

Effective Interventions to Reduce Indoor Radon Levels



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Introduction

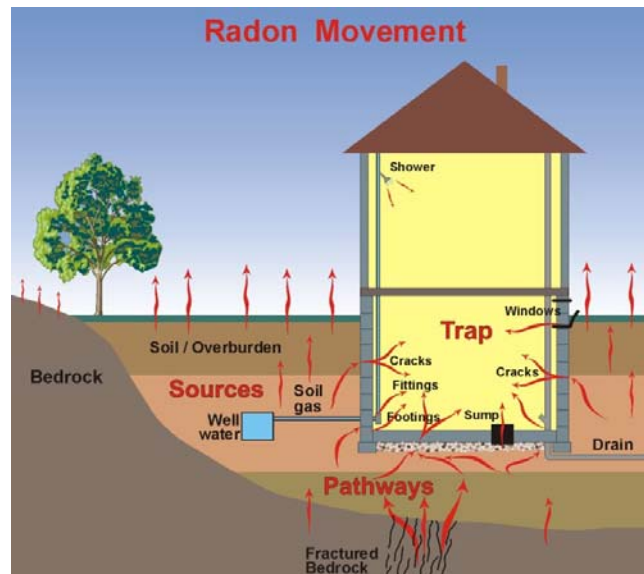
Radon is a naturally occurring gas that is emitted through a radioactive decay chain involving radium (Ra^{226}) and uranium (U^{238}) deposits in soil, rock, and water¹. Radon gas undergoes further radioactive decay to produce products (radon “progeny” or “daughters”), which also emit radiation. These progeny can attach to particles in the air, and when inhaled can deposit onto and irradiate cells lining the lower respiratory tract, thus creating a potential for lung cancer². Even outdoor air contains radon at low concentrations that cannot be reduced^{3,4}.

Radon concentrations vary in Canadian dwellings and are influenced by both geology⁵ and building construction^{3,4}. For dwellings located in areas with moderate to high concentrations of radioactivity in the soils, elevated indoor radon concentrations can result. Radon gas can enter buildings through a variety of routes, including uncovered dirt floors, gaps in floors, cracks in concrete walls, sumps, joints, and basement drains^{3,4,6,7}. Lower areas of a dwelling, including the basement and the main floor, contain the highest radon levels⁸.

The amount of radon within a dwelling is dependent upon a number of factors including the concentration of uranium in underlying soil and rocks and the presence of cracks and leaks in the home or building structure, as well as the air exchange within the dwelling. For this reason, radon concentrations can differ from area-to-area and from building-to-building within the same area, as well as within the same building from season-to-season or day-to-day.

The major route of an individual’s exposure to radon progeny is via inhalation of radon in the air, which accounts for greater than 95% of total exposure⁸. Another 1% of total inhalation exposure can come from radon dissolved in groundwater and released during activities such as showering and cooking⁸. The chance of this type of exposure increases if you use well water. Inhalation, rather than ingestion of radon progeny released from water, accounts for the majority of water-related radon exposure. Radon from building materials does not typically represent a significant source of exposure^{3,4,6,7}. Figure 1 summarizes the different ways that radon can enter a building.

Figure 1. Typical radon sources and entry routes into buildings, including homes⁶



Radon reduction interventions

Common radon remediation measures used for existing homes include sub-slab depressurization, sump-hole depressurization, sub-membrane depressurization, block wall suction, and passive and active ventilation, as well as sealing^{3,4,6,7,9-12}. Dwelling radon remediation studies undertaken, intervention types and results are outlined in Appendix A. These remediation strategies and relative effectiveness are summarized in Table 1. Sub-slab depressurization has been shown to be an extremely effective method of lowering indoor radon levels, with reductions greater than 80%^{3,4}. While active and passive ventilation may be useful in the summer, the use of fans, air conditioning, and open windows may not be practical during winter months. Additionally, in order for sealing to be effective, it must be ensured that all radon entry points are completely sealed, which is difficult to achieve. For this reason, sealing is recommended to be used in combination with other remedial measures¹³. In the case of large buildings or of dwellings having high radon levels, combination remediation strategies have been found to be more effective than single measures^{14,15}.

Table 1. Possible radon remediation strategies for existing homes with radon levels above the current Canadian guideline (200 Bq/m³), together with relative effectiveness.*

Strategy	Method of radon remediation	Relative Effectiveness
Depressurization		
Sub-slab depressurization	Polyvinyl chloride vent pipe(s) are inserted into the soil about 10 inches (25 cm) below the foundation. They extend outdoors where the radon-containing air is exhausted ^{14,16-20} . An exhaust fan located in the garage, outdoors, or in the attic, is used to draw air through the pipes.	Most effective
Sump depressurization	A variation of sub-slab depressurization, where the sump pump (which is used to drain water) is capped and serves as a vent pipe attachment location ^{18,20-26} .	
Sub-membrane depressurization	A high density plastic sheet or 'barrier membrane' (generally polyethylene) is used to cover the dirt floor of the crawl space and is sealed to the concrete foundation walls, thus preventing radon from entering the building. A vent pipe is installed through the plastic sheet, and radon-containing air is drawn through the pipe by an exhaust fan. The pipe extends outdoors where the radon-containing air is exhausted ^{20,27-29} .	
Block wall suction	A variation of sub-slab depressurization ²⁷ .	
Ventilation		
Active ventilation	Indoor-outdoor air exchange is increased or pressure differentials within the building are created via active ventilation (fans, air conditioning, or heat recovery ventilators) ^{13,20,30-32} .	Moderately effective
Passive ventilation	Indoor-outdoor air exchange is increased by the opening of windows and doors within the building ^{16,19,20} .	Less effective
Other		
Sealing (alone)	Physical sealing (e.g. caulking) of radon entry points in floors and walls of the home ^{13,18,20} .	Least effective

*Note: See Appendix A for summaries of and references to detailed remediation studies

For new homes and buildings, radon prevention strategies can be undertaken during construction to reduce residents' exposure to radon. New home radon prevention studies undertaken, intervention types and results are outlined in Appendix 2. These approaches include^{12,26,33,34,35}

- reducing radon entry points into the home or building, through installation of a polyethylene barrier membrane in the foundation, installation of traps in floor drains, and minimization of cracks in concrete materials
- construction of a block and beam supported concrete floor that allows for passive underfloor ventilation,
- reducing forces which draw radon-containing air into homes, through installation of fresh air and combustion air ducts, and/or
- putting in place provisions for an active soil depressurization system, through installation of polyvinyl chloride pipe in the floor slab onto which an exhaust pipe can be attached, if needed.

Barrier membranes and block and beam supported concrete floors have each been found to decrease radon levels by up to 50%. Used in combination, they have been found to decrease radon levels by up to 75%.^{28,35}

There is extensive literature supporting the cost-effectiveness of radon abatement compared with other healthcare and environmental interventions³⁶. For existing homes with radon levels above the action level, remediation measures can cost anywhere from a few hundred to a few thousand dollars^{3,4}. For new homes, radon prevention measures cost an estimated \$500-700^{15,33}. For more detailed descriptions of reduction methods in existing homes and preventive measures in new homes, see the Canadian Mortgage and Housing Corporation's Guide for Canadian Homeowners – Radon³⁶ and the British Research Establishment guide to radon remedial measures in existing dwellings¹¹.

Summary

- Radon represents one of the environmental exposures that can be reduced with effective and practical solutions, reducing an individual's risk of developing lung cancer^{1,3,4}.
- There is extensive literature supporting the cost-effectiveness of radon abatement compared with other healthcare and environmental interventions².
- Of the remediation measures evaluated to reduce indoor radon levels in already built homes, active systems were found to be better than passive ones^{12,14,19,20,32,37}.
 - Depressurization methods were the most effective remediation measures^{12,14,18,21,30,37}.
 - Active ventilation measures were the next most effective; passive ventilation was less successful^{12,14,18,21}.
 - Sealing (alone) was found to be the least effective method^{12,18,25,37}.
- In the case large buildings or of dwellings having high radon levels, combination remediation strategies have been found to be more effective than single measures^{14,15}.
- In new home construction both barrier membranes and block and beam construction have been demonstrated to be effective in reducing indoor radon levels to below the current Canadian guideline action level (200 Bq/m³)^{28,35}.
 - Barrier membranes have been found to reduce indoor radon levels by up to 50%.³⁵
 - Block and beam construction have been found to reduce indoor radon levels by up to 50%.³⁵
 - Barrier membranes used together with block and beam construction combine to reduce indoor radon levels by substantially greater amounts³⁵.

Appendix A: Summary of radon remediation studies undertaken, intervention types and results.

Principal author	Location	Monitoring Methodology	Intervention Type	Results
Depressurization (Sub-slab, sump and sub-membrane)				
Groves-Kirkby (2008) ³⁰	170 UK homes underwent radon remediation between 1993 and 2004.	<p>Main bedroom and living areas were monitored for radon for 3 month periods pre and post remediation, using track-etch detectors.</p> <p>Before remediation, mean radon concentrations were 487.6 Bq/m³.</p>	Sump depressurization (sub-slab depressurization utilizing conventional sump/pump technology).	<p>Post remediation mean radon concentrations were 64.6 Bq/m³.</p> <p>100% of the homes returned post remediation mean annual radon concentrations below the UK domestic Action Level of 200 Bq/m³.[†]</p> <p>More than 75% had radon 'reduction factors'[‡] (the ratio of pre to post remediation radon concentrations) >10.</p>
Synnott (2006) ¹⁴	Study of 375 classrooms in 93 schools in Ireland between 2000 and 2002.	<p>Radon measurements were carried out using CR-39 alpha track-etch detectors. Initial measurements were carried out for one full academic year (≈9 months).</p> <p>Post-remediation measurements included concurrent 3 months and 9 month measurements.</p> <p>Subsequent post-remediation measurements were carried out for 3 months in 24 schools three years after remediation.</p> <p>Of the schools chosen for remediation, 108 had mean pre remediation radon levels of 200-400 Bq/m³, 195 had levels between 400-1000 Bq/m³, and 72 had levels >1000 Bq/m³.</p>	<p>Methods chosen depended on initial radon levels, and included:</p> <ul style="list-style-type: none"> • Active under-floor ventilation (in some cases together with other methods) • Radon sump (in some cases together with other methods) • Increased background ventilation. This was only used on rooms having pre remediation radon levels of between 200 and 400 Bq/m³. 	<p>Post-remediation levels:</p> <ul style="list-style-type: none"> • All rooms remediated by active under-floor ventilation had post remediation radon levels of <200 Bq/m³. • 303 of 314 rooms (96.5%) remediated using radon sumps had levels <200 Bq/m³. • 147 of 175 rooms (84%) remediated by passive ventilation had levels <200 Bq/m³. <p>All methods of remediation were successful in reducing radon concentrations.</p> <p>Active systems, such as sumps, were found to be most effective in terms of mean radon reduction factors achieved. Fan-assisted under-floor ventilation was also very effective. Both achieved greater radon reductions than passive systems such as window or wall vents.</p>

Principal author	Location	Monitoring Methodology	Intervention Type	Results
Colgan (2004) ²¹	Study of radon levels in all ground floor offices and classrooms in 3,444 schools in Ireland, and remediation at 208 schools.	Pre-remediation radon measurements were carried out for 9 consecutive months. Cr-39 alpha track etch detectors were used. Remediation of 208 schools was subsequently carried out. Radon measurements were repeated post remediation.	In 100 schools having a mean 3 month pre remediation radon level of 392 Bq/m ³ , remediation involved the installation of an active sump. In 108 schools having a mean 3 month pre remediation radon level of 272 Bq/m ³ , remediation involved increasing ventilation.	Installation of sump pumps resulted in an average reduction of 82% to a mean of 71 Bq/m ³ . Increased ventilation resulted in a reduction of 47% to a mean of 143 Bq/m ³ .
Denman (2004) ²⁴	Eight National Health Services premises in Northamptonshire, UK.	Radon measurements were made for at least three months, both pre and post remediation. Alpha track etch detectors were used. Pre remediation radon levels ranged from 420 to 2870 Bq/m ³ , and the mean was 1219 Bq/m ³ .	Sump fitted with a fan was used to extract radon rich air and expel it to the atmosphere (e.g. 'sump extract fans').	In all cases remediation reduced the radon level to below the UK workplace radon Action Level of 400 Bq/m ³ . [†] The working hours mean radon reduction factor (10.2 ±10.5) was lower than the 24 hour mean radon reduction factor (13.8 ±14.7).
Coskeran (2002) ²²	110 homes in five regions of the UK between 1993 and 2000.	Radon measurements were taken pre and post remediation. Pre remediation mean radon levels were above the action level [†] in all regions. Overall average mean pre remediation radon level was 455 Bq/m ³ and the range was 180-1500 Bq/m ³ .	Sump fitted with a fan was used to extract radon rich air and expel it to the atmosphere (e.g. 'sump extract fans').	Post remediation, all house radon levels were below 200 Bq/m ³ . [†] The post remediation mean radon level was ≈54 Bq/m ³ and the mean reduction in radon levels was 400.0 Bq/m ³ .
Denman (2002) ²³	77 homes in Northamptonshire, UK. Cost effectiveness of different action levels were considered.	Radon levels were measured using etched track detectors for three month periods pre and post remediation.	Sump and pump method.	Post remediation average radon levels were well below 200 Bq/m ³ . [†]

Principal author	Location	Monitoring Methodology	Intervention Type	Results
Arvela (2001) ¹⁸	Study of radon levels in blocks of flats in Finland. The number in which remediation took place was not specified.	Testing of 900 flats found the average indoor radon levels in ground level flats to be 150 Bq/m ³ . In >10% of these the level exceeded 400 Bq/m ³ .	Study examined the reliability of: <ul style="list-style-type: none"> • radon wells • sub-slab depressurization • sealing entry routes and • installation of fresh air vents 	The best mitigation results were achieved using sub-slab depressurization and radon wells with radon reductions being 50-80%. Sealing entry routes resulted in radon reductions of 30-60% and the installation of fresh air vents led to radon reductions of approximately 50%.
Howarth (2001) ²⁵	Fifty six UK homes.	Radon measurements were made pre and post remediation, and annually thereafter for 6 years. All measurements were carried out using alpha track edge detectors for three months periods.	Study examined the reliability of: <ul style="list-style-type: none"> • sump • positive ventilation • mechanical underfloor ventilation • natural underfloor ventilation • sealing 	The mean percentage reduction achieved was highest with sump at 94.85%. The lowest reduction was seen with sealing at 59.4%.
Maringer (2001) ¹⁸	Three houses in Austria.	Pre and post remediation radon measurements were undertaken. One room of each house underwent 2-3 weeks of continuous monitoring using an Alpha-Guard ionization chamber, while other rooms were monitored using electrets or charcoal detectors. These results were combined to obtain radon concentrations. Pre remediation average indoor radon activity concentrations were: <ul style="list-style-type: none"> • Two family house: 500 Bq/m³. • Farm house: 900 Bq/m³. • Single family house: 600 Bq/m³. 	Study examined the reliability of: <ul style="list-style-type: none"> • Sub-floor depressurization in the two family house. • Sub-house depressurization in the farm house. • Passive sub-floor ventilation in the single family home. 	The post remediation average indoor radon activity concentrations were: <ul style="list-style-type: none"> • Two family house: 50 Bq/m³. • Farm house: 180 Bq/m³. • Single family house: 360 Bq/m³. All three mitigation methods resulted in decreases in radon levels. Active sub floor depressurization was the most successful, achieving a radon reduction factor of 10, [‡] while the fan was in operation. Passive sub-floor ventilation was the least successful method, with a reduction factor of 5. [‡]

Principal author	Location	Monitoring Methodology	Intervention Type	Results
Naismith (1998) ¹³	943 UK homes.	Radon levels were measured for 3 months pre remediation. Homeowners then arranged remediation, and radon levels were measured for 3 months post remediation. The geometric mean (GM) of pre remediation radon levels of groups of homes ranged from 370 to 630 Bq/m ³ .	Study examined the reliability of: <ul style="list-style-type: none"> • Subfloor depressurization • Positive ventilation (active) • Permanent natural ventilation (installed vents) • Active and passive underfloor ventilation • Sealing floors 	Subfloor depressurization was the most effective remedial measure, achieving GM radon reduction factors of 4 to 17 (as a function of house type and method of installation). Natural ventilation and sealing were the least effective measures, with GM reduction factors of 1.9 and 1.7, respectively.
Ennemoser (1995) ²⁷	Four homes in Austria.	Homes had been found to have indoor radon levels of up to 270 000 Bq/m ³ . Radon concentrations in the air were measured monthly for 1 year prior to mitigation. Three charcoal liquid scintillation detectors were used at each site and the duration of measurements was nominally 48 hours. In parallel with this, measurements were made using one alpha-track detector per site. Measurement time was a function of the expected radon levels, and ranged between 2 days and 3 weeks.	Study examined the reliability of: <ul style="list-style-type: none"> • Basement sealing • Sub-slab soil depressurization • A basement mechanical ventilation system with heat exchanger 	The most successful remediation technique was sub-slab soil depressurization using fans and drainage tubes. Basement radon levels in winter were reduced by a factor of 200 (e.g. from 100 000 to 500 Bq/m ³) and ground floor levels by a factor of 400. The mechanical ventilation system with heat exchanger could reduce radon levels from 200 000 to 2000-3000 Bq/m ³ . Basement sealing was found to be unsuccessful.
Ventilation (Passive and Active)				
Marley (2001) ³¹	Four workplaces in Northamptonshire, UK.	Average levels of radon and progeny were measured using track-etched passive detectors. Radon progeny levels were measured using a Thompson and Nielson radon working level (WL) meter. Radon measurements were taken	Mechanical systems affecting indoor air were examined: <ul style="list-style-type: none"> • Air conditioning (AC, 2 sites) • 'wet' central heating without air conditioning (2 sites) 	The reduction factors of radon and progeny ranged from 4 to 6 (radon being reduced from ca. 35-40 Bq/m ³ when the air conditioning was off to ca. 5-7 Bq/m ³ with the air conditioning on). 'Wet' central heating reduced radon levels by initiating change in advective gas flow.

Principal author	Location	Monitoring Methodology	Intervention Type	Results
		for 4 week periods at 3 locations and for 4 months at 1 location.		This occurred more gradually and less effectively than with AC.
Wang (1997) ³²	One occupied Northern England single family dwelling with a cellar.	Air radon measurements and air change rates were measured. Radon concentrations were measured using a continuous radon monitor. In the cellar the radon level was measured hourly for each of the 2-3 day periods that each ventilation method was employed. At the end of each interval the levels were also measured in the 4 bedrooms, as well as the living room, hallway and lounge, for 40-60 minute periods.	Substructure ventilation was studied using three different approaches, consecutively: <ul style="list-style-type: none"> • natural ventilation • extract (exhaust) ventilation and • supply ventilation. 	Natural ventilation was not efficient in reducing radon levels. Both extract ventilation and supply ventilation were deemed effective. Under conditions of low air change rates, extract ventilation was found to be more effective than supply ventilation.

[†]In the UK and Ireland the domestic dwelling radon Action Level is 200 Bq/m³ and the workplace radon Action Level is 400 Bq/m³. In the U.S. the radon action level for housing is 148 Bq/m³.²

[‡]The radon 'reduction factor' used in Appendices 1 and 2 is defined as the ratio of pre to post remediation radon concentrations. In some papers radon reduction factors were not stated, or were defined differently, but the data required to calculate them was provided. In these cases (designated by [‡]) we have calculated the radon reduction factors as defined above.

Appendix B: Summary of radon prevention studies in new homes, intervention types and results.

Principal author	Location	Monitoring Methodology	Intervention Type	Results
Barrier Membranes and Block and Beam floors				
Groves-Kirkby (2006) ²⁶	Study of radon reduction measures during construction of 64 new houses in Northamptonshire, UK. Results were compared with a study of post construction	During construction radon reduction measures were employed. Radon levels were measured after installation of protective measures. Main bedroom and living areas were monitored for radon for 3 month periods using track-etch detectors.	Radon barrier membrane.	Radon-barrier membrane installation during construction was found to provide some protection against radon ingress. Mean radon level after construction completion was 59.7 Bq/m ³ . However, it was estimated that installation of a barrier membrane had resulted in reduction of the mean annual radon concentration to below the Action Level [†] in

Principal author	Location	Monitoring Methodology	Intervention Type	Results
	remediation of houses (Denman, 2002 – see Appendix A) ²³			<p>only 40% of these houses.</p> <p>The post-construction remediation study (Denman, 2002)²³ found that more than 75% of the homes exhibited radon reduction levels of 10 or higher[†]. For the during construction homes, radon reduction factors were calculated using average mean radon levels for 1300 unremediated homes in the same postal code area. The result was a bimodal distribution of radon reduction factors, with approximately equal maxima of 3.33 and 2.[†]</p>
Scivyer (2001) ²⁸	Study comparing radon levels in 245 unprotected houses and 220 protected homes having passive radon barrier membranes in the UK.	<p>Radon levels were measured in unprotected houses (i.e. those having no barrier membrane) in affected areas as well as after installation of protective measures in new housing.</p> <p>Comparisons were made of 245 unprotected houses constructed prior to 1992, and 131 protected houses constructed in 1990-91 and another 89 in 1993-94.</p>	<p>A suspended block and beam concrete floor or an in-situ ground bearing concrete floor slab together with a radon barrier membrane made of 1200 gauge polyethylene was used to protect floors, and a cavity tray was used to protect walls. In higher risk areas, the membrane barrier was supplemented with natural underfloor ventilation.</p> <p>If elevated radon levels were found in the completed house, remediation involved fan assisted sump technology.</p>	<p>Protective measures were found to improve as they became more routinely installed.</p> <p>Unprotected houses having in-situ concrete floors had an average indoor radon level of 167 Bq/m³, and those having suspended beam and block floors had average levels of 78 Bq/m³.</p> <p>In 1994, the protected houses having in-situ concrete floors had an average indoor radon level of 68 Bq/m³, and those having suspended block and beam floors had average levels of 21 Bq/m³.</p> <p>In unprotected houses constructed with an in situ concrete floor, 20% had radon levels above the Action Level (200 Bq/m³)[†] and in those with block and beam floors, 18% were above the Action Level.[†]</p> <p>In the protected houses constructed with an in situ concrete floor, only 4% exceeded the Action Level in 1991 and 0% in 1994. In those built with block and beam floors, 0% exceeded the Action Level in either year.</p>

Principal author	Location	Monitoring Methodology	Intervention Type	Results
Woolliscroft (1994) ³⁵	Study comparing new house construction procedures in Devon and Cornwall, England. This involved 136 houses in 1989/90 and a further 287 houses in 1990/91.	<p>The main analysis involved 416 dwellings, of which 295 were in medium radon areas (where, with no prevention measures, 10-30% of houses would be expected to be above the Action Level) and 121 in high radon areas (where >30% would be expected to be above the Action Level).</p> <p>Radon measurements were carried out using alpha etched track detectors over three month periods in the winter of 1990-91. Detectors were placed in the living room and main bedroom. Results were seasonally corrected.</p>	<p>Four construction and protection procedures were compared:</p> <ul style="list-style-type: none"> • Block and beam floor with barrier membrane (2 houses in high radon area and 104 in medium radon area) • Block and beam floor without barrier membrane (38 houses in medium radon area) • <i>In situ</i> concrete with barrier membrane (49 houses in high radon area and 65 in medium radon area) • <i>In situ</i> concrete without barrier membrane (70 houses in high radon area and 88 in medium radon area) <p>The block and beam floor effect is essentially a ventilation effect.</p>	<p>The resulting mean annual indoor radon levels for these construction and protection approaches were:</p> <ul style="list-style-type: none"> • Block and beam floor with barrier membrane → 47 Bq/m³ • Block and beam floor without barrier membrane → 103 Bq/m³ • <i>In situ</i> concrete with barrier membrane → 87 Bq/m³ • <i>In situ</i> concrete without barrier membrane → 194 Bq/m³ <p>The significance level of the type of construction was found to be 5%, whereas that of the protection measure used (i.e. the presence or absence of a membrane) was greater than the 0.1% level.</p> <p>Both the use of a membrane and the block and beam floor (underfloor ventilation effect) roughly halved the indoor radon levels. In combination, they reduced the indoor radon levels by a factor of roughly 4.</p>

Useful Resources

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