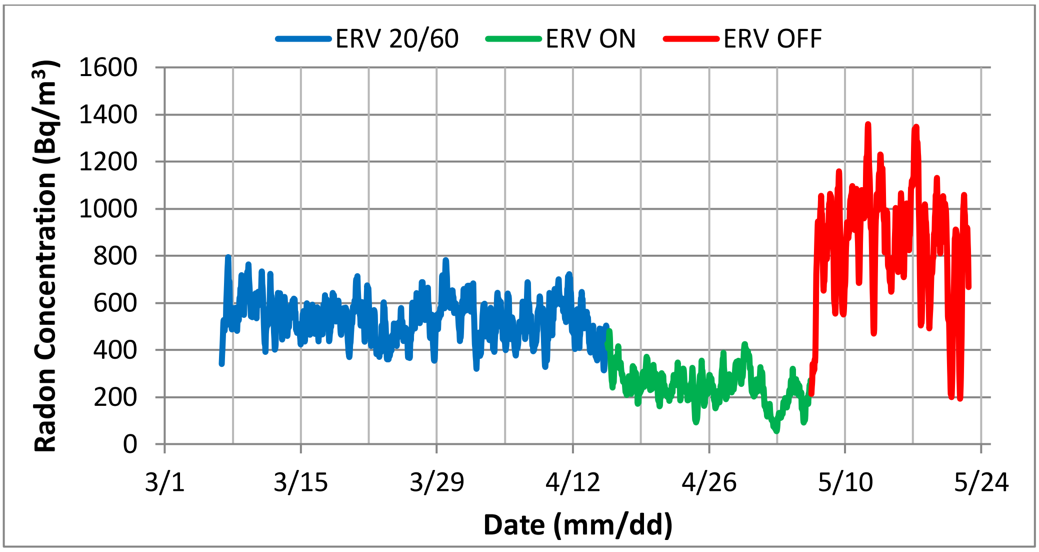

Figure 4: Home #2 long-term radon monitoring results for each ventilation strategy

For the period when the ERV was supplying outdoor air for 20 minutes per hour, the average radon concentration was 537 Bq/m^3. For the period when the ERV was constantly on, the average radon concentration was 242 Bq/m^3. For the period when the ERV was off, the average radon concentration was 872 Bq/m^3.

4.2.3 Summary of Results

Table 5 summarizes the key results obtained from the tracer gas decay tests and long-term radon monitoring. Included in Table 5 are the average, maximum, and minimum basement radon concentrations, as well as the air exchange rates for the home, for each ventilation strategy.

Table 5: Home #2 long-term radon monitoring results for each ventilation strategy

Control Strategy	**Average (Bq/m^3) Corentium**	**Minimum (Bq/m^3) Corentium**	**Maximum (Bq/m^3) Corentium**	**ACH (h^{-1})**
ERV 20/60	537	314	767	0.19
ERV On	242	58	424	0.28
ERV Off	872	193	1359	0.16

Table 5 shows the benefits of increasing the ventilation rate for radon control. When the ERV was off the air exchange rate of home #2 was low, 0.18 h^{-1}. This low air exchange rate resulted in a high average radon concentration, 872 Bq/m^{-3}, and a maximum concentration of 1359 Bq/m^{-3}. However, after increasing the ventilation to the home the measured radon concentrations lowered. Compared to no ventilation, periodic ventilation (ERV 20/60) increased the air exchange rate to 0.19 h^{-1} and decreased the average radon concentration to 537 Bq/m^{-3}, while constant ventilation increased the air exchange rate to 0.28 h^{-1} and decreased the average radon concentration to 242 Bq/m^{-3}

5 DISCUSSION

The first case study home displayed a positive effect of household ventilation for radon control. This provided justification to conduct long-term radon monitoring in a second home. Although it was valuable for the progression of this research, it was a short-term study, which can provide unreliable information, since indoor radon concentrations exhibit large temporal variability. For this reason, the second case study home will be the focus of this discussion, as long-term radon monitoring allows more reliable information to be obtained.

Constantly supplying ventilation with the ERV increased the air exchange rate from 0.16 h^{-1} to 0.28 h^{-1} and reduced the average radon concentration from 872 Bq/m^3 to 242 Bq/m^3. Due to the high initial air exchange rate (0.16 h^{-1}) and radon concentration (872 Bq/m^3) of the home, the ERV was unable to reduce the average radon concentration below the Canadian guideline of 200 Bq/m^3. However, the addition of the ERV did cause the air exchange rate to increase by a factor of almost 2 and reduced the radon concentration by approximately 72%. This shows that ventilation can effectively reduce radon concentrations in homes; however, it implies that when considering ventilation as a radon reduction technique, both the initial radon concentration and the natural ventilation rate of the home should be considered.

The researchers acknowledge the limitations of the conducted research. Due to equipment availability, the tracer gas decay tests were conducted at a different time than the radon monitoring in Home #2, this is a limitation, as the outdoor air temperature affects the air exchange rate of each ventilation strategy. In addition, it is not possible to make concrete conclusions regarding the effectiveness of ventilation for radon control with a small sample of case study homes, one of which consisted of only short-term monitoring. However, this research supports the long-term objective of the research team and lays the foundation for future work.

This research has supported the long-term objective of the research team with regards to ventilation for radon control; to consider both the initial radon concentration and the natural ventilation rate of the home. To accomplish the objective a better understanding of the impacts of building air exchange rate on radon in homes is required. Therefore, future work will focus on long-term radon monitoring in homes having various natural ventilation rates, radon concentrations, and mechanical ventilation strategies.

6 CONCLUSION

In this research, the ventilation rates in two homes were mechanically varied and the corresponding reduction in radon concentration was measured. In the first home, three ventilation strategies were implemented using two HRVs over a two-day span. This case study provided promising results, displaying benefits of ventilation for radon control. However, short-term radon measurements can be unreliable since indoor radon concentrations exhibit large temporal variability. For this reason, an additional case study was performed to evaluate the long-term effects of increasing the overall ventilation rate in homes. In the second home, three ventilation strategies were implemented using an ERV for approximately one month each. The second case study revealed two key findings: 1) studies using a larger number of homes would be beneficial for evaluating ventilation as a solution for radon control and 2) that when considering ventilation as a radon concentration reduction technique, both the initial radon concentration and the natural ventilation rate of the home should be considered. In the future, the research team will conduct long-term radon monitoring in a larger sample of air tight and leaky homes with elevated radon levels to better understand the impacts of building air exchange rates on radon levels in homes.

7 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".

8 REFERENCES

Airthings. 2019. "Corentium Plus - Specification." Retrieved May 30, 2019 (https://www.corentium.ca/ca_en/corentium-plus/).

Akbari, Keramatollah and Robert Oman. 2013. “Impacts of Heat Recovery Ventilators on Energy Savings and Indoor Radon in a Swedish Detached House.” *Management of Environmental Quality: An International Journal* 9(1):682–94.

American Cancer Society. 2015. “Radon and Cancer.”

Chao, C. Y. H. and J. S. Hu. 2004. “Development of a Dual-Mode Demand Control Ventilation Strategy for Indoor Air Quality Control and Energy Saving.” *Building and Environment* 39:385–97.

Health Canada. 2012. *Cross-Canada Survey of Radon Concentrations in Homes Final Report*.

Khan, Selim M., Daniel Krewski, James Gomes, and Raywat Deonandan. 2018. “Radon, an Invisible Killer in Canadian Homes: Perceptions of Ottawa-Gatineau Residents.” *Canadian Journal of Public Health*.

M. Jiranek and V.Kacmarikova. 2014. “Dealing With the Increased Radon Concentration in Thermally Retrofitted Buildings.” 160(1):43–47.

Saphymo. 2012. “AlphaGUARD - Portable Radon Monitor.”

Shammas, Nazih K. and Lawrence K. Wang. 2009. “Shammas 2009.Pdf.” in *Handbook of Advanced Industrial and Hazardous Waste Treatment*.

Socolow, Robert H. and Matesh N. Varma. 1994. *Exposure to Radon and Radon Progeny in the Indoor Environment*.

Turk, B. H., J. Harrison, R. G. Sextro, L. M. Hubbard, K. J. Gadsby, T. G. Matthews, C. S. Dudney, and D. C. Sanchez. 1988. “Evaluation of Radon Reduction Techniques in Fourteen Basement Houses: Preliminary Results.” Pp. 1–22 in *81st Annual Meeting of the Air Pollution Control Association*.

Turk, Bradley H., Richard J. Prill, William J. Fisk, David T. Grimsrud, Bradley H. Turk, Richard J. Prill, William J. Fisk, David T. Grimsrud, Bradley H. Turk, Richard J. Prill, William J. Fisk, David T. Grimsrud, and Richard G. Sextro. 1991. “Effectiveness of Radon Control Techniques in Fifteen Homes Effectiveness of Radon Control Techniques in Fifteen Homes.” *Journal of the Air & Waste Management Association* 723–34.

World Health Organization. 2009. *WHO Handbook on Indoor Radon: A Public Health Perspective*.

World Health Organization. 2016. “Radon and Health.” Retrieved (https://www.who.int/news-room/fact-sheets/detail/radon-and-health).

Zhukovsky, M. V. and A. V. Vasilyev. 2014. “Mechanisms and Sources of Radon Entry in Buildings Constructed with Modern Technologies.” *Radiation Protection Dosimetry* 160(1–3):48–52.