 DOI: 10.1111/risa.12570

Lung Cancer Risk from Radon in Marcellus Shale Gas in Northeast U.S. Homes

Austin L. Mitchell,[1] W. Michael Griffin,[1,2] and Elizabeth A. Casman[1,*]

The amount of radon in natural gas varies with its source. Little has been published about the radon from shale gas to date, making estimates of its impact on radon-induced lung cancer speculative. We measured radon in natural gas pipelines carrying gas from the Marcellus Shale in Pennsylvania and West Virginia. Radon concentrations ranged from 1,520 to 2,750 Bq/m^3 (41–74 pCi/L), and the throughput-weighted average was 1,983 Bq/m^3 (54 pCi/L). Potential radon exposure due to the use of Marcellus Shale gas for cooking and space heating using vent-free heaters or gas ranges in northeastern U.S. homes and apartments was assessed. Though the measured radon concentrations are higher than what has been previously reported, it is unlikely that exposure from natural gas cooking would exceed 1.2 Bq/m^3 (<1% of the U.S. Environmental Protection Agency's action level). Using worst-case assumptions, we estimate the excess lifetime (70 years) lung cancer risk associated with cooking to be 1.8×10^{-4} (interval spanning 95% of simulation results: 8.5×10^{-5}, 3.4×10^{-4}). The risk profile for supplemental heating with unvented gas appliances is similar. Individuals using unvented gas appliances to provide primary heating may face lifetime risks as high as 3.9×10^{-3}. Under current housing stock and gas consumption assumptions, expected levels of residential radon exposure due to unvented combustion of Marcellus Shale natural gas in the Northeast United States do not result in a detectable change in the lung cancer death rates.

KEY WORDS: Combustion; indoor air quality; Marcellus Shale; natural gas; radon

1. INTRODUCTION

All natural gas has some level of radioactivity from the radon that occurs naturally in the subsurface. Exposure to radon in natural gas occurs from the residential use of gas cooking and heating appliances that release some or all of their exhaust gases into the living space. Exposure is not increased by appliances that are vented to the atmosphere (e.g., furnaces or water heaters). Though the health risks of radon due to unvented exhaust in U.S. homes have been analyzed in multiple studies,[1–7] the development of the Marcellus Shale has reignited concerns. Its organic-rich facies contain levels of ^{238}U, a precursor of radon, ranging from 10 to 100 parts per million (ppm).[4,8] The global average concentration of uranium in shale is around 3.7 ppm.[9]

The Northeast natural gas market composed of Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, and Vermont is the prime outlet for gas produced from the Marcellus Shale. Approximately 3.8 trillion cubic feet of gas were consumed in the Northeast market in 2013 (16% of U.S. consumption). Of the 21 million houses and apartments in this region, 53% use natural gas for home heating and 47% for cooking.[10]

[1]Department of Engineering & Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA.
[2]Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA, USA.
*Address correspondence to Elizabeth Casman, Department of Engineering & Public Policy, Carnegie Mellon University, 5000 Forbes Avenue, Baker Hall 129, Pittsburgh, PA 15213, USA; tel: +412-268-2670; casman@andrew.cmu.edu.

 0272-4332/15/0100-0001$22.00/1

The majority of Northeast gas consumers live within a few hundred kilometers of a Marcellus Shale gas well. A consequence of this proximity is the shift away from a decades-old paradigm of gas transmission from distant producing centers (e.g., the Gulf of Mexico) to the Northeast. ICF International estimates that almost 90% of New York City's gas supply will originate from the Marcellus Shale by 2030(11) so there will be less time for radioactive decay of radon to occur in transit from the wellhead to consumers. Locally produced gas may be delivered to consumers the same day it was produced versus after one or two weeks under the old paradigm. This has implications for the risk to consumers, as the half-life of ^{222}Rn, the most stable radon isotope, is 3.8 days.

Concerns about radon in locally produced Marcellus Shale gas were behind recent attempts to block the construction of a new gas transmission pipeline to New York(12–14) and have been raised in legislative and regulatory forums.(15) Three recent studies (none peer reviewed) presented conflicting views of the health risk associated with radon in Marcellus Shale gas.(5–7) The largest difference in these studies was due to assumptions for estimating the radon concentration in natural gas delivered to homes. For lack of data on radon levels in gas delivered to homes, these studies relied on surrogates (e.g., gamma levels in the Marcellus Shale and transmission line radon measurements). To extend the prior work, we measured radon concentration in natural gas gathering systems from several regions of the Marcellus play and estimated radon-related lung cancer risk for scenarios where most or all of the natural gas consumed by the Northeast United States originates locally.

1.1. Radon Exposure and Lung Cancer

Radon occurs naturally in the environment, emanating from rocks and subsurface layers that contain its parent radionuclides. Most people receive their highest daily radiation dose from radon, and radon doses are usually highest in homes. Across all U.S. homes, the average indoor radon concentration is 48.1 Bq/m^3 (1.3 pCi/L).(16) Some of the highest indoor concentrations have been found in the Northeast.(16) The major routes of radon entry to homes are cracks and joints in home basements or foundations. Other potential and often much smaller sources are building materials and well water.(17,18)

When gaseous ^{222}Rn and its radioactive progeny, primarily ^{214}Pb and ^{218}Po, are inhaled, the progeny could deposit on the epithelial cells of the lung and release DNA-damaging alpha radiation.(19,20) Radon is the second leading cause of lung cancer deaths after smoking.(16,19) Current biological and epidemiological studies support a linear, no-threshold dose-response model for radon, which means lung cancer risk is proportional to the radon dose.(16,19,21) This implies that there is no safe level of exposure to radon. However, there is evidence for threshold or other nonlinear response models at low doses.(22–27) The U.S. Environmental Protection Agency (EPA) recommends mitigation if radon levels are higher than 148 Bq/m^3 (4 pCi/L) in indoor air, which it associates with a 7 in 1,000 (7×10^{-3}) lifetime lung cancer risk.(28)

In the last 10 years there have been numerous studies of residential exposure to radon and lung cancer risk. Krewski *et al.* (2005, 2006) combined data from seven case-control studies in North America and estimated an excess (i.e., due solely to exposure to radon in natural gas) lung cancer risk of 11% (95% CI, 0–26%) per 100 Bq/m^3. The excess relative risk was estimated at 21% (95% CI, 3–52%) for a subset of this population with well-defined exposure data.(29,30) Turner *et al.* (2011) used county-level radon data from the EPA(31) to study a cohort of over 800,000 people and 3,493 lung cancer deaths. A significant ($p = 0.02$) linear trend in lung cancer risk was found, indicating that exposure per 100 Bq/m^3 leads to a 15% (95% CI, 1–31%) lung cancer risk nationwide. Turner *et al.* reexamined the data by geographic area, and found a statistically significant lung cancer hazard ratio of 1.31 (95% CI, 1.12–1.53) per 100 Bq/m^3 exposure for the Northeast.(21)

1.2. Past Measurements of Radon in Natural Gas

The average radon concentration of natural gas produced from approximately 2,100 conventional gas wells in western and southern U.S. states across nine studies between 1952 and 1973 was 1,370 Bq/m^3 (37 pCi/L) with a range of 7–54,000 Bq/m^3.(1) Radon measurements from eight producing Devonian shale wells near the border of West Virginia and Kentucky were also performed as part of the Eastern Gas Shales Project (EGSP).(32) The production-weighted average concentration was 5,590 Bq/m^3 with a range from 962 to 9,139 Bq/m^3.

Rowan and Kraemer sampled gas from 19 wells in Devonian formations in southwestern Pennsylvania, 10 of which were Marcellus Shale wells.(33) The average radon concentration was 1,280 Bq/m^3 with a range from 37 to 2,923 Bq/m^3. For the subset of Marcellus Shale wells, the average radon concentration was 1,145 Bq/m^3. The Pennsylvania

Department of Environmental Protection (PADEP) measured the radon concentration in gas samples from 22 wells in seven counties. The average radon concentration of the 17 wells producing from the Marcellus Shale was 1,807 Bq/m^3, ranging from 111 to 5,476 Bq/m^3. The PADEP also measured gas at four compressor stations, which ranged in radon concentration between 1,066 and 2,150 Bq/m^3. Measurements performed by the PADEP at a processing plant showed a substantial drop (around 90%) in radon concentration after processing, while gas withdrawn from underground storage was typically less than half the concentration of gas that was injected.[(34)]

Radon concentrations in transmission and distribution systems serving Chicago, Denver, New York City, and the Southwest United States were studied in 1973.[2] A total of 48 gas samples, some duplicates, were collected, and the radon concentration ranged from 18.5 to 4,400 Bq/m^3. Radon concentration was highest near Denver and lowest in New York City, where the highest of 18 samples was 141 Bq/m^3. In 2012, the radon concentration of natural gas at eight locations leading to and on Spectra Energy's Texas Eastern transmission line was measured.[(7)] The Texas Eastern line runs through Pennsylvania to New Jersey where it connects with the Algonquin transmission line that carries gas to New England. The highest radon concentration, 1,628 Bq/m^3, was reported in southwestern Pennsylvania for gas entering the transmission line, and the lowest, 629 Bq/m^3, was reported for a mixed supply of gas in the main transmission line in northern New Jersey.

Variation in radon concentrations has been observed through detailed studies of radon in transmission and distribution systems conducted abroad. Natural gas samples taken from onshore transmission lines showed varying radon concentrations across the North Sea producing basins, from <50 to 600 Bq/m^3.[(35,36)] Wojcik performed daily measurements of radon activity (average 235 Bq/m^3) in a natural gas distribution system in Poland and reported significant daily and seasonal variations, varying by as much as a factor of 2.4.[(37)] The natural gas radon concentration was measured at various points between production and consumption in British Columbia, Canada. The radon levels measured in 15 gas gathering systems covering an area <40,000 km^2 varied by wide margins (range 7–921 Bq/m^3).[(38)]

1.3. Assessments of Residential Exposure to Radon from Natural Gas

Johnson (1973) and Barton *et al.* (1973) estimated potential population doses from unvented cooking and heating using U.S. wellhead and distribution system radon concentration measurements, respectively.[(1,2)] Both concluded that the potential risk from exposure was small compared to background exposure. Gogolak repeated these calculations in 1980 using radon concentration data from shale wells in the Appalachian Basin (non-Marcellus) with similar results.[(4)]

Three non-peer-reviewed reports have been published more recently on the potential health effects to people who cook with natural gas in New York. Resnikoff used a theoretical model to estimate a range of wellhead radon concentrations of 155–95,000 Bq/m^3. He projected 17–435 lung cancer deaths in New York State each year.[(5)] In response, Anspaugh[(7)] and Krewski[(6)] authored reports in 2012 in support of Spectra Energy's plans for constructing a gas pipeline to ConEdison customers in New York City.[(39)] Anspaugh computed a 30-year excess lung cancer risk of 10^{-5} using the same dilution factors as Resnikoff, but using the natural gas radon concentration of 629 Bq/m^3 measured on Spectra Energy's transmission pipeline. This concentration was also used by Krewski to calculate a lifetime (70-year) excess risk of 1.96×10^{-5} for New York residents. Krewski performed a sensitivity analysis that included radon concentration, size of residence, air exchange rate (AER), and occupancy fraction (time spent at home). The highest natural gas radon concentration examined was 740 Bq/m^3 and the "plausible maximal exposure" calculated from it was associated with a lifetime lung cancer risk of 8.95×10^{-5}. None of these reports considered exposure from unvented space heating, and all of them used questionable assumptions to estimate burner-tip radon concentrations. Resnikoff's report provided insufficient documentation of the methodology used to estimate wellhead radon concentrations, while the Anspaugh and Krewski reports were narrowly scoped, calculating risk for a small set of Northeast consumers using the lowest observed radon concentrations.

The PADEP estimated the potential radon exposure from residential use of unvented natural gas appliances assuming radon concentrations of 1,613 and 5,476 Bq/m^3. The lower radon concentration corresponded to exposure of 1.48 Bq/m^3, and the higher concentration to 4.81 Bq/m^3. The PADEP made a determination that this incremental change in exposure would not be detectable with typical monitoring techniques and that the associated dose was insignificant relative to the allowable dose for the general population (100 millirem/year).

1.4. Radon and Unvented Gas-Burning Appliances

Unvented residential gas appliances include gas stoves and ovens[40–42] and vent-free space heaters. The exhaust gases of these appliances will contain any radon present in the gas because radon is a chemically inert element and it will remain as the elemental gas after combustion. Forced ventilation systems are commonly installed with natural gas stoves and ovens, but only a small fraction of combustion exhaust is likely to be captured by these systems.[43] Even if exhaust gas is captured, systems that provide exterior ventilation are less common than those that simply recirculate the combustion gas through an activated carbon filter (to remove odors, smoke, grease, and steam) and discharge to the home.[44] Some radon may be absorbed onto these filters, but research in this area is very limited.[45] By design, vent-free space heaters (e.g., gas hearths, gas logs, etc.) direct all of the combustion exhaust into the living space.[46] Continuously burning pilot lights are not considered in this study because they are a small and decreasing fraction of the gas range market.[47]

1.5. Objective of the Present Study

The goal of this study was to assess the lung cancer risk due to unvented cooking and space heating with locally supplied natural gas in Northeast U.S. homes using radon concentrations that reflect the expected spatial and temporal variability. To do this we:

(1) Collected natural gas samples from Marcellus Shale gas gathering systems near the point of entry to transmission pipelines and measured their radon concentrations.
(2) Calculated the average natural gas radon concentrations at the burner-tip of Northeast U.S. homes using radon measurements of locally produced gas, taking into account supply mixing and transit time.
(3) Modeled residential radon exposure for unvented cooking and heating based on representative appliance use and settings in the Northeast United States.
(4) Calculated the projected excess lung cancer incidence from radon in natural gas using an epidemiological model.

2. CALCULATION OF RESIDENTIAL RADON EXPOSURE

Radon exposure is the integral of indoor air radon concentration over time spent indoors. Because we have assumed radon exposure is linearly related to lung cancer risk, the exposure calculations can be represented by a simple mass balance for average annual radon exposure from unvented cooking and space heating (Equation (1)):

$$C_{ia} = \frac{C_{gas}\, Q_{UV}}{V \cdot AER} \tag{1}$$

where C_{ia} is the indoor air radon concentration (Bq/m^3), C_{gas} is the natural gas radon concentration (Bq/m^3), Q_{UV} is the unvented gas use rate (m^3/hour), V is the volume of all freely connected living spaces in the home (m^3), and AER is the air exchange rate (1/hour).[48]

The following subsections detail the assumptions made for deriving the inputs to a Monte Carlo model based on Equation (1) for average annual excess radon exposure in all gas-consuming houses in the Northeast United States in which population-weighted average annual radon exposure was calculated by weighting residence-level exposures by occupancy and individual housing-stock factors for 1,044 types of housing configurations. This approach accounts for both occupancy and the representativeness of each residence in the population of NE homes and apartments.

Exposure estimates were not adjusted by the 70% occupancy factor typically applied when calculating exposure at home.[16] For the case of radon exposure from natural gas, assuming 100% occupancy was the conservative assumption because a majority of exposures to combustion byproducts occurs during and immediately after the use of unvented gas appliances.[48–50] Moreover, both cooking and supplemental heating are associated with occupancy, and at least one person is near source during cooking and probably more in an unvented space heating situation.

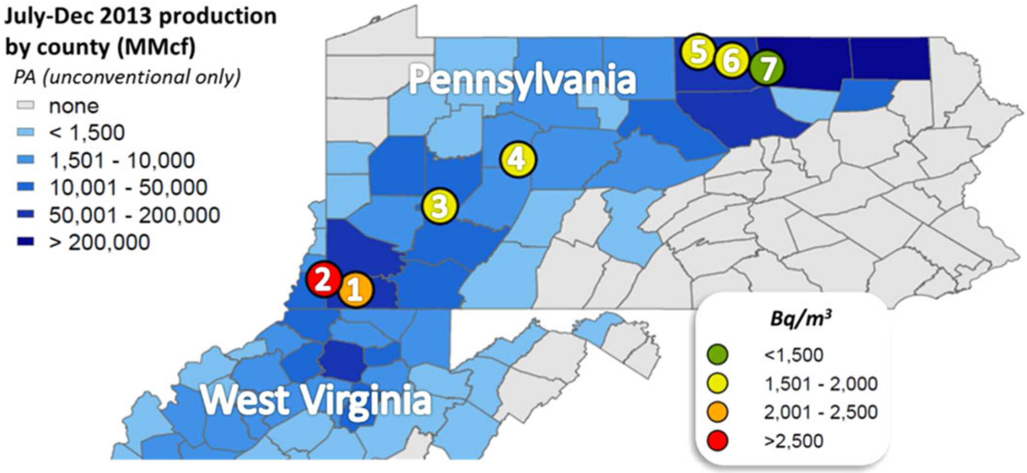

Fig. 1. Map showing seven locations where radon samples were collected. Each sampling location is numbered and colored to correspond with measured radon concentration (red is highest). (Colors visible in on-line version.) Counties are shaded according to natural gas production in the second half of 2013. For Pennsylvania, county production only includes unconventional natural gas production. Three sampling locations were in northeast Pennsylvania, gathering from producing wells as far east as Bradford County, Pennsylvania. The westernmost sampling location (#2) was in Marshall County, West Virginia.

Table I. Measured Radon Concentrations (Bq/m^3) from the Seven Gathering System Sampling Locations; Duplicate Samples Were Collected and Measured at Four Locations

Sample	Sample Date	Rn Concentration[a] (Bq/m^3)			Throughput[b] (MMcf/day)
1	9/3/2013	2,212.6	±	237	165.0
2	9/3/2013	2,749.1	±	292	67.5
3A	9/4/2013	1,916.6	±	204	60.1
3B	9/4/2013	1,924.0	±	204	60.1
4A	9/4/2013	1,579.9	±	167	5.4
4B	9/4/2013	1,546.6	±	163	5.4
5A	10/30/2013	1,650.2	±	174	2.7
5B	10/30/2013	1,801.9	±	192	2.7
6A	10/30/2013	1,520.7	±	163	91.0
6B	10/30/2013	1,542.9	±	163	91.0
7	10/30/2013	1,169.2	±	126	50.0

[a]The 95% confidence interval for each sample based on intercomparison to the EPA's target value, the calibration factor for the cell, and the uncertainty associated with the counting of the sample.[51]

[b]Throughput (MMcf/day) was read directly from on-site measurement equipment.

2.1. Radon Concentration Measurements for Marcellus Shale

Measurements of the radon concentration in natural gas were performed on samples of natural gas from seven gathering systems in Pennsylvania and West Virginia (Table I). Sampling locations are presented in Fig. 1. These gathering systems served as few as four Marcellus Shale wells to >100. Because the gas produced from each well was completely mixed at the sampling location, each measurement may be considered the production-weighted average of the radon concentration of all upstream wells. Sampling location 2 was the only gathering system to also serve conventional and coalbed methane gas wells, but production from those wells was a very small fraction of the total production into this system. The gas was sampled near the point of entry into transmission pipelines, which is desirable for two reasons. First, sampling the gas gathered from multiple wells reduces the well-to-well variability seen with wellhead sampling. Second, gas on the transmission system has been comingled with multiple sources, and the contribution from each source will change over time.

Access to sampling locations was granted by two Marcellus Shale gas producers and samples were collected in September and October 2013. Sampling locations 1–6 were the "retail" side of a compressor station and sample location 7 was a metering and regulating facility. All samples were collected from top-center mounted taps on a straight stretch of pipeline, following standard protocol for sample collection.[52] Duplicate samples were collected at four locations. Each sample consisted of approximately one liter of gas collected in a Tedlar® bag.

Table II. Minimum and Maximum Transit Times (in Days) by Month for Gas Entering the Transmission Pipelines Until Use in the Home

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Min	0.5	0.5	0.6	0.8	1.1	1.1	1.0	1.0	1.1	1.0	0.8	0.6
Max	3.1	3.0	3.6	4.8	6.4	6.5	6.1	6.1	6.7	6.3	4.8	3.6

After establishing chain of custody and recording collection data, samples were transported in thermal containers by a third party for independent testing by Bowser-Morner in Dayton, Ohio. The radon activity was measured using scintillation cells and reduced by 5.4%, a correction for higher alpha counting efficiency in lower density methane versus air.[51]

The measured radon concentration in the natural gas ranged from 1,520 to 2,750 Bq/m^3. Measured radon concentration decreased west to east, as does the heat content of the gas. The gas with the highest radon concentration (sample 2) was from a "wet gas" area, meaning it contained natural gas liquids. The sample was taken at a compressor station that discharged to a processing plant. Since radon partitions more strongly into the natural gas liquids during processing than methane,[3,34] it can be assumed that the radon in this gas would have been reduced when it entered the pipeline. The radon concentrations measured at the four compressor stations sampled by the PADEP were all in this range.[34] The highest radon concentration measured in this study was nearly twice the highest concentration reported for natural gas being injected into Spectra Energy's transmission line (1,632 Bq/m^3).[7] To be conservative, we included sample 2 in our calculations, and the resulting throughput-weighted average radon concentration was 1,983 Bq/m^3. Although the samples collected in this study cover a broad geographic area, these seven gathering systems moved only about 9% of daily production in the second half of 2013.

Eleven samples (including the four collected by the PADEP) are not enough to properly characterize the distribution of radon concentrations in Marcellus Shale gas entering the distribution system. Instead, a uniform distribution between the minimum and maximum measured concentrations was used in the radon exposure model to represent the radon concentration of natural gas entering the transmissions system.

2.2. Burner-Tip Radon Concentration: Supply Mixing and Radioactive Decay in Transit

The average radon concentration of the natural gas delivered to homes will be lower than average concentration at gathering systems due to mixing with other low radon supplies (e.g., imported or stored gas) and radioactive decay in the transmission and distribution systems. The effects of mixing of Marcellus Shale gas with nonlocal and/or stored natural gas on radon concentration were estimated by a simple relationship between supply and demand. Fig. 2 compares average daily consumption by month consumption (2002–2011)[53] with estimated Marcellus Shale production per day in Pennsylvania in 2013.[54] At this moment in time, annual gas production in Pennsylvania (92 billion m^3) was approaching the average Northeast natural gas consumption of around 106 billion m^3. Production in Pennsylvania alone now exceeds total demand in the Northeast, reaching around 110 billion m^3 (4 trillion ft^3) by the end of 2014.[55] However, there may still be high demand months (i.e., January, February, March, and December) when Northeast consumption will exceed local production levels. Two mixing scenarios are modeled: (1) no mixing with low-radon gas sources, which assumes that local production matches monthly consumption (most conservative), and (2) mixing natural gas with zero radon content with Marcellus Shale gas to meet demand, which reduces the average natural gas radon concentration in the months where demand exceeds supply.

Simple assumptions are used to estimate how much radioactive decay occurs in transit. Natural gas pipelines are operated within narrow pressure and temperature ranges. Therefore, the velocity of the gas (and thus the transit time) will be proportional to the throughput,[36,37,56] which is roughly equivalent to the consumption rate. Fig. 2 shows that average monthly consumption in the winter can be twice the rate in summer. For February, the month with the highest average consumption, pipeline transit times are randomly drawn from a uniform distribution of 12 hours to three days. This range is based on reported transmission velocities of 16–32 km/hour[4,38,57] and distances to population centers. For the radon exposure model (Equation (1) and Table III), transit times for all other months are scaled from February by assuming proportionality to demand, so the transit time in summer months is roughly twice that of winter months (Table II). The minimum and maximum transit

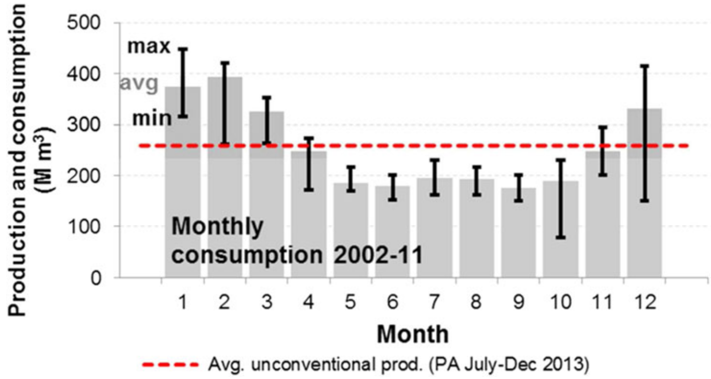

Fig. 2. Northeast average, minimum, and maximum daily consumption rates by month of natural gas between 2002 and 2011 (in millions of cubic meters).[53] The dashed red line is the average daily Marcellus Shale production in Pennsylvania from July to December 2013.[54] Production exceeded average consumption April through November.

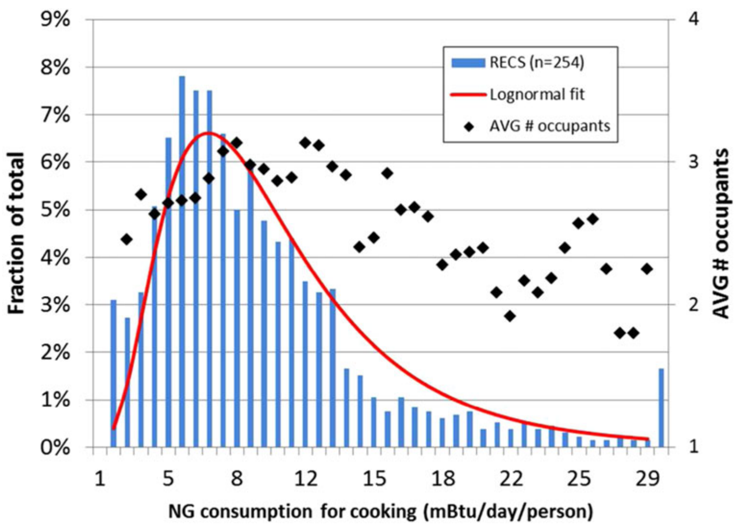

Fig. 3. Histogram of natural gas consumption in Btu/day/person for a subset of NE residences ($N = 254$) with the lognormal distribution (red line) fit to the data. Black diamonds indicate the average number of occupants for each consumption category.

time scenarios in Table II result in 20% and 72% reduction in annual average radon concentration due to decay prior to consumption, respectively. For each iteration of the radon exposure model, a February transit time is randomly drawn from a uniform distribution $U(0.5, 3)$ days, and transit times in all other months are scaled to this value.

2.3. Housing Stock

We used data collected in the Residential Energy Consumption Survey (RECS), which included a statistically representative sample of 2,066 mobile homes, single family (attached/detached) homes, and apartments in the Northeast United States, to characterize housing stock and natural gas usage.[10] Characteristics of each housing unit as well as natural gas billing were part of the survey. Natural gas cooking was reported by 1,044 respondents in the RECS survey, representing 47% of NE residences. Natural gas cooking varies across states and type of housing unit, being most likely in a New York apartment and least likely in a single-family home in New England (CT/DE/NH/ME/VT). Only 52 RECS survey respondents in the NE, representing (by weight) approximately 2.2% of NE residences, reported using natural gas cooking stoves for room heating, gas room heaters (vent type unknown), and "flueless" fireplaces.

2.4. Unvented Natural Gas Cooking and Heating Patterns

The Q_{UV} term in Equation (1) is the quantity of gas consumed in a home that is not directly vented to the outside. For the exposure model this is the

Table III. Distributions for Parameters Used in the Monte Carlo Radon Exposure Model

Parameter	Distribution	Values	Reference(s)
Radon concentration (Bq/m^3)	Uniform	[1,520, 2,750]	
February transit time (days)	Uniform	[0.5, 3]	
Supply mixing (binary)	Bernoulli	$p = 0.5$	
Cooking gas cons. (MBtu/person/day)[1]	Lognormal	$\mu = 14.97, \sigma = 0.55$	10
Heater rating			
Gas range (Btu/hour)	Uniform	[8,000, 20,000]	
Vent-free ($Btu/hour/m^3$)	Uniform	[67, 198]	56
Heater usage (hours/day)	Uniform	[2, 6]	55
Air exchange rate (1/hour)			66
Region 1 (annual / winter)[2]	Lognormal	$\mu = -1.159/-1.305, \sigma = 0.712/0.799$	
Region 2 (annual / winter)[3]	Lognormal	$\mu = -0.844/-0.798, \sigma = 0.698/0.673$	
Home occupancy factor[4]		100%	

[1]From RECS "other" gas cons. for 254 NE residences.
[2]CT, MA, ME, NH, RI, and VT.
[3]PA, NJ, and NY.
[4]Fraction of time spent in the presence of radon; EPA typically uses 70%.

annual quantity of natural gas used for unvented cooking and heating.

2.4.1. *Unvented Cooking*

A subset of NE residences ($N = 254$) were used to estimate natural gas consumption for cooking (Fig. 3). Residences in the subset only used natural gas for heating (space and/or water) and cooking,[3] and had estimated cooking-related consumption of <100 MBtu /day. The latter constraint eliminated 24 residences that had unrealistically high gas consumption for noncommercial cooking.

A lognormal distribution was fit to the NE data, representing average annual consumption per person (Btu/person) for cooking. In the radon exposure model, random draws from the gas consumption distribution are multiplied by total number of household members to estimate annual residential consumption for cooking (Btu/year) in every NE residence that cooks with gas.[4]

As modeled, the average gas consumption is 10 mBtu/day/person. To put this number in context, gas ovens (and broilers) typically consume 10–20 mBtu/hour while individual stovetop burners consume 4–12 mBtu/hour. Government surveys show that around 60 minutes is spent each day preparing meals in U.S. homes.(58,59) A survey of 118 apartment dwellers in New York City calculated average gas range usage of 126 and 184 minutes on weekdays and weekends, respectively.(40) For comparison, 1.5 hours of cooking per day at 10 mBtu/hour in a home with four occupants results in around 4 mBtu/day/person consumption.

2.4.2. *Unvented Heating*

In a large survey consisting of approximately 20,000 adults conducted between 1988 and 1994, unvented natural gas space heaters were reported by slightly more than 1% of adults living in the NE.(42) Furthermore, nearly 8% reported using their cooking stoves for heat at least once in the previous year, and among low-income adults the rate is approximately double. Fifty percent of respondents in a 1981 survey of 118 New York City apartments (90 rent-subsidized) reported using their natural gas ranges for heating.(40) Out of 79 homes surveyed in three Boston housing projects between 2002 and 2003, 27% reported heating with a gas range.(41)

Rather than estimate a fraction of residences using unvented gas appliances for heating, we ran a scenario analyses in which unvented heating was assumed for all residences that cook with natural gas. The U.S. Department of Housing and Urban Development assumed four hours of unvented stovetop heating per day to study impacts on indoor

[3]RECS used a nonlinear regression model to estimate the portion of annual gas consumption due to space and water heating and other, which included clothes drying, cooking, and less common uses (e.g., lighting). In the subset of 254 residences, natural gas cooking was the only "other" gas consuming activity.
[4]An energy content of natural gas of 36 Btu/L (1,025 Btu/ft^3) was assumed in the conversion from Btu/year to L/year.

air quality.[60] Similar usage of vent-free heaters was also observed in a study of 30 Chicago-area homes (29 single family and one condominium). Fourteen of the homes in this study ran their fireplaces for at least two hours continuously and five were used for at least four hours continuously over a three- to four- day period.[61] A 2011 industry trade group survey found average use of gas fireplaces among U.S. homeowners to be 2.6 hours per day and 52 days a year.[46] Use of stovetops/ovens or vent-free heaters as a primary heating source has also been observed.[40,46,61]

To estimate the amount of gas consumed for each of the different RECS houses, usage time was multiplied by the rating of the oven/stovetop or vent-free heater. Building code restrictions on vent-free heaters in some cities (e.g., New York City[62]) make it more likely that apartment dwellers would utilize stovetops or ovens. For apartments we estimated gas consumption as $U(8, 20)$ MBtu/hour. For single-family homes, guidelines adopted by New York State for vent-free heater sizing were used to estimate rating according to the volume of space in which the heater would be operated.[63] In "average" construction homes (referring to the air infiltration rate), approximately 140 $\frac{Btu}{hour \cdot m^3}$ is recommended. For "tight" and "loose" construction homes, 67 and 198 $\frac{Btu}{hour \cdot m^3}$ are recommended, respectively, so we calculated ratings as the product of dwelling space volume (m^3) and a random draw from a uniform distribution $U(67, 198)$ Btu/hour/m^3.

In the radon exposure model two scenarios were run: (1) a supplemental heating case where all residences used unvented natural gas appliances between two and six hours per day, and (2) a primary heating case with round-the-clock usage. In both cases the length of the heating season was 120 days.

2.5. Residential Dilution of Radon

The denominator in Equation (1) describes the dilution of radon in a freely connected space, which is assumed to occur uniformly and instantly. The V term is the volume of the space in which dilution occurs. For dilution of radon associated natural gas cooking, V was calculated from the product of RECS total floor area less estimated garage area (23–70 m^2), and average ceiling height of 2.5 m (3.5 m for high or cathedral ceilings) and an adjustment term to account for restricted air flow to some of the interior space. Adjustment of V is based on the observation that dilution across the entire living space volume can be a poor assumption, particularly in multistory residences where the closure of interior doors and vertical temperature differences ("stack effect") impede air movement.[64–67] The conservative assumption is to model dilution occurring within one level of an apartment or single-family home. Therefore, V is the total volume divided by the number of stories (including basement and attic) reported in RECS. In single-level apartments, reduced dilution is likely to occur when doors are closed, restricting air flow. Closed doors are assumed to restrict air flow to 25% of an apartment, studio apartments not included.

For unvented heating, V is determined from the floor area of the heated space instead of the total area. However, since vent-free heaters are sized to the space they will occupy, exposure is independent of heated volume for single-family homes. In non-studio apartments, a 25% reduction in available dilution volume is assumed, representing door closure.

The AER term in Equation (1) is the air exchange rate. It describes the rate at which air inside the home is replaced with air from outside of the home. AER depends on weather, home characteristics (e.g., leaky windows), and the behavior of occupants, all of which vary in time and space.[68–71] In this study, only the portion of AER due to infiltration, air leaking into and out of a home through cracks and gaps in its exterior, was considered. The AER term did not include natural ventilation (e.g., opening a window) or mechanical ventilation (e.g., attic fan).

Empirical AER distributions developed by Murray and Burmaster (1995) were used to simulate infiltration across all homes.[72] Separate empirical distributions exist for specific climate regions[5] and seasons (Table III). For natural gas cooking, random sampling from the lognormal average annual AER distribution is used. The average winter (Dec.–Feb.) AER is used for unvented gas heating.

2.6. Radon Exposure Simulation

The radon exposure model was run for 10,000 iterations. In each iteration the average annual *and* winter natural gas radon concentrations, C_{gas} in Equation (1), were estimated for a unique selection

[5] In order to use the empirical AER distributions, which were developed for climate regions, it was assumed that all RECS housing units in the New York State were in Murray and Burmaster "Region 2," while "Region 1" was assumed for all RECS housing units in the multistate domain that included CT, MA, ME, NH, RI, and VT (see Table III).

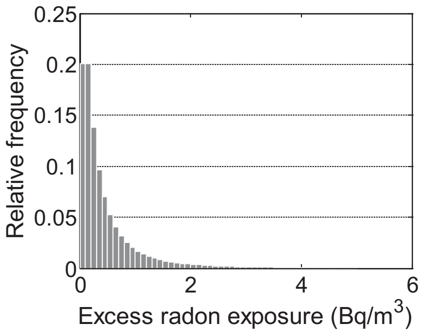

Fig. 4. Histogram of radon exposures (Bq/m^3) due to natural gas cooking in 1,044 NE U.S. homes and apartments.

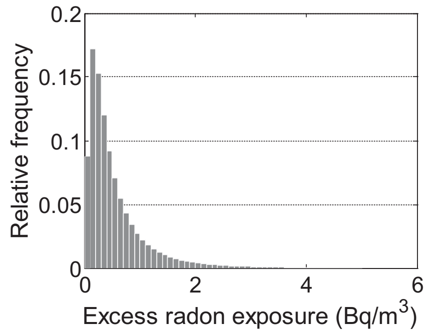

Fig. 5. Histogram of radon exposures (Bq/m^3) due to unvented natural gas heating in 1,044 NE U.S. homes and apartments.

of input parameters (Table III). The average annual C_{gas} was used for cooking and the winter C_{gas} was used for unvented heating. Average annual radon exposure from cooking and unvented heating was then calculated for each of the RECS 1,044 homes and apartments, using individual home characteristics and drawing from distributions for AER and gas consumption.

3. RESULTS

3.1. Radon Exposure Due to Unvented Gas Cooking

Fig. 4 presents a histogram of model realizations of radon exposures due to natural gas cooking. The total number of realizations is >10 million (1,044 RECS homes by 10,000 iterations).

The mean exposure is 0.5 Bq/m^3 (interval spanning 95% of simulation results: 0.03, 2.6). More than 93% of the model realizations are <1% of the EPA action limit for radon of 147 Bq/m^3. Only 0.5% of realizations of radon exposure exceed 5 Bq/m^3. These results affirm the findings of the PADEP report, which estimated 4.81 Bq/m^3 as the upper limit for exposure. They are also the product of conservative model assumptions.

3.2. Radon Exposure Due to Unvented Gas Space Heating

When unvented space heating provides supplemental heat for a few hours throughout the winter, the volume of gas that would be consumed by commercially available vent-free heaters will be similar to the volume of gas consumed for cooking throughout the entire year. As a result, the distribution for radon exposure due to unvented heating presented in Fig. 5 is similar to the exposures presented in Fig. 4.

The mean radon exposure due to unvented space heating is 0.6 Bq/m^3 (interval spanning 95% of simulation results: 0.06, 2.4). Only 0.33% of realizations of excess radon exposure exceed 5 Bq/m^3. These modeled exposures are conservative as the correlation between heating demand and AER was not modeled.

Higher levels of radon exposure could be possible if cooking stoves or unvented heaters were used for primary heating. Assuming that unvented heating occurs for 24 hours per day, the mean annual excess radon exposure would be 3.5 Bq/m^3 (interval spanning 95% of simulation results: 0.4, 13.7). However, because an unvented heater would not need to run continuously to provide sufficient heat in a confined space when AER is low, this is an overestimate.

3.3. Cancer Risk Due to Radon in Natural Gas

In 2009, 41,169 lung cancer cases were reported in the Northeast for a population of 55.2 million people.[73] This gives an incidence rate of 7.5×10^{-4} from all causes. There were approximately 4,200–6,200 radon-induced cancers in 2009 in this region, assuming 10–15% of all lung cancers are due to radon.[19] To assess the excess cancer risk due to locally sourced radon in natural gas, the modeled excess radon exposure estimates described above were used in the Turner *et al.* (2011) model of lung cancer incidence from radon exposure for the Northeast.[20]

Fig. 6(a) presents a histogram of population-weighted average annual radon exposure due to gas cooking, which is the weighted average of radon exposure weighted by RECS-provided factors. The 95% confidence interval (CI) NE U.S. radon hazard ratio (HR) calculated by Turner *et al.* (2011) is

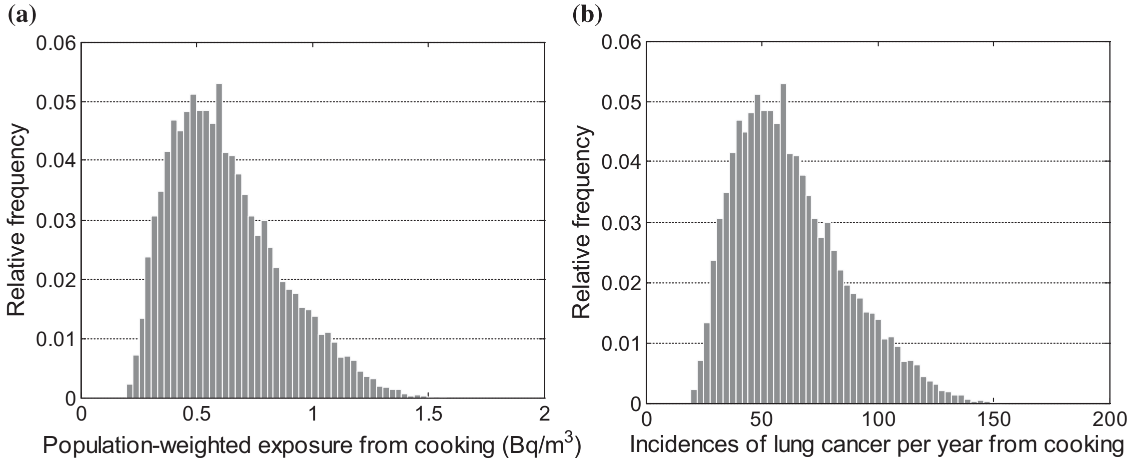

Fig. 6. Histograms of population-weighted average annual radon exposure (a) and excess incidences of lung cancer per year (b) due to natural gas cooking.

1.12–1.53 per 100 Bq/m^3. Additional incidences of lung cancer per year from cooking are the product of population-weighted exposure, HR, background incidence rate, and the RECS estimate for people cooking with gas. Fig. 6(b) presents a histogram of additional incidences of lung cancer per year from cooking associated with a HR of 1.53 (a conservative assumption).

The mean population-weighted annual average excess radon exposure for the histogram in Fig. 6(a) is 0.6 Bq/m^3 (interval spanning 95% of simulation results: 0.3, 1.2), which, for a HR of 1.53, corresponds to a mean lifetime (70-year) excess lung cancer risk of 1.8×10^{-4} (interval spanning 95% of simulation results: 8.5×10^{-5}, 3.4×10^{-4}). Additional incidences of lung cancer per year (Fig. 6(b)) are, on average, 62 (interval spanning 95% of simulation results: 28, 116). Therefore, radon in locally produced natural gas used for cooking will not have a measurable effect on lung cancer incidence in the NE, against a background of several thousand annual radon-related lung cancers.

Use of unvented gas appliances for supplemental heating has a similar risk profile as cooking because gas consumption is approximately the same. Even though there is comparatively less information about the population heating their homes with unvented heaters, the number of additional lung cancer cases associated with unvented heating will be a fraction of that calculated for cooking because the population is much smaller. The population using unvented gas appliances for primary heating is even smaller. Nonetheless continuous use of vent-free heaters and gas ranges is associated with the highest potential excess radon exposure, which we estimate conservatively to result in a 70-year lifetime excess lung cancer risk between 1.1×10^{-4} and 3.9×10^{-3}.

4. DISCUSSION

The magnitude of the potential risk to human health calculated in this study is larger than what was estimated by Krewski and Anspaugh. The main reasons for this result include the use of higher radon concentrations for natural gas in the residential supply and the use of the upper bound for the hazard ratio from a Northeast-specific lung cancer model. The maximum exposures calculated in this study are comparable with the maximum 4.81 Bq/m^3 exposure reported by the PADEP. At this time there is no support for the high mortality argument offered by Resnikoff.[(5)]

Based on current information, it is unlikely that use of Marcellus Shale gas in NE U.S. homes will result in a detectable change in the lung cancer death rates. Individual risk, however, is elevated for the people living in homes with low ventilation rates, especially those who use vent-free heaters or gas ranges to heat their living space. Although the number of people in this category appears to be small, they would be prime targets for risk communication concerning the importance of adequate ventilation when burning natural gas indoors. It is important to note that exposure to other combustion byproducts (e.g., nitrogen dioxide, carbon monoxide) would likely be a greater health concern with this level of unvented gas combustion and minimal air exchange.[41,44,48,60] Commercially available vent-free heaters are installed with oxygen sensors, which would likely prevent them from operating continuously in a confined space as was modeled. Gas ranges are not equipped with such features.

Though the potential exposures to radon in natural gas modeled in this study are very small compared to typical background levels in homes and outdoors, the individual perspective may be very different. The actual level of radon in natural gas distribution pipelines is not currently known. Without a thorough understanding of the concentration and variability of the natural gas radon concentration it is difficult to dismiss public concerns and to devise a measured regulatory approach, if one is needed, to this issue. Concerned members of the public can take simple steps to mitigate the risk. For example, opening windows can increase the AER by orders of magnitude,[65,74] which would dramatically reduce any potential radon exposure due to unvented natural gas cooking and heating.

4.1. Study Limitations

There are numerous limitations regarding this analysis, but only those that might lead to higher exposure are relevant. For example, it is known that people near a combustion source (e.g., the person cooking) will likely receive higher exposures compared to people in another part of the house. The mass balance, instantaneous mixing approach underestimates this maximum exposure.[48,49,61,75] In a recent study of air quality associated with cooking, Lobscheid *et al.* modeled near source exposure to be twice as high for the person cooking.[76] Traynor *et al.* found that maximum exposure to combustion byproducts from a gas range in a test house were underestimated by around 20%.[49] Higher near source exposure is not included in the population-weighted exposure calculations because the health effects model was specifically for averaged background rate, not acute or intermittent exposures.

The radon concentration data, though the best currently available, were insufficient to characterize the variability of this parameter. The existence of radon "hot" spots cannot be ruled out. There have not been any radon concentration measurements for gas produced from the Utica Shale, which is another Appalachian Basin shale with rapidly growing production.[77] Also, while RECS is a useful source of data on Northeast homes and energy consumption, the data represent a small sample of the 20 million homes in the Northeast, and certain features of the data are less representative than others. Errors in the RECS survey, end-use model, or weighting corrections could also impact these results.

AER models, including the one used in this study, have shortcomings.[68] The prevalence of "tight" construction homes in the population may be higher than the AER models published by Murray and Burnaster (1995). If "tight" construction homes are more prevalent, exposure could be underestimated. Gas consumption for heating and AER have been shown to be correlated;[78] however, we have no defensible way to account for this in our model.

Finally, the main limitations for the Turner *et al.* model of lung cancer risk also apply to this study, namely, that their study was based on mean county-level radon data as opposed to more direct measurements in homes.

5. CONCLUSION

Natural gas being supplied to Northeast U.S. residential consumers will contain higher levels of radon compared to conventional and geographically distant supplies that have sustained this region for decades. Radon concentrations measured in seven gathering systems ranged from 1,520 to 2,750 Bq/m^3, and the throughput-weighted average was 1,983 Bq/m^3. Radioactive decay in pipelines is expected to reduce the radon concentration in natural gas between 20% and 70% before it reaches consumers, depending on the season.

Cooking with locally produced Marcellus Shale gas is unlikely to cause excess average annual radon exposures above 2 Bq/m^3, which compared to national average indoor concentrations of radon on the order of 50 Bq/m^3 is insignificant.[28] When using conservative assumptions, the modeled population-weighted excess radon exposure due to cooking is 0.6 Bq/m^3 (interval spanning 95% of simulation results: 0.3, 1.2). The lung cancer risk for this level of exposure is not high enough to cause a measurable change in annual lung cancer incidence rates in the NE. As modeled, it is essentially smaller than the noise in the estimate of annual lung cancer incidence. Small segments of the population that continuously operate unvented gas appliances in poorly ventilated spaces will experience the highest excess lifetime lung cancer risk. For those people, the excess lifetime lung cancer risk could be as high as 3.9×10^{-3} (the 97.5 percentile of the simulation results distribution).

ACKNOWLEDGMENTS

This research was supported by the Climate and Energy Decision Making Center (CEDM), which was created through a cooperative agreement between the National Science Foundation (SES-0345798) and Carnegie Mellon University. Additional support came from the Gordon and Betty Moore Foundation and the John and Claire Bertucci Fellowship. We thank Richard Sextro (Lawrence Berkeley Lab) and Michael Kitto (New York State Department of Health) for their helpful discussions, as well as Phillip Jenkins (Bowser-Morner) for his assistance developing the sampling protocol. We are grateful to the two companies who assisted us in collecting natural gas samples, CONSOL Energy and another company that requested to remain anonymous, as well as the individuals from both companies who helped make this work possible, particularly Jim Locke (CONSOL). Co-author Austin Mitchell, who is currently employed by CONSOL Energy, conducted the radon sampling and analysis while a PhD candidate at Carnegie Mellon University.

All authors contributed to the writing of this article and all authors have given approval to the final version of the article.

REFERENCES

1. Johnson J, Raymond H, Bernhardt DE, Nelson NS, Calley J, Harry W. Assessment of Potential Radiological Health Effects from Radon in Natural Gas. Washington, DC: U.S. Environmental Protection Agency, 1973.
2. Barton CJ, Moore RE, Rohwer PS. Contribution of Radon in Natural Gas to the Natural Radioactivity Dose in Homes. Oak Ridge, TN: Oak Ridge National Laboratory, 1973.
3. Gesell TF, Johnson RH, Jr, Bernhardt DE. Assessment of Potential Radiological Health Effects from Radon in Liquefied Petroleum Gas. Washington, DC: U.S. Environmental Protection Agency, 1977.
4. Gogolak CV. Review of ^{222}Rn in Natural Gas Produced from Unconventional Sources. New York: U.S. Department of Energy, Environmental Measurements Laboratory, 1980. Available at: www.osti.gov/bridge/product.biblio.jsp/osti_id=6732903.
5. Resnikoff M. Radon in natural gas from Marcellus Shale, 2012. Available at: http://www.radonleaders.org/sites/default/files/Marcellus_Radon.pdf.
6. Krewski D. An assessment of the lung cancer risk associated with the presence of radon in natural gas used for cooking in homes in New York State. Final Report, Risk Sciences International, July 4, 2012. Ottawa, Ontario, 2012; p 20.
7. Anspaugh LR. Scientific issues concerning radon in natural gas, Texas Eastern Transmission, LP and Algonquin Gas Transmission, LLC New Jersey–New York Expansion Project, Docket No. CP11-56, 2012 Lynn R. Anspaugh Consulting PC, Henderson, NV.
8. Allard DJ. Marcellus Shale & TENORM. Annual Emergency Management Conference of Pennsylvania Emergency Management Agency, Harrisburg, PA, 2011. Available at: http://www.portal.state.pa.us/portal/server.pt/document/1203136/marcellus_shale_and_tenorm_pdf.
9. Turekian KK, Wedepohl KH. Distribution of the elements in some major units of the Earth's crust. Geological Society of America Bulletin, 1961; 72(2):175–192.
10. Energy Information Administration. Residential Energy Consumption Survey. Washington, DC: U.S. Department of Energy, 2009.
11. ICF International. Assessment of New York City Natural Gas Market Fundamentals and Life Cycle Fuel Emissions. Fairfax, VA. 2012. Available at: http://www.nyc.gov/html/om/pdf/2012/icf_natural_gas_study.pdf.
12. Cusick M. Does Pennsylvania's shale gas have too much radon in it? StateImpact, 2013. Available at: http://stateimpact.npr.org/pennsylvania/2013/05/15/does-pennsylvanias-shale-gas-have-too-much-radon-in-it/.
13. Stukane E. Spectra pipeline radon fear starting to catch fire. Villager, 2013. Available at: http://thevillager.com/2013/05/23/spectra-pipeline-radon-fear-starting-to-catch-fire/.
14. Johnson RH. FERC denies Marcellus Shale natural gas radon lung cancer risk claim. Energy Newsletter, 2012. Available at: http://www.kslaw.com/library/newsletters/EnergyNewsletter/2012/November/article6.html.
15. New York State Assembly. AN ACT to amend the public health law and the public service law, in relation to the protection of public health from exposure to radon in natural gas. In 2013–2014 Bill No. A06863B. Regular Sessions of New York State Assembly, 2013.
16. U.S. Environmental Protection Agency. EPA Assessment of Risks from Radon in Homes; Office of Radiation and Indoor Air. Washington, DC: U.S. Environmental Protection Agency, 2003.
17. Nero AV, Nazaroff WW. Charaterising the source of radon indoors. Radiation Protection Dosimetry, 1984; 7(1–4):23–39.
18. Ayotte JD, Gronberg JAM, Apodaca LE. Trace Elements and Radon in Groundwater Across the United States, 1992–2003. Reston, VA: U.S. Geological Survey, 2011.
19. National Research Council. Health Risks of Exposure to Radon: BEIR VI. Washington, DC: National Academy Press, 1999.
20. International Agency for Research on Cancer. Man-Made Mineral Fibres and Radon. Lyon, France: World Health Organization, 1988.
21. Turner MC, Krewski D, Chen Y, Pope CA, Gapstur S, Thun MJ. Radon and lung cancer in the American Cancer Society cohort. Cancer Epidemiology, Biomarkers & Prevention, 2011; 20(3):438–448.
22. Bogen K, Cullen J. Residential radon in U.S. counties V lung cancer in women who predominantly never smoked. Environmental Geochemistry and Health, 2002; 24(3):229–247.
23. Bogen KT. Mechanistic model predicts a U-shaped relation of radon exposure to lung cancer risk reflected in combined occupational and US residential data. Human & Experimental Toxicology, 1998; 17(12):691–696.
24. Bogen KT. Biologically based prediction of empirical nonlinearity in lung cancer risk vs. residential/occupational radon exposure. Human and Ecological Risk Assessment, 2001; 7(4):811–827.
25. Lehrer S, Rosenzweig KE. Lung cancer hormesis in high impact states where nuclear testing occurred. Clinical Lung Cancer, 2015; 16(2):152–155.
26. Scott BR. Residential radon appears to prevent lung cancer. Dose-Response, 2011; 9(4):444–464.
27. Thompson RE. Epidemiological evidence for possible radiation hormesis from radon exposure: A case-control study conducted in Worcester, MA. Dose-Response, 2011; 9(1):59–75.
28. U.S. Environmental Protection Agency. Why is radon the public health risk that it is? Available at: http://www.epa.gov/radon/aboutus.html, Accessed September 4, 2014.

29. Krewski D, Lubin JH, Zielinski JM, Alavanja M, Catalan VS, Field RW, Klotz JB, Letourneau E G, Lynch CF, Lyon JI, Sandler DP, Schoenberg JB, Steck DJ, Stolwijk JA, Weinberg C, Wilcox HB. Residential radon and risk of lung cancer: A combined analysis of 7 North American case-control studies. Epidemiology, 2005; 16(2):137–145.
30. Krewski D, Lubin JH, Zielinski JM, Alavanja M, Catalan VS, Field RW, Klotz JB, Letourneau E G, Lynch CF, Lyon JL, Sandler DP, Schoenberg JB, Steck DJ, Stolwijk JA, Weinberg C, Wilcox HB. A combined analysis of North American case-control studies of residential radon and lung cancer. Journal of Toxicology and Environmental Health: Part A, 2006; 69(7):533–597.
31. Marcinowski F, Lucas RM, Yeager WM. National and regional distributions of airborne radon concentrations in U.S. homes. Health Physics, 1994; 66(6):699–706.
32. Gogolak CV. Review of 222-Rn in Natural Gas Produced from Unconventional Sources. New York: U.S. Department of Energy, 1980.
33. Rowan EL, Kraemer TF. Radon-222 Content of Natural Gas Samples from Upper and Middle Devonian Sandstone and Shale Reservoirs in Pennsylvania: Preliminary Data. Reston, VA: U.S. Geological Survey, 2012.
34. Perma-Fix Environmental Services. Technologically enhanced naturally occurring radioactive materials (TENORM) study report. Harrisburg, PA, 2015. Available at: http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-105822/PA-DEP-TENORM-Study_Report_Rev._0_01-15-2015.pdf.
35. Wilkins BT. The Assessment of Radon and its Daughters in North Sea Gas Used in the United Kingdom. UK: National Radiological Protection Board, 1977.
36. Dixon DW. Radon exposures from the use of natural gas in buildings. Radiation Protection Dosimetry, 2001; 97(3):259–264.
37. Wojcik M. Long-term measurements of Rn and short-lived Rn daughter concentrations in natural gas from distribution line. Health Physics, 1989; 57(6):989–991.
38. Netten CV, Kan K, Anderson J, Morley D. Radon-222 and gamma ray levels associated with the collection, transmission, and utilization of natural gas. American Industrial Hygiene Association Journal, 1998; 59:622–628.
39. Harris KJ. Letter order granting Texas Eastern Transmission, LP's *et al* 5/17/13 request to commence construction re the Final Notice to Proceed for the New Jersey-New York Expansion Project under CP11-56. In Federal Energy Regulatory Commission (ed), 2013. Available at: http://investor.conedison.com/phoenix.zhtml?c=61493&p=irol-newsArticle&id=1375237.
40. Sterling TD, Kobayashi D. Use of gas ranges for cooking and heating in urban dwellings. Journal of Air Pollution Control Association, 1981; 31(2):162–165.
41. Zota A, Adamkiewicz G, Levy JI, Spengler JD. Ventilation in public housing: Implications for indoor nitrogen dioxide concentrations. Indoor Air, 2005; 15(6):393–401.
42. Centers for Disease Control and Prevention. Use of unvented residential heating appliances—United States, 1988–1994. MMWR, 1997; 1221–1224. Available at: http://www.cdc.gov/mmwr/preview/mmwrhtml/00050535.htm.
43. Delp WW, Singer BC. Performance assessment of U.S. residential cooking exhaust hoods. Environment Science & Technology, 2012; 46(11):6167–6173.
44. American Society of Heating Refrigerating and Air Conditioning Engineers. ASHRAE position document on unvented combustion devices and indoor air quality. Atlanta, GA, 2012; p. 15. Available at: https://www.ashrae.org/File%20Library/docLib/About%20Us/PositionDocuments/Position-Document—Unvented-Combustion-Devices-and-IAQ-Position-Document.pdf.
45. Hassan NM, Ghosh TK, Hines AL, Loyalk SK. Adsorption of radon and water vapor on commercial activated carbons. Separation Science and Technology, 2006; 30(4):565–583.
46. Hearth Patio & Barbecue Association. State of the Hearth Industry Report. Arlington, VA, 2011. Available at: http://www.hpba.org/media/hearth-industry-prs/2011-state-of-the-hearth-industry-report.
47. 10 CFR §430.32 and Chapter 11 of the accompanying Technical Supporting Documentation.
48. Traynor GW, Girman JR, Apte MG, Dillworth JF, White PD. Indoor air pollution due to emission from unvented gas-fired space heaters. JAPCA, 1985; 35(3):231–237.
49. Traynor GW, Apte MG, Dillworth JF, Hollowell CD, Sterling EM. The effects of ventilation on residential air pollution due to emissions from a gas-fired range. Environment International, 1982; 8:447–452.
50. Nagda NL, Koontz MD, Billick IH. Effect of unvented combustion appliances on air exchange among indoor spaces. 6th Air Infiltration Centre Conference, Netherlands, 1985.
51. Jenkins PH, Burkhart JF, Camley RE. Errors in measurements of ^{222}Rn in methane and carbon dioxide using scintillation cells calibrated for ^{222}Rn in air. Health Physics, 2014; 1063:397–404.
52. Kimmel K. Techniques for Natural Gas Sampling. The Woodlands, TX: YZ Systems, Inc., 2011. Available at: http://asgmt.com/wp-content/uploads/pdf-docs/2011/1/Q15.pdf.
53. U.S. Energy Information Administration. Consumption by End Use, July 31, 2013 ed. Washington DC: U.S. Department of Energy, 2013.
54. Pennsylvania Department of Environmental Protection. Jan – Jun 2013 (Unconventional Wells). Harrisburg, PA: Commonwealth of Pennsylvania. Available at: https://www.paoilandgasreporting.state.pa.us/publicreports/Modules/DataExports/DataExports.aspx, Accessed September 5, 2013.
55. Ferral K. Pa. shale gas production eclipsed 4 trillion cubic feet in 2014. Tribune Rev., 2015. Available at: http://triblive.com/business/headlines/7748482-74/based-wells-gas#ixzz3Tqm84kJK.
56. McAllister EW. Pipe Line Rules of Thumb Handbook: A Manual of Quick, Accurate Solutions to Everyday Pipeline Problems, 4th ed. Houston, TX: Gulf Publishing Company, 1998.
57. National Grid Natural Gas FAQs (Frequently Asked Questions). Available at: http://www.ngridenergyworld.com/ngsw/html/kids6.html#q16.
58. Mancino L, Newman C. Who has time to cook? How family resources influence food preparation. Washington, DC, 2007. Available at: http://www.ers.usda.gov/media/198978/err40_1_.pdf.
59. Bureau of Labor Statistics. American time use survey. Washington, DC, 2013. Available at: http://www.bls.gov/tus/tables/a1_2013.pdf.
60. Emmerich SJ, Howard-Reed C, Gupte A. Modeling the IAQ impact of HHI intervention in inner-city housing. National Institute of Standards and Technology, 2005.
61. Francisco PW, Gordon JR. Measured concentrations of combustion gases from the use of unvented gas fireplaces. Indoor Air, 2010; 20(5):370–379.
62. Installation and Maintenance of Gas-Fueled Water and Spacer Heaters in All Portions of Dwellings Used or Occupied for Living Purposes. 1 RCNY §40-39. Available at: http://www.nyc.gov/html/dob/downloads/rules/1_RCNY_40-39.pdf.
63. Requirements for Vent-Free Gas Space Heating Appliances, 10 NYCRR Part 71. New York, 1998. Available at: https://www.health.ny.gov/environmental/indoors/heaters/gas/vent-free/docs/manufacturer_requirements.pdf.

64. Du L, Batterman S, Godwin C, Chin J.-Y, Parker E, Breen M, Brakefield W, Robins T, Lewis T. Air change rates and interzonal flows in residences, and the need for multi-zone models for exposure and health analyses. International Journal of Environmental Research and Public Health, 2012; 9(2):4639–4661.
65. Howard-Reed C, Wallace LA, Ott WR. The effect of opening windows on air change rates in two homes. Journal of the Air & Waste Management Association, 2002; 52(2):147–159.
66. Etheridge D, Sandberg M. Building Ventilation: Theory and Measurement. Chichester and New York: John Wiley & Sons, 1996.
67. Ferro AR, Klepeis NE, Ott WR, Nazaroff WW, Hildemann LM, Switzer P. Effect of interior door position on room-to-room differences in residential pollutant concentrations after short-term releases. Atmospheric Environment, 2009; 43(3):706–714.
68. Breen MS, Schultz BD, Sohn MD, Long T, Langstaff J, Williams R, Isaacs K, Meng QY, Stallings C, Smith L. A review of air exchange rate models for air pollution exposure assessments. Journal of Exposure Science and Environmental Epidemiology, 2013; 24:555–563.
69. Chan WR, Nazaroff WW, Price PN, Sohn MD, Gadgil AJ. Analyzing a database of residential air leakage in the United States. Atmospheric Environment, 2005; 39(19):3445–3455.
70. Fabi V, Andersen RV, Corgnati S, Olesen BW. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. Building and Environment, 2012; 58(0):188–198.
71. Chan WR, Joh J, Sherman MH. Analysis of air leakage measurements of US houses. Energy and Buildings, 2013; 66(0):616–625.
72. Murray DM, Burmaster DE. Residential air exchange rates in the United States: Empirical and estimated parametric distributions by season and climatic region. Risk Analysis, 1995; 15(4):459–465.
73. Centers for Disease Control and Prevention. United States Cancer Statistics, 1999–2009 Cancer Incidence and Mortality Data. Atlanta, GA, 2011.
74. Marr D, Mason M, Mosley R, Liu X. The influence of opening windows and doors on the natural ventilation rate of a residential building. HVAC&R Research, 2012; 18(1–2):195–203.
75. Francisco PW, Gordon JR, Rose WB. Development of a Model of Cycling Unvented Fireplace Use, Buildings XI Conference, Clearwater Beach, FL, 2010.
76. Lobscheid AB, Klepeis NE, Singer BC. Modeling population exposures to pollutants emitted from natural gas cooking burners. Ernest Orlando Lawrence Berkeley National Laboratory, 2011.
77. Gorgen S. Ohio's Utica region now included in EIA's monthly drilling productivity report. Washington, DC: U.S. Energy Information Administration. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=17511.
78. Logue JM, Sherman MH, Walker IS, Singer BC. Energy impacts of envelope tightening and mechanical ventilation for the U.S. residential sector. Energy and Buildings, 2013; 65(0):281–291.