RADON CONTROL IN NEW HOMES:
A META-ANALYSIS OF 25 YEARS OF RESEARCH

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Abstract

Without effective radon control in new homes, national radon programs will fail to achieve risk-reduction goals. While there has been research and demonstration projects focusing on radon control in new low-rise residential houses over the past 25 years, the individual investigations have been limited in scope. This paper presents a meta-analysis of research on residential radon-control strategies, common problems with these strategies, and the relative efficacy on radon-control strategies in new homes. The conclusions of this analysis include passive soil depressurization (PSD), installed according to recognized standards and guidance, appear to produce about a 50-percent indoor radon reduction. A significant share of PSD systems are not installed according to generally accepted standards or guidance. Active soil depressurization (ASD) produces greater indoor radon reduction than PSD. Further research is needed to clarify the efficacy of passive barriers in new construction.

Keywords: radon, radon control, radon prevention, new homes, building codes, standards

Introduction

In this paper, radon concentrations are expressed, where possible, in both international units, becquerels per cubic meter (Bq m^{-3}), and in the unit used in the United States and the Republic of Korea, picocuries per liter (pCi/L).

Importance of Radon Control in New Residential Construction

Radon risk reduction is dependent on both mitigation of elevated radon in existing housing and radon control in the construction of new housing. Criticism of the lack of progress in the U.S. Environmental Protection Agency's radon program was, in large part, the failure to achieve effective radon control in new U.S. housing (Angell, 2008).

Alastair Gray, an Oxford University health economist, contributed a framework to the *WHO Handbook on Indoor Radon: A Public Health Perspective* (WHO, 2009). The framework was designed to assist countries to compare the cost and effectiveness of investing limited resources into a program emphasizing radon testing and mitigation of existing houses or a program emphasizing radon control in the construction of new dwellings. Gray presented a case study of areas in the United Kingdom where five percent or more of the houses exceeded an action level of 200 Bq m^{-3} and demonstrated that it was more cost-effective, from a population-based risk-reduction perspective, to emphasize radon control in new houses compared to mitigation. The dominant strategy for radon control in new construction involves only a passive membrane or air barrier; whereas, in the U.S., the primary control strategy for new houses emphasizes passive soil depressurization (PSD) as well as slab sealing. These and similar differences raise questions about the scientific foundation to determine the cost-effectiveness of different strategies for radon control in new houses.

Persistent Issues and Limitations with Assessing New House Radon Control Techniques

There are a number of fundamental issues and limitations of research into the efficacy of radon-control techniques overall as well as individual techniques. First, the significance of post-construction radon test results is open to question since there can be no preconstruction indoor radon measurements (Murane, 1988; National Association of Home Builders, 1991). Due to this problem, some investigators used a cross-sectional approach, comparing post-construction measurements in houses with radon-control features with those made in other new houses built without radon-control features (Murane, 1988) . There are serious validity issues with cross-sectional comparison; e.g., different house sizes, designs, and construction details.

Another approach to studies of PSD and active soil depressurization (ASD) radon-control strategies has involved pre- and post-PSD or ASD activation. This approach relies upon radon measurements conducted during different time periods, which introduces uncertainty in the comparison, especially if the measurements were made in different seasons or weather conditions.

A third challenge with assessing the efficacy of radon-control practices in new houses is “(t)here is … no method for precisely determining which single or combination of construction features contribute to the low radon levels” (Murane, 1988).

A further challenge is the question of how representative short-term measurements may be of annual radon concentration averages. To reduce the likelihood of a false negative, U.S. EPA (1999) recommends: winter short-term testing; and long-term follow-up measurements. With the exception of research in Finland and the United Kingdom, no studies reported long-term radon measurements.

Another issue involves post-construction assessments of the radon-control systems when not all elements of the system may be accessible for inspection; e.g., completion of subslab permeable layer, cold joints that may be hidden by finished assemblies.

Finally, many of the attempts to measure the performance of pre- and post-radon-control techniques were measuring relatively small concentrations of radon, and thus the precision of measurements is open to question. In addition, the limited numbers of houses in most studies limit the foundation to generalize the findings beyond that of the individual analysis.

Guidance Documents, Standards, and Building Codes

United States

U.S. guidance for radon control in new housing reflects a mix of EPA program office and research office publications, national voluntary consensus-based standards, EPA building code recommendations, and finally, national model building code appendices.

U.S. EPA (1987) was the first U.S. guidance document on radon control in new houses and it cites the involvement of the National Association of Home Builders Research Foundation. The ten-page guide presents three recommendations: 1) minimize soil gas entry pathways (e.g.: an overlapped, sealed 6-mil polyethylene subslab or crawlspace vapor retarder; sealed slab penetrations and joints); 2) maintenance of neutral pressure across the slab (e.g.: 4 inches of clean subslab aggregate with a perforated loop of drain tile and a passive stack); and 3) features that make it is easier for further radon reduction. The guide states, "Experience has shown that in homes with higher radon levels---above 20 pCi/L (740 Bq m^{-3})---convection (passive) venting may not produce acceptable radon reductions." EPA (1987) established the basic U.S. radon-control techniques for new residential construction through the present. U.S. EPA (2001) expanded on the 1987 guidance.

ASTM (1990), *Emergency Standard Guide for Radon Control Options for the Design and Construction of New Low Rise Residential Buildings*, represented the first volunteer consensus standard in the field. The standard was replaced by ASTM (1992) which specified two radon-control options: a passive or active (fan-powered) vent pipe as well as a subslab gas permeable layer and radon entry pathway reduction.

Clarkin and Brennan (1991), *Radon-resistant Construction Techniques for New Residential Construction*, was published by EPA's Office of Research and Development and it expanded on EPA (1987) with considerable detail. The 1991 publication provides an excellent summary of applied research on radon control in new housing coupled with builder guidance. Major parts of the Clarkin and Brennan document were soil depressurization, passive mechanical barriers, site evaluation and planned house ventilation.

Cummings (1992a) describes the opinions of a Florida heating, ventilation and air conditioning (HVAC) committee on prescriptive, performance, and marketplaces approaches for the HVAC section of the Florida Code for Radon-Resistant Construction and Mitigation.

U.S. EPA (1994), *Model Standards and Techniques for Radon Control in New Residential Buildings*, was published in direct response to Section 304 of Title III of the Toxic Substances Control Act (TSCA), 15 U.S.C. 2664, the Indoor Radon Abatement Act (IRAA) of 1988. The model standards were intended for adoption by U.S. building code organizations. The standards incorporated elements from Clarkin and Brennan (1991) and ASTM (1992).

The Council of American Building Officials' (1995) *One and Two Family Dwelling Code* was the first U.S. model building code to incorporate voluntary Appendix F for passive radon control in new residential construction. The emphasis of the CABO code was on PSD with a sealed subslab or crawlspace membrane with a permeable subslab material. The 1995 CABO code was revised in 1998 with a version published by the International Code Council (ICC) and later incorporated in ICC's (2000) *International Residential Code for One and Two Family Dwellings*.

EPA (1999) established a recommended protocol on how to measure the effectiveness of passive radon-resistant new construction. The protocol was intended to guide research by public officials and investigators and was based on the work of Lafollette and Dickey (2001) and the National Association of Home Builders Research Foundation (1991, 1996).

International

New construction guidance and building regulations are found in a number of countries such as Finland, Sweden, and the United Kingdom.

The National Building Code of Finland (Ministry of the Environment, 2003) contains provisions for radon control including installation of polyester-reinforced bitumen felt membrane strips at the perimeter slab cold joint, subslab radon pipes, and sealed slab penetrations.

Clavensjö and Åkerblom (1994) describe preventive radon measures in the design and construction of new Swedish housing. The preventive measures call for "radon-protecting design" in "normal-radon ground (10,000 to 50,000 Bq m^{-3} in the soil [270 to 1350 pCi/L])" and "radon-proof design" in "high-radon ground" (greater than 50,000 Bq m^{-3} [1350 pCi/L] in the soil). The radon-proof level of design involves passive sealing of potential radon entry routes as well as further air sealing and mechanical (fan) ventilation of crawlspaces and subslab aggregate.

Similar to the Swedish dual-tier new construction measures, Roserens, *et al.* (2000) describes the Swiss' "standard radon protection" and "additional measures for increased radon prevention." The standard techniques include sealing soil-contacted foundation surfaces including membranes and, when increased prevention is needed, progress to passive and active soil depressurization and additional house ventilation.

In the United Kingdom, the Building Research Establishment (BRE) (1999a, 1999b) offers guidance focused on two levels of radon protection: first, a complete subslab with a sealed, damp-proof membrane separating the indoors from the soil ("basic radon protection"); and second, in high radon areas, "full radon protection" consisting of ventilation of crawlspace or subslab via a passive or active radon stack. Before concern about radon, the sealed membrane was required by the Building Regulations but with radon concerns, extended membrane coverage through exterior wall cavities was added (similar to Figure 1).

Arvela, *et al.* (2008) described radon prevention and mitigation guidance in Finland. There are two techniques that differ from radon-control approaches in the U.S. In Finland, radon wells are used in areas with very permeable soils where airflows through the soil are too large for standard radon pipe diameters and standard radon fans. Another technique involves the use of a perimeter, sealed bitumen strip membrane as illustrated in Figure 1. By contrast, U.S. standards, guidance and model building codes for radon control in new houses emphasize a complete membrane

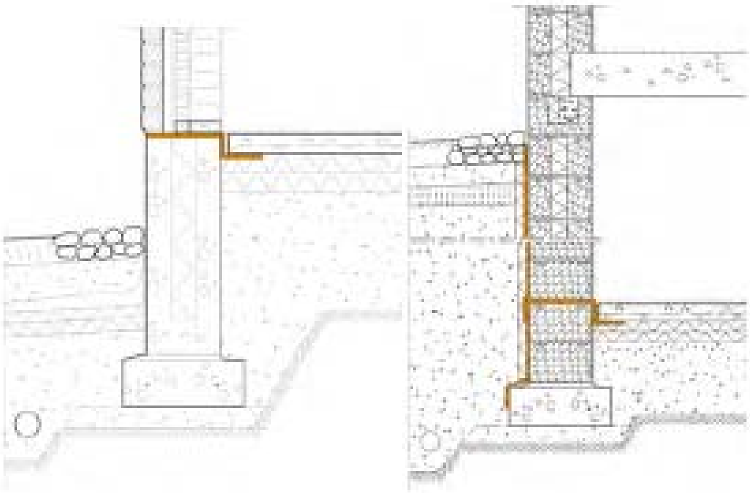

Figure 1. Sealed Bitumen Felt Strip Membrane

between the concrete floor slab and the underlying permeable layer. The bitumen strip membrane seams, penetrations, and corners are sealed by heating the bitumen and use of bitumen glue.

Methods

This analysis focused largely on North American research on radon-control techniques in the construction of new low-rise detached and attached single-family houses. The investigation also included several European research papers or reports of significance. The literature search centered on peer-reviewed papers in scholarly journals and conference proceedings including papers in the U.S. Environmental Protection Agency's (EPA) 1988-1992 International Symposium on Radon and Radon Reduction Technology proceedings, the American Association of Radon Scientists and Technologists' International Radon Symposium proceedings, EPA research reports as well as guidance documents, *Health Physics, Journal of Air & Waste Management Association*, and *Radiation Protection Dosimetry*. The search also included National Association of Home Builders Research Center research reports, government reports and, in some cases, unpublished reports.

Some research projects may be found in multiple publications. In these cases, only one of these papers or reports is cited in this analysis.

Each major paper was reviewed and summarized by the major topical areas in Table 1.

Discussion of results

The literature reviewed in this analysis includes papers and documents published between 1987 and 2012. Two of the pivotal documents were a paper by Murane (1988) describing EPA's New

House Evaluation program and an EPA (1999) guidance document or protocol on measuring the effectiveness of PSD systems.

Murane (1988) presented the first U.S Environmental Protection Agency (EPA) accounting on field-based radon-control techniques in new low-rise residential structures including radon-related construction details and limited radon measurement results with 148 houses built by five builders in Colorado and Michigan. The vast majority of the houses were built with passive sealing or isolating techniques with the average post-construction radon concentrations of the largest group (128) of houses being 192 Bq m^{-3} (5.2 pCi/L). One builder used two different sets of radon-control techniques: Method A in 101 houses involving a sealing and isolating approach; and Method B in 19 houses with a complete subslab membrane that extended between the foundation footing and wall as well as with a sealing and isolating approach. Unfortunately, radon measurements in the two sets of houses were made in different seasons, and thus comparisons cannot be made without resolving seasonal measurement bias.

The EPA (1999) passive radon-resistant effectiveness protocol established a standard for subsequent assessments of PSD as a radon-control technique in new houses. The standard calls for:

- Houses to be built to one of three similar sets of requirements:
    - *Model Standards and Techniques for Control of Radon in New Residential Buildings* (EPA, 1994);
    - *One and Two Family Dwelling Code* (Council of American Building Officials, 1995); or
    - *International Residential Code for One and Two Family Dwellings* (International Code Commission, 2000)
- Radon testing during the heating season
- QA should include:
    - Known exposure measurements (spiked samples);
    - Background measurements (blanks); and
    - Duplicate measurements
- Long-term follow-up measurements with the system operational

While U.S.-based research before 1999 cannot be expected to meet the EPA recommendations for pre- and post-PSD assessment, the standards serve as a benchmark to evaluate the quality of the studies.

Table 1 summarizes 36 research projects on radon control in new homes. Thirty-two of the studies were in the U.S. and, as a point of comparison, one of the studies was completed in the European Union (Holmgren and Arvela, 2011), one was a national radon survey in Finland (Keränen and Arvela 2008), another from Finland (Arvela *et al.*, 2008), and a study from the United Kingdom (Scivyer and Noonan, 2000). There are a number of other related international studies that were not captured in this analysis.

Tappan (1988) discussed mitigation-focused radon control from the 1970s and early 1980s in the U.S. His emphasis was on passive control techniques including sealants, dilution ventilation, and PSD. He concluded that the most important role of sealants was in conjunction with other techniques that decoupled the subslab pressure field from the habitable area of the structure. He summarized the experience of sealing 601 structures in Grand Junction, CO between 1973 and 1987 including 40 houses where only sealing techniques were applied. A year after sealing, 22 of the 40 homes exceeded the project's radon criteria, and thus it was concluded that sealing was unreliable. In the case of passive ventilation, he also viewed it important to consider the impact of ventilation on the house-to-soil air pressure relationship as well as dilution. He also commented on PSD and the use of a turbine to boost performance during warmer seasons.

Brennan, Clarkin, Osborne and Brodhead (1988) presented a summary of PSD and common radon-resistant details in four houses. The houses had very airtight foundations on the order of 10 to 100 times tighter than the tightest building shell. They concluded that passive barriers may be impractical with the ordinary amount of quality assurance found in house construction. Brennan and colleagues also compared PSD and active soil depressurization (ASD) performance in two houses; these results are discussed in a later section of this paper. They also acknowledged that the four houses only had one of four possible fundamental conditions: tight foundation on tight soils versus tight foundation on loose soils, loose foundation on tight soils, or loose foundation on loose soils[1].

Brennan, Clarkin, Osborne and Brodhead (1990) measured indoor radon concentrations to evaluate three techniques for radon control in two radon-resistant houses in northern Virginia and two in eastern Pennsylvania: foundation sealing; PSD; and ASD. Tracer gas was used to estimate the fraction of air that was being drawn into the houses through foundation cracks and holes, and it was found that a very small amount of below-grade leakage resulted in elevated indoor radon levels. Grab radon samples were taken in the subslab and averaged from less than 3,700 Bq m^{-3} (100 pCi/L) to more than 37,000 Bq m^{-3} (1,000 pCi/L).

Saum and Osborne (1990) monitored 16 Maryland and Virginia houses built by the same builder. Half of the houses had PSD systems and half had ASD systems. The paper has a good discussion on PSD theory.

National Association of Home Builders Research Center (NAHB) (1991) describes a project partially support by the U.S. Environmental Protection Agency (EPA) in New Jersey. Research was completed in only four homes, three with PSD and one with ASD. All the homes had radon concentrations in the basements above 150 Bq m^{-3} (4 pCi/L) but the PSD homes' first floors were below this threshold while the ASD first floor remained above. There was no explanation for the relative failures of these systems; although, it is interesting to note that: 1) the ASD house had the radon fan located in the basement, which could have leaked radon into the home; 2) one of the PSD houses had the passive vent stack located in the wall between the garage and the house and another appeared to have had the passive stack routed through the garage, which could have compromised the PSD performance. The report also discussed challenges with radon-control systems in new houses that are summarized in a later section of this paper.

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[1] Tight refers to high resistance to airflow while loose refers to low resistance to airflow.

Table 1. Overview of Research on Radon Control in New Houses by Topical Area

			Radon Testing			Differential Pressure					Techniques				Key/Notes:
Paper or Document	Number of Houses	Built to EPA PSD Recommendation	Seasonal ATD Radon Tests	Cap-on/off Radon Tests	ASD vs. PSD Radon Tests	Across Slab	Inside Stack to Indoors	Sublab Pressure Field Extension	Environmental Effects	House Depressurization	Sealing & Passive Techniques	Heating and Air Conditionong	Construction Problems Cited	Specifies QA Plan/ QC	● Paper column: first 2 initials of lead author's last name & year of publication ● Black = yes; Gray = minor reference; HVAC = Heating, Ventilation and Air Conditioning ● ASD = active soil depressurization; PSD = passive soil depressurization ● NA = not applicable; ~ = somewhat; mod = modified; __ day = length of Rn test ● TrG = tracer gas; crawl = crawl space foundation; ACH = air changes per hour ● ATD = Alpha Track Detector; B = blanks; C= calibration; D = duplicates; S = spikes
Al93	1	NA				■			■			■			Describes an HVAC controller to pressurize a FL research house for Rn control
Ar08	NA	NA									■			NA	Describes a strip subslab membrane technique in Finland
Br02	20			■											Passive stacks in New York State new houses not routed through conditioned spaces
Cl93	1	■			6+ day	■	■			▨	■	■			Leakage size not correlated with Rn concentrations; HVAC operation pressurizes basement and < Rn
De94	47	■	▨	14 day	14 day								■	D	10 communities; 11 builders; no membrane; some drain tile instead of aggregate; 13/47 >150 Bq m^{-3}
Du92	1	■						crawl		■	■		■		TN crawlspace house on karst; measurements before/after replaced with new house
Dy93	1	ASD				■	■		■	■				NA	1 house with ASD; focus on effects of forced air heating & cooling systems
Fa94	42	~				■							■	NA	2 states; investigation focused on system defects
Fo96	14	■				■				ACH				DSC	1 state (FL); 8 builders; assessed monolithic slab & slab in stem wall foundation Rn control
Fo06	66	■		■									■	D	93% had not tested PSD before survey; 26% >150 Bq m^{-3}
Ha03	13			■											12 of 13 houses did not have a permeable layer below the slab
Ha05	8	~		■									▩	DB?	1 community; compares construction problems with Sn03; 5 of 10 >150 Bq m^{-3}
Ke08	133				14 hou	TrG					■		■		5 communities; Finnish slab-on-grade houses; tracer gas analysis of air leaks from the soil
La01	46	mod		7 day									▨	D	1 community; 11 builders; no membrane; 22 cap-on/cap-off; 16 of 22 >150 Bq m^{-3}
Le99	12	▨			■								■		12 communities; 11/12 PSD > 150 Bq m^{-3}; 4/10 ASD >150 Bq m^{-3}
Mc10	NA	NA												NA	Argues suitability of PSD vs. ASD in new houses in 1 state
Mu88	148														3 commuities;12 subdivisions; 6 builders; passive techniqes; soil Rn & Ra measurements
Na91	22	■									■			BD	1 state; 7 builders; lists recommendations; 1 year Rn tests in 15 houses; reported QC problems
Na95	14	■		2 day										D	2 communities
Na96	22	■	14 day	14 day									■	D	8 states; summer/winter cap-on/cap-off Rn measurements; summer < winter; 6 of 16 >150 Bq m^{-3}
Na98	12	~													1 state; compares house with strips of drain matting vs. sumps; 1 of 12 >150 Bq m^{-3}
Ni94	NA	NA									▨				Modeled effectiveness of radon control techniques in FL slab-on-grade house
Ni96	NA	NA			model						model				Polyethylene membrane testing and modeled ranking of estimates of Rn control techniques
Nu91	1	NA									crawl			C	Novel field experiment with different house and crawl space ventilation for Rn control
Pr93	8	NA				■		■			■				1 community; focused on subslab pressurization and enhancement, e.g., subslab pit, slab sealing
Sa90	16	■		1 hou	1 hou						▨		■		2 states; 1 builder; good overview of PSD
Sa91	1														Tests 15W fan compared to 45W fan
Sa93													■		Discusses PSD problems; not based on empirical data
Sc00	73	NA		NA	NA						■				Assessed long-term performance of a passive subslab barrier for radon control in new UK houses
Sn03	24			7 day									■	D	1 community; 13 of 24 >150 Bq m^{-3}
Sp93	20	▨				■		■		■		■	■		Presented as a series of selective case studies with no overall average measurements
Ta88													▨		Reviews 1973-1987 passive Rn control techniques
Ty95	15			2 day	■	▨		■		ACH	■		■		1 state (FL); tested drainage mat under slab; subslab to house tracer gas leakage tests
Un87	NA	NA												NA	First U.S. EPA & National Association of Home Builders guidance
Un99		▨		▨										▨	U.S. EPA guidance on assessing radon control in new houses; calls for duplicates & blanks
We03	8			■		■	■	■	■	■			▨		2 WI communities; 1 builder; excellent data logging

Nuess and Prill (1991) reported two novel techniques for radon control in a new Washington State house with a modified, unvented crawl space. One technique involved continuous exhaust ventilation of the crawl space with the make-up coming from the house exhaust air. The second technique involved continuously supplying conditioned supply air to the house via earth tubes. It was concluded that, in a relatively airtight house, either continuous technique readily achieved indoor radon control.

Saum (1991) presents an experimental examination of the feasibility of using a ten-watt fan for radon mitigation compared to a 45-watt fan. The smaller fan reduced indoor radon from 370 Bq m^{-3} (10 pCi/L) to 78 Bq m^{-3} (2.1 pCi/L) while the 45-watt fan produced 30 Bq m^{-3} (0.8 pCi/L). Although the comparison was made in an existing house with no sealing of openings to the soil and a poor subslab permeable layer, the use of a lower wattage fan in new construction with a permeable subslab and well-sealed foundation could produce very good radon control at a lower operating cost.

Cummings, Tooley and Moyer (1992b) reported on pressure differential measurements in 70 central Florida houses built in the past five years. The findings are described in a later section of this report.

Dudney, Wilson and Dyess (1992) describe a Tennessee house built on a crawl space foundation. The house was destroyed by fire and rebuilt on the same foundation which allowed for comparison of different sets of radon-control strategies. In each case, the investigators monitored both the crawlspace and living area for: radon; temperature; relative humidity; building air leakage; and infiltration, exfiltration and interzonal transport rates. The original house had radon entry problems related to issues discussed in a later section of this paper and with the problems removed in the new house.

Al-Ahmady and Hintenlang (1993) is one of a series of studies on radon-control techniques in Florida houses with slab-on-grade foundations (Fowler *et al.*, 1996; Tyson and Withers, 1995; Najafi *et al.*, 1995; Najafi, 1998; Nielson *et al.*, 1994 and 1996; Spears *et al.*, 1993). The Florida studies represent some of the most complete assessments of radon-control strategy studies. Al-Ahmady and Hintenlang (1993) focused on atmospheric pressure variations, which are discussed in a later section of this paper.

Clarkin, Brennan and Brodhead (1993) compared foundation air tightening techniques, ASD, PSD, and basement pressurization using a typical heating and cooling system in one new, unoccupied Pennsylvania house. The foundation air tightening testing involved testing basement radon concentrations with different sized controlled floor slab openings. The original foundation had an equivalent leakage area, as determined with a blower door and tracer gas, of 0.2 square inches with an indoor radon concentration of 348 Bq m^{-3} (9.4 pCi/L). An opening of 10 square inches was associated with a radon concentration of 995 Bq m^{-3} (26.9 pCi/L) and an opening of 144 square inches was associated with radon level of 725 Bq m^{-3} (19.6 pCi/L). The original opening of 0.2 square inch was retested and had a radon concentration of 755 Bq m^{-3} (20.4 pCi/L). This series of experiments demonstrated the extreme difficulty of sealing radon out of a house. Clarkin, *et al.* also compared minor modifications to the forced-air heating system and its impact on pressure difference across the floor slab and basement radon levels (results are presented later in this paper).

Dyess, Brennan and Clarkin (1993) describe an experiment in a Pennsylvania house to reduce basement depressurization and indoor radon concentrations by using modifications in the air handling system. Further discussion about this study is found in the Pressure Differential Measurements section of this paper.

Prill, Fisk and Gadgil (1993) describe field experiments in eight new houses with basement foundations in highly permeable Spokane, WA area soils. The experiments were to determine the influences of the following variables on subslab pressures from subslab pressurization: soil and subslab aggregate permeability; slab sealing; a subslab pit; and subaggregate membrane. The findings were inconclusive; although, large improvements in pressure field extension (PFE) were observed with excavation of a 25-cm (10-inch) radius subslab pit and further enhanced when visible cracks in the slab were sealed.

Saum (1993) presents a qualitative view of PSD failures in the Washington, DC area. These failures are discussed later in this paper.

Spears, Rector and Wentling (1993) present an evaluation of 20 Florida new homes with slab-on-grade foundations and built according to the state's draft code. The assessment includes preconstruction soil permeability, radon, and radium measurements and post-construction measurements of subslab radon, indoor radon, duct leakage, air infiltration, air leakage, and radon entry (tracer gas).

Dewey, Nowak and Murane (1994) measured radon and assessed radon-control systems in 47 houses in eight states built by 12 volunteer builders who agreed to follow U.S. EPA's *Model Standards and Techniques for Control of Radon in New Residential Buildings*. The houses had basement, slab-on-grade, and crawl space foundations. The radon measurements were made with PSD systems capped and uncapped, and in 13 houses where the PSD was activated (results are reported later in this paper). Some of the radon measurements were made in different seasons, which complicated the analysis.

Fay, Tekverk and Gerard (1994) evaluated 42 Spokane, Washington and nearby northern Idaho houses allegedly built with radon-control features. The State of Washington houses were built under a state radon building code but virtually none met the code requirements. The defects Fay, *et al.* found are discussed in the New House Radon Control Installation Issues section of this paper.

Nielson, Rogers and Holt (1994) estimated the ratio of reference indoor radon levels where passive controls suffice. The estimates used the Radon Emanation and Transport into Dwellings (RAETRAD) model with variables believed to be common in Florida. The most effective radon control techniques were: ASD with passive techniques by a factor of 10, followed by passive techniques by a factor of 2 including subslab vapor retarder (membrane), increased house ventilation by a factor of 2, improved slab-foundation design, improved concrete quality, sealed slab cracks and openings, and sealed pipe openings.

Najafi, Shankar, Roessler and Hintenlang (1995) studied 14 new Florida houses and found weak correlation between preconstruction soil radon concentrations and post-construction subslab radon measurements. The passive barrier was sufficient to maintain indoor radon concentrations below 148 Bq m^{-3} (4 pCi/L) when subslab concentrations were less than 111,000 Bq m^{-3} (3,000 pCi/L). Cap-on and cap-off PSD testing is summarized in the next section of this report.

Tyson and Withers (1995) measured indoor radon concentrations in 15 new Florida slab-on-grade (SOG) houses; 11 of the houses had strips of Enkavent®[1] matting installed under the slab as a permeable layer and 4 had well-point suction pipes under the slabs. Originally, penetrations through the slabs were not sealed. Very extensive testing was undertaken: slab crack lengths were measured; PFE was tested; slab leakage was measured using tracer gas; blower door tests were made to estimate house natural ventilation rates and to stress test radon control systems; soil radon measurements were made; native soil and fill permeability was determined as was native soil and fill Ra-226 concentration. Pressure field extension (PFE) coverage was reported as adequate although not complete and short circuiting to the outdoors was observed when the ventilation mat or suction point was within six feet of the slab edge. The average crack length in the slabs was 13 feet in post-tension slabs, 36 feet in stem wall foundations, and 100 feet in monolithic slabs. Houses with unsealed pipe penetrations through the slab had 33 percent higher indoor radon concentrations.

The radon stress test of mitigation systems, using a blower door with the HVAC system on, did not produce meaningful results with short-term radon measurements. Total crack area, soil permeability, and Ra-226 did not correlate with indoor radon concentrations. Radon concentrations ranged from about 18,500 to 296,000 Bq m^{-3} (500 to 8,000 pCi/L). Subslab radon measurements varied by 100 percent or more from day-to-day and in different locations under the slab on the same day. Radium concentrations were higher in the fill material than in the native soil. The single factor that appeared to have the most direct relationship with indoor radon concentrations was the air pressure difference across the slab.

Fowler, McDonough and Williamson (1996) evaluated the effectiveness of two slab types in retarding radon entry in 14 new Florida houses, 8 with monolithic SOG foundations and 6 with slab-in-stem wall SOG foundations. The monolithic slab houses had less slab cracking than the slab-in-stem wall houses while the slab-in-stem wall systems had slightly higher radon entry and concentrations but the difference was not statistically significant perhaps due to the small sample size. The conclusion of the study was that both slab-type foundations proved to be effective in retarding radon entry especially with proper sealing.

A National Association of Home Builders Research Center (1996) report addressed opposite-season PSD cap-on/cap-off indoor radon tests in 22 of 44 houses reported by Dewey, *et al.* (1994). Overall, PSD reduced radon in the lowest levels of the houses by 52 percent in the winter and 50 percent in the summer. Numerous radon-control deficiencies were reported, and these are listed in the New House Radon Control Installation Issues section of this paper.

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[1] Colbond, Inc., Enka, North Carolina

Nielson, Holt and Rogers (1996) reported on an analysis of the radon resistance of five polyethylene vapor retarders and modeled ranking of the effectiveness of radon-control features in Florida SOG foundation houses. The air permeability of the retarders ranged from $1.1\text{x}10^{-13}$ to $3.3\text{x}10^{-16}$ cm^2 but there was no significant difference in the radon diffusion coefficient, which ranged from $2.26\text{x}10^{-7}$ to $4.38\text{x}10^{-7}$ cm^2 s^{-1}. The modeled ranking of radon-control feature effectiveness in Florida SOG houses was, from most to least effective:10.3 for ASD with slab sealing; 4.5 for ASD without slab sealing; 2.3 for sealing only; and 2 for enhanced ventilation.

Najafi (1998) described the effectiveness of subslab Enkavent®[1] porous matting versus a suction pit in 13 Florida houses. The houses were constructed by volunteer builders under supervision of the researchers. Soil-gas radon concentrations ranged from 33 kBq m^{-3} to 1,180 kBq m^{-3} (892 pCi/L to 32,000 pCi/ L). Enkavent® matting is a matrix of nylon filament, 20.3 mm (0.8 in) high, bonded to a filter fabric with 90 percent of its matrix being air space. Strips of the matting, 46 cm (18 inch) wide, were installed on the longest center axis of the subslab or diagonally across the subslab. Two suction pits, subslab holes 81 cm (32 in) diameter by 46 cm (18 inch) deep filled with gravel, were placed in each house. The13 houses included eight with stem wall SOG construction and five with monolithic SOG construction. Generally, the monolithic SOG houses had lower short-term indoor radon concentrations (average: 39 Bq m^{-3} [1 pCi/L]) than stem wall slab-on-grade foundations (average: 83 Bq m^{-3} [2.2 pCi/L]). The average indoor radon concentration for all 13 houses was 66 Bq m^{-3} (1.8 pCi/L). The performance of both Enkavent® matting and suction pits appeared to be effective.

Lewis (1999) investigated indoor radon concentration in 14 new Pennsylvania houses built with PSD, which were converted to ASD systems during the investigation. He also reported the most common construction-related problems that had the potential to compromise the performance of the radon-control systems. Details of the findings are reported in the next section of this paper.

Scivyer and Noonan (2000) assessed the long-term effectiveness of passive radon-control techniques in 73 houses in two areas of the United Kingdom by comparing winter 1989/90 and 1990/91 radon measurements in houses with less than 200 Bq m^{-3} (5.4 pCi/L) with winter 1999/2000 three-month measurements identical to those observed ten years earlier. They reported that all measurement results were less than 200 Bq m^{-3} (5.4 pCi/L) with two cases increasing to within 20 percent of the action level, and the remaining 71 dwellings reportedly increasing or decreasing. However, individual comparative results were not given. The primary radon-control feature was a full subslab membrane that extended through the exterior walls of the dwellings. They concluded that the membranes continued to perform ten years after construction without any signs of adverse side-effects.

LaFollette and Dickey (2001) tested indoor radon, under cap-on/cap-off conditions, in 46 Illinois houses built by 11 builders in a community with building code requirements for PSD radon control. Results are found in the Passive Soil Depressurization Cap-on/Cap-off Studies section of this paper.

Hagerty and Boka (2003) investigated PSD in 14 new houses in Muscatine, Iowa, which had adopted national model building code requirements for radon control in new construction. The houses had violations of the code requirements and modest radon reductions, both of which are reported in later sections of this paper.

Snead and Hanson (2003) and Hanson (2005) both evaluated the performance of PSD systems in new houses in Manhattan, Kansas built under a local building code adopted in 2001 based on the *International Residential Code* Appendix F (International Code Council, 2000). Both studies involved houses where the owners agreed to participate, both measured radon concentrations with PSD vent stacks capped and open (see Table 2), and both inventoried observed defects in the systems (see Table 5).

Weiffenbach and Marshall (2003) logged continuous radon, differential air pressures and other characteristics for eight occupied Wisconsin houses built with radon-resistant features: interior drain tile and a PVC tee in a six-inch deep bed of clean, coarse aggregate; a six-mil polyethylene membrane; slab with sealed cold joints; sealed covers on sumps; and indoor routed passive stacks. Air pressures were logged in the bases of the passive stacks. The results are presented in the Pressure Differential Measurements section of this paper. Wind speed, wind direction and outdoor temperature were monitored at a nearby airport. Basement radon measurements were made with PSD stacks capped and open. Base PSD vent stack air pressure measurements are presented in the Pressure Differential Measurements section of this paper.

The City of Fort Collins (2006), a northern Colorado community with a building requirement for radon control in new houses (Appendix F of the International Residential Code), measured the performance of PSD systems in 65 occupied houses. Indoor radon concentrations were measured in accordance with the protocol specified in EPA (1999), and the results from 65 houses represent the largest study of PSD cap-on/cap-off radon measurements (see Table 2). A contractor inspected the radon-control systems in each home and inventoried observed defects in the systems (see Table 5).

Arvela, *et al.* (2008) discussed radon-control techniques used in Finland including radon wells, which are effective only in highly permeable soils such as gravel and esker areas. In these areas, radon wells can reduce radon in houses at distances up to 30 meters (98 feet). The investigators reported that housing built since 1990 had indoor radon concentrations higher than houses built earlier. The first Finnish guidance for new construction was published in 1996 and called for sealing the slab-floor cold joint with elastic sealant and installation of a PSD system. As revealed in responses to a 2000-2001 questionnaire sent to 400 dwellings, the sealing recommendation became too tedious and uncommon. The revised guidance recommended using a sealed bituminous membrane on basement walls and, in SOG foundations, across the top of the foundation wall under the cold joint and along the edge of the floor slab.

Keränen and Arvela (2008) examined 133 dwellings in 5 Finnish communities built between 2004 and 2006. The houses were built under a 2003 guideline for radon control in new construction that called for a bitumen strip membrane at the foundation and slab perimeter as well as a passive stack. The previous guidance relied on elastic sealants to close the perimeter cold joint. Radon measurements were made by occupants. In 16 houses with SOG foundations, subslab air leakage measurements using nitrogen-hydrogen tracer gas were made to test the integrity of slab and membrane air tightness. In fourteen of the houses, the PSD systems were activated to test effectiveness. The results of the investigation resulted in new sealing recommendations.

McNees (2010) presents an argument that ASD in new house building codes should only be required in one state's high radon risk areas.

Arvela, Holmgren and Reisbacka (2011) present the results from the first national survey of radon-control systems in new Finnish houses. The 2009 survey was a random sample of 1561 owner-occupied houses built between 2004 and 2006 when new building code requirements were enacted. The new code required a loop of subslab radon pipe, sealing of the cold joint using a strip of sealed bitumen felt, and a radon vent pipe discharge above the roof. The results of the 2009 survey were compared to a 2006 nationwide sample survey of 2,866 owner-occupied houses (Keränen and Arvela, 2008).

The average indoor radon concentration in the 2009 survey was 95 Bq m^{-3} (2.6 pCi/L), 21 percent lower than in the 2006 survey with a median of 58 Bq m^{-3} (1.6 pCi/L), 23 percent lower than in the 2006 survey. Table 2 presents the average and median indoor radon concentrations by foundation type. Table 3 presents the average and median radon concentrations according to radon-control technique in SOG houses.

Table 2. Radon Concentration by Foundation Type

		Radon Concentration (Bq m^{-3})	
Foundation Type	**# Houses**	**Average**	**Median**
Slab-on-grade	798	97	68
Monolithic Slab	18	36	27
Crawlspace	231	43	29
Semi-basement and Basement	193	161	97
No Information	321	89	54
Total	1561	95	58

Table 3. Effects of Preventative Measures in Detached Houses with Slab-on-Grade Foundations

	Passive Preventive Measure		
	None	**PSD Piping & Sealing**	**PSD Piping & No Sealing**
Number of Houses	230	166	111
Average Rn Concentration (Bq m^{-3})	90	82	98
Median Rn Concentration (Bq m^{-3})	68	53	59
House Rn Compared to Local Rn Concentrations	0%	57%	41%

Size, Nature and Representativeness of Studies

As reflected in Table 1, the research reviewed in this analysis ranged from one house to 148 houses. The study with the largest number of houses (Murane, 1988) included only five houses with post-PSD radon measurements and none with pre-PSD radon tests.

All of the studies with pre- and post-PSD radon concentrations measurements involved volunteer builders, and thus were not representatives of all builders. Since the builders knew their radon-related work would be tested, the research further does not represent the radon-control work of builders who would be blind to the post-PSD testing. These two factors reflect selection bias in much of the PSD research.

By contrast, the Finnish survey of the effectiveness of radon-control techniques in all new houses in Finland is a representative survey that sets a high level of quality for research in the field (Arvela *et al.*, 2011).

Passive Soil Depressurization Cap-on/Cap-off Studies

As reflected in Table 4, 12 of the U.S. papers on radon control in new residential construction involved PSD cap-on/cap-off studies in multiple houses. Saum and Osborne (1990) was the first study involving cap-on/cap-off PSD, testing but it involved only one house.

Table 4. U.S. Passive Soil Depressurization Cap-on/Cap-off Studies

		Rn Conc (Bq m^{-3})			
Study (alpha order)	**Number Houses**	**Cap-on**	**Cap-off**	**%**	**Notes**
Brehm, 2002	20	105	93	-11	PSD compromised; 2 day Rn tests, location & season unspecified
Dewey, 1994 Basement	44	196	81	-59	Basement Rn tests; 36 tested same season
First Floor	44	81	44	-46	First floor Rn tests; 36 tested same season
Average		139	63	-55	
Fort Collins, 2006	65	296	148	-50	Houses built 2005; Rn tests length & location unspecified
Hagerty, 2003	13	344	278	-19	PSD compromised; 5-7 day Rn tests, season & location unspecified
Hanson, 2005	8	244	125	-49	PSD compromised; January basement Rn tests; test length unspecified
LaFollette, 2001	22	337	163	-48	7 day Rn tests on the lowest level suitable for occupancy
Najafi, 1995	2	252	257	+2	2 of 14 houses with PSD tested
NAHB, 1996 Winter	22	192	93	-48	PSD compromised; winter lowest level Rn tests; test length unspecified
Summer	22	133	67	-50	Summer Rn tests in lowest level; test length unspecified
Average		163	80	-49	
Saum, 1990	1	1110	278	-75	Cap-off approximate value; winter Rn tests
Snead, 2003	5	269	192	-25	PSD compromised; average 7 day winter Rn tests; location unspecified
Tyson, 1995	15	88	94	+7	Main floor 48 hour Rn tests; testing season unspecified
Weiffenbach, 2003	7	366	161	-56	Basement, 6+ day, winter Rn tests
Total	**224**				
Overall Weighted Average		**231**	**127**	**55%**	**Reduction**

Dewey, *et al.* (1994) reported a National Association of Home Builders analysis of 44 PSD systems in the operable and nonoperable modes. However, the analysis was compromised by the fact that eight of the houses had cap-on/cap-off radon tests done during different seasons. Of the eight houses, three had the PSD cap-on tests made in the winter and the cap-off test in the summer, which would tend to bias the effectiveness results lower and five had the PSD cap-on tests made in the summer and the cap-off test in the winter which would tend to bias the effectiveness results higher. The results of radon tests during the same season and in the lowest level of 36 houses were:

- in 27 houses with both radon tests made in the winter, 222 Bq m^{-3} (6 pCi/L) with the PSD stacks capped and 81 Bq m^{-3} (2.2 pCi/L) with the PSD stack open.;
- in 9 houses with radon tests made in the summer, 200 Bq m^{-3} (5.4 pCi/L) with the PSD stacks capped and 104 Bq m^{-3} (2.8 pCi/L) with the PSD stack open.

Najafi, *et al.* (1995) reported cap-on and cap-off PSD testing in nine new Florida houses. Their study revealed that PSD had a limited effect on reducing indoor radon. Indoor radon concentrations measured over 48 hours in the houses were 15 to 30 percent lower when stacks were uncapped versus capped.

A National Association of Home Builders Research Center (1996) study listed indoor radon concentrations in 22 houses in six states with PSD vent pipes capped and uncapped in both the winter and the summer. The average concentrations are listed in Table 5.

Table 5. Winter and Summer Indoor Radon Concentrations with PSD Capped and Uncapped in NAHB Houses (Bq m^{-3})

	Winter	Summer
Stack Closed	192 (5.2 pCi/L)	133 (3.6 pCi/L)
Stack Open	93 (2.5 pCi/L)	67 (1.8 pCi/L)
Percent Reduction	52%	50%

The results presented in Table 5 should be interpreted with caution since many of the houses had deficiencies in radon-control techniques.

LaFollette and Dickey (2001) reported indoor radon testing in 46 Illinois houses built in a community with building code requirements for PSD. Their study revealed an average indoor concentration of 337 Bq m^{-3} (9.1 pCi/L) with the PSD stack capped and 163 Bq m^{-3} (4.4 pCi/L) with the PSD stack open (52% reduction).

Brehm (2002) tested PSD systems in 20 Monroe County, New York houses with cap-on/cap-off and found that the average indoor radon concentration was 107 Bq m^{-3} (2.9 pCi/L) with the cap on and 93 Bq m^{-3} (2.5 pCi/L) with the cap off. The low radon concentrations and the small change make it difficult to assess the effectiveness of PSD.

Hagerty and Boka (2003) completed indoor radon testing in 13 new Muscatine, Iowa houses, which revealed an average concentration of 344 Bq m^{-3} (9.3 pCi/L) with the PSD stacks closed and 278 Bq m^{-3} (7.5 pCi/L) with the PSD stacks open. The poor performance of PSD was attributed to the use of sand under the slabs rather than clean aggregate. The one house with gravel subslab materials had an indoor radon reduction from 229 Bq m^{-3} (6.2 pCi/L) with the PSD stacks closed to 115 Bq m^{-3} (3.1 pCi/L) with the PSD stacks open. The city had adopted a building code requirement for radon control, but there were differences between code requirements and what was actually built.

Snead and Hanson (2003) and Hanson (2005) studies examined indoor radon concentrations in Manhattan, Kansas PSD houses built under a 2001 locally adopted building code based on the *International Residential Code* Appendix F (International Code Council, 2000). While each of the studies involved seven-day winter radon measurements over a two-year span, the average radon reduction was 39 percent in 2003 and declined to 19 percent in 2005. The small sample size for each study suggests caution in comparing the performance data is needed, but the pattern is concerning especially when the houses had been built under code requirements.

Weiffenbach and Marshall (2003) reported basement radon measurements in eight new Madison, WI area houses made with calibrated continuous radon monitors. In seven houses, there were both winter PSD stacks capped and opened. The measurements with the stacks closed/open were:

- 1073/444 Bq m^{-3} (29/12 pCi/L);
- 481/56 Bq m^{-3} (13/1.5 pCi/L);
- 370/130 Bq m^{-3} (10/3.5 pCi/L);
- 315/141 Bq m^{-3} (8.5/3.8 pCi/L);
- 241/185 Bq m^{-3} (6.5/5.0 pCi/L);
- 204/148 Bq m^{-3} (5.5/4.0); and
- 185/104 Bq m^{-3} (5.0/2.8 pCi/L).

In the Pressure Differential Measurements section of this paper, there is further discussion of indoor radon concentrations under different conditions of air pressure.

In the Fort Collins (2006) study, the performance of PSD systems in 65 occupied houses was assessed according to the cap-on/cap-off protocol specified in EPA (1999). The results from 65 houses represent the largest study of PSD cap-on/cap-off radon measurements. The radon measurements were conducted from March through May. Indoor radon with the PSD system capped averaged 296 Bq m^{-3} (8.0 pCi/L) and with the cap-off, 152 Bq m^{-3} (4.1 pCi/L) (-49%). The change ranged from a 707-Bq m^{-3} decrease to a 115-Bq m^{-3} increase (-19.1 to +3.1 pCi/L). The radon change is presented in Figure 2.

Passive versus Active Soil Depressurization

PSD versus ASD performance comparisons are found in Table 6.

Brennan, *et al.* (1988, 1990) compared PSD and ASD performance in two Pennsylvania houses. They concluded that ASD proved to be extremely effective but the small sample size limited generalization.

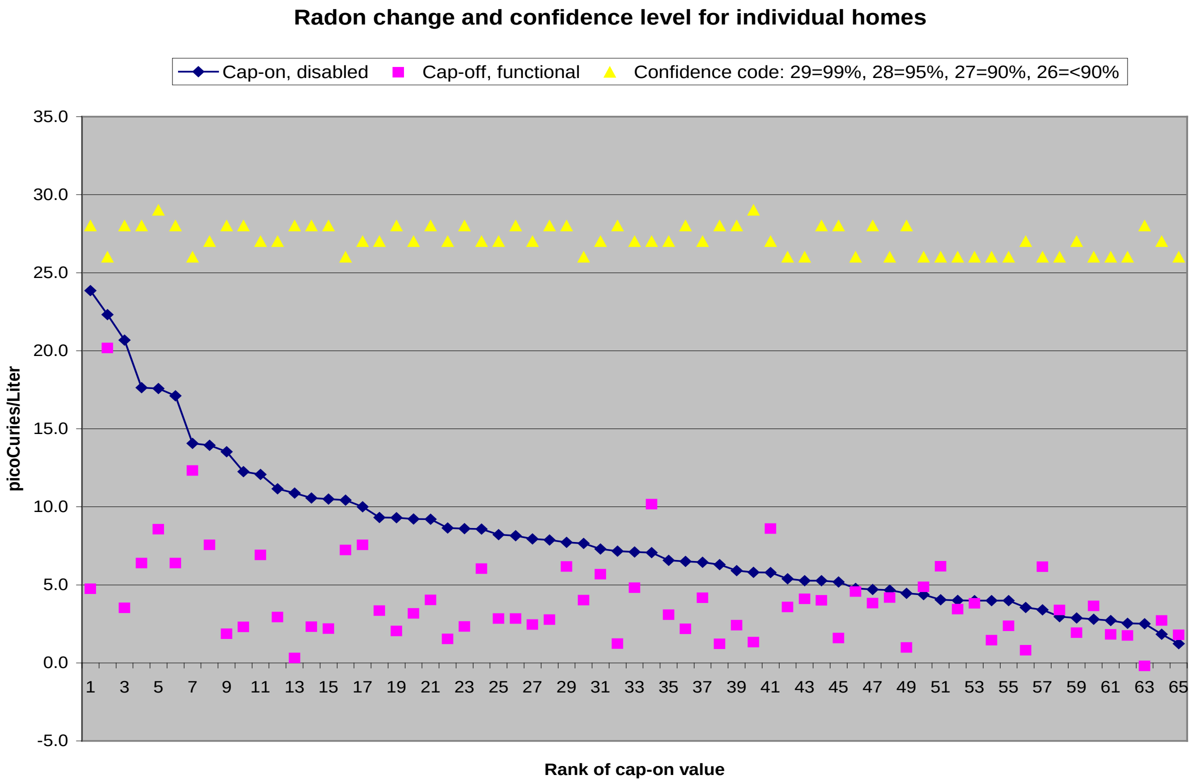

Figure 2. Radon Change and Confidence Level for Each House

Table 6. Passive versus Active Soil Depressurization Indoor Radon Concentrations

		Radon Tests (Bq m^{-3})			
Study	**No. of Houses**	**PSD Capped**	**PSD Open**	**ASD**	**Notes**
Brennan, 1988	2	270	250	30	Five day Rn tests, season & location unspecified
Clarkin, 1993	1		333	41	April-May, 6 day basement Rn tests
Dewey, 1994	13	250	161	60	Basement Rn tests
Keränen, 2008	14		630	130	Two month, first floor Rn test, seasons varied
Lewis, 1999	10		4735	555	Location, season & length of Rn tests generally unspecified
Najafi, 1995	13	81		53	Four first floor Rn tests, seasons & length of tests unspecified
Saum, 1990	1	1110	833	37	Location, season & length of Rn tests unspecified
Tyson, 1995	6	141	141	76	Main floor 48 hour Rn tests; testing season unspecified
Weiffenbach, 2003	1	1110	444	37	PSD Rn with poor sealing; ASD with sealing
Total	**61**				
Weighted Averages					
PSD Capped to ASD	**34**	**240**		**45**	**81% reduction**
PSD Open to ASD	**46**		**1360**	**195**	**86% reduction**

Clarkin, *et al.* (1993) compared PSD and ASD in a new, unoccupied Pennsylvania house.

Dewey *et al.* (1994) measured radon in 13 houses with PSD systems capped and uncapped and then converted to ASD systems. The houses were in eight states and built by 12 volunteer builders who agreed to follow U.S. EPA's *Model Standards and Techniques for Control of Radon in New Residential Buildings*. The houses had basement, slab-on-grade, and crawl space foundations. Some of the radon measurements were made in different seasons, which complicated the analysis.

Lewis (1999) reported on indoor radon concentrations in 10 new Pennsylvania houses built with PSD, which were converted to ASD systems during the investigation. The radon concentrations averaged 4735 Bq m^{-3} (128 pCi/L) with PSD operating and 555 Bq m^{-3} (15 pCi/L) with ASD operating. The averages were biased high by one house with 32,000 Bq m^{-3} (865 pCi/L) with PSD operating and 1850 Bq m^{-3} (50 pCi/L) with ASD operating. Dropping this very high radon house shows the remaining nine houses averaged 1702 Bq m^{-3} (46 pCi/L) with PSD operating and 444 Bq m^{-3} (12 pCi/L) with ASD operating. Lewis also reported that the new houses had numerous deficiencies that would challenge either PSD or ASD.

Najafi, *et al.* (1995) reported cap-on and cap-off PSD testing in nine new Florida houses. Their study revealed that PSD had a limited effect on reducing indoor radon. Indoor radon concentrations measured over 48 hours in the houses were 15 to 30 percent lower when stacks were uncapped versus capped.

Weiffenbach and Marshall (2003) discussed one Wisconsin house with incomplete cold joint sealing that had a radon concentration of 1110 Bq m^{-3} (30 pCi/L) with the stack closed and 444 Bq m^{-3} (12 pCi/L) with stack open. After sealing the cold joint, a14-watt fan was installed and reduced the radon concentration to below 37 Bq m^{-3} (1 pCi/L).

Keränen and Arvela (2008) tested 14 Finnish houses with PSD systems, which were later converted to ASD systems. The PSD systems produced an average indoor radon concentration of 630 Bq m^{-3} (17 pCi/L), a median concentration of 430 Bq m^{-3} (11.6 pCi/L) with 11 of the 14 below Finland's 200-Bq m^{-3} (5.4-pCi/L) guideline. With activation of the systems to ASD, average indoor radon concentration was 130 Bq m^{-3} (3.5 pCi/L); median was 30 Bq m^{-3} (0.8 pCi/L), but 3 of the 14 remained above the guideline.

New House Radon Control Installation Issues

Table 7 lists defects with the installation of radon-control components and systems as reported by 15 studies. Since the assessments did not involve a common set of criteria, the absence of cited problems in any specific study does not mean the problem was not present. Furthermore, many of the studies did not list the frequency of the problems, and thus one cannot conclude the relative frequency of the problems. Only the Finnish study was a nationally representative study, and thus the U.S. studies cannot be viewed as representative of all new homes built with radon-control techniques.

The numbers of problems reported over the two-decade span of the studies listed in Table 7 reflect the difficulty of achieving perfection in new construction radon-control systems. As reported in a couple of the investigations, defects decreased in frequency over time with these projects. Descriptions of highlights of the individual studies follow.

Based upon examination of eight Maryland and Virginia homes built by the same builder with PSD, Saum and Osborne (1990) identified the following main problems with poor performance: 1) basement volume depressurization due to leaks in basement return ducts; 2) multilevel slabs that were not connected to the PSD system; 3) PSD stacks routed through unheated space; and 4) PSD stack pipes blocked by construction debris.

Saum also noted that PSD "(p)erformance did not appear to be affected by pipe straightness." Some later investigators (Snead and Hanson, 2003; Hanson, 2005) cited the lack of straightness of the PSD vent pipe compromised system performance. There is no empirical evidence that clarifies the conflicting opinions on the effects of straightness of the vent pipe.

NAHB (1991) discussed challenges with radon-control systems in new houses including:

- Cannot install a 4" stack in standard 2x4" wall
- Complete sealing of the under-slab soil gas barrier is not feasible
  - But the barrier is still recommended to minimize contamination of the aggregate by concrete
  - Means caulking and sealing slab openings, cracks, and joint is still necessary
- Vertical runs of the stack without horizontal runs is difficult when interior walls do not line up vertically
- Tooling concrete joints presents a problem since it requires an additional step in the concrete finishing process
- Maintaining construction quality control was one of the most deficient aspects of the recommended construction methods
  - Many caulking and sealing details were overlooked by builders and site supervisors since most are not sufficiently aware of radon control
  - Low priority for laborers and tradesmen
- Too much emphasis on minimizing all potential entry routes
  - More appropriate to focus on adding a passive stack and sealing major entry routes

Many of the problems cited in NAHB (1991) were observed in later studies.

Saum (1993) listed a number of PSD failures he observed in the Washington, DC area. In respect to connecting a PSD vent pipe to a sump, he observed, "Most of the effective passive stacks that have been studied were sealed directly into the concrete slab, and not into sump lids." "It seems passive stacks will be defeated if there is any leak in their above ground components, and that attaching them to sump lids has a high probability of failure unless the whole lid is perfectly sealed."

Table 7. Problems Cited in New House Radon Control Systems

Problem	Murane, 1988	Saum, 1990	Saum, 1993	Dudney, 1992	Spears, 1993	Dewey, 1994	Fay, 1994	Tyson, 1995	Nat'l. Assoc. Home Blders, 1996	Lewis, 1999	Brehm, 2002	Hagerty, 2002	Snead, 2003	Hanson, 2005	Fort Collins, 2006	Keränen, 2008
HVAC Duct Leaks Depressurize Soil Contacted Area		■	■	■												
HVAC Blower Depressures Soil Contacted Area				■	■											
Subslab Permeable Layer Missing or Incomplete							■		■	■						
Sealing Incomplete							■		■	■					■	■
Sumps Unsealed			■									■	■	■		
Air Leaks Around PSD Stack Slab Penetration			■													
Excessive Floor Penetrations Above Crawl Space				■												■
Subslab or Crawl Space Membrane Missing or Incomplete						■	■		■	■	■					
Untrapped Condensation Drains Through Slab			■													
Uncapped Concrete Block Foundation Walls										■						
Air Leaks to the Outdoors										■						
Isolated Subslab or Submembrane Areas		■							■							
Foundation or Slab Sealing without PSD	■															
No PSD Vent Stack							■						■			
Horizontal PSD Pipe Lacking Drainage Slope			■													
PSD Pipes Blocked by Construction Debris																
PSD Pipes Blocked by Soil			■											■		
PSD Stack Pipe too Small (<7.6 cm [<3"])			■													
PSD Vent Routed Through Unheated Space										■	■		■			
PSD does not Discharge Above Roof			■						■				■			
PSD Pipe Joints Unsealed and Leaky			■											■		
PSD Discharge Lacks Bird Screen															■	
System Labels Lacking															■	
Radon Performance Tests not Done							■							■		

Dudney, *et al.* (1992) described a Tennessee house on a crawl space foundation. Radon entry problems that were observed included excessive floor penetrations, leaky forced air return ducts in the crawl space, and the air handler located in the crawlspace. The house was subsequently destroyed by fire with no damage to the foundation. The home was rebuilt on the original foundation with sealed floor and the forced air handlers and ducts removed from the crawl space. The new floor and new ducts reduced airflow from the crawl space by 60 percent and the relocated air handler reduced airflow from the crawl space by 80 percent. Despite these reductions in airflow from the crawl space, indoor radon concentrations remained unchanged.

Saum's (1993) review of PSD failures in the Washington, DC area were grouped into two basic categories: 1) poor installation; and 2) basement depressurization. The basement depressurization issues were due to imbalances in the forced air heating systems generally caused by leaks in the return ducts. Poor installation failures included: blockage of the stack pipe by bottoming the suction pipe in the soil or allowing construction debris to fill the suction pipe; leaky stack pipe due to poor or unsealed pipe connections; stacks terminating in the attic; leaky sump lids; leaks around the PSD pipe slab penetration; poorly trapped or untrapped condensation drains; stack pipes too small (less than 3" diameter); stack pipes routed through unconditioned space such as garages; and condensation traps in pipes. Saum adds, "Most of the effective passive stacks that have been studied were sealed directly into the concrete slab, and not into sump lids" and "It seems passive stacks will be defeated if there is any leak in their above ground components, and that attaching them to sump lids has a high probability of failure unless the whole lid is perfectly sealed."

Spears, *et al.* (1993) evaluated 20 new slab-on-grade homes in Florida and found pressure differentials between the indoors and outdoors of -10 Pa when the forced air handler was operating. The forced air system had a single air return. The houses with a subslab drainage matt soil gas collection system appeared to better transmit the influence of the air handler. However, the influence of the air handler on subslab depressurization was overwhelmed by ASD operation.

Dewey, *et al.* (1994) noted that 6-mil thick polyethylene membranes were not installed between the floor slabs and aggregate in four of eight states. It is not possible to determine from the paper if this omission had impact on radon control.

In a study of Washington State and Idaho homes, Fay, *et al.* (1994) found that none of the Washington houses had PSD stacks, permeable subslab areas, or membranes separating the slab and aggregate despite building code requirements specifying these features. Because of builder resistance to install a permeable subslab and a membrane under the slab, many installed ASD. In addition, most of the houses lacked a post-construction radon test.

The National Association of Home Builders Research Center (1996) examined passive radon control features in 22 houses in six states and found: 14 lacked a complete sealed subslab or crawl space membrane; 4 lacked a complete permeable layer under the slab; 2 had unconnected subslab areas; and 1 had a PSD vent stack that terminated in an attic.

Lewis (1999) examined 14 new Pennsylvania houses and found numerous deficiencies that would challenge either PSD or ASD. These defects included: lack of good, clean subslab aggregate; no suction pits; lack of connections to adjacent slab-on-grade rooms and garage; no subslab membrane; uncapped concrete block foundation wall cores; numerous entry points left unsealed; openings to daylight short-circuiting the active system; poor locations and convoluted routings for pipe runs from the basements to attic; and insufficient space in the attics to easily install fans.

An investigation by Brehm (2002) of 20 new houses in New York State revealed that the PSD vent stacks were routed through exterior wall cavities and some houses had no polyethylene membrane under the slab.

Hagerty and Boka (2003) reported 12 of 13 new Muscatine, Iowa houses that were evaluated had sand under the slabs rather than clean aggregate. The city had adopted a building code requirement for radon that specified a permeable subslab layer but the cost for delivery of clean aggregate was $235 more per house than for sand.

Snead and Hanson (2003) listed radon-control defects in eight new Manhattan, KS houses built in the first 18 months of enactment of a local PSD building code requirement: unsealed sump pits in seven of eight houses; excessive horizontal pipe routing; improperly sloped vent pipes; vent pipe routed through unconditioned space in one house; and PSD stack discharged at grade level rather than the roof in a house. The local code allowed for drain tile in sand fill to be used in lieu of a complete subslab permeable layer. Hanson (2005) did a follow-up testing of the Manhattan houses built more than 19 months after enactment of the local building code and found the following deficiencies: unsealed sumps; horizontal vent pipe runs; a PSD vent pipe routed through an unheated garage; and a PSD vent stack that separated in the attic due to lack of sealed connection. In essence, it appeared that quality remained poor over the year and a half.

The City of Fort Collins (2006) assessed 65 new houses built according to the International Residential Code's Appendix F and found the following frequent issues: lack of a bird screen on the PSD discharge; improper sealing/caulking of slab penetrations and joints or no sealing or caulking; and omission of system labels. It was noted that houses built later had fewer problems than those built earlier.

Keränen and Arvela (2008) used tracer gas to assess air leakage between the soil and indoors in 11 Finnish houses that had unsealed perimeter subslab membrane and reported that: ten houses had significant air leaks at "lead-throughs" (wiring or plumbing penetrations); 6 houses had air leaks at nonseamed bitumen felt strips in corners; five houses had air leakage at joints of slab and the bearing internal wall; four houses had air leaks at perimeter floor-wall cold joints; three houses had air leaks at electric wall sockets; and one house had air leaks at a fireplace foundation.

Pressure Differential Measurements

Cummings, Tooley and Moyer (1992b) reported on a study characterizing pressure differential measurements in 70 new (5 years or less old) and more air-tight houses in central Florida. They noted that pressure differentials between the house and the soil influences radon entry. The houses had forced air heating and cooling systems with one or two central returns and no transfer registers between rooms. Blower door tests revealed an average air tightness of 7.23 ACH at 50 Pa (ACH 50). Significant air leaks were commonly found in the forced air supply and return ductwork. When the ducts were sealed off from the houses, the house ACH dropped 11 percent to 6.4 ACH50. Differential pressure among the houses and subslabs were as follows:

- attic routed return duct leaks increased maximum whole house pressure by 5.5 Pa in reference to the outdoors;
- supply duct leaks decreased whole house pressure to -4.8 Pa in reference to the outdoors;
- closing interior doors resulted in a maximum house depressurization of -14.8 Pa; and
- turning on all exhaust fans and indoor clothes dryers depressurized houses 0 to -4 Pa and in one very tight house, -37 Pa.

By comparison, wind typically depressurized houses -0.5 to -1.5 Pa. Three recommendations were made by the investigators: 1) air distribution systems should be airtight; 2) return air pathways should be provide from each closable room; and 3) operation of exhaust devices should be minimized or make-up should be provided to eliminate depressurization.

Similar to Nuess and Prill (1991), Clarkin, *et al.* (1993) compared minor modifications to the forced air heating system and its impact on pressure difference across the floor slab and basement radon levels. He found that continuous operation of the air handler blower produced a 3.6-Pa positive pressure differential with reference to the outdoors and a basement radon concentration of 59 Bq m^{-3} (1.6 pCi/L) compared to 1.1 Pa and 714 Bq m^{-3} (19.3 pCi/L) with the blower off.

Al-Ahmady and Hintenlang (1993) focused on atmospheric pressure variations in a research house and the effect of a heating ventilation, and air conditioning (HVAC) pressure sensor controller to minimize radon entry. They found that indoor radon concentrations generally declined with a lower air pressure difference between the house and the outdoors with one significant spike in radon when the pressure difference approached 0 Pa (see Figure 3). Al-Ahmady attributed the spike to semi-diurnal atmospheric tidal barometric pressure differences in north central Florida. He concluded that use of an HVAC system to pressurize a house can create remarkable reductions in indoor radon concentrations. However, there is no discussion of the energy penalties associated with using outdoor air for pressurization.

Dyess, *et al.* (1993) describes an experiment in a Pennsylvania house to reduce basement depressurization and radon concentrations. The house had an ASD system, which was deactivated and capped during the experiment, a permeable subslab layer with drain tile loop, sealed slab penetrations, and electric heat pump with all forced-air ducts and the air handling unit located in the basement. The experiment involved sealing air ducts, cutting a 9.7-cm^2 (1.5-in^2) opening in the supply duct, and operating the blower continuously on a low setting. The result pressurized the basement in respect to the outdoors an average of 4 Pa (compared to -1 Pa), which produced a house ventilation rate of 0.53 ACH and reduced basement radon concentration from 148 to 41 Bq m^{-3}. Installation costs were $200 to $300 compared to $730 for the ASD system and electrical operating costs were $21 greater per year than ASD operating costs. The costs of conditioning additional air infiltration in the upper floor(s) were not given.

Spears, *et al.* (1993) studied 20 new Florida homes with slab-on-grade foundations and built according to the state’s draft code. They found pressure differentials up to -10 Pa between some rooms and the outdoors with single return heating and air conditioning systems operating. In Florida, most ducts are routed through attics and air handlers are located in carports or garages.

Tyson and Withers (1995) measured indoor radon concentrations in 15 new Florida SOG houses as well as slab crack lengths, PFE, slab leakage, estimated house natural ventilation rates, radon-control system stress testing, soil radon measurements, native soil and fill permeability, and native soil and fill Ra-226 concentration. PFE coverage was reported as adequate although not complete and short circuiting to the outdoors was observed when the ventilation mat or suction point was within six feet of the slab edge. The single factor that appeared to have the most direct relationship with indoor radon concentrations was the air pressure difference across the slab.

Weiffenbach and Marshall (2003) continuously logged differential air pressures in the base of PSD vent stacks and indoor radon in eight occupied Wisconsin houses. Air pressures in the

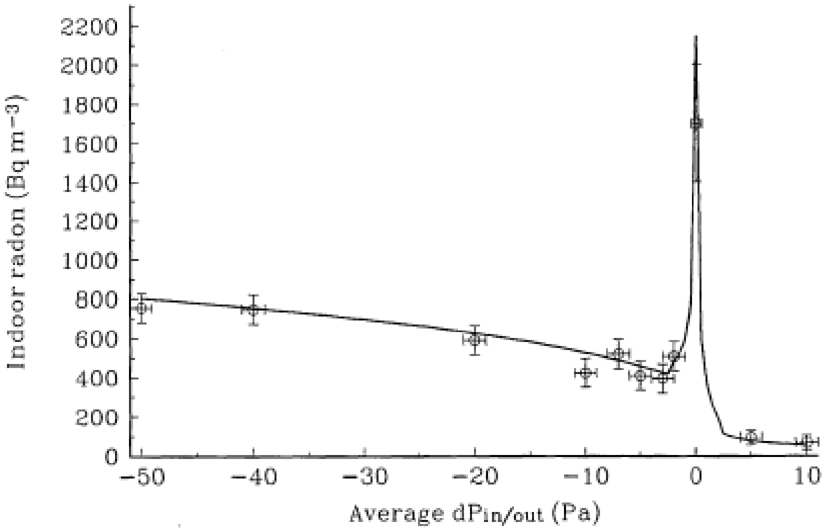

Figure 3. Indoor Radon Concentration as a Function of Whole House Pressure Conditions

passive stack bases were found to be predominantly less than basement air pressure. Wind speed, wind direction and outdoor temperature monitored at a nearby airport were found to affect the depressurization in the stack bases. In some houses, when appliance fans were exhausting indoors, the basement volume air pressure was reduced more than the PSD stack base pressure and bursts of indoor radon resulted. With the stacks closed, the pressures in their bases increased to about 2 Pa positive relative to the basement and indoor radon increased by factors of 1.3 to 8 among the houses.

Indoor radon concentrations were observed to increase in some houses with dropping barometric pressure and decreased with rising barometric pressure while indoor radon concentrations had little change or did not change in others. With PSD stacks open, indoor radon concentrations changed with wind speed, wind direction, and outdoor temperature as monitored at a nearby airport. Pressures in the base of the passive stacks and in the sealed sumps were predominantly less than basement air pressure. Pressures logged in sealed sumps revealed that the sumps were pressurized relative to the basements almost all of the time while the stack base was depressurized. In one house, wind perpendicular to the roof ridge increased stack depressurization suggesting a Bernoulli effect. Increasing perpendicular wind increased stack depressurization. The lower the outdoor temperature, the greater the stack depressurization; (about one Pa per degree Celsius). This pressure difference appears to be overestimated even in the very airtight houses that were evaluated.

In two of the Wisconsin houses, indoor radon concentration fluctuated with appliance fan operation (e.g., draft induced water heater, clothes dryer). When pressure in the stack base was briefly greater than that in the basement, indoor radon spiked. Operating appliance fans (the powered-draft fan of the water heater, bathroom and kitchen exhaust fans, clothes dryer fan pulled indoor air from the houses) caused an 8- to 12-Pa change in differential pressures. In these situations, air pressure in the base of the stack became positive in relationship to the basement.

However, in another house there were almost no events when the stack base went positive and radon increased; the one exception was at times when the outdoor-vented clothes dryer was in use. Based on blower door calculations, it was estimated that the ventilation rate of the two houses was about 0.1 air change per hour, a very low ventilation rate. One house with a wind turbine on the passive stack was compared to another identical neighboring house with the standard PSD stack and no changes in passive stack pressures or indoor radon were observed.

Radon Testing and Quality Assurance/Quality Control

U.S. Environmental Protection Agency (1999), "Design of a Program to Measure the Effectiveness of Passive Radon-resistant New Construction," recommends that new houses with radon-control systems be tested for radon during the heating season and that quality control measures should include: known exposure measurements (spiked samples); background measurements (blanks); and duplicate measurements. Furthermore, EPA recommends long-term follow-up measurements with the system operational.

As noted in Table 1, quality control (QC) measures were often not cited and thus, in those studies without QC, one must be cautious in interpreting radon measurement data. Ten of the studies that cited at least one QC measurement often mentioned completing only duplicates. Blanks, a measure of background, appear to have been made in only two studies and spikes, a measure of accuracy, were not reported in any of the studies. One of the reports (National Association of Home Builders Research Center, 1991) stated there were serious problems with blanks, ranging 4 to 226 Bq m^{-3} (0.1 to 6.1 pCi/L) of background, and with duplicates showing poor precision, differing as much as 100 percent.

Evidence-Based Assessment of New Construction Radon Control Research

Research in the efficacy of new house radon-control strategies may be graded using an evidence-based (E-B) framework. E-B approaches have evolved in medicine to further use the best available evidence for science to guide clinical decisions (GRADE Working Group, 2004). Evidence-based models are beginning to be used in public health (Kohatsu *et al.*, 2004) and, by extension, radon control is a public health strategy that needs to be weighed through E-B consideration. A good example of an evidence-based approach in the field of indoor air quality interventions is a paper by Custovic, *et al.* (2002) on controlling indoor allergens for the treatment of asthma. The authors ranked studies according to the Scottish Intercollegiate Guidelines:

- Ia evidence from meta-analysis of randomized controlled trials;
- Ib evidence from at least one randomized controlled trial;
- IIa evidence from a well-designed, controlled study without randomization;
- IIb evidence from at least one other type well-designed, quasi-experimental study;
- III evidence from well-designed, nonexperimental, descriptive studies such as comparative studies, correlation studies, and case studies; and
- IV evidence from expert committee reports or opinions and/or clinical experience of respected authorities.

In the field of radon control in new houses, there is no level Ia meta-analysis and there will not be until there is further randomized research similar to Arvela, *et al.* (2011). The Arvela, *et al.* (2011) study represents a level Ib contribution, the highest level of research completed in the field. Level IIa (well-designed, controlled study without randomization) research is represented by studies such as Dewey, *et al.* (1994), Fort Collins (2006), Keränen and Arvela (2007), Lewis (1999) and Weiffenbach and Marshall (2003). Dudney, *et al.* (1992) and a number of the Florida research papers may be considered level IIb evidence, e.g., Fowler, *et al.* (1996) and Tyson and Withers (1995). Level IV or the lowest level of evidence includes a number of the guidance references including American Society for Testing and Materials (1990 and 1991) as well as U.S. Environmental Protection Agency (1987, 1994 and 1999).

Conclusions

Effective radon control in new dwellings is imperative for the success of national and local public health programs intended to reduce lung cancer deaths. The research reviewed in this paper reflects important steps to that goal. However, there is an absence of research at the highest quality level needed to have confidence in approaches to low radon in new housing.

Need for Further Research

With the exception of the Finnish survey on the comparative effectiveness of passive radon-control techniques under two different guidance documents, there has not been research addressing effectiveness of radon-control techniques in a random sample of new homes. It is important that countries, including the U.S., implement random surveys of the efficacy of radon control in new houses. A nationwide random survey would help to determine the soundness of estimates of radon-related lung cancer deaths averted by radon control in new construction and help focus efforts to improve the performance of these systems.

The novel continuous ventilation approaches reported by Nuess and Prill (1991) and Clarkin *et al.* (1993) suggest promising radon-control strategies in new houses using continuously operating supply fans or air handler fans. In the Grimsrud, Hadlich and Huelman (1996) review of radon-control techniques for the U.S. Department of Housing and Urban Development, it was noted that low-cost control techniques had suffered from U.S. EPA's biased attention to ASD. They encouraged further research on use of an HVAC system as a promising technique deserving additional research.

There is further work that needs to be taken in using E-B grading of the research in radon control in new houses. This paper is a step in that direction but further analysis is needed.

In future research, there needs to be clear and explicit quality assurance plans and quality control measures. U.S. Environmental Protection Agency (1999) is a step in the right direction but more is needed to have confidence in radon measurement data.

While U.S. Environmental Protection Agency (1999) recommends long-term radon measurements, such measurements are a rare exception in the assessment of radon control in new houses. It is important that this gap be filled.

There is a notable absence of research on preventive radon-control techniques in new construction of multi-family buildings. It is important that these types of investigations begin. A paper by Valmari, Arvela and Reisbacka (2012) is a step in this direction. Valmari and colleagues examined radon in Finnish apartments and reported that newer ground-contact apartments had lower indoor radon concentrations than those built in the 1990s. The investigators postulated lower radon entry into newer apartments was the cause of this pattern.

It is important to state that this assessment focused on radon control in new houses. A logical next step would be to focus on what can be learned from control of vapor intrusion in new buildings.

There are a number of specific questions on radon control in new dwellings that need further research including that dealing with the relative importance of subslab membranes in radon control. The contrast between the emphasis of the U.S. and United Kingdom on complete subslab membranes and Finland's use of perimeter strip membrane illustrates this need. Another example of needed research is the question of what amount of a permeable layer is needed in PSD systems. For example, the basic U.S. guidance and code requirements specifies a complete permeable subslab layer but allows strips of drainage matt to be used without specifying the minimum amount of needed coverage. In addition, perimeter interior drain tile in a gravel envelope has been used, but the research is lacking to determine when and under what conditions this partial permeable approach may be acceptable.

Finally, a cost-effectiveness analysis comparing PSD and ASD using small fans is needed. This analysis could follow that outlined in WHO (2009).

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