COMMENT

Legal Tools to Reduce Radon's Risk: An Evaluation of Mandatory Radon-Resistant New Construction in Building Codes

by William C. Bellamy and Paul A. Locke

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According to the U.S. Environmental Protection Agency (EPA), residential exposure to radon gas represents the second-leading cause of lung cancer among smokers and the leading cause of lung cancer among nonsmokers in the United States.[1] EPA's evaluation of radon's hazards is based on a considerable body of scientific evidence, including consensus studies by national and international scientific organizations.[2] Based on this extensive scientific record, EPA has postulated that radon is associated with 21,000 deaths from lung cancer in the United States each year, and that approximately 18,000 of these deaths occur among smokers and approximately 3,000 occur among nonsmokers.[3] In cases of co-exposure (i.e., tobacco smoking and radon exposure), a synergistic relationship between radon exposure and cigarette smoking significantly increases lung cancer risk.[4] This makes exposure to radon in the home particularly risky for smokers.

The most common isotope of radon, radon-222, results from the decay of radium in the earth's crust as part of the uranium-238 decay chain.[5] As a gas, radon can move up through soil and enter indoor environments through cracks in foundations and other openings and accumulate in buildings, especially homes.[6] With a half-life of 3.8 days, radon decays into solid products that can become attached to dust particles before being inhaled.[7] The decay products, known as radon progeny, deposit in the lungs and expose the basal and secretory cells in the bronchial epithelium to ionizing alpha particles during continued radioactive decay.[8] Alpha particles lead to DNA damage that can trigger the development of lung cancer through the multistage process of carcinogenesis.[9]

A pooled analysis of 13 epidemiological studies in Europe and a pooled analysis of seven epidemiological studies in North America provide strong support for the relationship between exposure to radon in residential environments and lung cancer, and are consistent with earlier studies among miners.[10] Efforts to model the increase in lung cancer risk resulting from exposure to radon suggest a linear,

Authors' Note: This Comment arose out of and extended William C. Bellamy's undergraduate senior thesis project, of which Paul A. Locke served as the supervising faculty.

1. *See* U.S. EPA, *Health Risk of Radon*, https://www.epa.gov/radon/health-risk-radon (last updated Aug. 27, 2018).
2. *See* National Research Council, Health Effects of Exposure to Radon: BEIR IV (1999); International Commission on Radiological Protection, ICRP Publication No. 126, Radiological Protection Against Radon Exposure (2014). While several of these reports are based on data from miners exposed to radon, more recent epidemiologic studies in homes have confirmed, and strengthened, these findings. *See infra* note 10 and accompanying text.
3. *See* U.S. EPA, *supra* note 1.
4. While cigarette smoking is the main cause of lung cancer risk, active smokers who are exposed to radon are at risk for developing lung cancer at a rate that is submultiplicative; it is beyond that which would be expected if the increases in risk from each factor alone were simply added, and less than (but closer to) the increase in risk if these two factors were multiplied. *See* National Research Council, *supra* note 2, at 10-12.
5. The "uranium decay chain" represents the series of compounds that are created as uranium (and its decay) emits ionizing radiation. These unstable atoms transform every time they emit radiation (i.e., decay), resulting in the creation of a different compound. Radioactive decay continues until a stable compound is reached. Radon is the only gas in the radioactive decay chain of uranium. Jerome S. Puskin & Anthony C. James, *Radon Exposure Assessment and Dosimetry Applied to Epidemiology and Risk Estimation*, 166 Radiation Res. 193 (2006); U.S. EPA, *Radioactive Decay*, https://www.epa.gov/radiation/radioactive-decay (last updated Dec. 21, 2017).
6. *See* U.S. EPA, *Radon in Homes and Buildings*, https://www3.epa.gov/radtown/radon-homes-buildings.html (last updated Mar. 12, 2018).
7. *See* National Research Council, *supra* note 2, at 20-22.
8. Puskin & James, *supra* note 5, at 201. An alpha particle, or alpha radiation, is a heavy, short-range particle that has the same atomic structure as a helium nucleus (two protons and two neutrons). *See* Health Physics Society, *What Types of Radiation Are There?*, https://hps.org/publicinformation/ate/faqs/radiationtypes.html (last visited Sept. 30, 2018).
9. *See* National Research Council, *supra* note 2, at 36-68.
10. Sarah Darby et al., *Radon in Homes and Risk of Lung Cancer: Collaborative Analysis of Individual Data From 13 European Case-Control Studies*, 330 Brit. Med. J. 223 (2005); Daniel Krewski et al., *Residential Radon and Risk*

no-threshold dose-response relationship.[11] EPA maintains an "action level" of four picocuries per liter (pCi/L),[12] at or above which the Agency recommends that individuals act to lower radon concentrations in their homes. Due to the hypothesized dose-response relationship for radon and lung cancer, this action level does not constitute a safe level of exposure, but rather one based on technological feasibility and cost in addition to risk.[13]

To reduce the lung cancer risk associated with inhaling radon, EPA, and almost all states, have created programs to protect the public. Among other things, federal and state programs recommend that all existing homes be tested for radon and that homes found to have high levels undergo mitigation. Many programs also recommend that new homes incorporate radon-resistant new construction (RRNC) techniques, which include depressurization systems and sealants to prevent the entry of radon from the underlying soil.

This Comment evaluates the lung cancer risk reduction potential of one legal tool, a radon-resistant new construction ordinance. Easton, Pennsylvania, enacted such an ordinance; it required RRNC in all new homes beginning July 2004. Part I of this Comment summarizes federal laws that relate to radon. Part II details state laws both in general and specific to Pennsylvania, and also discusses measures taken at local levels in Pennsylvania. Part III introduces the Pennsylvania radon database, and explains the methodology used to estimate the impact of RRNC on household radon levels in Easton.

In Part IV, we provide a summary and interpretation of the results of the data analysis of radon measurements in homes, RRNC, and other dependent and independent variables associated with radon levels and radon reduction. Part V contextualizes the reduction in radon levels achieved by RRNC in terms of lung cancer risk and discusses uncertainties in the analysis and potential directions for future research in this area. It also offers conclusions based on the data evaluated in this Comment. We suggest that EPA should be more assertive in taking advantage of the regulatory authority provided to it pursuant to federal laws. In addition, states, cities, towns, and counties should continue to exercise leadership in lung cancer risk reduction by using legal tools such as RRNC to reduce radon levels in homes.

The data analysis in this Comment shows that homes built after the adoption of an RRNC ordinance by the city of Easton are more likely to have low levels of radon than homes built before its adoption. This evidence supports the effectiveness of RRNC techniques, as well as building codes mandating them, and further shows that RRNC is an effective legal tool to reduce exposure to a known lung carcinogen. In other words, RRNC is a valuable public health intervention that policymakers should employ; jurisdictions should follow the example of Easton and adopt RRNC. While further research would reduce some of the uncertainties in data analysis, we do not believe it would substantially change our findings.

I. Federal Laws Addressing Radon

Radiation is covered by a number of federal statutes, including environmental laws that regulate contaminants, such as the Clean Air Act[14] and the Safe Drinking Water Act[15]; laws governing the workplace, such as the Occupational Safety and Health Act[16]; and statutes that address other uses of radiation, such as medical devices (Federal Food, Drug, and Cosmetic Act) and nuclear power (the Atomic Energy Act).[17] However, this part focuses on the only two federal laws that directly address environmental radon—the Indoor Radon Abatement Act (IRAA) and the Indoor Air Quality and Radon Gas Act of 1986 (Radon Gas Act).[18]

A. *The IRAA*

The IRAA was enacted in 1988. The IRAA sets as a national goal that the radon level indoors should be as low as the radon level out-of-doors.[19] It authorizes EPA to publish a citizen's guide to radon, and provides that the citizen's guide shall contain, among other things, a discussion about radon's health hazards, its costs of mitigation, and the costs and technical feasibility of reducing radon levels in buildings. The IRAA also instructs EPA to determine an "action level" for radon.[20] EPA is told to work with relevant organizations, to the extent possible, in preparing national building code construction standards and techniques that will reduce radon.[21]

of Lung Cancer: A Combined Analysis of 7 North American Case-Control Studies, 16 Epidemiology 137-45 (2005).

11. Darby et al., *supra* note 10; Krewski et al., *supra* note 10; *see also* U.S. EPA, *Radiation Health Effects*, https://www.epa.gov/radiation/radiation-health-effects (last updated July 13, 2018). "The [linear no-threshold] model assumes that the risk of cancer due to a low-dose exposure is proportional to dose, with no threshold. In other words, cutting the dose in half cuts the risk in half." This relationship presumes that the risk of lung cancer increases proportionately with increases in radon exposure and that some risk of lung cancer exists at any level of exposure to radon.
12. When radiation is measured in picocuries per liter in air, it is a measure of radiological activity, expressing the amount of radioactivity produced in a liter of air. It is not a direct measure of lung cancer risk. Converting radon levels in picocuries per liter into estimates of lung cancer risk requires additional information about exposure time, exposure conditions, and other factors, such as radon equilibrium in air. *See*, *e.g.*, U.S. EPA, Technical Support Document for the 1992 Citizen's Guide to Radon app. E (1992) (EPA 400-R-92-001) [hereinafter Technical Support Document].
13. *See* Technical Support Document, *supra* note 12, ch. 7; U.S. EPA, A Citizen's Guide to Radon (2012) (EPA 402/K-12/002) [hereinafter Citizen's Guide], *available at* https://www.epa.gov/sites/production/files/2016-02/documents/2012_a_citizens_guide_to_radon.pdf. The citizen's guide contains testing recommendations for U.S. homes and dwellings.
14. 42 U.S.C. §7401-7671q, ELR Stat. CAA §§101-618. In particular, see *id.* §7412(b) (list of pollutants).
15. *Id.* §300(f)-300j-26, ELR Stat. SDWA §§1401-1465. In particular, see National Primary Drinking Water Regulations for Radionuclides, 40 C.F.R. pt. 141.
16. 21 U.S.C. §§301 et seq.
17. 42 U.S.C. §§2011-2021, 2022-2286i, 2296a to 2296g-4.
18. 15 U.S.C. §§2661-2761; 42 U.S.C. §7401.
19. 15 U.S.C. §2661.
20. *Id.* at §2663. EPA set an action level of 4 pCi/L, as explained earlier.
21. *Id.* at §2664.

The IRAA provides EPA with authority to establish a state grant program to combat radon contamination, and this program was created very soon after the IRAA was passed. It has been a centerpiece of EPA's radon program since its inception.[22] While the state grant program under the IRAA remains in effect today, federal funding for radon-related activities has significantly declined in the past 30 years. Research published in 2008 noted a decline of more than 60% in funding for the U.S. radon program from 1997 to 2007.[23]

The IRAA authorizes EPA to promulgate regulations to implement its provisions; it does not appear that EPA has used its regulatory authority to promulgate regulations that directly control radon in buildings.[24] According to a report issued by EPA's Office of Inspector General:

> Although the 1988 IRAA does not require EPA to issue regulations to address indoor radon, it does not prohibit EPA from doing so either. Congress authorized the EPA Administrator in Section 310 "to issue such regulations as may be necessary to carry out" the provisions of the IRAA. To date, 19 years after the IRAA was enacted, EPA has not proposed any indoor radon regulations.[25]

B. The Radon Gas Act

The Radon Gas Act is not codified, but instead was established in a note to the U.S. Code.[26] In this Act, the U.S. Congress directed EPA to establish a research program for radon and other issues of indoor air quality.[27] Congress listed the operations of the research program to include compiling information, providing guidance for research and development of radon testing and mitigation technology, and evaluating radon mitigation efforts by the federal government. The Radon Gas Act explicitly limits EPA's ability to regulate radon. Section 404 of this legislation states: "Nothing in this title shall be construed to authorize the Administrator to carry out any regulatory program or any activity other than research, development, and related reporting, information dissemination, and coordination activities specified in this title."[28]

The two federal laws that directly address environmental radon have spawned a number of EPA-administered voluntary programs, including a state grant program; have been used to establish a radon action level; have resulted in scientific research, and communications efforts, such as *A Citizen's Guide to Radon*; and have encouraged EPA to partner with organizations to encourage radon testing and mitigation. However, in the 30 years since the passage of the IRAA, it does not appear that EPA has utilized its regulatory program under the IRAA to directly control indoor radon.

II. State Laws and Local Ordinances Addressing Radon

To supplement the voluntary efforts of the federal government to address radon in homes, states have passed a variety of different radon-related laws and some local jurisdictions have enacted radon ordinances. Many of these state laws apply to real estate transactions and radon professional services certification and licensure. Local ordinances, and some state laws, cover building codes, especially RRNC. After describing these laws generally, this part examines the major radon laws, regulations, and ordinances of the commonwealth of Pennsylvania and one of its local jurisdictions, because Pennsylvania has an extensive and successful radon program, and because the data analysis set out in Part III was collected in, and is directly applicable to, a Pennsylvania town.[29]

A. State Laws and Local Ordinances Generally

1. State Radon Laws

State radon laws and policies are reviewed and compiled by several organizations, including the Environmental Law Institute (ELI). These compilations illustrate that, unlike federal radon programs, states have often adopted regulatory programs applicable to radon, especially regarding radon testing and mitigation, and licensure or certification of radon professionals.[30] ELI has published numerous reports and other information on state radon laws, including a database of state indoor air laws that covers radon, and which is updated annually.

In its October 2012 report, ELI notes that 32 states require home sellers to disclose certain information about radon to homebuyers, though none require radon testing.[31] The report also notes that 13 states have "laws that establish a state radon certification program, including mini-

22. *Id.* at §2666. *See also* Office of Inspector General, U.S. EPA, Report No. 08-P-0174, More Action Needed to Protect the Public From Indoor Radon Risks (2008).
23. William J. Angell, *The U.S. Radon Problem, Policy, Program, and Industry: Achievements, Challenges, and Strategies*, 130 Radiation Protection Dosimetry 8, 12 (2008).
24. The radon programs established under the IRAA are voluntary. *See* Office of Inspector General, *supra* note 22.
25. *Id.* at 17.
26. It is not clear why this Act was not codified into the U.S. Code. *See* Pub. L. No. 99-499, 100 Stat. 1758.
27. *See* 42 U.S.C. §7401, note 1; *see also* R. Bruce Dickson, *Regulation of Indoor Air Quality: The Last Frontier of Environmental Regulation*, 9 Nat. Resources & Env't 21 (1994).
28. Pub. L. No. 99-499, 100 Stat. 1760.
29. *See infra* Part III.
30. *See* ELI, Radon in Homes: Strengthening State Policy to Reduce Risk and Save Lives 35 (2012) [hereinafter ELI 2012 Report]. In this report, ELI examines 25 years of state radon laws and policies, concluding that "[i]n light of the number of people at risk of dying from radon-related lung cancer, states can benefit from enacting stronger radon laws and regulations." *See also* ELI, Database of State Indoor Air Quality Laws, Database Excerpt: Radon Laws (2018), https://www.eli.org/sites/default/files/docs/greenbuilding/radon_2018.pdf. This database has been updated through December 2017 [hereinafter ELI 2018 Database].
31. *See* ELI 2012 Report, *supra* note 30 at 13; State common law might also require disclosure of known high radon levels, if under state common law such levels would be considered "materials defects." *See, e.g.*, Sheldon Wincour, *Clearing the Air on Radon Testing: The Duty of Real Estate Brokers to Protect Prospective Homebuyers*, 15 Fordham Urb. L.J. 767, 773 (1987), *available at* https://ir.lawnet.fordham.edu/ulj/vol15/iss3/7.

mum qualifications and standards of practice," and that additional states "require radon testers, mitigators, and/or laboratories to obtain third-party certification in order to practice, but do not issue their own state certification or carry out a certification oversight program."[32]

Regarding building code amendments requiring RRNC, ELI notes that Connecticut, Illinois, Maryland, Massachusetts, Michigan, Minnesota, New Jersey, Oregon, and Washington "incorporated such mandatory radon control requirements for new home construction into their residential building codes."[33] States have also enacted other forms of laws related to radon. For instance, Illinois mandates state approval of devices used for sampling and measurement of radon. Misrepresenting the capabilities of such a device constitutes a misdemeanor under state law.[34]

2. Local Radon Ordinances

One approach to addressing residential radon at the state level and especially at the local level is to adopt a building code requiring the use of RRNC techniques. This strategy is often the preferred approach for addressing high radon levels in newly constructed dwellings. RRNC techniques vary, but generally rely on a sub-slab depressurization system, which consists of a vent pipe that runs from beneath the house up through its roof, thereby linking the sub-slab space to the outdoor air.[35] This system has been shown to effectively vent radon gas from the soil below the slab into the air above the house.[36]

If indoor radon concentrations following the construction of a house with RRNC require further action to reduce radon levels, the *passive* sub-slab depressurization system can be converted into an *active* system by the addition of a fan. An active system further reduces sub-slab air pressure relative to indoor air pressure by more forcefully pulling air from the sub-slab space through the vent pipe. Other requirements include a layer of gravel covered by plastic sheeting or a vapor retarder under the slab of the house and the use of sealants to prevent entry of radon into homes.[37]

The International Code Council (ICC), ASTM International, and the National Fire Protection Association have each issued model RRNC building codes. In our study, we examined the impact of RRNC under ICC's Appendix F of the International Residential Code.[38]

3. Pennsylvania State Radon Laws

Pennsylvania has one of the oldest, and most comprehensive radon control programs in the United States. High radon levels in homes first came to the attention of the public because of a Pennsylvania home.[39] There are three primary laws that make up the Pennsylvania radon program. The first establishes a demonstration program for radon testing and remediation in homes and buildings, and requires the Pennsylvania Department of Environmental Protection (DEP) to work with homeowners in areas of high radon potential to avoid unscrupulous or unqualified radon contractors.[40] This law also instructs the DEP to establish minimum standards for radon contractors participating in the demonstration project. Under this act, the Pennsylvania Housing Finance Agency has been ordered to create a low-interest loan program for radon remediation.[41]

The second law, the Radon Certification Act,[42] requires (1) that the DEP[43] establish certification programs for radon testers and mitigators; and (2) that testers and mitigators disclose all services performed, and the addresses at which such services were performed, to the DEP. All such reported data are confidential, and cannot be shared by the DEP except for "use in conducting legitimate scientific studies."[44] The DEP has promulgated regulations to carry out the purposes of this Act.[45] The third law requires the Pennsylvania Real Estate Commission to create a radon disclosure statement for use in residential real estate transactions so that sellers will disclose knowledge about the presence of radon at the property.[46]

4. Pennsylvania Local RRNC Ordinances

In Pennsylvania, the townships of Amity, East Earl, East Hempfield, Ephrata, Hanover, Manheim, Martinsburg Borough, Mount Pleasant, Pequea, Peters, Warrington, and West Hempfield, and the city of Easton have adopted RRNC ordinances, specifically Appendix F.[47]

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32. *See* ELI 2012 Report, *supra* note 30 at 5.
33. *See* ELI, Radon Control in New Home Construction: Developments in State Policy, https://www.eli.org/buildings/radon-control-new-home-construction-7 (last updated Oct. 31, 2018).
34. *See* ELI 2018 Database, *supra* note 30 at 8-9.
35. International Code Council, *2018 International Code for One- and Two-Family Dwellings: Appendix F Radon Control Measures*, https://codes.iccsafe.org/public/document/IRC2018/appendix-f-radon-control-methods (last visited Sept. 30, 2018).
36. Citizen's Guide, *supra* note 13.
37. U.S. EPA, *Radon-Resistant Construction Basics and Techniques*, https://www.epa.gov/radon/radon-resistant-construction-basics-and-techniques (last updated Aug. 27, 2018).
38. *See* U.S. EPA, *Building Codes for Radon-Resistant New Construction (RRNC)*, https://www.epa.gov/radon/building-codes-radon-resistant-new-construction-rrnc (last updated Aug. 27, 2018).
39. Philip Shabecoff, *Radioactive Gas in Soil Raises Concern in Three-State Area*, N.Y. Times, May 19, 1985.
40. *See* Pa. Stat. tit. 35, ch. 43 (Radon Gas Demonstration Project and Home Improvement Loan Act).
41. *Id.* at §7503.
42. *See id.* at tit. 63, ch. 34 (Radon Certification Act).
43. The language of this statute empowers the Pennsylvania Department of Environmental Resources to carry out this Act. This department was split into the DEP and the Department of Conservation and Natural Resources in 1995 (*see* Conservation and Natural Resources Act, cl. 27, Act of June 28, 1995, Pub. L. No. 89, No. 18, http://www.legis.state.pa.us/WU01/LI/LI/US/PDF/1995/0/0018.PDF). The DEP now administers the radon program.
44. *Id.* at §2009.
45. *See* 25 Pa. Code ch. 240 (Radon Certification), https://www.pacode.com/secure/data/025/chapter240/chap240toc.html (last visited Sept. 30, 2018).
46. Pa. Stat. tit. 68, §§7301 et seq.
47. *See* U.S. EPA, *supra* note 37.

III. Data, Methodology, and Analysis

A. Overview of RRNC/Lung Cancer Risk Study

After obtaining radon testing data from the commonwealth of Pennsylvania through a data-sharing agreement,[48] we sought to evaluate the effectiveness of RRNC in reducing household radon levels—and, by extension, lung cancer risk—in a community with a mandatory RRNC building code. Our research goal required us to obtain radon measurements taken in homes built with and without RRNC and to determine the most appropriate statistical methods for comparing radon levels between the two groups of homes. We chose Easton as the site for our study, because the city adopted Appendix F in June 2004 and afforded us the ability to gather all of the data necessary for our study.[49]

B. Easton—Demographic Overview

The U.S. Census Bureau estimates that Easton had a total of 11,065 housing units in 2016, compared to 9,848 housing units in 2009.[50] The Census Bureau also estimates that, in 2016, 65.4% of the city's housing stock was built before 1939. According to the spreadsheet provided by the chief code administrator of Easton, 166 permits for one- and two-family dwellings and townhouses have been issued from the adoption of Appendix F to September 2016. The Census Bureau finds that the proportion of owner-occupied housing units in Easton has declined in recent years, from 51.4% of all housing units in 2011 to 45.6% in 2016.[51]

According to the Census Bureau, the population of Easton stood at 27,109 as of July 1, 2017.[52] Easton is diverse, with African Americans (20.9%) and Asians (4.5%), as well as Hispanics/Latinos (23.1%), accounting for significant percentages of its overall population, as of 2016.[53] The Census Bureau estimates that in 2016, the percentage of foreign-born residents of Easton stood at 12.8%, and 21.4% of individuals older than five years lived in households speaking a language other than English.[54] In 2016, the median household income in Easton stood at $45,361.[55]

C. Easton—Radon and Construction Data

The principal data sources for this evaluation included the radon data obtained from the Pennsylvania DEP and publicly available data of homes built after the passage of Appendix F in Easton.[56] The DEP database—geocoded by other researchers at Johns Hopkins University[57]—contains 1,983,705 observations of radon tests conducted from 1986 to 2013. For each observation, the database provides the radon level measured by the test, the location of the test, the address of the house, the house type, and the geological formation beneath the house, among other variables. From this database, we obtained an initial data set of 15,635 radon measurements conducted in Easton from 1988 to 2013. These measurements spanned the period before the enactment of the RRNC ordinance (1988 to early 2004), as well as after (late 2004 to 2013). Easton adopted the RRNC ordinance in June 2004 and it became effective in July 2004.[58]

D. Data Analysis, Methodology, and Corrections

We began by identifying all observations in the DEP radon testing database that occurred in Easton. We found 15,635 observations for addresses matching those provided by the city of Easton, and identified 73 observations of radon tests conducted at 37 addresses matching those homes in which RRNC was installed.[59] After further examining the data to eliminate inconsistencies in address and location, we reduced our sample size of RRNC homes from 37 to 29. The existence of multiple test observations in many of the homes required us to further edit our data to prevent redundancies from affecting summary statistics and analyses.[60] Additionally, we chose to drop test observations associated with three incorrectly coded identification (ID) variables and those occurring in schools, trailers, and commercial buildings. These corrections reduced the number of observations from more than 15,000 to 11,100. After

48. To facilitate scientific studies about radon in Pennsylvania, the Johns Hopkins Bloomberg School of Public Health and the Pennsylvania DEP entered into a confidential data-sharing agreement under which Hopkins obtained approximately 1.9 million data points that represented Pennsylvania residential radon tests carried out between 1986 and 2013.

49. The study protocol was reviewed and approved by the Johns Hopkins Bloomberg School of Public Health Institutional Review Board (IRB Review No. IRB00007606, approved Dec. 30, 2016).

50. U.S. Census Bureau, American Fact Finder, *Community Facts: Easton City, Pennsylvania*, https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml (last visited Sept. 30, 2018). The increase in homes in Easton from 2009 to 2016 (1,217 homes added) appears to outpace the number of permits issued for new homes (166) from 2005 to 2016 according to the data provided by the city of Easton. However, the estimates of the Census Bureau must be interpreted with caution, taking into consideration significant margins of error in the Census data.

51. *Id.*

52. *Id.*

53. *Id.*

54. *Id.*

55. *Id.*

56. *See supra* note 48 for additional information about the DEP radon database. The data on homes built in Easton were provided by Easton's chief code administrator, based on public records. Private Communication With Stephen Nowroski, Chief Code Administrator, Easton, Pennsylvania (Sept. 20, 2016).

57. Joan A. Casey et al., *Predictors of Indoor Radon Concentrations in Pennsylvania, 1989-2013*, 123 Envtl. Health Persp. 1130-37 (2015).

58. Easton, Pa., Code §245-8 (2004), https://ecode360.com/9641786.

59. We found the addresses to be inconsistently coded, with frequent differences in capitalization and abbreviation for the same address. We were able to better classify dwellings on the basis of longitude and latitude.

60. It is not surprising to find that there were duplicate tests in the same location—both the citizen's guide and the home buyer's and seller's radon guide testing protocols call for duplicate, or simultaneous, testing. *See* U.S. EPA, Home Buyer's and Seller's Guide to Radon (2018) (EPA 402-K-13/002); Citizen's Guide, *supra* note 13. In this database, complete duplicates possessed the same radon measurement, test location, and test date, while partial duplicates possessed the same test location and test date, but different radon measurements.

data cleanup, our data set consisted of 36 radon observations in 29 homes built with RRNC techniques and 11,064 radon observations in 6,499 homes built without RRNC techniques.

We next examined the data by plotting it and discovered that the radon test measurements were lognormally distributed[61] (see Figure 1). In a lognormal distribution, the majority of observations lie at lower values, and a few observations lie at very high values. A substantial number of data points are in lower ranges, with a long "tail" extending out to the data points at higher levels (see Figure 2). The term "lognormal distribution" comes from the fact that taking the logarithms of the observations can produce the "normal," bell curve-shaped distribution, which is a prerequisite for the application of many statistical methodologies.[62] In addition, descriptive statistical methods also revealed censoring in the distribution of radon measurements taken in Easton, in the form of a cutoff at 0.5 pCi/L.[63] Either due to limits of detection of the radon testing devices or to reporting standards, observations lower than 0.5 pCi/L were listed as 0.5 pCi/L rather than their true values, creating a spike in the distribution at this point.

Figure 1. Distribution of Natural Logarithms of Radon Measurements in Homes Built Without RRNC

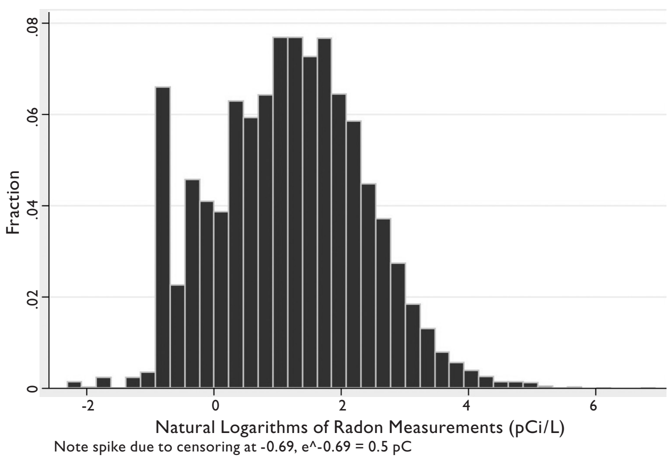

Figure 2. Distribution of Natural Logarithms of Radon Measurements in Homes Built With RRNC

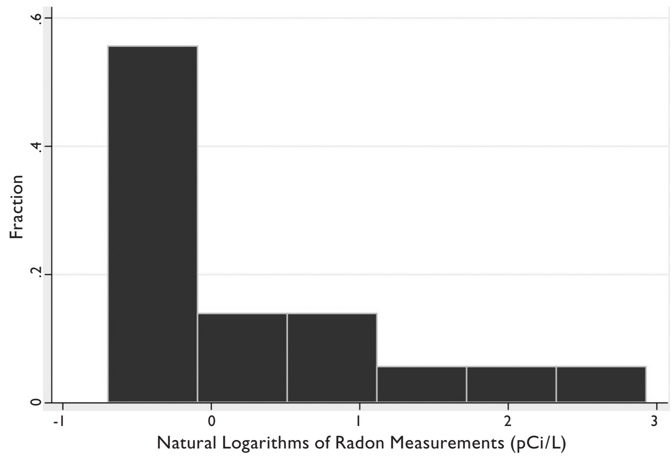

Figure 1 depicts the distribution of radon measurements in non-RRNC homes on a natural logarithmic scale and mirrors the histogram for radon measurements in all homes, as measurements in non-RRNC homes account for the vast majority of all measurements in the data set. Figure 2 depicts the distribution of radon measurements in RRNC homes on a natural logarithmic scale and the lack of a bell-curve shape further illustrates the need to use statistical techniques not dependent upon assumptions of normality, such as logistic regression.

The combination of the logarithmic distribution and data censoring influenced our decision to use logistic regression for data analysis, and for comparing the radon measurements in RRNC and non-RRNC homes. Logistic regression is the statistical tool that best fits, and is appropriate for, data sets such as the one in this study. Applying logistic regression, we can obtain a statistic known as the "log odds" as the function of independent variables. More specifically, in this study, we used logistic regression to estimate whether RRNC could achieve a reduction in the odds of a test measurement matching or exceeding the EPA action level of 4 pCi/L and matching or exceeding 1 pCi/L. Using the log odds ratio, we can then evaluate whether RRNC has been effective in reducing radon levels, and, correspondingly, in reducing lung cancer risk.

To strengthen our logistic model, we recognized that a number of factors in addition to RRNC can influence residential radon levels. These factors include house type (multifamily residence versus single detached home), test location (radon levels tend to be higher at lower levels of homes) and season (radon levels tend to be higher during winter months). We therefore incorporated variables for test location, house type, and test season into the logistic model so that the model would adjust for the influence of these important factors.

In addition, we considered how other independent variables (i.e., other factors that can affect the outcome vari-

61. A lognormal distribution was expected and is consistent with radon measurement distributions in other studies. Zornitza Daraktchieva, *Radon, the Lognormal Distribution, and Deviation From It*, 34 J. Radiological Protection 184 (2014).
62. It is standard statistical practice to log transform such data sets so that they can be analyzed using traditional statistical techniques.
63. Censoring occurs when the value of a measurement is only partially known (e.g., when measured by a device with a detection limit of 0.5 pCi/L, a home with radon levels below 0.5 pCi/L will produce a measurement of 0.5 pCi/L, allowing us to conclude only that the household radon level is 0.5 pCi/L or lower). *See* U.S. EPA, Indoor Radon and Radon Decay Product Measurement Device Protocols (1992) (EPA 402-R-92-004).

able being studied)[64] should be handled in our analysis. When we could, we used descriptive statistical techniques to make decisions regarding the inclusion, and adjustment, of these independent variables. For instance, the DEP database noted eight categories of test location, including a category for unknown locations, but we opted to distinguish between observations with basement or slab on grade as the test location (85.12%) and tests conducted elsewhere (14.88%). We made this decision due to the tendency of measurements recorded at the lowest level of the home—the basement or slab on grade—to exceed the action level at a much higher frequency than observations recorded in other locations. Similarly, we chose to distinguish between tests conducted (0.73%) and not conducted (99.27%) in apartments and tests conducted (26.11%) and not conducted (73.89%) during summer months, rather than including every house type or month in the model.

Missing data prevented us from accounting for geological formation in the logistic models of RRNC's impact, as 52.77% of observations in homes with RRNC lacked data regarding this variable.[65] Additional variables in the DEP data set included test year, test duration, and test sequence number, but we opted not to incorporate these variables due to a lack of a clear impact on radon levels. Additionally, we chose to exclude test device from the model on the basis that different test devices are unlikely to bias the impact of RRNC or other variables upward or downward. We used the Stata 13[66] cluster option with the unique ID variable to account for the presence of multiple test observations in many of the homes involved in our study and employed jackknifing[67] to obtain more robust margins of error for the increases and decreases in radon levels associated with the independent variables of our model.

E. Results of Logistic Regression

We ultimately ran our statistical analyses on a subset of observations. From the initial cleaned data set of 11,100 radon measurements, we dropped 5,026 that occurred prior to the institution of Appendix F in order to ensure greater similarity between the RRNC and non-RRNC observations. We also excluded 1,351 observations that were missing information about the test location, house type, or both from the analysis. All observations listed the month and the season in which they occurred. These changes left us with 4,723 radon measurements (33 in 27 RRNC homes, 4,690 in 3,030 non-RRNC homes) taken July 2004 to December 2013.

Among observations in homes built without RRNC, 2,613 are equal to or exceed the action level and 3,425 fall below it. Therefore, the odds of a measurement in the non-RRNC group matching or exceeding the action level are 2,613 to 3,425 or 2,613/3,425 = 0.7629. Similarly, five measurements in RRNC homes match or exceed the action level and 31 fall below, so the odds of a test measurement of 4 pCi/L or higher are 5 to 31 or 5/31 = 0.1613. We can then take the natural logarithm (ln) of the two sets of odds to obtain the log odds of matching or exceeding the action level for measurements in RRNC homes (-1.8245) and non-RRNC homes (-0.2706). If we subtract -0.2706 from -1.8245, we obtain a difference of -1.5539, which becomes 0.2114 when transformed back from the log odds (e^-1.5539). From here, we can obtain the percent reduction in the odds of matching or exceeding 4 pCi/L (1 -0.2029 * 100 = -78.86%), comparing homes built with RRNC to homes built without RRNC. As explained above, the models used in this study are more complex than this example, as they adjust for multiple variables and account for multiple tests within the same home.

IV. Results and Discussion

A. Impact of RRNC on Radon Levels in Easton

Focusing on the 6,074 measurements taken after June 2004, the median radon measurement in homes built with RRNC was calculated to be .775 pCi/L, whereas the median measurement in homes built without RRNC stood at 3.3 pCi/L (see Figure 3). Regarding the action level of 4 pCi/L, 13.89% of measurements conducted in homes with RRNC matched or exceeded 4 pCi/L, compared to 43.28% of measurements in homes without RRNC. Additionally, 44.44% of measurements in RRNC homes matched or exceeded 1 pCi/L, while 82.73% of measurements in non-RRNC homes matched or exceeded this level.

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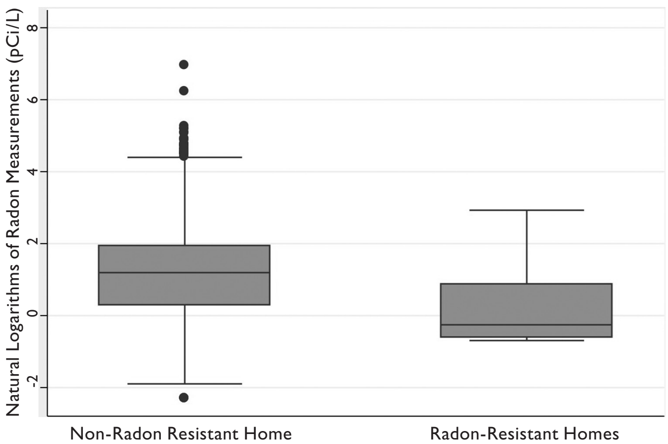
64. Linda L. Wright & David A. Lake, Basics of Research for the Health Professions ch. 3.2, *available at* http://www.pt.armstrong.edu/wright/hlpr/text/3.2.indvar1.htm (last visited Sept. 30, 2018).
65. For a fuller discussion about geologic formations, see *supra* Section B.4.
66. Stata 13 is a commercial product—a statistical software package commonly used in public health studies.
67. Jackknifing consists of rerunning the statistical model on numerous iterations of the data, each missing measurements from one of the homes included in the study and then combining the results to estimate a statistic's standard error. Jackknifing provides a means of testing the robustness of the statistical findings. Bradley Efron, *Nonparametric Estimates of Standard Error: The Jackknife, the Bootstrap, and Other Methods*, 68 Biometrika 589 (1981).

Figure 3. Box Plots of Radon Measurements After Log Transformation by RRNC



Median Measurement for Non-RRNC Homes: 1.194, e^1.194 = 3.3 pCi/L,
Median Measurement for RRNC Homes: -.255, e^-.255 = .775 pCi/L

The line in the middle of each box plot represents the median, the top edge of the box represents the 75th percentile, the bottom edge of the box represents the 25th percentile, and the dots at the edges of the structures represent particularly high or particularly low radon measurements, also known as outliers. In this case, the median radon measurement on a natural logarithmic scale in non-RRNC homes exceeds the 75th percentile measurement in RRNC homes, indicating that measurements in non-RRNC homes tend to be higher than in RRNC homes.

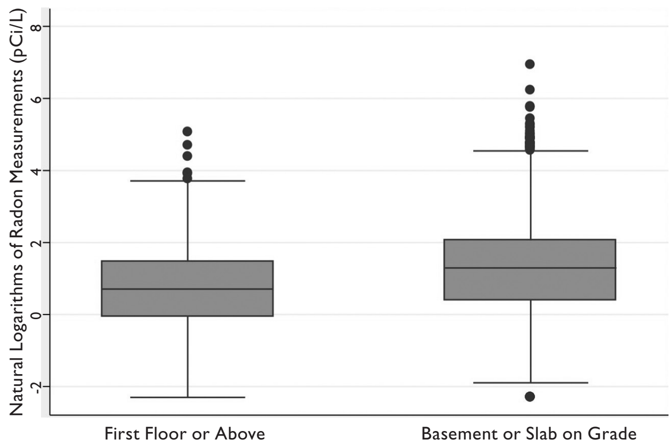
After accounting for house type, test location, and seasonality, we saw a -70.75% change in the odds of a test measurement matching or exceeding the action level comparing homes built with RRNC to those homes built without RRNC. Jackknifing produced a non-statistically significant 95% confidence interval of (-93.97%, 42.01%). RRNC was also associated with a -76.59% change in the odds of a test result of 1 pCi/L or higher, holding all else constant. In this instance, the 95% confidence interval (-91.01%, -39.08%) derived from jackknifing was statistically significant. With the exclusion of observations missing data for the independent variables, both the 4 pCi/L and 1 pCi/L models incorporated 4,723 test measurements in 3,057 homes, with 33 tests conducted in 27 RRNC homes and 4,690 tests conducted in 3,030 non-RRNC homes.

B. Additional Independent Variables and Their Potential Impact on Radon Measurements

1. Test Location

Among 10,915 measurements with test location data taken from 1988 to 2013, the median of radon measurements taken at the lowest level of a home—basement or slab on grade—was 3.7 pCi/L compared to a median of 2 pCi/L for measurements on the first floor and above (see Figure 4). Approximately 47% of measurements conducted at the lowest level matched or exceeded 4 pCi/L and 84.92% matched or exceeded 1 pCi/L, while 27.59% and 74.75% of measurements taken at the first floor or above matched or exceeded 4 pCi/L and 1 pCi/L, respectively.

Figure 4. Box Plots of Radon Measurements After Log Transformations by Test Location (1988-2013)



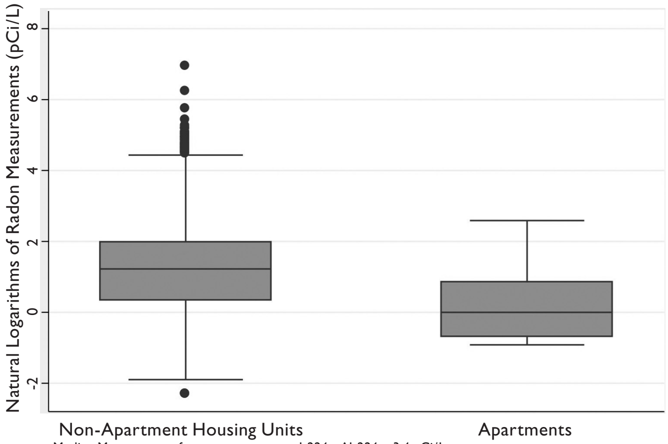
Median measurement for first floor/above: .708, e^.708 = 2.03 pCi/L,
median measurement for RRNC Homes: 1.295, e^1.295 = 3.65 pCi/L

Figure 4 indicates that the median of radon measurements on a natural logarithmic scale taken at the lowest possible test locations (basement or slab on grade) is greater than the median of measurements taken on the first floor and above.

2. Apartments

The data included a limited number of observations in apartments (63 measurements in 53 units), but suggested that apartments possess lower radon levels, on average, than other types of homes (8,606 measurements in 4,748 units). The median of radon measurements taken in apartments stood at 1 pCi/L compared to a median of 3.4 pCi/L for measurements in non-apartments (see Figure 5). Among tests in apartments, 14.29% of measurements matched or exceeded the action level and 50.79% matched or exceeded 1 pCi/L compared to 44.31% and 83.24% of measurements in non-apartments, respectively.

Figure 5. Box Plots of Radon Measurements After Log Transformation by House Type (1988-2013)



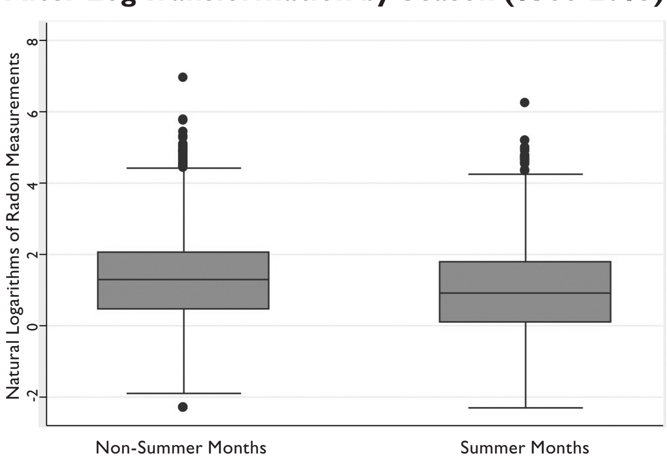
Median Measurement for non-apartments: 1.224, e^1.224 = 3.4 pCi/L,
Median Measurement for apartments: 0, e^0 = 1 pCi/L

Figure 5 indicates that the median radon measurement on a natural logarithmic scale in apartments in Easton falls below the 25th percentile measurement in non-apartment housing units, indicating that radon measurements in apartments tend to be lower than measurements in non-apartment housing units.

3. Month of Testing

Every observation in the data set listed the month in which it occurred. Among 2,898 measurements taken during the summer months of June, July, and August, the median was 2.5 pCi/L, while among the 8,202 measurements taken during non-summer months, the median was 3.65 pCi/L (see Figure 6). Among tests conducted during summer months, 36.37% of measurements matched or exceeded 4 pCi/L and 79.19% matched or exceeded 1 pCi/L, compared to 46.94% and 84.44% of measurements during non-summer months, respectively.

Figure 6. Box Plots of Radon Measurements After Log Transformation by Season (1988-2013)



Median measurement for non-summer months: 1.295, e^1.295 = 3.65 pCi/L,
median for summer months: .916, e^.916 = 2.5 pCi/L

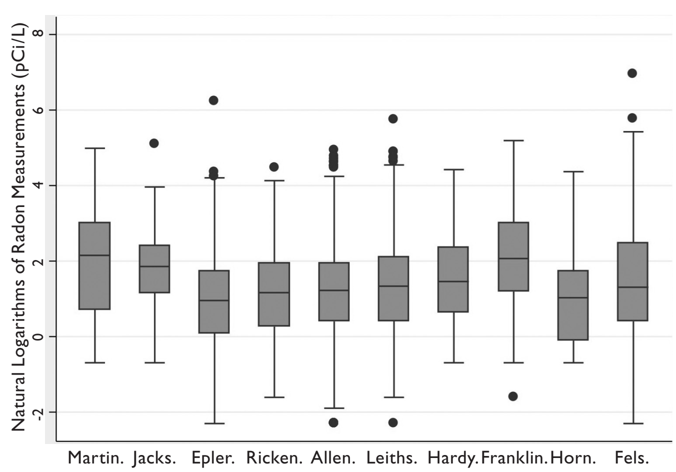
Figure 6 indicates that the median radon measurement on a natural logarithmic scale in homes during summer months (June, July, August) is less than the median measurement in homes during non-summer months.

4. Geological Formation

Information about the geological formations underlying homes tested for radon is important. Among other things, different formations are known to contain different levels of uranium and other minerals, and these differences can create significant disparities in the radon potential of the soils underlying homes.[68] Of the 11,100 indoor radon measurements, 10,159 included data regarding geological formations. The data set included observations for 10 geological formations: the Allentown, Epler, Felsic Mafic Gneiss, Franklin Marble, Hardyston, Hornblende, Jacksonburg, Leithsville, Martinsburg, and Rickenbach Formations.

Of the measurements with data on geological formation, 5,929 occurred in 3,479 units located on the Allentown Formation with a median radon concentration of 3.4 pCi/L. The median radon concentrations for the Epler Formation (1,300 measurements in 761 units) and Rickenbach Formation (838 measurements in 540 homes) in our data set fell below that of the Allentown Formation at 2.6 pCi/L and 3.225 pCi/L, respectively. Conversely, the median radon concentration of the 1,027 measurements taken in 521 homes on the Leithsville Formation slightly exceeded that of the Allentown Formation at 3.7 pCi/L. Data for the other formations in Easton are limited, but suggest that some of these formations possess particularly elevated radon concentrations. The median of 359 radon measurements in 145 homes on the Franklin Marble Formation stood at 7.9 pCi/L, nearly twice the action level (see Figure 7).

Figure 7. Box Plots of Radon Measurements After Log Transformations by Geographical Formations



68. U.S. Geological Survey, Scientific Investigations Report No. 2013-5143, Distribution of Indoor Radon Concentrations in Pennsylvania, 1990-2007, at 5 (2013).

Figure 7 highlights how the distributions of measured radon levels on a natural logarithmic scale differ across the geological formations in Easton, with the Franklin Marble, Jacksonburg, and Martinsburg Formations all appearing to possess elevated levels of radon relative to the other formations, as evidenced by the differences in the median levels, represented by the line in the middle of each box.

Although we could not evaluate fully its influence, these findings also raise important questions about the impact of RRNC in homes on geological formations with elevated radon levels. The radon measurements in RRNC homes in our data occurred on either the Allentown or Leithsville Formations or lacked identification of geological formation. The median radon concentrations measured in homes on the Allentown Formation (3.4 pCi/L) and on the Leithsville Formation (3.7 pCi/L) do not substantially exceed the median concentration measured in homes in Easton as a whole (3.35 pCi/L). However, the reduction in household radon levels associated with RRNC overall suggests that RRNC would have the greatest impact on both radon levels and lung cancer risk on formations with elevated levels.

V. Conclusions and Areas Requiring Further Analysis

A. *Lung Cancer Risk Reduction Potentially Attributable to RRNC*

The results set out in this Comment provide a basis for rough estimates of the reductions in lung cancer risk achieved by RRNC. This analysis begins by noting that the combined analysis of seven epidemiological studies in North America found the excess odds ratio for lung cancer to be .11 per 100 becquerels/meter^3 (Bq/m^3) (~2.7 pCi/L) during an exposure window of five to 30 years before the development of lung cancer.[69] Applying this information and given the model's parameters of exposure, the relative odds of developing lung cancer is 1.1628 at the action level of 4 pCi/L (148 Bq/m^3) (1 + .11(148/100)), 1.0407 at 1 pCi/L (37 Bq/m^3) (1 + .11(37/100)), and 1.0204 at 0.5 pCi/L (18.5 Bq/m^3) (1 + .11(18.5/100)). For reference, relative odds of 1.1628 imply that the odds of developing lung cancer are ~16% greater with exposure to radon at 4 pCi/L than the odds of developing lung cancer with exposure to radon at 0 pCi/L.

A combined analysis of 13 epidemiological studies in Europe[70] found that, by the age of 75, the absolute risk of lung cancer is 0.4%, 0.5%, and 0.7% for nonsmokers at radon concentrations of 0 Bq/m^3 (0 pCi/L), 100 Bq/m^3 (2.7 pCi/L), and 400 Bq/m^3 (10.8 pCi/L), respectively. For smokers, the absolute risk of lung cancer by age 75 is estimated to be much higher: 10% at 0 pCi/L, 12% at 2.7 pCi/L, and 16% at 10.8 pCi/L. Thus, according to both the Darby and Krewski models, the effectiveness of RRNC in reducing radon levels not only below 4 pCi/L, but also below 1 pCi/L—as observed by our study—equates to significant reductions in lung cancer risk at the population level, particularly for smokers.

B. *Conclusions About the Effectiveness of RRNC*

Based on our analysis of radon data from Easton, Pennsylvania, this study provides evidence that RRNC building techniques are effective in reducing radon levels and, by extension, lung cancer risk. Historically, efforts to communicate the danger posed by radon in homes to the public have struggled in part due to perceptions regarding the risk of exposure to radon. Inability to perceive a colorless, odorless, and tasteless gas and the latency period between exposure and development of lung cancer, among other factors, lead people to discount the risk radon poses to them.[71] For this reason, communications by local, state, and federal agencies, as well as other actors, have failed to drive individuals to test and mitigate their homes to the necessary extent.

On the other hand, a mandatory requirement such as an RRNC building code has been demonstrated by this study to reduce the risk of lung cancer from inhaling radon. This research supports the widespread adoption of RRNC as a way to save lives. With hundreds of thousands of new homes built every year in the United States,[72] widespread adoption of building codes mandating RRNC can protect the health of new owners and tenants.

C. *Areas of Future Research*

Before concluding our analysis, it is important to point out that our evaluation would be strengthened by addressing several uncertainties. While we do not believe that these call into question the fundamental finding that RRNC produces meaningful reductions in household radon levels and, accordingly, lung cancer risk, it is nevertheless important to explicitly discuss them. First, it is possible that the true reductions in the odds of exceeding 4 pCi/L and 1 pCi/L achieved by RRNC could exceed our estimated reductions, because we lack data regarding the mitigation status of the non-RRNC homes. Like homes built with RRNC, mitigated homes incorporate depressurization systems that reduce household radon levels and likely do not constitute an appropriate comparison population of non-RRNC homes. Our data set for Easton contained homes with multiple tests measuring decreasing radon levels over

69. Krewski et al., *supra* note 10, at 137.
70. Darby et al., *supra* note 10, at 223.

71. *See* Paul A. Locke & Patricia I. Elliott, *Caveat Broker: What Can Real Estate Licensees do About Their Potentially Expanding Liability for Failure to Disclose Radon Risks in Home Purchase and Sale Transactions?*, 25 Colum. J. Envtl. L. 71 (2000); Paul A. Locke, *Promoting Radon Testing, Disclosure, and Remediation: Protecting Public Health Through the Home Mortgage Market*, 20 ELR 10475 (Nov. 1990).
72. News Release, U.S. Census Bureau & U.S. Department of Housing and Urban Development, Monthly New Residential Construction, September 2018 (Oct. 17, 2018), https://www.census.gov/construction/nrc/pdf/newresconst.pdf.

time, possibly indicating the implementation of mitigation techniques. Including mitigated homes in our comparison group would tend to bias our odds ratio, diminishing its true impact.

Second, uncertainty also exists among the homes built with RRNC regarding passive versus active status of the depressurization systems. The data we obtained did not distinguish between homes with passive RRNC and those with active RRNC. Accordingly, we could not estimate the reduction achieved by passive systems alone in Easton, nor the additional reduction produced by transitioning to active systems.

Finally, as discussed above, we were not able to account for the influence of geological formation on measured household radon levels. Both the rock and soil contained in geological formations can affect radon levels aboveground, as certain kinds of rock have higher uranium contents on average and certain soils are more permeable.[73] In our statistical analysis, we observed that several geological formations in Easton produced significantly elevated radon measurements. We anticipate that we can partner further with the Pennsylvania DEP to obtain additional data that can close some of these uncertainty gaps.

D. *The Need for More Assertive Legal Action to Protect Against Radon's Hazards*

As explained above, no federal radon initiatives currently take advantage of the regulatory authority provided by the IRAA. The clearly demonstrated lung cancer risk reduction associated with RRNC raises the question as to whether EPA should be more assertive in deploying its regulatory authority to require RRNC in new homes. Federal actions to regulate in this arena would be supported by the results of this analysis. While it is beyond the scope of this Comment, it is reasonable to speculate that radon remediation in currently existing buildings would also greatly reduce potential lung cancer risk. In short, our study provides an evidence base that could validate more aggressive federal intervention to require radon remediation in new and existing homes.

In the continued absence of federal action, this study supports state and local efforts to enact and enforce the use of RRNC and also suggests that RRNC efforts should be expanded. Local jurisdictions should follow the lead of Easton in adopting RRNC, which is shown by the analysis here to be an effective public health intervention. RRNC systems are effective in reducing radon's lung cancer risk, especially for smokers who are at much greater risk for lung cancer if they live, and smoke, in higher-radon environments. In addition, this study demonstrates that in states, such as Pennsylvania, a strong radon certification and licensing program, coupled with data collection, can be used to demonstrate how legislative action and regulatory programs reduce cancer risk and, accordingly, potentially save lives.

Pennsylvania's laws and regulations have led to the establishment of a comprehensive radon program. This program has led to the creation of a group of radon professionals that serve the needs of the citizens of the commonwealth, and it assures that these professionals are well-qualified and trained. In addition, as Pennsylvania law demands, it protects against unscrupulous and deceptive practices.[74] The establishment and maintenance of a scientifically valid database is an important ancillary benefit of Pennsylvania's laws. Because radon professionals are certified and licensed, researchers are confident that the data collected under such a system are of high quality.

73. *See* Section IV.B.4.

74. *See* Section II. A.3.