Radon Mitigation Literature Review
for the Harford County, Maryland Health Department
July 2014

I. Introduction

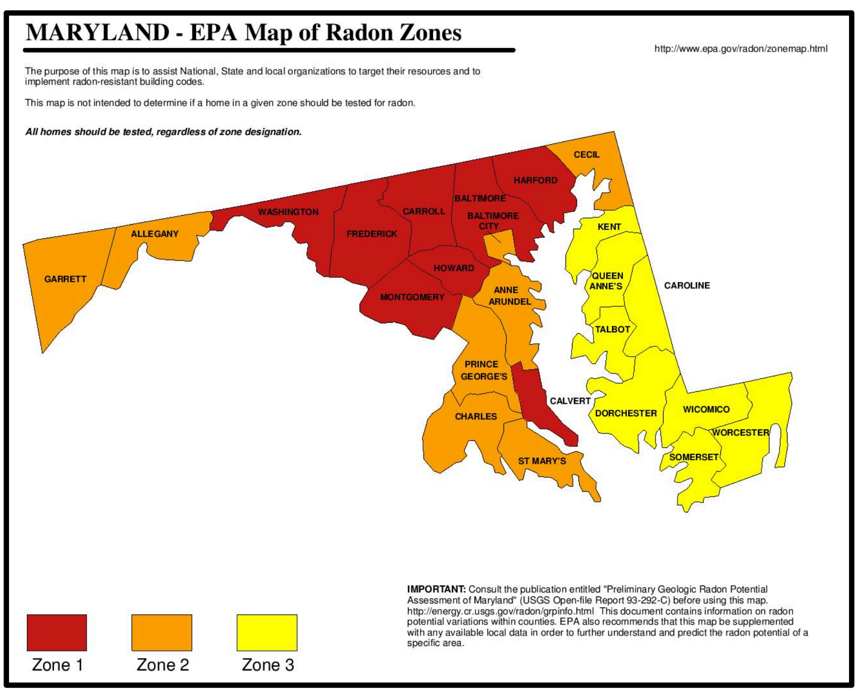
In response to a request from the Harford County, Maryland Health Department Johns Hopkins Bloomberg School of Public Health graduate students conducted a literature review to assess radon mitigation effectiveness, as well as the potential impacts of mitigation on population health. Findings are summarized below.

II. Background

- Radon is a radioactive gas that can infiltrate residential buildings and collect in high concentrations in indoor structures.
- Radon gas exposure is a public health concern because of its link to lung cancer.
- The U.S. Environmental Protection Agency (EPA) recommends residential housing undergo radon mitigation if the radon level is 4 pCi/L (picocuries per liter) or more.
- Harford County is coded by the EPA as a high radon risk county (Zone 1) with a predicted average indoor residential radon screening level above 4 pCi/L (picocuries per liter).

Radon, a product of decaying uranium, is a radioactive gas that naturally exists in the earth's crust, soil, and rock foundation. Radon is a colorless, odorless gas that permeates fractures and porous substrates in the foundations of buildings and can collect in high concentrations in indoor facilities (Sandel, et al., 2010). Sometimes, radon enters housing units through community water systems with groundwater as the main water source. Radon gas exposure is linked to lung cancer. It is the leading cause of lung cancer amongst nonsmokers, causing between 21,000-22,000 deaths annually in the United States (Sandel, et al., 2010) (Zielinksi, Carr, Krewski, & Repacholi, 2006). Moreover, there are synergistic effects between smoking and radon exposure (United States Environmental Protection Agency, 2012). Researchers estimate that roughly 60% of radon-related deaths involve smokers, 30% former smokers and 10% never smokers (Gagnon, et al., 2008).

Radon levels vary across the country, with certain regions having higher concentration levels than others. However, any residential home can contain dangerous levels of radon. The U.S. EPA has mapped counties by radon risk (Sandel, et al., 2010). Harford County is coded as Zone 1, the highest potential for heightened levels of radon in residential housing with predicted average indoor radon screening level greater than 4 pCi/L (picocuries per liter), which is equivalent to 150 Bq/m^3 (becquerels per cubic meter) (United States Environmental Protection Agency, 2012). The EPA officially recommends homes undergo radon mitigation if the radon level is 4 pCi/L (150 Bq/m^3) or more. However, there is no known safe level of exposure to radon; as such, the EPA



(United States Environmental Protection Agency, 2012) recommends homeowners consider mitigation if their home is between 2 and 4 pCi/L (74 and 150 Bq/m^3). Across the United States, the average indoor residential radon concentration is 1.3 pCi/L (48.1 Bq/m^3) (United States Environmental Protection Agency, 2012).

III. Literature Review Methods

A literature review was completed for the Harford County Health Department in July 2014 by the Johns Hopkins Bloomberg School of Public Health to assess radon mitigation effectiveness and its potential impact on population health. Literature review methods included the following:

- A search of the peer-reviewed literature using a list of relevant keywords
- Review of eleven articles deemed relevant to residential radon mitigation for the Harford County population

The literature reviewed aimed to assess the effectiveness of radon mitigation and remediation in residential homes and the long-term potential impact of such efforts on health, especially lung cancer. The Ovid Medline database was searched for published reports, reviews, and studies. Search terms employed included "radon," "radon resistant," "radon mitigation," "radon regulation," "construction," "new home," "new housing," "residential," "building codes," "preventive measures," "remedial measures," "effectiveness," "health," "indoor air quality," and "lung cancer."

IV. Literature Review Results

Eleven Articles Reviewed

The database search identified 721 unique articles for title and abstract review. Nearly 60% of the identified articles were excluded from the review based on publication dates prior to 2005, as radon research is quickly evolving and advancing. Articles outside the realm of residential settings, such as the health impact of radon on miners or industrial workers, were excluded. Additionally, articles were excluded if the population of study was too narrow, such as an assessment of nonsmoking women or persons in specific age categories. Additionally, studies that dealt with the scientific mechanisms underlying the health impact of radon were excluded. Eleven articles were identified for full review based on presumed relevancy to the examination of the relationship between residential radon mitigation and health and pertinent to the population of Harford County, Maryland. (Breysse, et al., 2011) (Coskeran, Denman, Phillips, & Tornberg, 2005) (Denman, Groves-Kirkby, Coskeran, Parkinson, Phillips, & Tornberg, 2005) (Gagnon, et al., 2008) (Gray, Read, McGale, & Darby, 2009) (Sandel, et al., 2010) (Steck, 2012) (Tracy, Krewski, Chen, Zielinkski, Brand, & Meyerhof, 2007) (Wilcox, et al., 2008) (Zhang, et al., 2012) (Zielinksi, Carr, Krewski, & Repacholi, 2006). Findings from this review are presented below. Findings on radon's impact on health/lung cancer risk are summarized in table 1 (pg. 7) and on mitigation effectiveness in table 2 (pg. 8).

Radon Exposure and Lung Cancer Risk

- The majority of case-control studies find a positive correlation between radon exposure and risk of lung cancer
- Radon affects the risk of lung-cancer in a dose-response manner

There is general consensus among the scientific community that exposure to high radon levels increases risk of lung cancer over the lifetime. While some singular case-control studies have not found a statistically significant heightened risk of lung cancer for high radon exposures (Wilcox, et al., 2008), the majority of case-control studies, especially when pooled together, find a positive correlation between radon exposure and risk of lung cancer. For example, a 2012 meta-analysis of 22 case-control studies determined that a 2.7 pCi/L (100 Bq/m^3) increase in residential radon exposure is associated with a 7% increase in lung cancer risk (Zhang, et al., 2012). This meta-analysis further determined that the combined odds ratio for all 22 case-control studies for highest exposure compared to lowest exposure was 1.29 (95% CI 1.10-1.51), indicating those with the highest radon exposure were 29% more likely to acquire lung cancer than those with the lowest exposure (Zhang, et al., 2012). These conclusions indicate residential radon exposure significantly raises the risk of lung cancer in a dose-response manner (Zhang, et al., 2012). Findings from a 2007 meta-analysis by Tracy et al also indicated that radon exposure affects the risk of lung cancer in a dose-response manner (Tracy, Krewski, Chen, Zielinkski, Brand, & Meyerhof, 2007).

Radon Remediation

- Radon remediation has been found to reduce the long-term risk of lung cancer

Radon remediation aims to lower the population's exposure to radon to improve health, specifically a reduction in lung cancer incidence. As clinical trials to this end are unethical, establishing scientific proof of this hypothesis is not feasible. However, some studies have assessed the affects of radon remediation on the risk of lung cancer. One such study in the United Kingdom by Gray et al concluded that "the cumulative lifetime risk of death from lung cancer for a member of the general population falls from 6.38% at pre-prevention radon concentrations to 6.14% post-prevention, equivalent to a reduction of 5.7 deaths per 1000 households of average size who remediate" (Gray, Read, McGale, & Darby, 2009). A 2012 observational study by Steck in Minnesota found >90% reductions in radon following remediation. Building on this finding, Steck then hypothesized that if these observed reductions were maintained over the lifetime of the 1.2 million Minnesotans living in single-family homes with living space above the EPA's action level, roughly 50,000 lives could be extended for an average of 17 years (Steck, 2012). For reductions of more than 8 pCi/L (300 Bq/m^3), Steck estimated an average lifetime risk reduction of around 4%. Overall, the EPA estimates that for the U.S. population the estimated life-time lung cancer mortality risk is 1.5×10^{-4} per Bq/m^3 (0.03 pCi/L) (Steck, 2012). Therefore, it follows that a reduction in radon exposure will reduce the risk of lung cancer mortality risk.

Radon Mitigation Effectiveness

- Radon mitigation effectiveness studies demonstrate that radon mitigation interventions are effective in reducing radon concentrations in residential buildings
- Radon concentrations were reduced by 80-97% following remediation
- Active radon remediation systems are the most effective way to reduce radon levels in residential buildings
- Passive radon remediation systems are less effective than active remediation, but may offer a a potentially viable, cost-effective solution for newly constructed homes

Building on the finding that lowered levels of radon exposure are associated with decreased risk for lung cancers, the scientific community investigated whether radon mitigation and remediation interventions are effective in reducing residential radon levels. There are two types of radon remediation systems: passive and active. Passive systems involve radon-resistant construction techniques that create a pressure barrier to radon entry and use a pipe to redirect radon gas safely to the outdoors. Active radon remediation systems additionally include a fan to pull radiation from the soil into a vent pipe where it is then exhausted outside the residence (United States Environmental Protection Agency, 2010). Overall, studies of radon mitigation effectiveness indicate that active radon mitigation systems are effective in reducing radon concentrations in residential dwellings. Much of this research has been conducted in Minnesota. A 2011 study by Breysse of 25 Minnesota residential units with pre-renovation short-term radon tests above the EPA's 4 pCi/L (150 Bq/m^3) action level found a decrease in radon concentration to less than 2 pCi/L (75 Bq/m^3) following mitigation (Breysse, et al., 2011). Another study in

Minnesota similarly observed residential reductions on average of more than 90% following active radon mitigation (Steck, 2012). Long-term post-mitigation radon measurements over several years found that 97% of these homes maintained radon levels (average level of .81 pCi/L (30 Bq/m^3) well below the EPA's action level of 4 pCi/L (Steck, 2012).

Additional research on the effectiveness of radon mitigation was conducted in the United Kingdom. In a 2005 United Kingdom study, pre- and post- radon remediation levels indicated that active radon remediation significantly decreased radon levels for 86 domestic properties in which remediation work using sumps had been executed by a single contractor (Denman, Groves-Kirkby, Coskeran, Parkinson, Phillips, & Tornberg, 2005). In this cohort, initial radon levels were between 4.5 and 40.5 pCi/L (168 and 1500 Bq/m^3) while final radon levels were between 0.22 and 5.4 pCi/L (8 and 200 Bq/m^3). This was associated with a collective dose reduction of 4.41 Man-Sievert per year for the 212 occupants of the 86 homes (Denman, Groves-Kirkby, Coskeran, Parkinson, Phillips, & Tornberg, 2005). Findings from another study in the United Kingdom mirrored these results: remediation of properties following best practice guidelines resulted in average post-remediation radiation levels comfortably below standard action levels. For this sample, reductions in average readings of radon levels per household were found to be over 80% (Coskeran, Denman, Phillips, & Tornberg, 2005).

In 2010, Sandel and colleagues reviewed multiple studies to determine which types of radon mitigation interventions are most effective and which types need more research before they are fully recommended (Sandel, et al., 2010). Their conclusion was that radon air mitigation through active soil depressurization—the formation of a negative pressure zone under the building foundation so that soil gases are exhausted through the roof rather than entering the residence—is an effective means to reduce exposure to radon in indoor spaces to less than 4 pCi/L (150 Bq/m^3), the EPA's recommended maximum exposure level to protect health and well-being (Sandel, et al., 2010). This conclusion was based on seven studies involving a substantive number of residences, ranging from 73 to 238 housing units. Sandel's review also cites two national surveys from the 1990s by Brodhead, et.al. and Dehmel that showed 95% of homes had been remediated to less than 4 pCi/L (150 Bq/m^3) (Brodhead, 1995) (Dehmel, 1993). Sandel's conclusions are also supported by an EPA report that determines 97% of houses with high baseline levels of radon (>10 pCi/L [>370 Bq/m^3]) could be remediated with active radon mitigation systems to less than 2 pCi/L (74 Bq/m^3) (Sandel, et al., 2010). Notably, Sandel et.al.'s meta-analysis shows that active mitigation systems are far more effective than passive systems, such as foundation membranes installed during construction (Sandel, et al., 2010). Sandel concludes that passive radon mitigation systems need more substantial research before they can be recommended as standard practice for existing homes, though they do present a potentially viable, cost-effective option for radon-resistant new construction (Sandel, et al., 2010).

Cost-Effectiveness of Radon Remediation Programs

- The cost-effectiveness of radon remediation in avoidance of lung cancer varies substantially across geographical regions
- The cost-effectiveness of a radon remediation program increases with the total number of houses remediated
- Radon remediation efforts, from a cost-effectiveness perspective, should be targeted to areas with a high level of properties above standardized action levels, but current rates of remediation are low
- Radon remediation measures in newly constructive homes are more cost effective than implementing changes in already existing homes

Another important consideration is the cost-effectiveness of radon remediation programs and implementation. Epidemiologists often use life-years gained as an economic indicator of an intervention's success. However, the cost per life-year-gained following remediation in avoidance of lung cancer varies significantly across regions (Coskeran, Denman, Phillips, & Tornberg, 2005). Moreover, the number of houses above standardized action levels, such as those set by the EPA, does not necessarily correlate with cost-effectiveness estimates (Coskeran, Denman, Phillips, & Tornberg, 2005). Instead, the cost-effectiveness of a radon remediation program increases with the number of houses that are in fact remediated (Tracy, Krewski, Chen, Zielinkski, Brand, & Meyerhof, 2007). Therefore, expected adherence to suggested policies is of primary concern when designing radon remediation protocols. To maximize cost-effectiveness, radon remediation efforts should be targeted to areas where the percentage of properties above standardized action levels is high, but current remediation rates are low (Coskeran, Denman, Phillips, & Tornberg, 2005) (Denman, Groves-Kirkby, Coskeran, Parkinson, Phillips, & Tornberg, 2005) (Tracy, Krewski, Chen, Zielinkski, Brand, & Meyerhof, 2007). A policy of requiring basic preventive measures in all newly constructive homes, as opposed to implementing changes in already existing homes, was found to be the most cost-effective option (Gray, Read, McGale, & Darby, 2009) (Sandel, et al., 2010).

Governmental Action

- States vary widely in their approaches to codifying radon-resistant new construction best practices into law
- In Maryland, many counties have local building codes related to radon-resistant new construction

State approaches to radon-resistant new construction legislation are varied. The laws primarily focus on passive radon systems, which do not require the installation of an exhaust fan. The EPA maintains a list of state and local codes related to radon-resistant new construction (United States Environmental Protection Agency, 2013). Currently, twenty-four states and three districts/territories[1] do not have statewide nor local jurisdictions that have radon-resistant new construction codes. Eighteen states[2] do not have statewide radon-resistant codes, but do have local jurisdictions with their own radon-resistant new construction codes. Four states[3] have statewide radon-resistant new construction codes, but they are not mandatory unless local jurisdictions choose to adopt them (United States Environmental Protection Agency, 2013). Seven states[4], including Maryland, have statewide radon-resistant new construction codes that apply only to certain, designated jurisdictions. In Maryland, Baltimore County, Frederick County, Howard County, Montgomery County, Washington County, and the City of Rockville have local building codes related to radon-resistant new construction (United States Environmental Protection Agency, 2013)

[1] AK, AZ, AR, CA, CT, DE, DC, GA, GU, HI, IN, KY, LA, MA, MS, NV, NH, NC, ND, PR, SD, TX, UT and VT

[2] Al, CO, ID, IA, KA, MO, MN, NE, NM, NY, OH, OK, PA, SC, TE, WV, WI, WY

[3] FL, ME, RI, VA

[4] IL, MD, MI, MN, NJ, OR, WA

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Literature Review Summary					
Table 1: Radon's Impact on Health/Lung Cancer Risk					
Primary Author	**Study Title**	**Year**	**Location**	**Sample**	**Key Findings**
Gagnon, Fabien	Assessment of the Effectiveness of Radon Screening Programs in Reducing Lung Cancer Mortality	2008	Quebec, Canada	449 residential units	• The implementation of a universal screening program would prevent less than one death per year on a province-wide scale, equivalent to an overall reduction of 0.19%. • The implementation of a targeted screening program in the region with the highest radon concentrations would decrease radon-related mortality by 1%.
Gray, Alastair	Lung cancer deaths from indoor radon and the cost effectiveness and potential of policies to reduce them	2009	United Kingdom	Multiple Samples	• The cumulative lifetime risk of death from lung cancer for a member of the general population falls from 6.38% at pre-prevention radon concentrations to 6.14% post-prevention, equivalent to a reduction of 5.7 deaths per 1000 households of average size who remediate.
Tracy, Bliss L	Assessment and Management of Residential Radon Health Risks: A Report from the Health Canada Radon Workshop	2007	Canada	Multiple Samples	• Reviews findings from multiple case studies, concludes that radon exposure increases the probability of developing lung cancer.
Wilcox, H.B	Case-Control Study of Radon and Lung Cancer in New Jersey	2007	New Jersey, United States	1,391 Subjects (651 Cases; 740 Controls)	• No significant increases of risk of lung cancer with increasing levels of radon concentrations were observed.
Zhang, Zeng-L	Residential Radon and Lung Cancer Risk: An Updated Meta-analysis of Case control Studies	2012	Multiple Locations	34,482 Subjects (13,380 Cases; 21,102 Controls)	• The combined odds ratio of lung cancer for the highest exposure to the lowest exposure was 1.29 (95% CI 1.10-1.51). • Dose-response analysis found that every 100 Bq/m-3 increment in residential radon exposure was associated with a 7% increase in lung cancer risk.
Zielinksi, Jan M	World Health Organization's International Radon Project	2007	Multiple Locations	Multiple Samples	• Although radon is the leading cause of lung cancer in nonsmokers, most radon-related lung cancers occur in smokers. • Radon is considered to be responsible for 10% of the human lung cancer burden in developed countries.

Table 2: Radon Mitigation Effectiveness					
Primary Author	**Study Title**	**Year**	**Location**	**Sample**	**Key Findings**
Breysse, Jill	Health Outcomes and Green Renovation of Affordable Housing.	2011	Minnesota, United States	31 residential units	• Of the units having pre-renovation short-term radon tests, seven had radon levels equal to or greater than the EPA's 4-picocuries-per-liter (pCi/L) action level. Following mitigation radon was <2 pCi/L.
Coskeran, Thomas	A cost-effectiveness analysis of domestic radon remediation in four primary care trusts located in Northhamptonshire, UK.	2005	Northampton-shire, United Kingdom	91 residential units	• Reductions in average readings of radon levels per household were >80% following remediation.
Denman, Antony	Evaluating the health benefits and cost-effectiveness of the radon remediation programme in domestic properties in Northamptonshire, UK.	2005	Northampton-shire, United Kingdom	86 residential units	• Pre- and post-radon remediation levels indicated that radon remediation decreased radon levels by 85% on average in the residential units.
Sandel, Megan	Housing Interventions and Control of Health-Related Chemical Agents: A Review of the Evidence	2010	Multiple Locations	Multiple Samples	• Between 95 and 97% of houses with high baseline radon levels could be remediated with active soil depressurization systems to less than 4 pCi/L. • Passive radon systems need more research to determine their effectiveness.
Steck, Daniel J	The Effectiveness of Mitigation for Reducing Radon Risk in Single-Family Minnesota Homes	2012	Minnesota, United States	140 residential units	• Long-term post-mitigation radon measurements found 97% of homes had radon concentrations below the EPA's action level of 150 Bq/m^3, even for years after the mitigation was completed. • The average post-mitigation radon in the tested houses was 30 Bq m^3, which corresponded to an observed reduction of >90% on average for the houses in the study.